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MATERIAL SELECTION FOR THERMOPLASTIC PARTS

Practical and Advanced Information for Plastics Engineers

Michel Biron

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Amsterdam • Boston • Heidelberg • London • New York • Oxford • Paris
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William Andrew is an imprint of Elsevier

William Andrew is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

ISBN: 978-0-7020-6284-1

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

For information on all William Andrew publications
visit our website at http://store.elsevier.com/

Publisher: Matthew Deans
Acquisition Editor: David Jackson
Editorial Project Manager: Peter Gane
Production Project Manager: Susan Li
Designer: Greg Harris

Typeset by TNQ Books and Journals
www.tnq.co.in

Printed and bound in the United States of America

Preface

Engineers who work in many industrial segments that utilize plastic parts are not plastics experts. According to recent studies, about 60% of plastics failures come from a wrong selection of the used grade. Time-dependent properties, environmental stress cracking (ESC), chemical resistance, notched rupture, thermal degradation, dynamic fatigue, creep, and ultraviolet (UV) resistance are the main issues. The aim of this book is to provide easy-to-understand and easy-to-use tools for a systematic approach of a preliminary material selection. Of course, this solution has the disadvantages of its simplicity and cannot replace the knowledge and experience of plastics specialists.

To ease the work of the reader, innumerable thermoplastics grades (more than 30,000) are sliced into about 300 subfamilies. For each subfamily, about 20 properties are assessed by a minimum and a maximum values coming from a screening of industrial grades. (Of course, all the grades are not examined and it is possible that other data exist.) As for all general books, certain opinions may be unsuitable for some cases and it is almost inevitable that errors and misconceptions have found their way in the mass of data.

The selected subfamilies cannot be directly used and the reader must word deeper on the subject to choose the suitable grade in the selected subfamilies and use the actual data measured on this grade for final computing, designing, economic study, etc. The advice of plastics specialists is irreplaceable, and obviously, prototypes and tests under operating conditions are essential.

This book is only one of the tools aiming to help the preselection of thermoplastic materials for the manufacture of thermoplastics parts. It proposes an overview of the situation, a method of thinking among others for material selection, and property data allowing to lead to a first preselection. Obviously, it cannot cover all cases but it gives some starting points for innovative thinking of the reader to select information relating to his/her own case and to search elsewhere complementary and corroborating information.

Chapter 1 aims helping to define the problem, pointing out the difficulty of a right choice of a defined plastic material taking into account a broad range of interactive parameters linked to the polymer properties, on the one hand, and surrounding stresses and media, on the other hand.

Some thermoplastic features can surprise designers usually working with steels and other metals: the sensitivity to temperature, humidity, creep, chemicals, and viscoelasticity. The final choice results from numerous iterations leading to a subtle balance of technical requirements, economic considerations, environmental issues, and targeted lifetime.

The ins and outs linked to the main interactions between thermoplastics properties (mechanical, physical, aging, sensorial), surrounding parameters (temperature, time, stresses, chemicals, and so on), economics, regulations, green trends, and lifetimes are briefly examined.

A checklist of 125 good questions concludes this chapter.

Chapter 2 makes the reader aware of some specificities of thermoplastics and helps clarify quickly some particular features of the plastics language. Industrial plastics are based on organic macromolecules, which lead to specific features such as viscoelasticity, various levels of crystallinity, time and temperature dependency, various levels of anisotropy, and so on. Apart from elemental composition, molecular weight, chain architecture, glass transition, and supramolecular structure are also of high importance. Industrial grades are upgraded and customized mixtures of polymer(s) and additives having specific roles. Main induced effects of additives include reinforcement thanks to glass and carbon fibers, minerals, and glass beads; improvement of general behavior thanks to impact modifiers, plasticizers, protective agents; optimization of special features thanks to dedicated additives such as fire retardants, electrically or thermally conductive, Antifriction, Magnetic and other additives.

Statistical analyses of some properties of more than 200 marketed thermoplastic grades give a more precise idea of neat and reinforced thermoplastic grades.

Sensory properties (optical properties, touch, scratch resistance, acoustic comfort, odor, taste, fogging) are examined before another burning issue, the dimensional stability linked to thermal expansion, mechanical stresses including residual ones, shrinkage, warpage, water uptake, and releasing of organic additives.

Chapter 3 helps clarify quickly the actual consumption, uses, and costs of thermoplastics including thermoplastic elastomer and bioplastics. After an overview of the global plastics industry (up to 2020), the market shares of the various thermoplastic families, main concerned regions (Asia, Europe, America, BRIC), main application sectors, and importance of the various processing methods are examined.

Plastic costs are studied according to raw material, additive and reinforcement costs, and processing costs. Some good reasons to use thermoplastics and a few examples of success stories are examined.

Two important issues linked to costs and drying up of crude oil are detailed through the modeling of polymer cost and the potential use of bio-sourced plastics.

Finally, a table displays, without any warranty, price index hypotheses for 279 plastics.

Chapter 4 aims to provide tools for using a complementary preselection approach, generally called, for example, design-by-analogy method or something like that. The concept is to search analogies with existing solutions solving an analogous problem. Knowledge can be provided by the designer experience, specialized databases, and all readily available information sources. This chapter is a specialized database providing more than 1500 couples of parts or products and the related used thermoplastic(s). Analogies can concern the product itself, the domain, or the functionalities of more or less similar products being of other domains.

Parts or products come from the 10 top thermoplastic domains, that is to say, packaging; building and civil engineering; automotive and transportation; electrical and electronics; household, entertainment, and office appliances; mechanical engineering; sports and leisure; medical market; furniture and bedding; and agriculture.

Chapter 5 aims to provide some information and examples to avoid some pitfalls leading to project failures. Obviously, it is essential to fairly estimate part requirements and to fairly understand the exact meaning of gathered properties of the used compound to objectively fill the checklist. Difficulties include the selection of the useful mechanical properties: at break, at elastic limit, at yield, after creep or relaxation.

As for many other materials, provided properties are average data when failures are induced by weakest points that must be estimated from statistical results.

Chemical behavior can hide several traps linked to the nature of chemicals, test duration, temperature, and so on without forgetting that ESC can worsen damages.

Plasticization and decrease of insulating properties by ambient moisture are also examined for certain plastics.

Designers must be aware of abrupt evolutions of some properties such as glass transition, yield, knees, frequency-dependent characteristics, leading to some pitfalls linked to modeling and property comparisons, very useful if carefully used but very hazardous in other cases.

Chapters 6–9 aim providing examples of densities, conventional mechanical and thermal properties for numerous subfamilies of thermoplastics including neat grades, alloys, and special versions containing fibers, carbon nanotube, minerals, glass beads, conductive additives, wood plastic composite, flame retardant, etc.

Of course, density (Chapter 6) is of prime importance for weight of parts, costs per volume, and actual weight savings. Density reduction is of a great interest and is briefly examined through structural foam techniques and hollow parts.

For comparison, some property examples of traditional materials are quoted, pointing out the drawbacks of their higher densities.

Chapter 7 warns designers that thermoplastics are not ideal materials obeying to simple physical laws and that testing methods are diverse, leading to published data that can lead to common and important point of lack of understanding or misinterpretation. First of all, it is necessary to fully understand information and make designer's requirements understandable by plastics players.

This chapter provides data examples of usual mechanical properties including tensile strength and strain at yield, tensile, and flexural moduli. Compressive properties, uniaxial compression, bulk compression, shear properties, and elongation work are also briefly examined.

Impact behavior (notched and unnotched Charpy and Izod) and surface hardness (Rockwell M & R, Shore D) are also examined in detail with their numerous nonequivalent methods leading to difficult and hazardous comparisons.

Chapter 8 points out the temperature-dependent properties of thermoplastics with special behaviors at high and low temperatures. Plastics can be softened at temperatures as low as 40 °C and can be brittle at subzero temperatures or even at a few degrees above room temperature.

Several tables display numerous examples of glass transition temperatures, heat deflection temperatures (HDT or DTUL A and B), general assessments concerning continuous use temperatures for unstressed materials. More limited examples relate to UL relative temperature index and Vicat softening temperatures.

Low-temperature behavior is featured through expected minimum service temperatures (more than 200 examples). More limited examples relate to Izod and Charpy impact tests at low temperatures and brittleness.

Chapter 9 is devoted to dimensional stability negatively affected by the viscoelastic behavior, low modulus, high coefficient of thermal expansion (CTLE), water and moisture uptake, possible release of ingredient, shrinkage, and warpage. Data examples of usual dimensional properties include CTLE, mold shrinkage, water uptake. Some effects of the structure, the morphology, certain additives, orientation, releasing of ingredients, relaxation, hysteresis, and so on are also briefly examined.

Sometimes it is forgotten that part sizes increase with temperature, which can block a device and can induce high stresses if the part has not a sufficient space to expand. In the same way, cold temperatures reduce part sizes.

Chapter 10 points out the specific time and temperature dependency of polymer properties, atypical Poisson's ratios, and particular tribological behaviors. This chapter provides the basics and many examples (21 tables) for those advanced properties.

Immediate retentions of strength and modulus are extensively examined for temperatures above room temperature. Some examples relate to elongation at break, tensile strength, and modulus at subzero temperatures.

Basic features of long-term resistance to heat aging and conventional accelerated aging tests in air are examined with numerous examples of property retentions after aging. Examples of creep, stress relaxation, and dynamic fatigue illustrate the time dependency of mechanical properties.

Tribological behavior is examined through coefficients of friction, PV factors, wear factors, Taber's abrasion for tribological, and general purpose thermoplastics.

Chapter 11 can surprise designers usually working with steels and other metals or glass. This chapter aims to draw attention to some aspects of the fire behavior of thermoplastics and requirements. Fire regulation is overabundant and always evolving: the designer has the responsibility to search elsewhere specific and general rules applicable to its own problem.

Oxygen indexes give a rough and sometimes misleading idea of this fire sensitivity because, in the end, all thermoplastics can burn with usual fire damages and, in addition, smoke emission of potential asphyxiating and corrosive gases.

Flame-retardant (FR) solutions, which prevent a fire or limit its development, are examined as well as actual trends related to halogen-free FR suppressing emission of hydrogen halides, which favors a reduction of toxicity and corrosivity. Increasing flame, smoke, and toxicity requirements aim at reducing smoke opacity, toxicity, and corrosivity. Properties of FR and general purpose grades (28 examples) are compared when possible.

Chapter 12 deals with the most common applications of thermoplastics that need electrical insulation but the most demanding uses relate to more or less conductive plastics. This chapter aims helping to define electrical requirements that must be selected among the most common electrical properties: Volume resistivity, permittivity or dielectric constant, loss or dissipation factor, dielectric strength, arc resistance.

Electrostatic dissipative compounds are compared to general purpose grades based on the same polymer for surface or bulk resistivity or resistance.

Some examples briefly highlight the effects of frequency, temperature, and moisture on the main electrical properties.

At the end, a specific section gives information concerning formulation to make thermoplastics conductive.

Chapter 13 is about sensory properties that are inevitable requirements for many applications. This chapter gives experimental data and ways of thinking for optical properties, aesthetics, touch, odor, noise vibration harshness (NVH), and taste transfer. Esthetics is a complex and subjective characteristic depending on the shape, color, gloss, clarity or opacity, surface quality, shaping defects, aging, and more generally people's opinion. Degradation of esthetics during service life can shorten the lifetime as for the engineering properties. Grade selection, designing, modeling, simulation, prototyping, processing enhancement, coloration, decoration, and overmolding contribute to obtain a satisfying aesthetics and touch.

Odor, taste transfer, and NVH are other issues more or less important according to the targeted application.

Chapter 14 defines thermoplastics (as other materials) are sensitive to chemicals, UV, light, and weathering. The goal of this chapter is to provide ways of thinking and practical information helping designers to do a basic selection and a primary rejection of thermoplastic families from this point of view.

Chemical behavior of more than 30 thermoplastics regarding immersion of unstressed samples in more than 60 chemicals representative of 14 chemical functions are overviewed (hydrocarbons, oils and fuels, inorganic acids, organic acids, bases, amines, alcohols, aldehydes, ketones, esters, ethers, phenols, chlorinated hydrocarbons, oxidants).

Basics of ESC are examined and some assessments are quoted for the main thermoplastics.

Polymers do not rust but as other organic materials are sensitive to natural or artificial UV radiations, light, and some are also sensitive to moisture and hydrolysis. After a review of the basics, assessments relating to weathering concern more than 40 thermoplastics from commodities up to high-tech resins through alloys and thermoplastic elastomers.

Chapter 15 is about ecodesign, life-cycle assessment (LCA), environment, sustainability, pollution, and renewability that are rising concerns for designers, needing innovative thinking. Plastic sustainability is based on native resource preservation, renewable sources, energy saving, pollution and carbon footprint reduction, recycling, end cost optimization, and so on.

Well-established routes relate to long-lasting parts, design optimization by modeling, weight and cost savings, and smart coatings. Repairing and use of recycled plastics save money, energy, resources, and pollution but must satisfy technical requirements and comply with specific regulations.

Replacement of fossil polymers by bioplastics includes thermoplastic starch, polylactic acid, cellulosics, aliphatic polyesters (polyhydroxyalkanoate, polyhydroxybutyrate), liquid wood, proprietary alloys, biocomposites.

Conventional polymers synthesized from biosourced chemical bricks offer more innovative ways including, i.e., polyolefins, polyamides, thermoplastic polyesters, polyurethanes, and acrylics. Reinforcement with natural fibers and additives from renewable resources contribute to higher biocontents.

Thermoplastics versatility allows energy savings during the use phase, which is pointed out through examples related to energy-efficient house, car industry, and packaging.

Main environmental indicators and benchmarks relating to LCA are reviewed in relation with the impacts of polymer production, fiber production, polymer processing, end-product manufacturing, and recycling.

Once again, note this book is not an encyclopedia for a definitive selection of thermoplastics but is only one of the tools aiming to help the preselection of thermoplastics. Generally speaking, a single book cannot cover all situations and cannot replace the intelligence of a team of designers and specialists of plastic. Team is the ultimate decision maker and is solely responsible for the final selection (Figures 1 and 2).

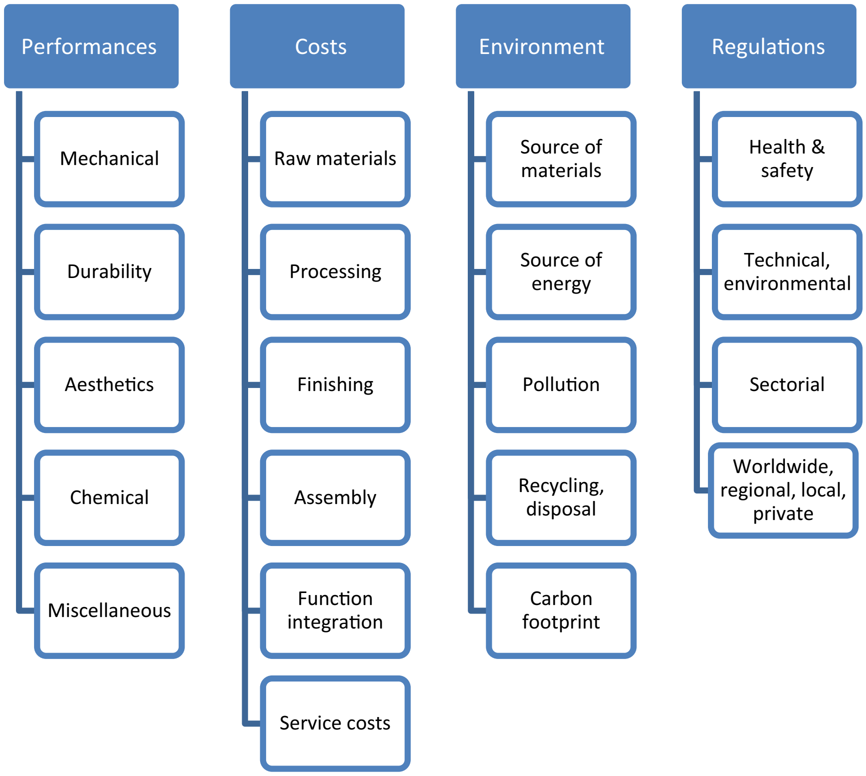

Figure 1 Conclusion: Main requirements concerning plastics solutions.

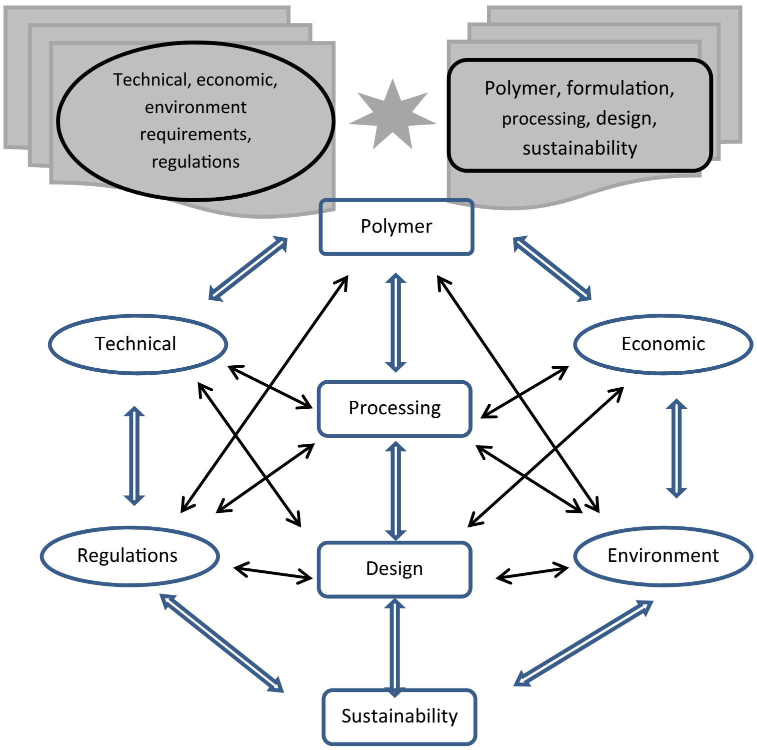

Figure 2 Conclusion: Main possible interactions between parameters of production and requirements.

Disclaimer

This book is not an encyclopedia for a definitive selection of thermoplastics but gathers some property data and suggests a method among others for the material selection for thermoplastics parts. Obviously, it cannot cover all cases and it is the responsibility of the reader to select information relating to his/her own case and to search elsewhere complementary and corroborating information. This book is only one of the tools aiming to help the preselection of thermoplastics. The reader is the only responsible of his/her selection and, of course, he/she must absolutely cooperate with polymer specialists for the selection of the definitive solution system.

All the information contained in this book, collected from reliable documentation and verified as far as possible, is aimed at experienced professional readers. We cannot accept responsibility for the accuracy, availability, timeliness, content, or completeness of data, processing methods, machinery, information and ideas.

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Acronyms and Abbreviations

5V	UL Fire Rating
AAGR	Average annual growth rate
ABS	Acrylonitrile–butadiene–styrene
ACM-V	Vulcanized Acrylate Rubber
ACS	Acrylonitrile chlorinated Polyethylene styrene
AES or AEPDS	Acrylonitrile EPDM styrene
AMC	Alkyd molding compound
ArF or AF	Aramid fiber
ASA	Acrylonitrile styrene acrylate
ASTM	American Society for Testing and Materials
ATBC	Acetyl tributyl citrate
ATH	Aluminum trihydrate
BF	Boron fiber
BMC	Bulk molding compound
BMI	Bismaleimide
BOD	Biochemical oxygen demand
BOPLA	Biaxially oriented polylactic acid
BOPP	Biaxially oriented polypropylene
BRIC	Brazil–Russia–India–China
CA	Cellulose acetate
CAB	Cellulose acetobutyrate
CAD	Computer-aided design
CAGR	Compound annual growth rate
CBT	Cyclic Polybutadiene terephthalate
CE	Cyanate ester
CF	Carbon fiber
CFC	Chlorofluorocarbon
CFRP	Carbon fiber-reinforced plastic
CFRTP	Carbon fiber-reinforced thermoPlastic
CIC	Continuous impregnated compound
CM or CPE	Chlorinated polyEthylene
CNT	Carbon nanotube
COC or COP	Cyclic olefin copolymers or Cyclic olefin polymers
COD	Chemical oxygen demand
Conc.	Concentrated Solution
COP or COC	Cyclic olefin polymers or Cyclic olefin copolymers
COPE or TPEE	Copolyester TPE
CP	Cellulose propionate
CPE or CM	Chlorinated polyEthylene
CPVC or PVC-C	Chlorinated PVC
CS	Compression set
CTI	Comparative tracking index

CTLE	Coefficient of thermal linear expansion
CUT	Continuous use temperature Under Unstressed State
Cy	Polycyanate
DAP	DiAllyl phthalate
DCPD	Poly(Dicyclopentadiene)
DMC	Dough molding compound
DMTA	Dynamic mechanical thermal analysis
DRIV	Direct resin injection and venting
DSC	Differential scanning calorimeter
DTA	Differential thermal analysis
DWNT	Double-wall nanotubes
EB	Elongation at break
EBA, EGMA, EMAH, EEA, EAA	Ethylene-acid and ethylene-ester copolymers, e.g., Ethylene-butylacrylate
ECO	Prefix concerning ECOlogy or the environment, i.e., Eco-profile
ECTFE	Ethylene monochlorotrifluoroethylene
EE, E&E	Electrical and electronics
EMA	Ethylene-methacrylate ionomers
EMI	Electromagnetic interference
EP	Epoxy
EPA	Environmental Protection Agency
EPDM rubber	Terpolymer ethylene, propylene, diene
EPS	Expandable (or Expanded) polystyrene
ESBO	Epoxidized soybean oil
ESC	Environmental stress cracking
ESD	Electrostatic discharge
ETFE	Ethylene-tetrafluoroethylene
EU	European Union
EVA, E/VAC, EVAC, VAE, EVM	Ethylene-vinylacetate copolymers
EVOH	Ethylene-vinyl alcohol copolymers
F-PVC	Flexible PVC
FDA	Food and Drug Administration
FEP	Fluorinated ethylene propylene
FIM	Film insert molding
FR	Fire retardant
GB	Glass bead
GF	Glass fiber
GFRP	Glass fiber-reinforced plastic
GFRTP	Glass fiber-reinforced thermoplastic
GHG	Greenhouse gas
GMT	Glass mat thermoplastic
GWI	Glow wire ignition
GWP	Global warming potential
HB	UL fire rating
HDPE or PE HD	High-density polyethylene
HDT	Heat deflection temperature
HFFR	Halogen-free fire-retardant
HIPS	High impact PS
HPGF	High-performance short glass fiber-reinforced polypropylene
HSCT	High speed civil transport (aircraft)
HTPC	Hybrid thermoplastic composite
HTV	High temperature vulcanization

HVAC	Heating, ventilation, and air-conditioning
HWI	Hot wire ignition
ICP	Inherently conductive polymer
IDP	Inherently dissipative polymer
ILSS	Interlaminar shear strength
IMC	In-mold coating
IMD	In-mold decoration
IML	In-mold labeling
IPN	Interpenetrating polymer network
IRHD	International rubber hardness
IRM	International referee material
ISO	International standardization organization
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCP	Liquid crystal polymer
LCTC	Low-cost tooling for composites
LDPE or PE LD	Low-density polyethylene
LED	Light-emitting diode
LEFM	Linear elastic fracture mechanics
LFRT	Long fiber-reinforced thermoplastic
LFT	Long fiber-reinforced thermoplastic
LGF	Long glass fiber
LIM	Liquid injection molding
LLDPE	Linear low-density polyethylene
LOI	Limiting oxygen index
LRI	Liquid resin infusion
LRTM	Light RTM
LSR	Liquid silicone rubber
LWRT	Lightweight-reinforced thermoplastic
MABS	Methylmethacrylate–acrylonitrile–butadiene–styrene
MAH	Maleic anhydride
MBS	Methyl methacrylate–butadiene–styrene
MDPE	Medium-density polyethylene
MF	Melamine
MFI	Melt flow index
MPR	Melt processable rubber (TPE)
MVTR	Moisture vapor transmission rate
MWNT	Multiwalled carbon nanotubes
NB	No break
NF	Natural fiber
NOx	Nitrous oxides
NVH	Noise vibration harshness
O&M	Organization and methods department
OIT	Oxygen induction time
OLED	Organic light-emitting diode
OPET	Oriented PET
OPP	Oriented PP
OPS	Oriented PS
OTR	Oxygen transmission rate
PA	Polyamide
PA-T	Transparent amorphous polyamide

PAA	Polyarylamide
PAI	Polyamide imide
PAEK	Polyaryletherketone
PAN	Polyacrylonitrile
PAS	Polyarylsulfone
PB	Polybutene-1 or Polybutylene-1
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PBI	Polybenzimidazole
PBO	Polyphenylenebenzooxazole
PBT or PBTP	Polybutyleneterephthalate
PC	Polycarbonate
PCB	Printed circuit board
PC-HT	Polycarbonate—high temperature
PCL	Polycaprolactone
PCT	Polycyclohexylene-dimethylene terephthalate
PCTA	Terephthalate/isophthalate
PCTFE	Polychlorotrifluoroethylene
PCTG	Polycyclohexylene-dimethylenediol/ethyleneglycol terephthalate
PDMS	Polydimethylsiloxane
PE	Polyethylene
PEAA	Polyethylene acrylic acid
PEAR	Polyetheramide resin
PEBA	Polyether block amide
PECVD	Plasma-enhanced chemical vapor deposition
PEEK	Polyetherether ketone
PEF	Polyethylene furanoate
PEG	Polyethylene glycol
PEI	Polyetherimide
PEK	Polyetherketone
PEKK	Polyetherketoneketone
PEN	Polyethylene naphthalenedicarboxylate
PES or PESU	Polyethersulfone
PET or PETP	Polyethylene terephthalate
PETG	Polyethylene glycol modified
PETI	Phenylethynyl with imide terminations
PEX	Cross-linked polyethylene
PF	Phenolic resin
PF1Ax	PF general purpose, ammonia-free
PF2Cx	PF heat-resistant, glass fiber-reinforced
PF2Dx	PF impact-resistant, cotton-filled
PF2E1	PF mica-filled
PFA	Perfluoroalkoxy
PGA	Polyglycolic acid
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PHBH	Polyhydroxybutyrate-hexanoate
PHBV	Polyhydroxybutyrate-co-hydroxyvalerate
PHV	Polyhydroxyvalerate
PI	Polyimide
PIR	Polyisocyanurate

PK	Polyketone
PLA	Polylactic acid
PMI	Polymethacrylimide
PMMA	Poly methylmethacrylate
PMP	Polymethylpentene
PO	Polyolefin
POE	Polyolefin elastomer
POM	Polyoxymethylene or Polyacetal
POP	Polyolefin plastomer
POSS	Polyhedral oligomeric silsesquioxane
PP	Polypropylene
PPA	Polyphthalamide
PPE	Polyphenylene ether
PP/EPDM	Unvulcanized EPDM blended with polypropylene or block copolymerized PP-EPDM (reactor TPO)—(TPE) (TPO)
PP/EPDM-V	Vulcanized EPDM dispersed in polypropylene (TPE) (TPV)
PP/IIR-V	Vulcanized butyl rubber dispersed in polypropylene (TPE) (TPV)
PP/NBR-V	Vulcanized nitrile rubber dispersed in polypropylene (TPE) (TPV)
PPO	Polyphenylene oxide
PPS	Polyphenylene sulfide
PPSU	Polyphenylenesulfone
PPT or PTMT or PTT	Polypropylene terephthalate
Prepreg	Preimpregnated
PS	Polystyrene
PSU	Polysulfone
PS-X or XPS	Cross-linked polystyrene
PTFE	Polytetrafluoroethylene
PTMT or PBT	Polytetramethylene terephthalate or Polybutyleneterephthalate
PTMT or PPT or PTT	Poly(trimethylene terephthalate)
PTT	Polytrimethylene terephthalate
PUR	Polyurethane
PV	Pressure*velocity
PVA or PVAL or PVOH	Polyvinyl alcohol
PVAC	Polyvinyl acetate
PVAL or PVA or PVOH	Polyvinyl alcohol
PVB	Polyvinyl butyrate
PVC	Polyvinyl chloride
PVDC	Polyvinylidene chloride
PVC-C or CPVC	Chlorinated PVC
PVC-U	Unplasticized PVC
PVDF	Polyvinylidene fluoride
PVF	Polyvinyl fluoride
PVOH or PVAL or PVA	Polyvinyl alcohol
r	Recycled, i.e., rPET, rPP
REACH	Registration Evaluation Authorization and Restriction of CHemicals
RF	Radio frequency
RFI	Resin film impregnation
RH	Relative humidity or hygrometry
RIM	Reaction injection molding
RIRM	Resin injection recirculation molding
RoHS	Restriction of hazardous substances

RP	Reinforced plastic
RRIM	Reinforced reaction injection molding
RT	Room temperature
RTI	Relative thermal index
RTM	Resin transfer molding
RTP	Reinforced thermoplastic
RTV	Room temperature vulcanization
SAN	Styrene acrylonitrile
SAP	Super absorbent polymer
SATUR	Saturated solution
SB	Styrene butadiene
SBC	Styrenic block copolymer
SBS	Styrene–butadiene–styrene (TPE)
SCRIMP	Seeman's composite resin infusion molding process
SEBS	Styrene ethylene/butylene styrene (TPE)
SEPS	Styrene ethylene/propylene styrene (TPE)
SFRT	Short fiber-reinforced thermoplastic
SGF	Short glass fiber
Si	Silicium
Si	Silicone
SiOx	Silicon oxide
SIS	Styrene isoprene styrene (TPE)
SMA	Styrene maleic anhydride
SMC	Sheet molding compound
SMMA	Styrene-methyl methacrylate
SN curve	Plot of stress or strain (S) leading to failure after N cycles of repeated loading
SOL	Solution
SP-polyimides	Condensation polyimides
SPC	Statistical process control
SPDF	Super plastic diaphragm forming
SR	Self-reinforced
SRRIM	Structural (reinforced) resin injection molding
SWNT	Single-walled carbon nanotubes
TAC	Triallyl cyanurate
TDI	Toluene-2,4-disocyanate
TFE	Tetrafluoroethylene
T_g	Glass transition temperature
TGA	Thermogravimetric analysis
TGV	High-speed train
TMC	Thick molding compound
toe	Ton of oil equivalent
TP	Thermoplastic
TPE	Thermoplastic elastomer
TPE/PVC	PVC-based TPE, alloys of PVC and rubber (TPE) (TPO or TPV)
TPEE or COPE	Thermoplastic elastomer ester
TPI	Thermoplastic imide
TPO	Thermoplastic olefin
TPR	Thermoplastic rubber
TPS	Thermoplastic styrenic
TP/Si-V	TPV of a vulcanized silicone rubber dispersed in a thermoplastic phase
TPU	Thermoplastic polyurethane

TPV	Thermoplastic vulcanizate
TR	Temperature-retraction procedure
TS	Tensile strength
UD	Unidirectional composite
UF	Urea-formaldehyde
UHMWPE or PE-UHMW	Ultrahigh molecular weight PE
UL	Underwriters laboratories
Unkn.	Unknown
UP	Unsaturated polyester
USB	United Soybean Board
UV	Ultraviolet
V0 to V2	UL fire rating
VAE	Ethylene-vinylacetate copolymers
VARI	Vacuum-assisted resin injection
VARTM	Vacuum-assisted RTM
VE	Vinylester
VGCNF	Vapor-grown carbon nanofibers
VIP	Vacuum infusion process
VOC	Volatile organic compounds
VST	Vicat softening temperature
WPC	Wood plastic composite
XLPE	Cross-linked LDPE
XPE or PEX	Cross-linked polyethylene
XPS or PS-X	Cross-linked polystyrene
ZMC	A highly automated process using molding compounds

1 Thermoplastic Material Selection: Some Ways of Thinking for a Systematic Approach

OUTLINE

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00001-5

According to recent studies, about 60% of plastics failures come from a wrong selection of the used plastic grade. That points out the difficulty of a right choice of a defined plastic material taking into account a broad range of interactive parameters as briefly displayed in Figure 1.1.

In addition to general design rules, plastics parts must obey specific plastics rules related to the geometry of the part, technical requirements, esthetics and other sensorial properties, economics, regulations, health and safety requirements, and "green" factors.

Some rules can surprise designers usually working with steels and other metals: the sensitivity to environment temperatures, humidity, creep, chemicals, and viscoelasticity. The final choice results from numerous iterations leading to a subtle balance of technical requirements, economic considerations, and targeted lifetime.

The remainder of the book deals with major material issues and does not take into account particular cases and other facets of designing such as part drawing, mold design, molding process, etc.

1.1 Specific Plastics Design Issues: Some Ins and Outs among Others

This chapter targets helping the designer to think about some tracks allowing to build efficient and realistic specifications. It is not possible to cover all cases and it is the responsibility of the reader to choose the suitable tracks and to add specific constraints related to his own problem.

1.1.1 Overview

In addition to general design rules, plastics part design must obey specific rules taking into account (see Figure 1.2) specific advantages and disadvantages of thermoplastics, mainly viscoelastic behavior, sensitivity to heat and low temperatures, aging behavior, chemical resistance…

Of course, regulations, safety requirements, and specific and general standards applied in the various countries to the manufacture, application, and disposal of plastics products must be fulfilled.

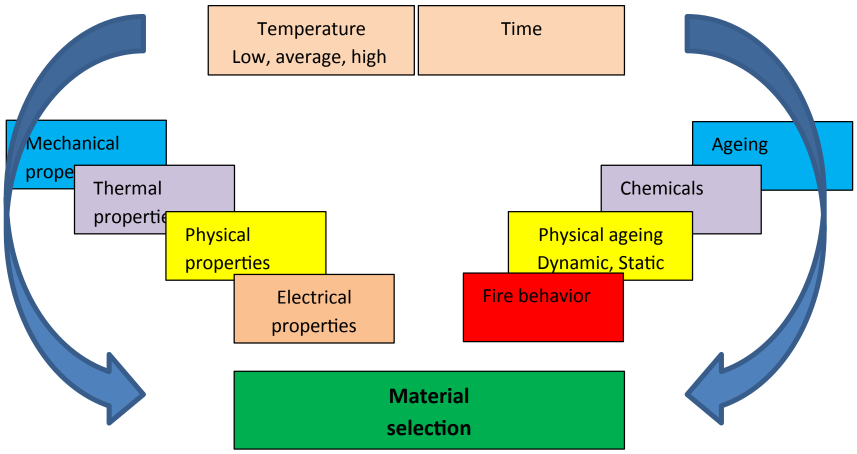


Figure 1.1 Diagrammatic material selection process.

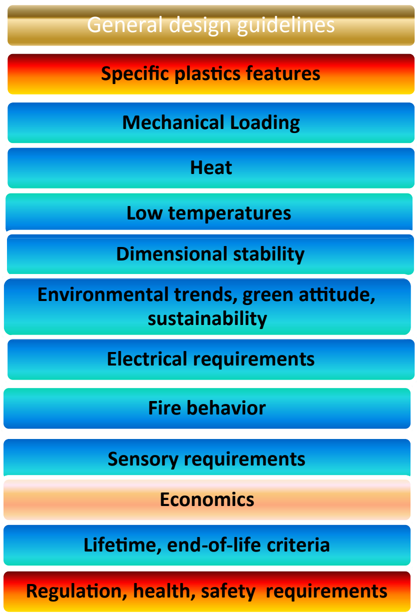


Figure 1.2 Specific plastics design rules.

An often neglected point is the pollution of the near environment by the plastic parts desorbing low-molecular-weight polymers or additives.

Of course, economic features are of prime importance as plastics are often used to reduce cost of devices usually made of metals or other traditional materials.

Last but not least, green trends are growing fast in the plastics area.

1.1.2 *Mechanical Loading: Some Ins and Outs*

Most likely, loading is the most common constraint with temperature. Uniaxial loading is the most studied.

Table 1.1 Statistical Analysis of Main Tensile Properties of About 500 Thermoplastic Grades

	Yield Strength, MPa	Strain @ Yield, %	Tensile Modulus, GPa
Median	70	3	3.55
Minimum	2	0.3	0.001
Maximum	323	75	37
Samples	492	402	552

Multiaxial loadings are rarely treated in the literature; very special tests have to be conducted for their study. Remember that bulk modulus is several times higher than uniaxial modulus.

Note that mechanical loading can be involuntary, resulting from residual stresses induced by the manufacturing process.

Formerly, we remarked that actual mechanical behavior is not an intrinsic property but depends on numerous parameters including, among others, the shape of the part, the processing conditions, and the general historical past of the part.

To provide a general rough idea of thermoplastics properties, Table 1.1 displays statistical analysis of tensile properties for about 500 grades including commodities, engineering, and high-performing thermoplastics.

Note that yield strength and tensile modulus of commodity thermoplastics are lower than these medians and consequently, results for actual molded commodity thermoplastics are also lower.

Mechanical behavior is time- and temperature-dependent (see Figure 1.3) resulting in the need to

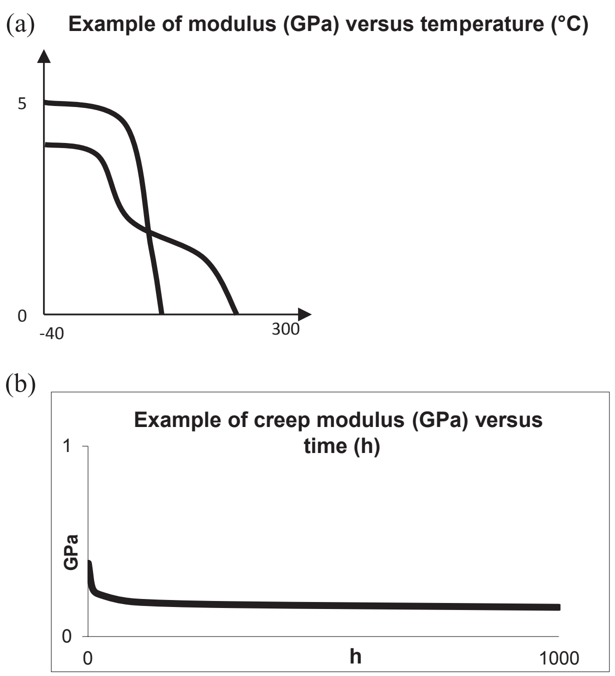


Figure 1.3 Examples of modulus variations versus (a) temperature or (b) time for two thermoplastics.

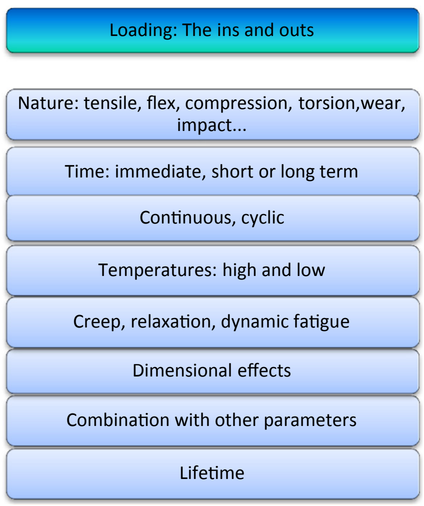


Figure 1.4 Loading: ins and outs.

simultaneously consider the three-pillar system: load–time–temperature.

Figure 1.4 displays the main ins and outs related to mechanical loading.

1.1.2.1 Temperature Effect

It can be noticed that even little changes in little temperature lead to significant loading behavior differences. For example, 10 °C or 30 °C is not room temperature for some soft plastics as we can see for the following examples given to provide a rough idea of the significant differences.

- The tensile strength at 30 °C is about 85% of the value at room temperature for a defined soft commodity thermoplastic.
- The tensile strength at 30 °C is about 90% of the value at room temperature for a defined hard commodity thermoplastic.

For other examples, the decrease can be much lower or even negligible.

Low temperatures first lead to an increase in modulus and then to a brittleness of the part.

1.1.2.2 Loading Type Effect

The type of loading is important. For thermoplastics considered in this book, tensile and flexural properties are often more or less similar but compressive or torsional behaviors are different when wear is very atypical. Impact resistance is an often-tested special property.

1.1.2.3 Strain Rate or Time Effect

Designers can be tricked by interpretation of standard data.

First, test pieces have optimized shapes and are manufactured in the best conditions, leading to the highest mechanical properties.

Second, most of the loading tests are short uniaxial loadings being not representative of high-speed loadings, on the one hand, and creep or relaxation, on the other hand.

The following tensile behaviors are only examples given to provide a rough idea of the huge differences. For a given soft commodity thermoplastic, tensile stresses leading to a 1% elongation at room temperature are about:

- 9 MPa according to standard tensile tests
- 7 or 8 MPa according to 1 h creep tests
- 4 MPa according to 100 h creep tests
- 2 MPa according to 50-year creep tests.

For other examples, the decrease can be much lower or even negligible.

1.1.2.4 Impact Behavior

Impact tests measure the absorbed energy during a specified impact of a standard weight striking, at a

Table 1.2 Statistical Analysis of Notched Izod Impact Strength (J/m) for About 450 Thermoplastic Grades

Median	93
Minimum	4
Maximum	Non-break
Samples	448

given speed, a test sample clamped with a suitable system. The hammer can be a falling weight or, more often, a pendulum. In this case, the samples can be smooth or notched. The results depend on the molecular orientation and the degree of crystallization of the material in the sample, its size, the clamping system, the possible notch and its form, the mass, and the strike speed. The values found in the literature, even for instrumented multiaxial impact (ISO 6603–2:2000), can only be used to help choose and do not replace tests on real parts.

The Izod and Charpy impact tests are mostly used. A defined pendulum strikes the specimen sample, notched or unnotched, clamped with a defined device. The absorbed energy is calculated and can be expressed for notched impacts:

- in kJ/m^2: the absorbed energy divided by the specimen area at the notch
- J/m: the absorbed energy divided by the length of the notch, which is also the thickness of the sample.

There is no true correlation between the two methods. The notched impact tests tend to measure the notch sensitivity rather than the real impact strength of the material. It corresponds better to parts with sharp edges, ribs, and so on.

To provide a general rough idea of thermoplastics properties, Table 1.2 displays statistical analysis of notched Izod impact strength for about 450 grades.

1.1.2.5 Hardness

The most usual test methods are:

- Rockwell R, M, and others
- Shore A for soft polymers
- Shore D for hard polymers
- Ball indentation.

Table 1.3 Statistical Analysis of Rockwell M Hardness for About 350 Thermoplastic Grades

Median	50
Minimum	~0
Maximum	125
Samples	352

There are no mathematical correlations between the various methods.

To provide a general rough idea of thermoplastics properties, Table 1.3 displays statistical analysis of Rockwell M hardness for about 350 grades.

1.1.2.6 Dynamic Fatigue

The repeated mechanical loading of a polymer leads to a speedier failure than an instantaneous loading. The Wohler curves (or SN curves) plot the level of stress or strain (S), leading to failure after N cycles of repeated loading. Two basic types of tests coexist at defined stress or at defined strain. Results are very different. Thermoplastics being sensitive to creep, the fatigue tests at defined strain are generally less severe than those at defined stress for comparable original stresses.

The results depend on the stress type and level, the frequency, the surrounding temperature, and the geometry of the sample.

For a pipe made of a commodity soft thermoplastic suitable for 100,000 cycles in defined conditions, load must be reduced by:

5%	for 500,000 cycles
12%	for 1,000,000 cycles
26%	for 5,000,000 cycles
32%	for 10,000,000 cycles

These examples are given to provide a rough idea of the significant differences. Other very different data can be found elsewhere.

1.1.2.7 Dimensional Effects

Obviously, loading modifies the shape of the part according to its nature. For example, a uniaxial tensile stress leads to an elongation in the stress direction and a retraction in the transverse directions. Please note that Poisson's ratios are inferior to 0.5.

1.1.2.8 Combination with Other Parameters

Loading must be reduced in the case of simultaneous exposure to light, UV, water, chemicals, pressure, radiations, etc. For example, for a pipe made of a commodity soft thermoplastic bearing a defined load, service load must be reduced by:

- 20% for water supply
- 50% for natural gas
- 50% for compressed air
- 55% for LPG

1.1.2.9 Lifetime

Lifetime results in a balance between thermoplastic mechanical resistance, service load, temperature, time, creep, relaxation, dynamic stresses, light, UV, water, chemicals, pressure, radiations, etc. Other parameters being unchanged, a loading reduction generally leads to an increase in the lifetime.

1.1.3 Heat: Some Ins and Outs

Formerly, we remarked that thermal behavior is not an intrinsic property but depends on numerous parameters including, among others, the shape of the part, the processing conditions, and the general historical past of the part.

Figure 1.5 displays the main ins and outs related to heat behavior of thermoplastics.

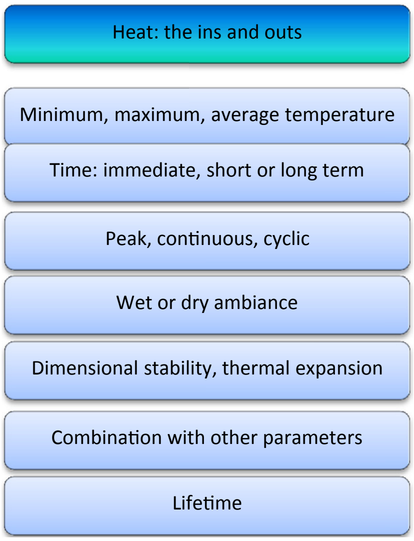


Figure 1.5 Heat: ins and outs.

A temperature rise causes two different phenomena as stated below.

- Immediate physical effects: decay of the modulus and other mechanical and physical properties, physicochemical softening, reversible thermal expansion, and, eventually, irreversible shrinkage and warpage. After a return to the room temperature, modulus and other mechanical properties recover their initial values.
- Long-term effects: irreversible creep and relaxation for stressed parts, irreversible chemical aging, and related degradation of the material with decr ease in mechanical properties, even after a return to the room temperature.

The maximum service temperatures depend on the duration of service and the possible simultaneous application of mechanical stresses or other constraints. For aging studies, temperature can be combined with hum idity, which often leads to more severe degradations.

1.1.3.1 Average Temperature

For little temperature variations, it is possible to use an average material temperature determined with respect to time. The average temperature (T_m) may be considered to be the weighted average of temperatures (T_n) in accordance with the proportion of time (L_m) spent at each temperature.

$$T_m = T_1L_1 + T_2L_2 + \ldots + T_nL_n$$

For broad temperature variations, a more complex procedure must be formulated taking into account a model of the degradation as a function of the temperature. The Arrhenius equation is one of the best-known models for assessing the lifetime of polymers and is commonly used to predict the combined effects of temperature and time. The Arrhenius relationship is

$$K_T = A \exp(-E/RT)$$

where:

K_T is the reaction rate for the process

E is the reaction energy

R is the gas constant

T is the absolute temperature

Other models are also used but generally speaking it must be noticed that a model is an equation giving a result in all cases. In real life, results can be completely different and the part can fail when the model predicts a longer life (or conversely). The user must be aware of the risks.

Conventional heat measurements and arbitrary evaluations include:

- continuous use temperature (CUT)
- Underwriters' Laboratories (UL) temperature index
- heat deflection temperature (HDT)
- Vicat softening temperature (VST)
- accelerated aging.

1.1.3.2 Continuous Use Temperature

The CUT is an arbitrary temperature resulting from general experience and observation. It is the maximum temperature that an unstressed part can withstand for a very long time without failure or loss of function even if there is a significant reduction in the initial properties.

This subjective value is not measurable and is deduced from aging test interpretations and information collected in the technical literature.

To give some idea, CUTs for thermoplastics are in a range from 50 °C up to 400 °C for exceptional families. Please note that samples are unstressed, which is not realistic for numerous applications.

1.1.3.3 UL Temperature Index

The temperature index, derived from long-term oven-aging test programs, is the maximum temperature that causes a 50% decay of the studied characteristics in the very long term. The UL temperature index depends on:

- the tested grade
- the thickness of the tested samples
- the studied characteristics.

Influence of Grade

For two grades of mineral-filled nylon 66, of the same thickness and for the same properties, the UL temperature indices are 65 and 80 °C.

For three grades of epoxy resins, of the same thickness and for the same properties, the UL temperature indices are 160, 170, and 180 °C.

Influence of Thickness

The UL temperature indices increase with the thickness of the samples. For example, for a defined polymer grade, the UL temperature indices are:

- 200 °C for a 2.1 mm thickness
- 50 °C for a 0.4 mm thickness.

Influence of the Characteristics Studied

There are three categories of UL temperature indices:

- electrical properties only
- electrical and mechanical properties, impact excluded
- electrical and mechanical properties, impact included.

For the same grade in the same thickness, the three indices can be identical or different.

To give a general idea, UL temperature indices of thermoplastics are in a range of 50 °C up to more than 200 °C for exceptional families.

Like all the laboratory methods, the temperature index is an arbitrary measurement that must be interpreted and must constitute only one of the elements by which judgment is made.

1.1.3.4 Heat Deflection Temperature

The HDT is the temperature at which a standard deflection occurs for defined test samples subjected to a given bending load and a linear increase in temperature. The stresses usually selected are 0.46 MPa (HDT B) or 1.8 MPa (HDT A) and must be indicated with the results. In any case, the polymer cannot be used under this load at this temperature.

Generally, HDTs are in a range of 20 °C up to more than 400 °C for exceptional families. For a given ther moplastic family, HDT is affected by reinforcements, fillers, and plasticizers.

1.1.3.5 Vicat Softening Temperature

The VST is the temperature at which a standard deflection occurs for defined test samples subjected to a given linear temperature increase and a compression loading from a defined indenter of a specified weight. The load used is often 10 N (Vicat A) or 50 N (Vicat B) and must be indicated with the results.

In either case, the polymer cannot be used under this compression load at this temperature.

For a given thermoplastic family, VST is affected by reinforcements, fillers, and plasticizers.

HDT and VST are not strictly linked but there is a certain relationship and when HDT is low, VST is also low.

1.1.3.6 Accelerated Aging

Conventional accelerated aging tests consist in exposing defined samples to controlled-temperature air in ovens protected from light, ozone, and chemicals, for one or more given durations. The degradation is measured by the variation at room temperature of one or several physical or mechanical characteristics during the aging. The variations of impact resistance, hardness, tensile or flexural strength, and color are the most frequently studied.

Sometimes, properties are measured at the aging temperature, which is a more severe method.

Accelerated aging is an arbitrary measurement that must be interpreted and must constitute only one of the elements used in making a judgment:

- Under identical conditions, the properties do not all degrade at the same rate.
- It is impossible to establish a direct relationship between the accelerated aging of a part and its real lifespan. For an unknown polymer, the results of accelerated aging must be compared with those obtained on a known polymer of a very similar formula.

1.1.4 Low Temperatures: Some Ins and Outs

Figure 1.6 displays the ins and outs of low temper atures.

A fall in temperature has only physical effects:

- Increase in the modulus and rigidity. The modulus can be up to 100 and more times higher than that measured at room temperature.
- Reduction in the impact resistance. The material can become brittle. For example, commodity thermoplastics can have low temperature of service of −110, −10, 0, or even 20 °C.
- Eventually, crystallization for semicrystalline polymers.

Apart from mechanical effects, low temperatures reduce degradations by aging and are sometimes used to store parts, which lead to longer lifetimes.

A temperature decay leads to a retraction according to the coefficient of thermal expansion (CTE).

To provide a general rough idea of minimum service temperatures, Table 1.4 displays statistical analysis of low-temperature service for about 350 thermoplastic grades. The minimum service temperature is an arbitrary temperature resulting from general experience and observation.

1.1.4.1 Low-Temperature Tests

There are many methods to test low-temperature behavior but none can be used directly needing careful interpretations. The possibility to use a thermoplastic at low temperature depends on the service conditions including loading and impacts. Some grades can be used at −200 °C or less if there are no impacts. Some other thermoplastics can be brittle at ambient temperature like the polystyrene used for yoghurt packaging.

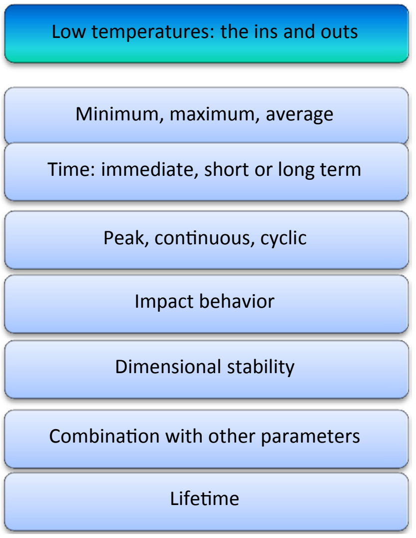


Figure 1.6 Low temperatures: ins and outs.

Table 1.4 Statistical Analysis of Minimum Service Temperatures for About 350 Thermoplastic Grades

Median	−40
Minimum	−250
Maximum	20
Samples	362

It is necessary to distinguish:

- short-term tests: brittle point, low-temperature impact test, low-temperature rigidity, and elastic recovery for elastomers such as silicone
- long-term tests: crystallization tests, which make it possible to detect a slow crystallization by the evolution of hardness with time.

1.1.4.2 Brittle Point

The—very fuzzy—definition of the brittle point is based on a more or less sudden reduction in the impact resistance or the flexibility. The indicated values must be carefully considered.

- Low-temperature impact tests: cooled samples are subjected to a conventional impact test. Generally, the most often used temperatures are −20, −30, or −40 °C.
- Low-temperature brittleness or toughness: the samples are cooled to a temperature far lower than the supposed temperature of brittleness and then gradually warmed up. At each selected temperature step, the test specimens are subjected to a specified impact. The temperature at which specimens deteriorate or fail is the "brittle point." In some other tests, the lowest temperature to which specimens can be cooled without deterioration is regarded as the limiting temperature of "toughness" or "no brittleness."
- Low-temperature flexibility of thin products: the product is rolled up on a specified mandrel at one or several temperatures.

1.1.4.3 Rigidity in Torsion: "Clash & Berg" and "Gehman" Tests

These tests are based on the evolution of the static or dynamic torsion modulus when the temperature decreases. Results can be:

- plotted versus the temperature
- expressed as the value of the modulus for specified temperatures
- recorded as the temperatures for which the modulus is 2, 5, 10, 100 and more times higher than that measured at room temperature.

1.1.4.4 Crystallization Test

The crystallization test consists of measuring the evolution of hardness at a specified temperature over several weeks. This method is of special interest for those polymers that can slowly crystallize at service temperatures.

The combination of low-temperature periods and immersion in chemicals at higher temperatures lead ing to chemical uptake can induce worsening of existing defects by volume increase in solidified chemicals by cooling.

1.1.5 Dimensional Stability: Some Ins and Outs

Too little (or too large) a polymer part can disturb a device made by assembling several parts of various materials. Sometimes, the dimension is fair but a more or less strong warpage prevents a correct assembly.

These phenomena are the consequences of:

- The CTE
- The mold shrinkage
- The anisotropy of fiber-reinforced thermoplastics
- The water uptake particularly known for polya mides
- The absorption of chemicals
- The desorption and bleeding of humidity or additives such as plasticizers or other low-molecular-weight organic additives.

In addition, a wrong drawing can induce warpage of isotropic compounds. Anisotropic variations of the above parameters can also be responsible of warpage.

Moreover, plastics and rubbers are often simultaneously used with conventional materials, notably metals, whose coefficients of thermal expansion can be 10 to 100 times lower. This can promote high stresses and eventually failure of the device including these different materials.

Dimensional variations can be immediate (thermal expansion) or progressive (water uptake) or delayed after a given time of aging.

Figure 1.7 displays the ins and outs concerning the dimensional stability.

1.1.5.1 Thermal Expansion or Retraction

The CTE can be volumetric or more frequently linear. It is defined as the fractional variation of volume (volumetric coefficient) or length (linear coefficient) per unit change in temperature. The volumetric coefficient is roughly three times the linear one.

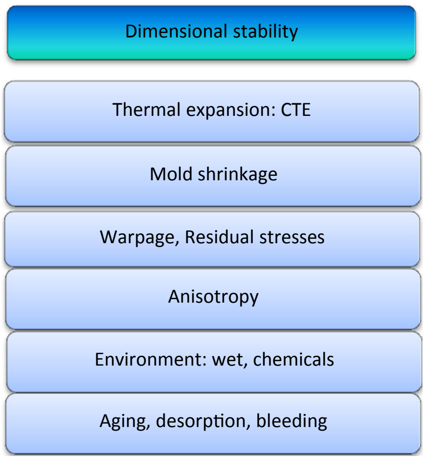


Figure 1.7 Dimensional stability: ins and outs.

Table 1.5 Statistical Analysis of Coefficients of Thermal Linear Expansion for About 200 Thermoplastic Grades

Median	10^{-5}/K	9
Minimum	10^{-5}/K	3
Maximum	10^{-5}/K	30
Samples		218

Of course, a temperature decay leads to a retraction.

Being thermal dependent, the validity range of test temperatures must be indicated.

Thermoplastics intrinsically have high coefficients of thermal expansion in the order of 10^{-4}–10^{-5}/K.

To provide a general rough idea of thermoplastics coefficients of thermal linear expansion, Table 1.5 displays statistical analysis for about 200 unfilled grades.

These values must be compared to those of other materials:

- Steel and iron: 1–2 × 10^{-5}/K
- Other common metals: 2–4 × 10^{-5}/K
- Low CTE metals: 0.4–1 × 10^{-5}/K
- Ceramics, oxides, carbides, nitrides, carbon, graphite: 0.2–1 × 10^{-5}/K

The CTE is significantly changed by:

- The temperature, particularly if the glass transition temperature is reached
- The structure and morphology of the polymer
- The additives eventually used.

1.1.5.2 Shrinkage

Shrinkage after molding is a universal problem depending on:

- The CTE: for given conditions, the shrinkage increases with the CTE.
- The molding temperature: for given conditions, the shrinkage increases with the molding temperature.
- The additives.
- The orientation of the macromolecules.
- The orientation of fibers or acicular fillers.
- The crystallinity: a possible crystallization after molding leads to a volume increase that minimizes the total shrinkage.

1.1.5.3 Warpage

Warpage or distortion can be due to:

- Anisotropy
- Internal stresses
- Shrinkage variations induced by local changes of formulation or processing parameters.

Colorants, for example, can nucleate the polymer and locally favor shrinkage.

Fibers and acicular fillers can accumulate in certain spots of the mold leading to local decreases of CTE, shrinkage, increases of moduli… leading to warpage.

Calcium carbonate fine powder and other spheroid fillers such as microballoons or glass beads decrease shrinkage and easily flow in the mold, reducing warpage.

1.1.5.4 Water or Chemicals Uptake

All the polymers absorb more or less humidity or water in quantities depending on:

- The form of the water: humid air, liquid water, pure or polluted water
- The temperature
- The recipe of the compound
- The crystallinity of the polymer…

The volume of absorbed water causes a dimensional increase. For example, for a given polyamide the length increase is about 2.6% for a water content of 8% at equilibrium. Really, the absorption of water is very slow, and in the case of atmospheric changes, the equilibrium is not always reached damping the effects of humidity variations.

Chemicals have the same effects but the swelling can be much higher and absorption rate can be faster.

1.1.5.5 Aging, Desorption, Bleeding, and Releasing of Organic Components

Residual monomers, oligomers, organic additives, particularly plasticizers can degas, the more so as the temperature and the airflow rise. Consequently, dimensions decrease. Components can also migrate toward other materials or bleed.

Released organic components pollute other materials and surroundings.

1.1.6 General Environmental Trends, Pollution of Near Environment, Green Attitude, Sustainability: Some Ins and Outs

In recent years, the concept of sustainability was developed and then normalized (ISO 14000) to help the economic and industrial players to think about ways able to improve or minimize the degradation of our Earth.

All the industrial activities consume resources and energy, pollute and compromise the future of the planet by global warming, atmospheric ozone depletion, accumulation of pollutants often under organic forms particularly harmful for human, animal, vegetal, and aquatic life. To preserve the essential needs of future generations during a maximum time, it is essential to think all our actions and to design all the products and goods for a better sustainability. There are no perfect answers to this important problem but several more or less easy ways allow a more or less substantial improvement of sustainability.

Sustainability can be schematized as a tripod based on:

1. Environmental requirements: the basis axiom can be simplified as follows "Today acts must not compromise the environment of the planet for tomorrow" or "present acts must not compromise the needs of future genera tions."
2. Economic growth: sustainable products must be efficient, competitive, cost-effective, and beneficial for everybody.
3. Social progress including fair labor standards, equal treatment of women and minorities… This aspect is not included into the framework of this book.

The standards and regulations limit the pollution and increase the level of recycled wastes.

1.1.6.1 Global Warming Due to the Greenhouse Effect of Emitted Gases

The greenhouse effect allows solar radiations to pass through the Earth's atmosphere, but prevent infrared radiations to pass from the Earth's surface and lower atmosphere toward space. This natural process is magnified by an overproduction of carbon dioxide and other greenhouse gases such as water vapor (H_2O), methane (CH_4), nitrous oxide (N_2O), freons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and so on.

Atmospheric concentrations of CO_2, mainly due to fossil fuel combustion (hydrocarbon-based fuels formed by the decomposition of prehistoric flora and fauna, for example, oil, natural gas, coal, tar sands, and peat), are now about 30% above preindustrial levels.

Combustion of polymer wastes transforms the carbon content into more than three times its weight of CO_2 and consumes more than two times its weight of oxygen.

For polyethylene, only made of carbon and hydrogen, combustion:

- produces a weight of CO_2 and water greater than four times the polyethylene weight
- consumes an oxygen weight greater than three times the polyethylene weight.

1.1.6.2 Pollution of Air, Water, and Land

Pollution of air and water includes some less known effects such as:

- Acidification of the environment due to a formation of acids higher than their neutralization. Acidification can be harmful to forest and aquatic life.
- Eutrophication stimulates the growth of aquatic plants and can cause algal blooms that deoxygenate

water and smother other aquatic life. It is due to nitrates and phosphates from organic material or surface runoff.

Major pollutants include:

- Gases such as carbon dioxide, carbon monoxide, hydrocarbons, nitrogen oxides, sulfur dioxide… On a weight-for-weight basis, the contribution of N_2O to the greenhouse effect is roughly 300 times greater than that of carbon dioxide. Sulfur dioxide and other sulfur oxides are formed during the incineration of fossil fuels and wastes, contributing to acidification.
- Volatile organic compounds (VOCs), formaldehyde, for example, form a broad category of volatile chemical compounds, some of which pose a health hazard. The presence of VOCs in the atmosphere can also lead to greenhouse effect, ozone layer depletion, and acidification.

Pollutants of polymers and compounds come from:

- Macromolecules of the polymer that can include halogens, nitrogen, sulfur…
- Catalysts and other polymerization additives
- Compounding additives such as certain plasticizers, fire retardants (FRs), curing agents, blowing agents…

1.1.6.3 Aging, Desorption, Bleeding, and Releasing of Organic Components

Residual monomers, oligomers, organic additives, particularly plasticizers can degas, the more so as the temperature and the airflow rise. Consequently, dimensions decrease, compound properties evolve and surrounding materials can be polluted.

Components can also migrate toward other materials or bleed.

Released organic components pollute other materials and surroundings, leading to optical and electrical dysfunctions.

Figure 1.8 displays the main ins and outs related to environment and plastic interactions.

1.1.6.4 Volatile Organic Compounds

VOCs form a broad category of chemical compounds, some of which pose health hazards and can

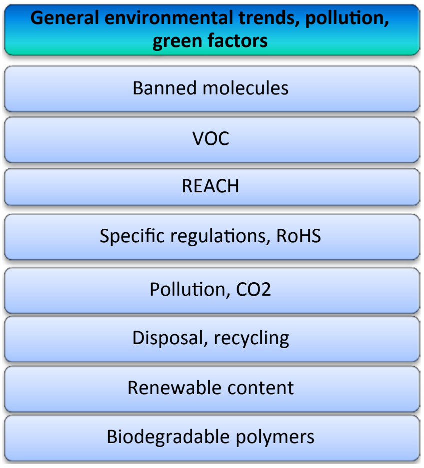


Figure 1.8 Environment trends: the ins and outs.

also lead to greenhouse effect, ozone layer depletion, and acidification of the globe atmosphere.

For example, among other things, remember that:

- Some VOCs are well known or intuitively suspected such as solvents used for paints, varnishes, cleaning and degreasing, chlorofluorocarbons (CFCs), halogenated fluorocarbons, perfluorinated carbons, hydrofluorocarbons, freons and other halogenated gases, toluene, xylene, styrene, naphthalene, ethanol, trichloroethylene and other chlorinated solvents… Their use is now regulated or banned in many countries.
- Not so well-known VOCs may be initiated by photochemical oxidants.
- VOCs include various tiny solid or liquid particulates such as soot, dust, fumes, or mist. Dust can penetrate into a person's lungs and pose health hazard. Asbestos is a well-known example.

Other chemicals, more hidden and pernicious, are often neglected such as, for example, plasticizers, organic FRs, curing agents, residual monomers, oligomers…

Plasticizers are of particular interest because they are used in significant amounts, sometimes several tens of percent, to assume their technical and economic roles. Liquid plasticizers, even having high melting points and, of course, higher ebullition temperatures, have a non-negligible volatility, the more so as they are incompatible with their polymer host.

1.1.6.5 Banned or Regulated or Suspect Substances

Without claiming to be exhaustive, let us quote, for example:

- Heavy metals, including mercury, zinc, copper, cadmium, vanadium, and lead, are harmful if spread in the environment.
  - Mercury (Hg) is used in catalysts and is released by the combustion of fossil fuels and wastes. Organic mercury compounds act as cumulative poisons that affect the nervous system.
  - Zinc (Zn) is used as curing activator for rubber and for polyvinylchloride (PVC) stabilization.
  - Copper (Cu) is used in pigments for plastics and rubbers.
  - Cadmium (Cd) is a cumulatively toxic element.
  - Lead (Pb) accumulates in biological systems and is linked to behavioral changes, paralysis, and blindness. It was used as a curing activator or stabilizer for certain polymers.
- Phosphorus derivatives. An excess of phosphorus compounds in surface water leads to eutrophication and algal bloom.
- Some plasticizers and FRs… such as:
  - Chloroparaffins or chlorinated paraffins that are stable organic compounds resistant to degradation and oxidation. Used as softeners and/or as flame retardants in plastics and rubbers; they are harmful primarily to aquatic life.
  - Polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs). These biologically persistent organic compounds containing bromine are used as FRs in plastics, for example, in housings for electrical equipment.
  - Polychlorinated biphenyls (PCBs) are biologically persistent organic compounds containing chlorine, particularly toxic to marine life. Sometimes used in rubber seals for electrical transformers and capacitors, they are now being phased out and disposed of.

Related legislation evolves with countries, application sector, companies, etc. needing complete studies by the designer and its team.

1.1.6.6 REACH

REACH can be an European Directive but also a China regulation dealing with new chemical substance notification to the Chemical Registration Centre (CRC) of the Ministry of Environmental Protection (MEP) for the new chemicals irrespective of annual tonnage, i.e., chemicals other than approximately 45,000 substances currently listed on the Inventory of Existing Chemical Substances Produced or Imported in China (IECSC).

REACH Directive of the European Union was adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. REACH is the acronym for Registration Evaluation Authorization and Restriction of Chemicals.

Failure to register will mean that the substance cannot be manufactured or imported into the EU market.

For chemicals used in significant quantity, industry must ensure that risks for human health and environment are avoided or adequately controlled. Enterprises that manufacture or import more than a defined quantity (1 tonne) of a chemical substance per year will be required to register the chemical in a central database.

Higher quantities (above 10 tonne per year) additionally require the submission of a Chemical Safety Report (CSR) to document the safety assessment of the substance.

Several steps must be considered:

- Registration: Companies have the responsibility of collecting information on the properties and the uses of substances that they manufacture or import at or above 1 tonne per year. They also have to make an assessment of the hazards and potential risks presented by the substance.
- Authorization: The authorization procedure aims to assure that the risks from substances of very high concern are properly controlled and that these substances are progressively replaced by suitable alternatives while ensuring the good functioning of the EU internal market.
- Restriction: Restrictions are a tool to protect human health and the environment from unacceptable risks posed by chemicals. Restrictions

may limit or ban the manufacture, placing on the market or use of a substance.

- Ban: Use of the concerned chemical is banned.

1.1.6.7 Examples of Specific Regulations or Specifications, RoHS, WEEE

The RoHS directive restricts certain hazardous substances commonly used in electrical and electronic equipment. Do not confuse EU RoHS and China RoHS: Both target similar goals but approaches are different concerning the product categories, the restrictions, the application schedule.

EU RoHS deals with:

- Heavy metals, including mercury, cadmium, hexavalent chromium, and lead, are harmful if spread in the environment.
  - Mercury (Hg) is used in catalysts and is released by the combustion of fossil fuels and wastes. Organic mercury compounds act as cumulative poisons that affect the nervous system.
  - Cadmium (Cd) is a cumulatively toxic element.
  - Chromium (Cr^{6+}) is a toxic element entering the air, water, and soil.
  - Lead (Pb) accumulates in biological systems and is linked to behavioral changes, paralysis, and blindness. It was used as a curing activator or stabilizer for certain polymers.
- Organic species
  - PBBs and PBDEs. These biologically persistent organic compounds containing bromine are used as FRs in plastics, for example, in housings for electrical equipment.

Numerous other hazardous substances exist and can be involved in other regulations such as, for example:

- Metals: zinc, copper, vanadium, etc.
- Organic species: PCBs, toluene, xylene, styrene, chloroparaffins or chlorinated paraffins, naphthalene, ethanol, trichloroethylene, and other chlorinated solvents…
- Phosphorus derivatives…

Be aware that some countries, departments or even localities, and companies have specific legislations.

1.1.6.8 Renewable Content or Biocarbon Content

Biomass can be used in very different manners from all-natural route up to renewable products copolymerized, alloyed, or mixed with synthetic ones. There are numerous examples such as:

- Renewable polymers with synthetic ones
- Renewable fibers with synthetic matrices
- Renewable matrices with synthetic fibers
- Renewable polymers with synthetic additives
- Renewable additives with synthetic polymers.

Finally, it is also possible to extract monomers or oligomers from the biomass and use them, alone or in combination with oil-based monomers, to synthesize conventional polymers.

Natural-sourced levels can range from 20% up to near 100%.

For an identical formula of polymers, properties of natural and fossil polymers can be slightly different. For dissimilar formulae, properties are generally dissimilar. Compound formulations must be adapted to the used polymer.

Fibers have a similar effect in natural and fossil polymers. For some technical properties, natural fibers are not as performing as glass fibers.

Be cautious with some preconceived notions such as:

- Natural polymers are biodegradable. In fact, some are biodegradable, but others are not.
- Natural polymers are environment-friendly, not systematically. That depends on the farming and processing conditions.

1.1.6.9 (Bio)Degradable Plastics

Biodegradable polymers are polymers that can be broken down, predominantly by the enzymatic action of microorganisms during a specified time limit, in carbon dioxide, methane, water, inorganic compounds, and biomass. Biodegradable is sometimes improperly used for degradation by hydrolysis, photolysis, solubility…

Compostable polymers: A polymer is "compostable" when it is biodegradable under composting conditions that is to say principally under the action of microorganisms to lead to a total mineralization into CO_2, H_2O, inorganic compounds, and biomass.

The degree of degradability, measured according to ASTM D 5338-92, must be similar to that of cellulose to meet the compostability criteria.

1.1.6.10 Carbon Footprint

The carbon footprint is not an intrinsic characteristic of a polymer but depends on the actual sources of monomers, polymerization method, processing, transportation, use, energy sources, recycling routes, level of recycled, and virgin materials. Consequently, data can dramatically differ according to the sources for a same polymer. The following examples aim to provide a rough idea, and other very different data can be found elsewhere. For example, a production of 1 tonne of:

- Fossil PVC emits 1.6 up to 2.5 tonne CO_2 according to the conditions
- Fossil polyethylene emits 1.9 up to 2 tonne CO_2
- Fossil polypropylene emits 1.9 up to 2 tonne CO_2
- Fossil polyethylene terephthalate emits 3 up to 3.5 tonne CO_2.

By contrast, the growth of plants leading to renewable raw materials absorbs CO_2 and their growing footprint is negative but the footprint is positive for polymerization and processing.

Statistical analysis of some tens of fossil and bio-sourced polymers emphasizes a CO_2 saving in the order of 75%, thanks to renewable raw materials.

For the used energy, an electricity production of 1000 kW h emits 0.8 up to more than 1 ton of CO_2 for coal, 0.650 ton for oil, 0.500 ton for gas, 0.050 ton for photovoltaic, and 0.005 ton for hydro, wind, or nuclear sources.

Recycling and reuse of commodity thermoplastics such as polyethylene, PVC, styrenics, and engineering plastics from polypropylene and thermoplastic polyester up to polyamide lead to an average CO_2 saving of 50% with contrasted situations depending on the waste sources and reuse levels.

Burning 1 ton of polyethylene, only made of carbon and hydrogen, produces a weight of CO_2 greater than 3 tons…

1.1.6.11 Life-Cycle Assessment

Life-cycle assessment depends on the methods of production of raw materials, the processing methods, the type of the used energy, logistics, and transport issues, etc. The following data are not rules but very few examples. Results are briefly expressed as some ratios concerning the nonrenewable energy, the greenhouse effect or CO_2 emission, the pollution - sulfur oxides (SO_x), carbon dioxide, carbon monoxide, nitrogen oxide (NO_x) emissions, acidification and carcinogenicity indicators, water emissions (phosphates, nitrates), terrestrial ecotoxicity, and human toxicity.

Table 1.6 shows an example of differences between a glass and a natural fiber. The natural fiber has a unique balance of eco-performances except for water pollution with nitrates and phosphates due to their cultivation.

Table 1.6 Life Cycle of a Natural Fiber Compared to a Glass Fiber

	Glass Fiber (GF)	Natural Fiber (NF)	
	Data	Data	% of GF Data
Energy use (MJ/kg)	48.33	3.64	8
COD to water (mg/kg)	18.81	2.27	12
SO_x emissions (g/kg)	8.79	1.23	14
BOD to water (mg/kg)	1.75	0.36	21
Particulate matter (g/kg)	1.04	0.24	23
Carbon dioxide emissions (kg/kg)	2.04	0.66	32
NO_x emissions (g/kg)	2.93	1.07	37
CO emissions (g/kg)	0.80	0.44	55
Phosphates to water (mg/kg)	43.06	233.6	543

1.1.7 Electrical Properties: Some Ins and Outs

Figure 1.9 displays the main ins and outs related to the electrical behavior of plastic.

Traditional polymers are naturally insulating but can be made more or less conductive. They can be characterized, among other test methods, by:

- The volume resistivity and surface resistivity
- The dielectric strength
- The arc resistance
- The high voltage arc tracking rate (HVTR).

1.1.7.1 Volume Resistivity—ASTM D257 and IEC 93

The volume resistivity is the electrical resistance of a polymer sample of unit area and unit thickness when electrodes placed on two opposite faces apply an electrical potential across it. The volume resistivity is expressed in ohm·cm (Ω·cm).

Classification of polymers varies depending on the country and application. Each case must be examined in its context and the following data are only examples:

- insulating polymers: resistivity higher than 10^9 Ω·cm
- conductive polymers: resistivity lower than 10^5 Ω·cm
- polymers for electrical heating: resistivity lower than 10^2 Ω·cm.

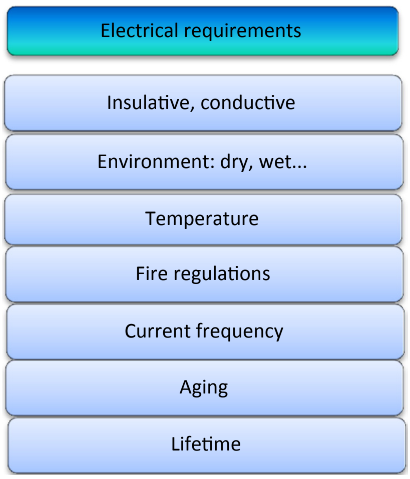


Figure 1.9 Main ins and outs related to electrical behavior of plastic.

To provide a general rough idea of thermoplastics volume resistivities, Table 1.7 displays statistical analysis for about 560 grades including 416 insulating ones.

1.1.7.2 Surface Resistivity—ASTM D257 and IEC 93

The surface resistivity is the electrical resistance between two electrodes placed on the same face of a polymer sample. The surface resistivity is expressed in ohms (or in ohms per square).

Classification of polymers depends on the country and application. Each case must be examined in its context and the following data are only examples:

- insulating polymers: resistivity higher than 10^{12} Ω per square
- dissipative polymers: resistivity in a range from 10^5 up to 10^{12} Ω per square
- antielectrostatic parts for coalmines: resistivity lower than 10^9 Ω per square
- conductive polymers: resistivity lower than 10 Ω per square.

1.1.7.3 Dielectric Strength

The dielectric strength is the maximum voltage before breakdown divided by the thickness of the sample. It is expressed in kV/mm. Data depend on the test conditions.

1.1.7.4 Arc Resistance

The arc resistance is the time necessary to make the polymer surface conductive by the action of a high-voltage, low-current arc. It is expressed in seconds.

1.1.7.5 High-Voltage Arc Tracking Rate

Thermoplastics can be sensitive to tracking appearing when a high-voltage source current creates an

Table 1.7 Statistical Analysis of Volume Resistivities for All-Purpose and Insulating Grades

	All Grades	Insulating Grades
Median	10^{13}	10^{14}
Minimum	10^{-1}	10^9
Maximum	10^{18}	10^{18}
Samples	566	416

unwanted path across the surface of a plastic part. HVTR is denoted as the rate, in millimeters per minute, that a tracking path can be produced on the surface of the material under standardized test conditions. A note is made if ignition on the material takes place. The results of testing the nominal 3 mm thickness are considered representative of the material performance in any thickness.

HVTR range can be less than 10 and up to more than 150 millimeters per minute.

Apart from these electrical properties, E & E are also subjected to fire and service temperature laws, standards, and regulations such as UL94 fire ratings, UL temperature index, and many other international, national, regional, or application sector specifi cations.

1.1.7.6 Frequency, Temperature, Moisture, Physical, and Dynamic Aging Effects

All electrical properties may be modified by the current frequency, the actual temperature and moisture content of the thermoplastic, historical heat, and mechanical aging.

For example, certain conductive thermoplastics may be insulating after dynamic loading.

A few thermoplastics can have piezoelectric properties.

1.1.8 Fire Behavior: Some Ins and Outs

In the US alone, it is estimated that there are approximately 400,000 residential fires each year, 20% involving electrical distribution and appliances; another 10% concerning upholstered furniture and mattresses. These fires kill about 4000 people, injure another 20,000 people, and result in property losses totaling about $4.5 billion. Across Europe, fires kill about 5000 people.

This brief overview shows the need of FR plastics in sectors such as E & E, building and construction, automobile, transportation, etc. Moreover, it is pointed out that the use of flame-retardant materials had cut fire deaths by 20% in recent years, although there is a marked increase in the number of electric and electronic devices in every home.

Due to their organic nature, thermoplastics have specific fire behavior depending, initially, on the nature of the polymer. Apart from inherently fire-resistant polymers, the only other solution is the addition of FR additives to conventional plastics, a market with annual growth rates exceeding the plastics one.

Flammability and smoke-generating characteristics of plastics have come under scrutiny in recent years and a variety of laboratory-type tests have been developed to define these properties. Agencies within the Federal Government, as well as outside organizations such as the American Society for Testing Materials, the Underwriters' Laboratories, Inc., and many industrial corporations have contributed to new test development. Currently, a large number of procedures for defining many aspects of flammability are available for setting up safety and acceptability standards. For example, a single laboratory proposes 101 standards and methods for fire testing.

The individual tests are generally intended to predict the behavior of the material during burning or during exposure to intense heat, as in a burning building or aircraft. Conditions and procedures are legion. The correlation of laboratory test data with actual conflagration remains controversial. The major contribution of the tests is to rank the various materials relative to each other and to the particular specifications. Often, plastics parts have long lifetimes, so fire resistance must withstand the application conditions during long periods. For instance, certain standards such as UL94 fire rating include tests after accelerated aging.

Worldwide, national and local regulations, standards, industrial corporation and company specifications, and application sector rules are numerous and evolutionary.

> Of course, regulations, safety requirements, specific, and general standards applied in the various countries to the manufacture, application, and disposal of plastics products must be fulfilled.
>
> Please note that certain tests required for fire agreement must be run by accredited certifiers.
>
> It is the responsibility of the reader to search the specific rules applicable to his own problem.

The following tests are only a short panel of examples but many other testing methods are used around the world. Generally speaking, they relate to:

- the tendency for combustion: UL94 ratings, oxygen index, for example
- the smoke opacity
- the toxicity and corrosivity of the smoke.

1.1.8.1 UL94 Fire Ratings

The UL94 fire ratings provide basic information on the material ability to extinguish a flame, once ignited. The positioning of the sample (horizontal: H; or vertical: V), the burning rate, the extinguishing time, and dripping are considered. The main categories are:

- V0: the most difficult to burn, extinguished after 10 s, no drips
- V1: extinguished after 30 s, no drips
- V2: extinguished after 30 s, flaming particles or drips permitted
- 5V: extinguished after 60 s, flaming particles or drips permitted
- HB: burning horizontally at a 76 mm/min maximum rate.

The UL rating depends on the exact grade and the sample thickness. For the same grade of polyphenylene sulfide (PPS), the UL ratings are:

- V1 for a 1.6 mm thickness
- V0 for a 6 mm thickness.

1.1.8.2 Oxygen Index

The oxygen index is the minimum percentage of oxygen in an atmosphere of oxygen and nitrogen that sustains the flame of an ignited polymer sample.

Generally, oxygen indices range from 15 up to 60 and more, for example, 95 for polytetrafluoroethylene (PTFE).

There is no true link between UL94 rating and oxygen index but a thermoplastic with a low oxygen index cannot satisfy to UL94 V0.

To provide a general rough idea of thermoplastics oxygen indexes, Table 1.8 displays statistical analysis for about 400 grades.

Table 1.8 Statistical Analysis of Oxygen Indexes for About 400 Thermoplastic Grades

Median	22
Minimum	16
Maximum	96
Samples	398

1.1.8.3 Smoke Opacity, Toxicity, and Corrosivity

Smoke opacity is measured by optical density. For smoke density according to ASTM D-2843, a specimen is burned in a special chamber under continuous ignition. The generation of smoke causes a reduction in the intensity of a light beam. This is measured through the duration of the test, and results are expressed in terms of maximum percent light absorption and a smoke density rating. The procedure is intended to provide a relative ranking of the smoke production under controlled standardized conditions.

This test method serves to determine the extent to which plastic materials are likely to smoke under conditions of active burning and decomposition in the presence of flame. The instrumental observations from this test compare well with the visual observations of the smoke generated by plastic materials when added to a freely burning large outdoor fire. The usefulness of this test procedure is in its ability to measure the amount of smoke obscuration produced in a simple, direct, and meaningful manner under the specified conditions. The degree of obscuration of vision by smoke generated by combustibles is known to be affected by changes in quantity and form of material, humidity, draft, temperature, and oxygen supply.

Federal Aviation Administration standard (FAR 25.853) defines FST (fire, smoke, toxicity) requirements.

1.1.8.4 Cone Calorimeter

Cone calorimeter is used to study the fire behavior of small samples of various materials in condensed phase. It gathers data regarding the ignition time, mass loss, combustion products, heat release rate, and other parameters associated with its burning properties. Optional devices can include:

- Carbon dioxide and carbon monoxide analyzers.
- Integrated fume cupboard.
- Fourier transform infrared spectroscopy (FTIR) toxicity test system.

1.1.8.5 Ignition Temperature

Flash ignition temperature is the lowest temperature at which the material supplies enough vapor to be ignited by an external flame. For example, for a given grade of polyacetal, flash ignition is at 320 °C and self-ignition is at 375 °C.

1.1.8.6 Rate of Burning

For example, FMVSS (Federal Motor Vehicle Safety Standards) 302—Flammability of Interior Materials—Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses—specifies burn resistance requirements for materials used in the occupant compartments of motor vehicles. Its purpose is to reduce deaths and injuries to motor vehicle occupants caused by vehicle fires, especially those originating in the interior of the vehicle from sources such as matches or cigarettes.

The test is conducted inside a test chamber where the test specimen is mounted horizontally. The exposed side of the test specimen is subjected to a gas flame from underneath. The burnt distance and the time taken to burn this distance are measured during the test. The burning rate is expressed in mm/min. For example, a given grade of polyacetal burns slowly at rates around 50 mm/min for a 1-mm thick horizontal sample.

1.1.8.7 Glow Wire Test

The glow wire test (IEC 695-1) simulates the thermal conditions that may be produced by incandescent sources of heat and ignition, in order to evaluate the fire hazard. Values vary with the thickness of the specimen and are expressed in °C. For example, a given grade of polyacetal passes the test at 550 °C, at a thickness of 1 mm.

1.1.9 Sensory Properties: Some Ins and Outs

The user–plastic part interface was sharply oriented to direct functionalities such as toughness, durability, cost, and so on, but, more or less recently, new concepts have been devised concerning sensory properties and secondary or indirect objectives such as appealing marketing features, new safety concepts, or more generally, interactions between the user or the environment and the plastic part or the system including plastic parts. Some examples concern the sense satisfaction, the best known aspect, or the use of the user's senses to achieve the targeted aims, the latest and the most promising way to enhance the capability and attractiveness of all the devices.

Figure 1.10 displays the main ins and outs related to sensory properties of plastic parts.

The market appeal of plastics is of prime importance for numerous applications such as packaging, automotive, appliances… Color, transparency, gloss, haze, touch, acoustics, odor, and taste transfer contribute to make a plastic part attractive, unappealing, or repulsive.

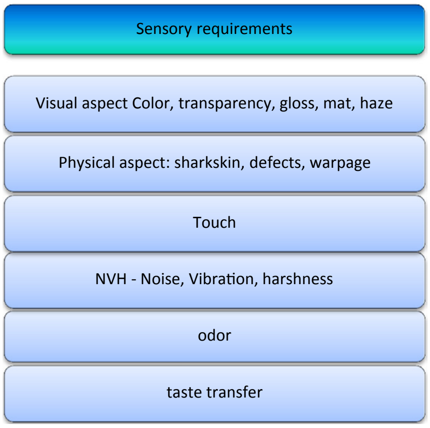


Figure 1.10 Sensory properties: the ins and outs.

As the other properties, sensory properties evolve during aging, which can limit the lifetime of plastics parts still having satisfying mechanical properties.

1.1.9.1 Complementarity of Instrumental Measurements and Sensory Panel Evaluations

Analysis instruments have neither brains nor psychological faculties but they are never in a good or bad mood, tired, ill, and other human hazards. They are perfect to identify or quantify chemical entities or physical properties but are unable to make the link between the obtained results and the satisfaction or dissatisfaction of plastics part users.

Sensory evaluation by people panels aims to fill this gap.

Sensory evaluation was defined by the Sensory Evaluation Division of the Institute of Food Technologists (1975) as "the scientific discipline used to evoke, measure, analyze, and interpret those reactions to characteristics of foods and materials as perceived through the senses of sight, smell, taste, touch and hearing." The complex sensation that results from the interaction of our senses is used to measure product quality in programs such as quality control and new product development.

Later, ASTM established the Subcommittee E18.05 on Sensory Applications, which focuses on test methods for the evaluation of molded polymer in terms of its perceived odor and the transfer of package-related odors or flavors, or both, to the food being packaged.

This evaluation may be carried out by panels of a small number of people or by several hundreds of people depending on the type of information required. Sensory analysis panels can be grouped into four types: highly trained experts (1–3 people), trained laboratory panels (10–20 people), laboratory acceptance panels (25–50 people), and large consumer panels (more than 100 people).

The first and simplest form of sensory analysis is made by the researcher who develops the new products, making his own evaluation to determine the interest of designed products.

Skilled laboratories and consumer panels develop sensory analysis in a more formal and scientific manner.

The Subcommittee 18.05 has published several standards that deal with odor/taste.

- ASTM E1870, Standard Test Method for Odor and Taste Transfer from Polymeric Packaging Film—This standard deals with rigid containers and closures in terms of their perceived odor and the transfer of package-related odors or flavors to the food being packaged.
- ASTM D1292-10, Standard Test Method for Odor in Water—This test method covers the determination of the odor of water. The odor intensity may be expressed in terms of odor intensity index or threshold odor number.
- ASTM E460-12, Standard Practice for Determining Effect of Packaging on Food and Beverage Products During Storage—This practice is designed to detect the changes in sensory attributes of foods and beverages stored in various packaging materials or systems, or both. It is not a practice intended to determine shelf life. This practice may be used for testing a wide variety of materials in association with many kinds of products.
- ASTM E2454-05(2011) Standard Guide for Sensory Evaluation Methods to Determine the Sensory Shelf Life of Consumer Products.
- ASTM E2609-08 Standard Test Method for Odor or Flavor Transfer or Both from Rigid Polymeric Packaging.
- ASTM STP 434, Manual on Sensory Testing Methods—Sensory testing is concerned with measuring physical properties by psychological techniques. As part of the field of psychometrics, sensory methods are used for measurements that cannot be made directly by physical or chemical tests.
- ASTM STP 758, Guidelines for Selection and Training of Sensory Panel Members.

People being used as a measuring instrument, it is necessary to control all testing methods and conditions rigidly to overcome all kinds of extraneous influences caused by psychological factors. All precautions must be taken to provide the best physical and mental conditions of the panelists and minimize the influence of the testing environment affecting their sensory evaluations. According to ASTM STP 758 "Within both discrimination and descriptive sensory methods, performance records should be maintained for each panelist and should be periodically reviewed by the panel leader. The performance of each panel member should be compared with the performance of the panel as a whole. Panelists whose performance has declined should be interviewed by the panel leader in an attempt to determine the cause. Wherever possible, assistance should be offered in an attempt to restore performance."

Instrumental and panel sensory analyses complement each other:

- Instrumental analysis leads to precise data for each feature (odor, taste, vision…) by use of traditional physical or chemical instruments or more specific devices such as electronic nose, electronic tongue, and visual analyzer.
- Sensory panel evaluation leads to human evaluations expected to be representative of the satisfaction or dissatisfaction of plastics part users.

1.1.9.2 Visual Aspect

Color may be obtained by adding colorants to compounds, or encapsulating the part with a continuous film of another colored or printed polymer: in mold decoration (IMD), painting, multilayer sheets for thermoforming… Color ages as other properties. Discoloration comes from overheating, light exposure, irradiation, chemical attack…

Clarity and transparency are intrinsic properties of polymers but can be degraded by certain additives or enhanced by adding clarifiers.

Haze is the cloudy appearance of a transparent polymer caused by light scattering. Haze may appear after long exposure to moisture.

The refractive index of a polymer is defined as the ratio of the speed of light in vacuum divided by the speed of light in the substance.

Matting may be obtained by adding special mineral fillers, another secondary polymer that is miscible to a greater or lesser degree with the main polymer, or proprietary additives.

Glossy polymers may be obtained by mold polishing, post-molding into perfectly polished molds, layout of films, IMD, film insert molding (FIM), in mold coating, painting…

The choice of a solution depends on numerous parameters concerning the nature of the polymer such as the processing constraints (notably heat exposure, mixing technology), end-product esthetics, the durability under service conditions of the end product, relevant regulations, and cost.

Traditional characterization of plastics parts uses color matching cabinets, photocolorimeters, brightness meters, yellowing index, light transmission, and refractometers.

Contrary to photocolorimeters and spectrophotometers that measure an average color and do not actually assess what the human eye sees in the object, Alpha MOS (http://www.alpha-mos.com) proposes its visual analyzer that performs an overall visual evaluation of the different colors and shapes. This evaluation is closer to the consumer vision, thanks to a high-end technology based on in-depth image analysis.

1.1.9.3 Physical Aspect

Manufacture of plastic parts is a complex process, which may lead to various physical defects. Table 1.9 proposes some defects without claiming to be exhaustive.

1.1.9.4 Touch

Touch can be as varied as rubber-like, metallic, or mimicking cloth, wood, and leather. Touch also depends on surface properties such as hardness and surface texture, for example, smooth, highly polished, ground, grained, or textured. Now a soft touch is particularly in fashion.

Touch may be modified by overmolding, surface treatments, FIM, etc.

Touch may be degraded by tack or stickiness of the plastic surface, scratches, cracks, and so on.

1.1.9.5 Odor and Taste Properties and Transfer

Some virgin plastics and recycled grades may develop unpleasant odors during and after processing or after aging. To avoid or reduce that, it is needed to choose odorless grades or to add deodorants or specific fragrances marketed for polymers.

Bactericides or preservatives avoid growth of microorganisms, fungi, and so on, limiting emissions of related odors during service life.

Odor and taste can be tested by traditional physicochemical instruments (gas chromatography, gas chromatography/mass spectrometry, for example), by specific instruments called electronic or e-nose and e-tongue (for example, Alpha-MOS, http://www.alpha-mos.com; Electronic Sensor Technology, http://www.estcal.com/; Sensigent, www.sensigent.com), or by evaluation panels.

For evaluation by panels, ASTM edits E1870-11 Standard Test Method for Odor and Taste Transfer from Polymeric Packaging Film. This test method is designed for use by a trained sensory panel experienced in using an intensity scale or rank ordering and familiar with the descriptive terminology and references associated with the packaging materials. Data analysis and interpretation should be conducted by a trained and experienced sensory professional. This test method should be considered as a screening technique for suppliers and end users to assess flavor impact of packaging films. The application of this test method will result in a performance score or rank data. The determination for suitability of a packaging film for a particular end use should be based on a set of predetermined criteria including the performance score or rank score. Information obtained from the transfer tests can also be used to evaluate the origin of any transferred tastes or odors. The focus of this test method is the evaluation of the plastic in terms of its perceived inherent odor and the transfer of package-related odors or flavors, or both, to water and other model systems (bland food simulants).

1.1.9.6 Noise, Vibration, and Harshness

For example, considering automotive industry, since 20 years, exterior noise emissions of personal cars have been reduced by 8, mainly due to regulations evolutions. As interior noise is decreasing as well, some secondary emission sources previously

Table 1.9 Examples of Physical Defects

Bleed, migration	To give up undesired color by contact with water, solvent, oily products, or other adjacent materials
Bloom	A visible exudation or efflorescence on the surface of a material
Chalking	Powdery residue on the surface of a material often resulting from degradation
Concentricity	Shape in which various cross-sections have a common center
Crater	A small, shallow surface imperfection
Crazing	Tiny cracks near or on the surface of plastic materials. Fine cracks may extend in a network on or through a plastic material
Discoloration	Any change from the right color, often caused by overheating, light exposure, irradiation, or chemical attack
Fish eye	Defect in transparent or translucent plastics materials appearing as a small globular mass and caused by incomplete blending of the mass with surrounding materials
Flash	Extra plastic attached to a molding along the parting line; generally it must be removed before the part can be considered finished
Flash line	A raised line appearing on the surface of a molding and formed at the junction of mold faces
Flow line or weld line	A flow line is a mark on a molded part resulting from the meeting of two flow fronts during molding. Generally, this spot has weaker mechanical properties
Flow marks	Wavy surface appearance of an object molded from thermoplastic; caused by improper flow of the resin into the mold
Granular structure	Nonuniform appearance of finished plastic material
Orange skin	Unintentionally rough surface resembling orange peel
Parting line	Mark on a molding where halves of mold met in closing
Resin pocket	Accumulation of resin in a small, localized section visible on molded surfaces
Shark skin	A surface irregularity of a thermoplastic part in the form of finely spaced sharp ridges caused by a relaxation effect of the melt
Sink mark	A shallow depression or dimple on the surface of an injected part due to collapsing of the surface following local internal shrinkage. May also be an nascent short shot
Stress crack	A crack, either external or internal, in a plastic caused by tensile stresses less than its short-time mechanical strength
Sweating	Exudation of small drops of liquid, usually a plasticizer or softener, on the surface of a plastic part
Thermal stress cracking	Crazing or cracking which results from overexposure to elevated temperatures
Weld lines	A mark on a plastic part caused by incomplete fusion of two streams of molten polymer
Weld mark	A mark on a molded plastic piece made by the meeting of two flow fronts during the molding operation

masked by the most dominant sources are now emerging. Among these sources, we find fuel tank slosh noise caused by fuel wave motion inside the tank, and fuel pump noise.

Generally speaking, conventional plastics have sound and vibration dampening properties that conventional metals have not. But plastic parts can also initiate unwanted noises by vibration. For example, certain automotive parts can vibrate at frequencies of engine rotation. Plastics rubbing on other plastics or various materials can also emit annoying noises.

The noise testing seems easy at a first glance but, in fact, is very complex due to its dependence of the frequency; the mode of propagation (air, transmission by solids…); the psychological aspects entering in the perception of noise; the diversity and heterogeneity of the standards; the application to specific areas such as automotive, building, aeronautic, household appliances, air conditioning, and others. Noise measurements must be carried out by skilled laboratories or staffs, thanks to special devices such as reverberant chamber, progressive wave tube arrangement, reverberation chambers, anechoic or semianechoic chambers, high-precision acoustic power generators… Measurement methods are as varied as sound power levels, sound energy levels, sound transmission loss (STL); acoustic sensitivity, impact sound insulation, emission sound pressure levels, impact sound insulation between rooms, transmission of indoor sound to the outside; buzz, squeak and rattle testing (BSR), an automotive acoustic test for determining fit and wear of vehicle components as they are perceived acoustically; and many other methods and procedures.

The brief sampling (see Table 1.10) of ISO standards for general applications and SAE standards for automotive and transportation markets displays the diversity of measurements, methods, and application areas.

1.1.10 Economics

Polymeric materials are intrinsically expensive, but their use becomes appealing if one takes into account the processing costs, the new technical possibilities that they permit, and the total cost at the end of their lifetime. Of course, the end cost highly depends on the lifetime.

The part cost depends on the used compound, the processing cost, and the recycling possibilities. To solve a same problem, it is sometimes possible to choose between very different economic routes. For example, choose a cheaper polymer and more expensive additives and/or reinforcements.

Figure 1.11 displays the main ins and outs related to economics of plastic parts.

1.1.10.1 Part Costs

The following figures for processing costs are some examples of the orders of magnitude for specific cases; a different context can lead to a very different cost.

For the fully industrialized countries, the average cost of most plastics parts is about €5 ($6.5) in the range of €4.4 ($5.7)–14 ($18) per kg.

For a given processing technology, the processing costs are highly dependent on the following:

- The annual production. For example, for a given part, the cost per unit for an annual production of 100,000 parts may be 2.5 times that of the same part produced by 1,000,000 parts per year.
- The size, weight, and shape of the parts. For example, thick walls increase cycle times.
- The mold. Varying greatly on complexity, quality, metal, and size, a mold can cost from $2000 for a simple, single cavity mold, up to $60,000–$100,000 or more for a high production, multicavity mold made with hardened tool steel. It may be more interesting to build a multicavity mold of the same part or a family mold producing a set. For example, for an electronic enclosure, an in-depth study of the mold can lead to a mold with cavities for a front, back, battery door, and a button. Those parts could all be molded at once in a family mold.
- The precision level. High precision parts need reinforced checking, use of special machines and tools, skilled workers, selection of the parts. Obviously the cost increases.
- The material cost.
- The processing difficulties slowing down outputs and increasing wastes. Is it more beneficial to use an expensive compound running well or a cheaper compound more difficult to process?
- The recycling possibilities. Recycling saves material costs as far as prices of virgin resins are soaring. Obviously, there are also environmental advantages.

Table 1.10 Examples of ISO and SAE Standards Dealing with Noise, Vibration, and Harshness

Examples of ISO standards	
ISO 1996-1:2003	Acoustics—Description, measurement, and assessment of environmental noise—Part 1: Basic quantities and assessment procedures
ISO 2671:1982	Environmental tests for aircraft equipment—Part 3.4: Acoustic vibration
ISO 3382-1:2009	Acoustics—Measurement of room acoustic parameters—Part 1: Performance spaces
ISO 3382-2:2008	Acoustics—Measurement of room acoustic parameters—Part 2: Reverberation time in ordinary rooms
ISO 3382-3:2012	Acoustics—Measurement of room acoustic parameters—Part 3: Open plan offices
ISO 3744:2010	Acoustics—Determination of sound power levels and sound energy levels of noise sources using sound pressure—Engineering methods for an essentially free field over a reflecting plane
ISO 5347-15:1993	Methods for the calibration of vibration and shock pickups—Part 15: Testing of acoustic sensitivity
ISO 6721-3:1994	Plastics—Determination of dynamic mechanical properties—Part 3: Flexural vibration—Resonance curve method
ISO 10140-3:2010	Acoustics—Laboratory measurement of sound insulation of building elements—Part 3: Measurement of impact sound insulation
ISO 10846-2:2008	Acoustics and vibration—Laboratory measurement of vibroacoustic transfer properties of resilient elements—Part 2: Direct method for determination of the dynamic stiffness of resilient supports for translatory motion
ISO 10846-3:2002	Acoustics and vibration—Laboratory measurement of vibroacoustic transfer properties of resilient elements—Part 3: Indirect method for determination of the dynamic stiffness of resilient supports for translatory motion
ISO 10846-4:2003	Acoustics and vibration—Laboratory measurement of vibroacoustic transfer properties of resilient elements—Part 4: Dynamic stiffness of elements other than resilient supports for translatory motion
ISO 10846-5:2008	Acoustics and vibration—Laboratory measurement of vibroacoustic transfer properties of resilient elements—Part 5: Driving point method for determination of the low-frequency transfer stiffness of resilient supports for translatory motion
ISO 11201:2010	Acoustics—Noise emitted by machinery and equipment—Determination of emission sound pressure levels at a work station and at other specified positions in an essentially free field over a reflecting plane with negligible environmental corrections
ISO 11202:2010	Acoustics—Noise emitted by machinery and equipment—Determination of emission sound pressure levels at a work station and at other specified positions applying approximate environmental corrections
ISO 11204:2010	Acoustics—Noise emitted by machinery and equipment—Determination of emission sound pressure levels at a work station and at other specified positions applying accurate environmental corrections
ISO 11820:1996	Acoustics—Measurements on silencers in situ

Table 1.10 Examples of ISO and SAE Standards Dealing with Noise, Vibration, and Harshness—cont'd

ISO 15665:2003	Acoustics—Acoustic insulation for pipes, valves, and flanges
ISO/TS 15666:2003	Acoustics—Assessment of noise annoyance by means of social and socioacoustic surveys
ISO 15712-2:2005	Building acoustics—Estimation of acoustic performance of buildings from the performance of elements—Part 2: Impact sound insulation between rooms
ISO 15712-4:2005	Building acoustics—Estimation of acoustic performance of buildings from the performance of elements—Part 4: Transmission of indoor sound to the outside
ISO 17201-3:2010	Acoustics—Noise from shooting ranges—Part 3: Guidelines for sound propagation calculations
ISO 18233:2006	Acoustics—Application of new measurement methods in building and room acoustics
ISO 18437-4:2008	Mechanical vibration and shock—Characterization of the dynamic mechanical properties of viscoelastic materials—Part 4: Dynamic stiffness method
ISO 18437-5:2011	Mechanical vibration and shock—Characterization of the dynamic mechanical properties of viscoelastic materials—Part 5: Poisson ratio based on comparison between measurements and finite element analysis
ISO 26101:2012	Acoustics—Test methods for the qualification of free-field environments
Examples of SAE standards	
J1030	Maximum Sound Level for Passenger Cars and Light Trucks
J1060	Subjective Rating Scale for Evaluation of Noise and Ride Comfort Characteristics Related to Motor Vehicle Tires
J1074	Engine Sound Level Measurement Procedure
J1096	Measurement of Exterior Sound Levels for Heavy Trucks Under Stationary Conditions
J1160	Operator Ear Sound Level Measurement Procedure for Snow Vehicles
J1161	Operational Sound Level Measurement Procedure for Snow Vehicles
J1169	Measurement of Light Vehicle Exhaust Sound Level Under Stationary Conditions
J1207	Measurement Procedure for Determination of Silencer Effectiveness in Reducing Engine Intake or Exhaust Sound Level
J1281	Operator Sound Pressure Level Exposure Measurement Procedure for Powered Recreational Craft
J1287	Measurement of Exhaust Sound Pressure Levels of Stationary Motorcycles
J1400	Laboratory Measurement of the Airborne Sound Barrier Performance of Flat Materials and Assemblies
J1470	Measurement of Noise Emitted by Accelerating Highway Vehicles
J1477	Measurement of Interior Sound Levels of Light Vehicles
J1490	Measurement and Presentation of Truck Ride Vibrations

Continued

Table 1.10 Examples of ISO and SAE Standards Dealing with Noise, Vibration, and Harshness—cont'd

J1492	Measurement of Light Vehicle Stationary Exhaust System Sound Level Engine Speed Sweep Method
J1637	Laboratory Measurement of the Composite Vibration Damping Properties of Materials on a Supporting Steel Bar
J1782	Ship Systems and Equipment Hydraulic Systems Noise Control
J1805	Sound Power Level Measurements of Earthmoving Machinery—Static and In-Place Dynamic Methods
J184	Qualifying a Sound Data Acquisition System
J192	Maximum Exterior Sound Level for Snowmobiles
J1970	Shoreline Sound Level Measurement Procedure for Recreational Motorboats
J2005	Stationary Sound Level Measurement Procedure for Recreational Motorboats
J2103	Acoustics—Measurement of Airborne Noise Emitted By Earthmoving Machinery—Operators Position—Stationary Testing Condition
J247	Procedure and Instrumentation for Measuring Acoustic Impulses from Deployment of Automotive Inflatable Devices
J2521	Disc and Drum Brake Dynamometer Squeal Noise Matrix–Noise Test Procedure
J2531	Impulse Noise from Automotive Inflatable Devices
J2625	Automotive Vehicle Brake Squeal Test Recommend Practice
J2694	Anti-Noise Brake Pads Shims: T-pull Test
J2747	Hydraulic Pump Airborne Noise Bench Test
J2786	Automotive Brake Noise and Vibration Standard Nomenclature
J2805	Measurement of Noise Emitted by Accelerating Road Vehicles
J2825	Measurement of Exhaust Sound Pressure Levels of Stationary On-Highway Motorcycles
J2846	Laboratory Measurement of the Acoustical Performance of Body Cavity Filler Materials
J2883	Laboratory Measurement of Random Incidence Sound Absorption Tests Using a Small Reverberation Room
J2889	Measurement of Minimum Noise Emitted by Road Vehicles
J2920	Measurement of Tire/Pavement Noise Using Sound Intensity
J3002	Dynamometer Low-Frequency Brake Noise Test Procedure
J3013	Friction Material Elastic Constants Determination through FRF Measurements and Optimization
J336	Sound Level for Truck Cab Interior
J34	Exterior Sound Level Measurement Procedure for Pleasure Motorboats
J377	Vehicular Traffic Sound Signaling Devices (Horns)
J47	Maximum Sound Level Potential for Motorcycles
J57	Sound Level of Highway Truck Tires

Table 1.10 Examples of ISO and SAE Standards Dealing with Noise, Vibration, and Harshness—cont'd

J671	Vibration Damping Materials and Underbody Coatings
J88	Sound Measurement—Off-Road Work Machines—Exterior
J903	Passenger Car Windshield Wiper Systems
J919	Sound Measurement—Off-Road Work Machines—Operator—Singular Type
J919	Sound Measurement—Off-Road Work Machines—Operator—Singular Type
J986	Sound Level for Passenger Cars and Light Trucks

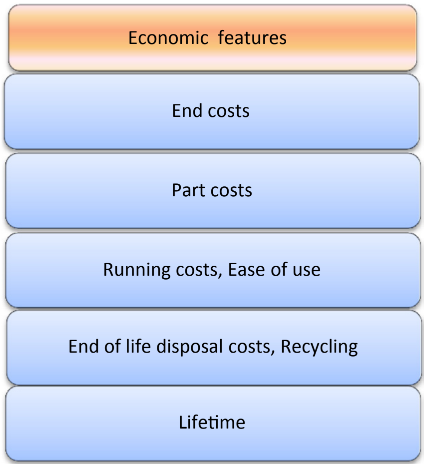


Figure 1.11 Economics: some ins and outs.

For an average part, the injection molding cost of a part may roughly represent the price of the raw polymer. The average selling prices are in the order of:

- €8 ($10)/kg for building purposes
- €12 ($15.6)/kg for consumer goods
- €14 ($18)/kg and more for technical parts.

Each different design of parts requires the machining of a specific mold whose cost (for example, €55,000 ($71,000)) or much more is charged to the series of manufactured parts.

1.1.10.2 Raw Material Costs

The price per liter varies from about €1 to more than €100 according to the nature of the polymer itself, the formulation of the grades, and the inclusion of high-cost reinforcements including carbon fibers and so on.

The highest prices relate to the polymers with the highest performances, which are also the least used. Very broadly speaking, prices per liter increase from commodities up to specialty plastics as follows:

- Commodities: €1 ($1.3) up to €3 ($3.9)
- Engineering plastics: €2 ($2.6) up to €10 ($13)
- Specialty plastics: €4 ($5) up to €50 ($65)
- Fluoroplastics: €20 ($26) up to €180 ($230).

Those data are not rules but examples.

1.1.10.3 Examples of Additive Costs

Apart from the reinforcements, the additives are numerous and some are more expensive than the raw polymer.

Average prices for overall additives are roughly estimated from €1.6/kg ($2/kg) to €2/kg ($2.6/kg) with a broad range of individual prices from less than €1/kg ($1.3/kg) for cheap fillers up to tens of €/kg (or $/kg) for specialty additives.

To solve the same problem, it is sometimes possible to choose between very different economic routes. For example:

- Compatibility between fillers and polymers can be obtained with silanes ranging from €10/kg ($13/kg) up to €20/kg ($26/kg) or with functionalized polymers ranging from €3/kg ($3.9/kg) up to €5/kg ($6.5/kg).
- UV protection can be obtained with cheap specific carbon blacks (but color is gray to black) or with expensive photostabilizers.

The final choice depends on the specifications and the end user's requirements.

1.1.10.4 Examples of Reinforcement Costs

For the global advanced composites market, the average cost of high-performance fiber reinforcements (carbon, aramid, high-modulus polyethylene, boron, R/S/T-glass, and some E-glass) is estimated from €5 ($6.5) to €70 ($90). This moderate price is due to the decrease in the carbon fiber price. Some grades could fall to less than €20 ($26)/kg in the short or medium term.

The price of the fibrous reinforcements depends on the nature of the fibers and the form of the reinforcement: continuous or chopped fibers, mats, rovings, 2D or 3D fabrics or unidirectional.

The prices of fibers cover a large range, which partly explains the weak consumption of fibers other than those of E-glass. For example, without any warranty:

• According to a recent study of Research and Markets (http://www.researchandmarkets.com), the average price of carbon fiber is around $35/kg. Now, low-cost carbon fiber such as Panex 35 by Zoltek Companies Inc. (www.zoltek.com) may be less than $19/kg.	
• Carbon fiber sleeves	€70 ($90) up to €270 ($350)
• Carbon and aramid fiber sleeves	€70 ($90)–€90 ($110)
• Aramid fiber sleeves	€60 ($80) up to €73 ($95)
• Basalt fiber	€25 ($30)
• Glass fiber chopped strand mat	€0.9 ($1.2)
• Fiber glass woven rovings	€0.7 ($0.9) up to €7 ($9)

1.1.10.5 An Economic Requirement: Compensate for Higher Plastic Costs

The cost of a plastic part is generally higher than that of its metal counterpart and the "overspend" must be compensated for by:

- the redesign of the parts, the integration of several functions
- the choice of new assembly technologies that save costs
- the decrease in operating costs.
- the maintenance cost savings, mainly due to corrosion resistance (but beware of aging).

The automotive, aerospace, and railway sectors are excellent examples of the compensation of material overspend by operating cost savings. The weight savings from the use of polymers and composites offer higher performances, increased payload and/or higher speeds, and/or decreased fuel consumption. Consequently, the operating costs are reduced.

The overspending allowed for a traditional solution compared with a polymer solution is roughly:

- 0 per kg gained for common applications
- €300 ($390) per kg gained for a helicopter
- €1200 ($1560) per kg gained for a satellite.

A few examples illustrate these features:

- For surgical parts, the replacement of stainless steel by liquid crystal polymer (LCP) leads to a material cost in the same order, but the ease of LCP processing compared to metal results in a lower final cost. The cost savings are about 50% for some standard parts and up to 90% for high-tech parts.
- Material for endoscopic surgery: two thermoplastics can replace a metal part. A 40% carbon fiber-reinforced polyamide was initially used, which satisfied the mechanical and economic requirements but led to some processing troubles. A glass fiber-reinforced LCP, of very similar properties, was then selected for its great fluidity, which made it possible to mold long parts with thin walls in much shorter cycle times (16 s instead of 26 s). The low thermal dilation coefficient in the direction of the flow is also an advantage. The matrix is more expensive but reinforcement is cheaper and, with a 38% shorter cycle time, the overall cost saving is 42%.
- Framework of load compensator on plane wings: injection molding of carbon fiber-reinforced polyetheretherketone (PEEK) replaces the aluminum alloy previously used. This part plays a critical role in plane safety and must resist the static and dynamic stresses and hydraulic fluids.

The grade selected after many tests has a high fluidity allowing the manufacture of parts with dimensions of 200 mm by 400 mm. With 30% carbon fiber reinforcement, this PEEK grade saves weight; and saves finishing costs because the part is ready for use when it exits the press without finishing operations, in contrast to the metal part; PEEK also improves the behavior with the hydraulic fluids.

- Thermostat casing for automotive cooling system: a new design with PPS makes it possible to integrate 8 of the 12 components of the previous device. The 40% glass fiber-reinforced grade has a medium fluidity that allows injection of complex shapes and resists hot glycols well. Benefits are weight saving, processing, finishing, and assembling cost savings, thanks to the integration of 67% of overall components and the ability to use the plastic part directly at the exit of the press without finishing operations, in contrast to the metal part.
- Replacement of metal bearings by a self-lubricating polymer. Metal bearings must be lubricated and are damaged by accidental breaks in lubrication or by accidental use of aqueous lubricants. Special self-lubricating grades of polyamide imide perform well and modifying the graphite, PTFE or other lubricating filler levels can optimize the performances. If there is any overspending versus metal, it can be compensated for by a lighter weight and the maintenance cost savings thanks to the lubrication break cuts.
- For the electricity and electronics markets, six engineering thermoplastics reinforced with glass fibers and UL94 V0 rated may be used. The designer can choose between four levels of costs, five levels of water absorption, and several levels of mechanical and thermal properties according to the requirements.

1.1.10.6 Effect of Lifetime on Cost

Longer lifetimes allow to reach cheaper end-of-life costs and can reduce the recycling or disposal issues.

For given service conditions, the lifetime depends on the used polymer, the used additives and reinforcements, the processing parameters, and the recycled polymer use. To solve a same problem, it is often possible to choose between very different economic routes. For example, it is possible to choose different strategies such as:

- a cheaper compound leading to a fair lifetime
- an expensive compound based on a high-performing polymer leading to a longer lifetime and, at end, a cheaper end-of-life cost.

1.1.11 Lifetime and End-of-Life Criteria

Designers using polymer-based materials are increasingly requiring for assurance of product lifetime, particularly for components that cannot be easily inspected or may fail in service leading to disastrous hazards. While the life expectancy of products in nondemanding applications have traditionally been predicted from previous in-service experience, the use of plastics in long-term or critical applications requires a far better understanding of the failure mechanisms and the use of accelerated aging conditions to generate data usable in predicting models.

Lifetimes are rigidly linked to end-of-life criteria, which leads to two major issues.

- All the selected properties age at different rates and the lifetime is reached when one (or several) property leads to a part failure. Mechanical performances, heat, and low-temperature behaviors are rarely forgotten but aging of some other characteristics are sometimes neglected. Let us quote, for example, without claiming to be exhaustive, sensory properties, electrical and fire behaviors, weathering, and chemical issues.
- Other points difficult to control are the end-of-life criteria because the actual conditions of use are unknown or specifications for use are not followed by the user.

For given conditions of application, the lifetime depends on the used polymer, the used additives and reinforcements, the processing parameters, and the recycled polymer use. To reach a same lifetime, it is often possible to choose between very different technical routes. For example, it is possible to choose opposite strategies such as, on the one hand, a cheap polymer and expensive protective agents and, on the other hand, an expensive compound without use of additives.

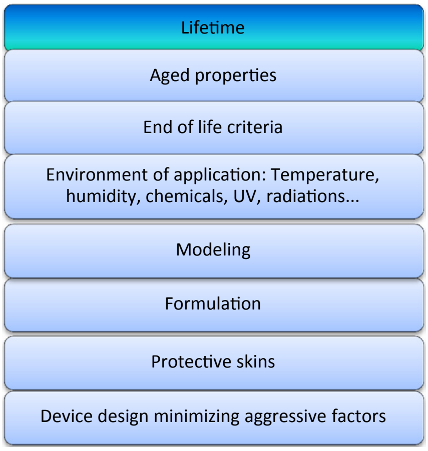


Figure 1.12 Lifetime: some ins and outs.

All properties including sensory properties degrade during aging, which may limit the lifetime of plastics parts still having satisfactory mechanical properties. A multitude of properties are not previously listed but may be occasionally encountered such as, for example, without claiming to be exhaustive, biological degradation, thermal conductivity, antimicrobial behavior, microwave transparency, plating, painting or printing ability, X-ray opacity, and sterilization resistance.

Biological degradation is not a common form of degradation as most commonly used traditional thermoplastics are resistant to microbiological attack. Until recently, the only cases of biological attack influencing the lifetime were related to certain polyurethanes and some low-molecular-weight additives in PVC. However, some biodegradable plastics are developing and the biodegradation must be more in-depth considered. Some standards deal with biological resistance.

Last but not least, longer lifetimes allow to reach cheaper end-of-life costs and can reduce the recycling or disposal issues.

Figure 1.12 displays the main ins and outs related to plastic part lifetimes.

1.1.11.1 Environment of Service

Generally speaking:

- Other parameters being unchanged, a mechanical loading reduction generally leads to an increase in the lifetime
- Higher temperatures speed up aging
- Lower temperatures decrease impact resistance but slow down the chemical aging
- Humidity can speed up aging of certain polymers as far as the temperature is higher
- Chemicals speed up aging but sometimes some chemicals protect polymers from oxygen
- Environmental stress cracking speeds up degradation of sensitive polymers
- Weathering and UV exposure speeds up aging according to the type of the used polymer. It must be noticed that weathering is highly dependent on the country of service
- High-energy radiations speed up degradation but are used to cure certain polymers.

1.1.11.2 Modeling

For long lifetimes, testing in actual conditions is not useable and it is necessary to run accelerated testing in more severe conditions and use mathematical models to predict the lifetime in actual conditions.

Be careful on the accelerated aging conditions: More severe conditions can activate chemical reactions different of those observed at service conditions, which can lead to false predictions. For example, degradation at 150 °C of commodity plastics is not of the same nature as the degradation at room temperature.

Kinetics may change during long-term tests in steady conditions. For example, aging kinetics can suddenly evolve with abrupt changes, thresholds, knees or sudden failure, and so on. Generally speaking, it must be noticed that a mathematical model is an equation giving a result in all cases. In real life, results can be completely different and the part may fail when the model predicts a longer life. The user must be aware of those risks. So, certain predictions can be disastrous, leading to completely false estimations. In the optimistic cases, modeling can save time and money by reducing trials and property testing. The mathematical laws binding the effect of one property and a parameter such as time suppose that the property continuously evolves without abrupt changes. So, it is necessary to multiply the number of different models. A first step will model the first phase of kinetics, a second step will model the first "accident" (knee or other abrupt change of kinetics), a third step will model the second smooth phase of kinetics, etc. These laws cannot predict thresholds or knees or sudden failure and so on. These phenomena must be specifically modeled.

1.1.11.3 Lifetime Enhancement Thanks to Part Protection and/or Minimization of Aggressive Factors

Smart design can minimize the intensity of the aggressive factors. For example, a device can be set up further from the heat source; a plastic part can be hidden by another device or part to obviate light or UV degradation…

Polymers can be protected, thanks to a smart formulation including protective additives or by shielding with another material, metal, or other polymer, resistant to the aggressive factor.

The protective additives can be, for example, processing stabilizers, antioxidants, light and UV stabilizers, UV absorbers, hydrolysis stabilizers, FRs, etc.

Coatings, films, overmolding or co-molding with another thermoplastic, surface treatments, painting, and metallization isolate the thermoplastic from surroundings, allowing to obtain surface properties completely different from those of the core and vice versa.

Two inherent problems for coatings are the permanent cohesion between the treated part and the coating, the abrasion and wear of thin films, and coatings occurring in service.

1.1.12 Regulation, Health, and Safety Requirements

The following is a limited and incomplete reminder. The reader must search the suitable standards, regulations, directives, approvals, laws… related to his own case and is solely responsible for the chosen solutions.

Design, processing, and application of thermoplastics and composites are professional activities needing specific skills and involving industrial and financial risks, health hazards, toxicity, fire hazards, regulation compliance, etc. Standards, directives, regulations, approvals, laws, codes… depend on the regions of processing, commercialization, use and application, and disposal.

Beware of names and acronyms that can cover different requirements according to countries or industrial sectors. For example, for a same part, requirements can be different in the country of processing and in the country of commercialization.

It is the responsibility of the reader to search, study, and verify the compliance of the chosen solution with processing rules; safety precautions; health hazards; existing national and corporate laws and regulations emitted by countries of processing, commercialization, use, and application; and disposal.

Regulations and specifications including general regulations related to industrial and commercial activities concern workers at all steps of the part life, users and all people implied in handling, processing, storage, disposal, etc.

Of course, in addition to rule compliance, prototypes and tests under operating conditions are essential.

Figure 1.13 displays some ins and outs related to plastic regulations, standards, directives, approvals, laws, etc.

Government and private agencies have specifications and approval cycles for many plastic parts. For instance, for the USA, a few examples of US agencies include, without claiming to be exhaustive:

- Underwriters' Laboratories (UL) for electrical devices
- Military (MIL) for military applications
- Food and Drug Administration (FDA) for applications with food and bodily fluid contact
- United States Department of Agriculture (USDA) for plastics in meat and poultry equipment
- National Sanitation Foundation Testing Laboratory, Inc. (NSF) for plastics in food-processing and potable-water applications
- USP—U.S. Pharmacopeia Convention (http://www.usp.org/)
- Federal Aviation Administration (FAR)
- U.S. Fire Administration (USFA)
- U.S. Department of transportation, National Highway Traffic Safety Administration (NHTSA) that issue Federal Motor Vehicle Safety Standards (FMVSS)
- And many others.

Figure 1.13 Regulations, standards, directives, approvals, laws, etc.: some ins and outs.

Generally speaking, be aware of the following points among others:

- International or national standards can be mandatory or not.
- Two standards or specifications can seem similar but some details can be different and results can be different.
- Always check for compliance and approval from appropriate agencies.
- Corporate associations have also their standards and specifications such as building or medical sector.
- A name or acronym can relate to several standards, regulations, directives, approvals, laws… For example, REACH may be an European Directive but also a China regulation dealing with new chemical substance notification to the Chemical Registration Centre (CRC) of the Ministry of Environmental Protection (MEP) for the new chemicals irrespective of annual tonnage, i.e., chemicals other than the approximately 45,000 substances currently listed on the Inventory of Existing Chemical Substances Produced or Imported in China (IECSC).
- Private companies can also have specific standards and specifications such as automakers and aircraft manufacturers.

1.2 Checklist Proposal

We propose a checklist of usual questions; it is the responsibility of the reader to choose those adapted to his own problem and to give suitable answers understandable by the converter. The difference of language between the designer and the converter is often a cause of failure to understand. The reader must also add special questions linked to his own particular case.

The order of the following checklist and the examined parameters must be adapted to your own part study.

Each parameter is deliberately repeated several times according to the combinations of factors. Generally speaking, most crucial properties are first studied.

Overestimated requirements lead to outperforming thermoplastics, more expensive parts, higher weights…

Underestimated requirements lead to unacceptable properties, premature failures, expensive repairs, operating losses…

Undefined properties lead to uncertain reliability, risks of inability to the targeted functions, premature failures, expensive repairs, operating losses…

1.2.1 Mechanical Loading

Table 1.11 proposes a related checklist without claiming to be exhaustive.

Table 1.11 Mechanical Loading

Initial requirements	Temperature: minimum, average, maximum	Time: sudden; short up to long term
Static loading type	Tensile, flexural, compression	Strain rate, high speed rate
Impact behavior	Method, notched, unnotched, special	Temperature, speed
Hardness	Procedure	Time, temperature
Long-term requirements	Time, temperature	Equivalent temperature/time
Creep, relaxation	Tensile, flexural, compression	
Dynamic fatigue	Minimum, average, maximum load Stress or strain Frequency, cycle type	Duration, temperature
Dimensional variations	Maximum acceptable deformations	Recovery
Special loading	Multiaxial, wear, others…	
Combination with other parameters	Esthetic, chemicals, ESC, electric current, weathering, UV	
Lifetime	End-of-life criteria	

1.2.2 Heat

Table 1.12 proposes a related checklist without claiming to be exhaustive.

1.2.3 Low Temperatures

Table 1.13 proposes a related checklist without claiming to be exhaustive.

1.2.4 Dimensional Features

Table 1.14 proposes a related checklist without claiming to be exhaustive.

1.2.5 General Environmental Trends, Pollution of Near Environment, Green Attitude, and Sustainability

Table 1.15 proposes a related checklist without claiming to be exhaustive.

1.2.6 Electrical Properties

Table 1.16 proposes a related checklist without claiming to be exhaustive.

Table 1.12 Heat

Service and storage temperatures/time	Minimum, average, maximum, cycles	Equivalent temperature/time
Thermal expansion	Acceptable maximum deformation	Temperature range
Aging	Temperature, time	Degradation criteria
Long-term dimensional variation	Acceptable deformations	Temperature, time
Glass transition temperature	Procedure	
Heat deflection temperature (HDT)	Method, applied load	
Vicat softening temperature (VST)	Method, applied load	
Aging cycles	Heat/wet/cold Salt spray	Time, cycles Temperature/time/cycles
Thermal shock	High and low temperatures, cycle times	
Combination with other parameters	Humidity, weathering, UV, loading, dimensional variations, chemicals…	
Lifetime	End-of-life criteria	

Table 1.13 Low Temperatures

Service and storage/time	Temperatures: minimum, average, maximum, cycles	Time
Impact at low temperature	Brittle point	Method
Dimensional variation	Maximum retraction	Temperature range
Mechanical properties at low temperature	Tensile, flexural, compression Creep, relaxation	Temperature
Glass transition temperature	Method	
Crystallization	Long-term evolution	Temperature, time
Thermal shock	High and low temperatures, cycle times	

Table 1.14 Dimensional Features

Thermal expansion and retraction	Temperature: minimum and maximum	Differential CTE with other material in contact
Shrinkage	Mold shrinkage Postmolding shrinkage	Annealing
Loading	Tensile, flexural, compression Creep, relaxation Uniaxial, isostatic	Temperature/time
Warpage	Temperature/time effects Residual internal stresses Anisotropic absorption and/or desorption	Annealing
Water or chemicals uptake	Immersion, splash, spray Immersion/emersion cycles High-pressure gases	Temperature/time
Short- and long-term aging, desorption, bleeding, releasing of organic components	Temperature/time Fluid pressure Vacuum	

Table 1.15 General Environmental Trends, Pollution, Green Attitude, and Sustainability

Global warming	Greenhouse effect of emitted gases Nature and level of gases	
Pollution of air, water, land	Nature and level of pollutants	
Water or chemicals uptake	Time/temperature	Pressure
Aging, desorption, bleeding, releasing of organic components	Nature and level of organic components Time/temperature	
Volatile organic compounds (VOCs)	Nature and level of VOCs Time/temperature	Pressure
Banned or regulated or suspect substances	Regulations, standards, directives, approvals, laws, etc.	
REACH compliance	Involved countries	
Specific regulations or specifications, RoHS, WEEE…	Involved countries	
Use of recycled materials	Maximum level	Beware of regulations
Renewable content or biocarbon content	Standards	
(Bio)Degradable plastics	Beware of definition	
Carbon footprint	Beware of calculation	

Table 1.16 Electrical Properties

Material type	Insulator, conductive, ESD, EMI/RFI, antistatic	Current frequency/temperature/humidity
Electrical resistivity	Bulk or/and surface resistivity	Current frequency/temperature/humidity
Dielectric constant		Current frequency/temperature/humidity
Loss factor		Current frequency/temperature/humidity
Dielectric strength		Current frequency/temperature/humidity
Arc resistance		Current frequency/temperature/humidity
High voltage arc tracking rate (HVTR)		Current frequency/temperature/humidity
Fire behavior, smoke	Part thickness, method Countries, application sectors	Regulations, standards, directives, approvals, laws, etc.
Aging	Current frequency, temperature, moisture, time Chemicals Static and dynamic loading	
Regulations	Temperature/time/current frequency, part thickness	Banned products Disposal Recycled polymer use

1.2.7 Fire Behavior

Table 1.17 proposes a related checklist without claiming to be exhaustive.

1.2.8 Sensory Properties

Table 1.18 proposes a related checklist without claiming to be exhaustive.

1.2.9 Economics

Table 1.19 proposes a related checklist without claiming to be exhaustive.

1.2.10 Lifetime and End-of-Life Criteria

Table 1.20 proposes a related checklist without claiming to be exhaustive.

1.2.11 Regulation, Health, Safety, and Fire Requirements

Table 1.21 proposes a related checklist without claiming to be exhaustive.

1.2.12 Other Specific Properties Not Listed Above

Examples of specific properties among others without claiming to be exhaustive:

- antiblocking, blocking
- antifogging
- antifriction, tribological
- antimicrobial, microbicidal
- antirodent
- antisliding, sliding
- antislipping, slipping
- clarified
- clean
- copper stabilized
- cross-linked, cured
- cryogenic temperature
- delayed crystallization
- detergent stabilized
- dirt repellent
- drug contact

Table 1.17 Fire Behavior

Region of processing	Agency, administration, corporate association, department, ministry	Recognized testing organisms
Region of commercialization	Agency, administration, corporate association, department, ministry	Recognized testing organisms
Region of use	Agency, administration, corporate association, department, ministry	Recognized testing organisms
Documents	Standards, directives, regulations, approvals, laws, codes, etc.	Recognized testing organisms
Sector of application	Automobile, aerospace, building, medical, transport, etc.	Recognized testing organisms
UL94 fire ratings	Part thickness Aging	Procedure, recognized testing organisms
Other corporative regulations	Building, aeronautics, transportation, etc.	Country, procedure, recognized testing organisms
Smoke	Opacity, toxicity, corrosivity	Country, procedure, sector, recognized testing organisms
Oxygen index		Procedure, recognized testing organisms
Cone calorimeter		Country, procedure, sector, recognized testing organisms
Rate of burning		Country, procedure, sector, recognized testing organisms
Ignition temperature		Country, procedure, sector, recognized testing organisms

Table 1.18 Sensory Properties

Testing methods	Instrumental measurements and sensory panel evaluations	
Visual aspect Initial and aged	Transparent, translucent, opaque Haze Gloss/mat Color Discoloration, chalking, crazing, cracking…	Weathering/UV, wet exposure
Dust loading, clogging	Method	
Mar and scratch resistance	Method	
Physical aspect	Defects, surface roughness	Polished, brushed, grained, textured
Touch	Soft/hard Dry/silky	
Odor and taste properties and transfer	Initial odor and taste Aged odor and taste Transfer of odor and taste	
Noise, vibration, harshness (NVH)	Frequency Maximum sound level Squeal acceptance Sound absorption Damping	

Table 1.19 Economics

Part costs	Cost/performance ratio Processing cost/end-of-life cost	
Polymer costs, additive, and reinforcement costs	Choice between high polymer cost and low polymer cost + high-cost additives	
Smart design	Compliance with plastic drawing rules	Function integration, decrease of part number
Processing cost	Choice between high [cost/more performing] tools and [cheaper/less performing] tools	Multicavity mold, family mold
Production	Long/short runs	Multicavity mold, family mold
Quality requirements	Size, aspect requirements	
End-of-life	Disposal or recycling	
Lifetime/end-of-life criteria	End-of-life cost	

Table 1.20 Lifetime and End-of-Life Criteria

Environment of storage	Temperature, moisture/time	
Environment of service	Temperature, moisture/time	
Mechanical loading	Static/dynamic Stress Creep, relaxation	Temperature, moisture/time
Weathering, UV	Direct, indirect exposure	Temperature, moisture/time
Chemicals	Nature, level, impurities	Temperature/time
Brittleness	Low temperature	
Lifetime enhancement	Part protection and/or smart design	Minimization of aggressive factors
Lifetime prediction	Accelerated aging	Modeling

Table 1.21 Regulation, Health, Safety, and Fire Requirements

Region of processing	Agency, administration, corporate association, department, ministry
Region of commercialization	Agency, administration, corporate association, department, ministry
Region of use	Agency, administration, corporate association, department, ministry
Documents	Standards, directives, regulations, approvals, laws, codes
Sector of application	Automobile, aerospace, building, medical, transport, etc.

- food contact
- gamma ray-resistant
- good organoleptic properties
- heavy compounds, light compounds
- high fluidity
- high molecular weight, ultrahigh molecular weight
- high purity
- hydrolysis stabilized
- IR reflective; IR absorbent
- laser engraving, laser marking
- low extractables
- manganese or cobalt stabilized
- medical applications
- microwave transparency
- NSF compliant
- painting or printing ability
- pharmaceutical applications
- physiological inertia
- radiation resistance
- self-healing
- self-lubricating
- shape memory
- sterilization resistance
- stress cracking resistant…
- thermally conductive
- ultrahigh molecular weight (UHMW)
- ultrahigh refractive index, ultralow refractive index
- water-repellent
- X-ray opacity and
- many other specific properties

1.2.13 Processability

Of course, verify the processability (moldability, extrudability, etc.) of the selected thermoplastics. Some ones cannot be injection molded such as PTFE or polybenzimidazole.

Of course, part size, processing temperatures, and other parameters must be suitable for the used machines and tools.

Further Reading

Web sites

Apme.com, http://www.plasticseurope.org/, http://spmp.sgbd.com.nerdydata.com/, worldsteel.org, www.world-aluminium.org.

Papers

[1] M. Biron, Thermosets and Composites – Technical Information for Plastics Users, Elsevier Ltd, 2013.

2 Thermoplastic Specific Properties

OUTLINE

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00002-7

Polymers have some specific properties due to their organic nature. Thermoplastics (TPs) are independent organic macromolecules with some sensitivity to environmental parameters: temperature, moisture, oxidation, deleterious solids, liquids, gases, and other chemical products. They are also sensitive to mechanical loading, especially cyclic loading. Their specific properties, such as electrical or optical properties, are also important for their applications.

All the properties are influenced by the additives used with the TP matrices, notably the reinforcements but also stabilizers, plasticizers, colorants, and others.

2.1 Do not Confuse Raw Polymer and Plastic Grade (or Compound)

Used TPs (see Figure 2.1) are rarely pure polymers but are more or less complex compounds including numerous additives in addition to the polymer(s). Properties are broadly affected by the elemental composition, chain architecture, molecular weight of the polymer(s), on the one hand, and mixing and alloying with additives and possibly other polymer(s), on the other hand. It is essential to well distinguish between general polymer properties and actual properties of the actual used grade. For computing and final designing, properties to be considered are properties measured on the actual used grade.

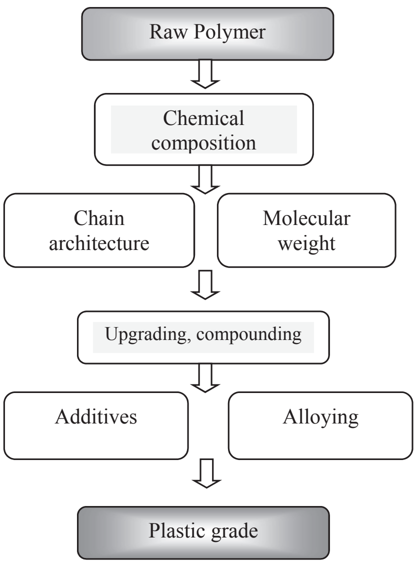


Figure 2.1 Example of ways from the raw polymer up to the actual used grade.

Figure 2.1 reminds example of ways from the raw polymer up to the used grade.

Table 2.1 displays some properties of three subfamilies of polystyrene (PS), a commodity TP. Gray cells point out distinctive properties (better or not) for each subfamily.

General-purpose grades being the reference:

- Impact grade is highly resistant to impact at room and low temperature but other mechanical performances are not so good
- Fire-retardant (FR) grade is rated V0 with a much higher oxygen index. Notched impact strength is fairly better but mechanical performances are not so good and density is higher.

2.2 Raw TPs Are Organic Macromolecules

Plastics are organic macromolecules generally made out of carbon, hydrogen, and some other chemical elements such as oxygen, azote, chlorine, sulfur, fluorine, silicon. All the properties depend on the composition, the chain architecture, the molecular weight, and so on.

2.2.1 Elemental Composition Is Essential

Obviously, carbon and other chemical element content are essential for the plastic feature as we can see in Figure 2.2 showing TPs made out of carbon (C) and hydrogen (H) for polyethylene (PE) and PS, or for more complex molecules containing also oxygen (O) and azote (N).

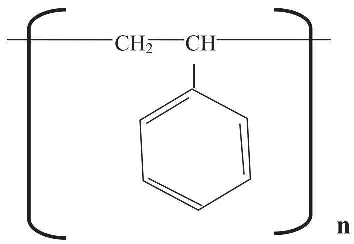
Table 2.2 relates to examples only and cannot be generalized. Data cannot be used for design purposes. General chemical properties are general assessments of behavior for given grades after prolonged immersion in a range of chemicals at room temperature. These results are not necessarily representative of all examined TPs. These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions.

Table 2.1 Polystyrenes: Examples of Properties

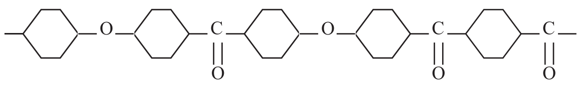
	General Purpose		Impact Modified		Fire-Retardant	
	Minimum	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Miscellaneous Properties						
Density, g/cm^3	1.04	1.05	1.03	1.06	1.13	1.17
Shrinkage, %	0.1	0.7	0.2	0.7	0.3	0.6
Absorption of water, %	0.01	0.04	0.05	0.30	0.05	0.30
Mechanical Properties						
Shore hardness, D	85	90	60	75	60	80
Stress at yield, MPa	35	60	20	40	20	30
Strain at yield, %	1	4			0.9	1
Tensile strength, MPa	35	60	20	45	15	30
Elongation at break, %	1	4	20	65	2	50
Flexural modulus, GPa	2.5	3.5	1.5	3.0	2	2.5
Notched impact strength ASTM D256, J/m	20	25	100	350	60	150
Thermal Properties						
HDT B (0.46 MPa), °C	75	100	75	100	85	100
HDT A (1.8 MPa), °C	70	90	70	80	80	85
Brittle point, °C	20	20	–40	–20	–40	–20
Fire Behavior						
Oxygen index, %	18	19	18	19	28	28
UL94 fire rating	HB	HB	HB	HB	V0	V0

- Polyethylene $-(CH2 - CH2 - CH2 - CH2 - CH2)_n-$

- Polystyrene



- Polyaryletherketones – PAEK



- Polyetherimide - PEI

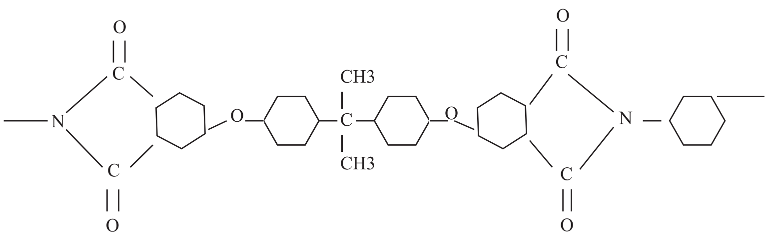


Figure 2.2 Examples of polymer formulas.

Although a limited panel of chemical elements is involved in TP formulas, the composition is a determining factor for properties. For example, property spectrum of commodity and common engineering thermoplastics (ETPs) may be as broad as:

Density	0.917 up to 1.32
Shrinkage, %	0.1 up to 1.1
Shore hardness, D	40 up to more than 95
Tensile strength, MPa	10 up to 100
Tensile modulus, GPa	0.130 up to 3.9
Notched impact strength, J/m	20 up to nonbreak
HDT A (1.8 MPa), °C	30 up to 200

Continuous use temperature, °C	80 up to 250
Glass transition temperature, °C	–110 up to 215
Coefficient of thermal expansion, 10^{-5}/°C	4 up to 20
Dielectric loss factor, 10^{-4}	1 up to 30
Oxygen index, %	17 up to 47
UL94 fire rating	HB up to V0
UV behavior	Unsatisfying up to satisfying
Chemical behavior	Unsatisfying up to satisfying according to chemicals

Table 2.2 Examples of Properties of Different Thermoplastics

	LDPE		PS		PEEK		PEI	
Miscellaneous Properties								
Density, g/cm^3	0.917	0.940	1.04	1.05	1.27	1.32	1.27	1.3
Shrinkage, %	2	4	0.1	0.7	1.1	1.1	0.7	0.8
Absorption of water, %	0.005	0.015	0.01	0.04	0.1	0.5	0.2	0.3
Mechanical Properties								
Shore hardness, D	40	50	85	90	85	>95	95	>95
Rockwell hardness, M			60	75	55	100	109	112
Stress at yield, MPa	10	15	35	60			100	110
Strain at yield, %			1	4			7	7
Tensile strength, MPa	10	20	35	60	70	100	90	100
Elongation at break, %	200	600	1	4	30	150	60	60
Tensile modulus, GPa	0.130	0.300	2.5	3.5	3.6	3.9	3	3
Flexural modulus, GPa	0.245	0.235	2.5	3.5	3.7	3.9	3	3.3
Notched impact strength ASTM D256, J/m	Nonbreak	Nonbreak	20	25	80	85	50	60
Thermal Properties								
HDT B (0.46 MPa), °C	40	50	75	100			195	210
HDT A (1.8 MPa), °C	30	40	70	90	140	160	190	200
Continuous use temperature, °C	80	100	65	80	250	250	170	180
Glass transition temperature, °C	–110	–110	90	90	143	143	215	215
Coefficient of thermal expansion, 10^{-5}/°C	10	20	5	8	4	6	5	6
Electrical Properties								
Volume resistivity, ohm·cm	10^{16}	10^{18}	10^{16}	10^{17}	10^{16}	10^{17}	10^{15}	10^{17}
Dielectric constant	2.3	2.3	2.4	2.7	3.2	3.2	3.1	3.2

Continued

Table 2.2 Examples of Properties of Different Thermoplastics—cont'd

	LDPE		**PS**		**PEEK**		**PEI**	
Loss factor, 10^{-4}	3	4	1	28	30	30	13	25
Dielectric strength, kV/mm	16	28	16	28	20	20	28	33
Fire Behavior								
Oxygen index, %	17	18	18	19	24	35	47	47
UL94 fire rating	HB	HB	HB	HB	V1	V0	V0	V0
	PE		PS		PEEK		PEI	
Light	UV stabilizers and/or black color are needed		Risks of yellowing and embrittlement		UV-sensitive, needs efficient stabilization		UV- and hydrolysis-resistant	
Weak acids	Good behavior		Good behavior		Good behavior		Good behavior	
Strong acids	Good behavior except oxidizing acids		Good to limited behavior except oxidizing acids		Attacked by oxidizing and concentrated acids		Good behavior with dilute acids	
Weak bases	Good behavior		Good behavior		Good behavior		Good behavior limited to pH<9	
Strong bases	Good behavior		Good behavior		Good behavior		Behavior limited to pH<9	
Food contact	Possible for special grades		Possible for special grades		Possible for special grades		Possible for special grades	

2.2.2 Molecular Weight and Chain Architecture Are Also of High Importance

Albeit having a simple chemical formula, $–(CH_2–CH_2)_n–$, PE is a broad family with versatile properties (see Table 2.3) that depend on the molecular weight and the used polymerization process:

- Free radical vinyl polymerization, the oldest process, leads to branched low-density polyethylene (LDPE). Macromolecules have numerous short branches, which reduce the melting point, tensile strength, and crystallinity. Polymers are relatively flexible because of the high volume of the branched molecule and the low crystallinity.
- Ziegler–Natta polymerization leads to linear unbranched PE, the so-called high-density polyethylene (HDPE), which is denser, tougher, and more crystalline. By copolymerization with other alkenes, it is possible to obtain linear low-density polyethylene (LLDPE) with better mechanical properties than LDPE. Blends of LLDPE and LDPE are used to combine the good final mechanical properties of LLDPE and the strength of LDPE in the molten state.
- Metallocene catalysis polymerization is the most recent technique, growing fast to produce a consistent, uniform distribution of molecular weight resulting in enhanced toughness, impact and puncture strengths, better cold behavior, and optical properties. These advantages allow the downgauging or enhancement of performances for the same weight of polymer. Metallocene catalysis allows for the production of all densities, from ultralow density to ultrahigh-molecular-weight PEs.
- Ultrahigh-molecular-weight polyethylene (UHMWPE) having molecular weights in the order of approximately 3,000,000 (and higher) that is to say 10 times more than previous PE.

2.3 Supramolecular Structure

2.3.1 TPs and TP Elastomers

2.3.1.1 Thermoplastics

TPs have the simplest molecular structure, with chemically independent macromolecules (Figure 2.3). By heating, they are softened or melted, then shaped, formed, welded, and solidified when cooled. Multiple cycles of heating (at suitable temperatures) and cooling can be repeated without severe damage, allowing reprocessing and recycling.

Often some additives or fillers are added to the TP to improve specific properties such as thermal or chemical stability and UV resistance.

TP consumption is roughly 80% or more of the total plastic consumption.

Alloys of compatible TPs allow applications benefiting from the attractive properties of each polymer while masking their defects.

Some TPs are cross-linkable and are used industrially in their two forms, thermoplastic and thermoset; for example, PEs or vinylacetate-ethylene (VAE) copolymers (the links created between the chains limit their mobility and possibilities of relative displacement).

Advantages of TPs:

- The softening or melting by heating allows for welding and thermoforming.
- The processing cycles are very short because of the absence of the chemical reaction of cross-linking.
- Processing is easier to monitor, because there is only a physical transformation.
- TPs do not release gases or water vapor if they are correctly dried before processing.
- The wastes are partially reusable as virgin matter because of the reversibility of the physical softening or melting.

Disadvantages of TPs:

- When the temperature rises, the modulus retention decreases, due to the absence of chemical links between macromolecules.
- For the same reason, the creep and relaxation behaviors are not as good as for the thermosets.
- During a fire, fusibility favors dripping and annihilates final residual physical cohesion.
- There are few materials workable in the liquid state.

The "pyramid of excellence" (see Figure 2.4) arbitrarily classifies the main families of TPs according

Table 2.3 Examples of Properties of Different Polyethylenes

	LDPE	Linear PE	HDPE	UHMWPE
Miscellaneous Properties				
Density, g/cm^3	0.917–0.940	0.915–0.950	0.940–0.970	0.930–0.950
Shrinkage, %	2–4	2–2.5	1.5–4	4.0
Absorption of water, %	0.005–0.015	0.005–0.010	0.005–0.010	0.005–0.010
Mechanical Properties				
Shore hardness, D	40–50	55–56	60–70	60–70
Stress at yield, MPa	10–15	10–30	25–30	20–25
Strain at yield, %		3–16	10–15	
Tensile strength, MPa	10–20	25–45	30–40	39–49
Elongation at break, %	200–600	300–900	500–700	200–500
Tensile modulus, GPa	0.130–0.300	0.266–0.525	0.500–1.100	0.3–1
Flexural modulus, GPa	0.245–0.235	0.280–0.735	0.750–1.575	0.4–1
Notched impact strength ASTM D256, J/m	NB	54 to NB	20–220	NB
Thermal Properties				
HDT B (0.46 MPa), °C	40–50		60–90	68–82
HDT A (1.8 MPa), °C	30–40		44–60	40–50
Continuous use temperature, °C	80–100	90–110	80–120	100–120
Glass transition temperature, °C	–110	–110	–110	–110
Melting temperature, °C	110–120	122–124	130	120–135
Minimum service temperature, °C	–70	–70	–70 to –100	–150 to –200
Thermal conductivity, W/m.K	0.32–0.35	0.35–0.45	0.40–0.50	0.4–0.5
Specific heat, cal/g/°C	0.55	0.55	0.55	0.55
Coefficient of thermal expansion, 10^{-5}/°C	10–20		6–15	13–20
Electrical Properties				
Volume resistivity, ohm·cm	10^{16} to 10^{18}	10^{16} to 10^{18}	10^{16} to 10^{18}	10^{16} to 10^{18}
Dielectric constant	2.3	2.3	2.3	2.1–3
Loss factor, 10^{-4}	3–4		2–20	2–10
Dielectric strength, kV/mm	16–28		17–45	25–45
Fire Behavior				
Oxygen index	<20	<20	<20	<20
UL94 fire rating	HB	HB	HB	HB

to their performances, consumption level, and degree of specificity:

- PE, PP, PVC, PS: commodity TPs
- ABS, SAN: copolymers with more specific applications
- PA, PC, PMMA, POM, PPE, PET, PBT…: ETPs
- PSU, PEI, PPS…: ETPs with more specific performances
- ETFE, PEEK: high-tech uses, limited consumption
- LCP, PTFE, PFA, FEP, PI: high-tech uses, more limited consumption
- PBI: highly targeted uses and very restricted consumption.

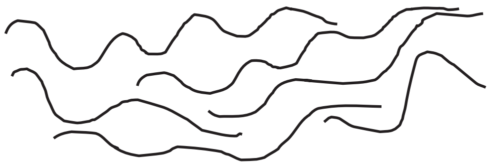


Figure 2.3 Schematic structure of a thermoplastic.

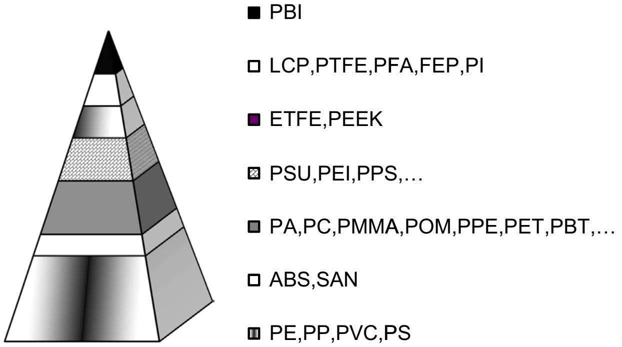


Figure 2.4 Pyramid of excellence for some thermoplastic families.

2.3.1.2 Thermoplastic Elastomers

Thermoplastic elastomers (TPEs) are copolymers or compounds of TPs and rubber.

The elasticity of TPEs (Figure 2.5(a) and (b)) comes:

- either from the structure of the macromolecules with alternating soft and hard segments, the latter gathering together to constitute the nodes of a physical lattice; or
- from a dispersed phase of soft elastomer, vulcanized or not, forming microscopic droplets in a continuous phase of a hard TP. This structure allows for processing in accordance with TP techniques. The rubber provides elasticity.

TPEs account for roughly 1% of total plastic consumption.

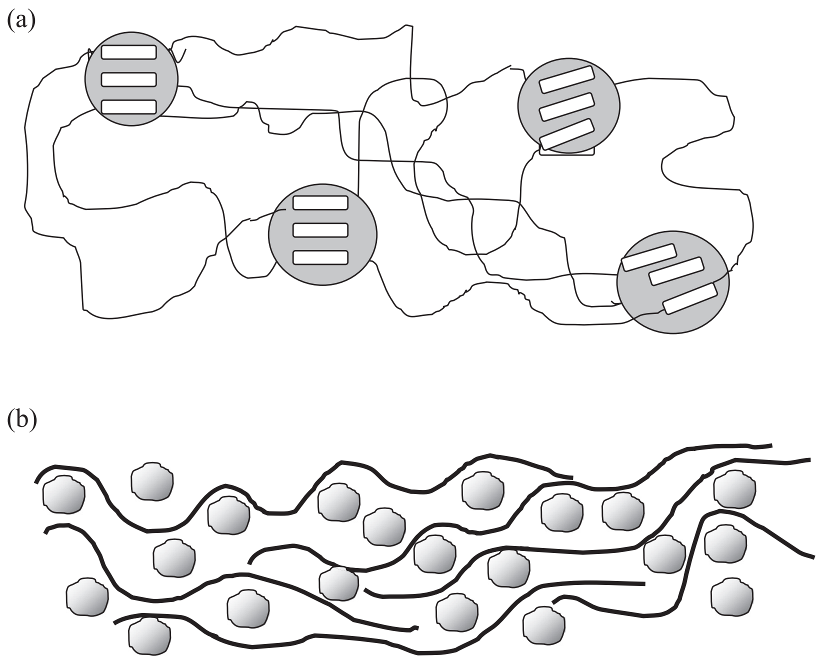


Figure 2.5 Schematic structure of thermoplastic elastomers: (a) Copolymer with hard segments arranged in domains; (b) Compound of rubber particles dispersed in thermoplastic matrix.

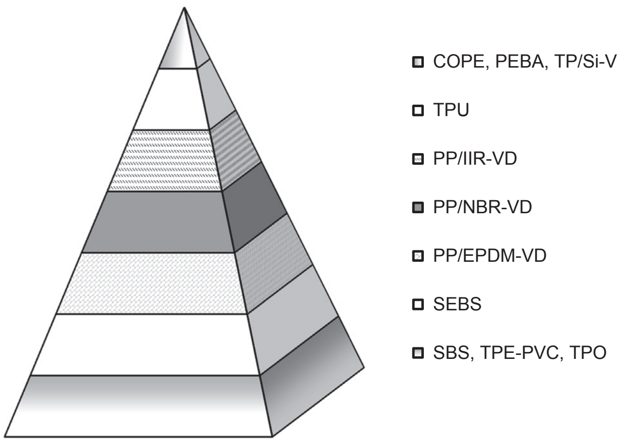


Figure 2.6 Pyramid of excellence for some thermoplastic elastomer families.

They lead to a combination of interesting properties:

- elasticity in a limited range of temperatures
- ease of TP processing without curing and, often, without a mixing step
- ease of recycling as for all the TPs.

On the other hand, their mechanical properties decrease as the temperature rises because of their thermoplasticity.

The "pyramid of excellence" (see Figure 2.6) arbitrarily classifies the main families of TPEs according to their performances, consumption level, and degree of specificity:

- SBS, TPE-PVC, TPO: the less elastic TPEs, fair thermal resistance
- SEBS: same elasticity but better thermal behavior
- PP/EPDM-V: better elasticity and good thermal resistance
- PP/NBR-V: same elasticity plus oil resistance
- PP/IIR-V: same elasticity plus gas impermeability
- TPU: high mechanical properties
- COPE, PEBA, TPE/Si-V: high performances but high prices.

2.3.2 Thermosets

Thermosets before hardening, like TPs, are independent macromolecules. But in their final state, after hardening, they have a three-dimensional (3D) structure obtained by chemical cross-linking produced after or during the processing (for example, compression or injection molding). Figure 2.7 schematizes the molecular arrangements of these polymers.

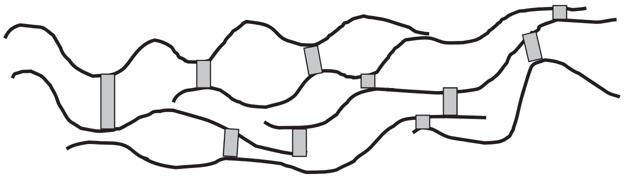


Figure 2.7 Thermoset after cross-linking.

Some polymers are used industrially in their two forms, thermoplastic and thermoset; for example, the PEs or the VAE. Thermoset consumption is roughly 12–20% of the total plastic consumption.

The links created between the chains during the cross-linking limit their mobility and possibilities of relative displacement and bring certain advantages and disadvantages.

Advantages:

- Infusibility: after cross-linking, thermosets are degraded by heat without passing through the liquid state. This improves some aspects of fire behavior: except for particular cases, they do not drip during a fire and a certain residual physical cohesion provides a barrier effect.
- When the temperature increases, the modulus retention is better due to the 3D structure.
- Better general creep behavior, the links between the chains restricting the relative displacements of the macromolecules, one against the other.
- Simplicity of the tools and processing for some materials worked or processed manually in the liquid state.

Disadvantages:

- The chemical reaction of cross-linking takes a considerable time that lengthens the production cycles and, often, requires heating, which is an additional expenditure.
- The processing is often more difficult to monitor because it is necessary to take care to obtain a precise balance between the advance of the cross-linking reaction and the shaping.

Figure 2.8 Micrographs of polypropylene: (left) amorphous; (right) highly crystalline.

- Certain polymers release gases, in particular, water vapor, during hardening.
- The wastes are not reusable as virgin matter because of the irreversibility of the hardening reaction. At best, they can be used like fillers after grinding.
- The infusibility prevents assembly by welding.

2.3.3 Crystalline and Amorphous TPs, Glass Transition Temperature

Polymers can be amorphous (randomly arranged chains), crystalline (well-ordered chains), or semicrystalline (see Figure 2.8).

2.3.3.1 Amorphous Polymers

Amorphous chains of an amorphous polymer are randomly arranged. The degree of crystallinity (the weight fraction or the volume fraction of crystalline material) is zero. Amorphous polymers slowly soften when heated above their glass transition temperature (Tg).

As examples, we can quote among others, polymethylmethacrylate (PMMA), polycarbonate (PC), polyvinylchloride (PVC), styrene acrylonitrile (SAN), acrylonitrile butadiene styrene (ABS), PS, polyphenylene ether (PPE), polysulfone, special amorphous polyamides (PAs), and so on.

When the temperature rises, mechanical properties decrease relatively slowly until the threshold of the glass transition temperature, which is the boundary of their ability to withstand low continuous efforts and also limits their dimensional stability under stress. In the absence of a constraint, dimensional stability can be maintained up to 20–50 °C above the glass transition temperature. Above Tg, these TPs are extremely viscous liquids and it is necessary to reach significantly higher temperatures to sufficiently lower viscosities allowing the extrusion or injection. Only amorphous TPs can be transparent.

2.3.3.2 Crystalline and Semicrystalline Polymers

For crystalline polymers, crystalline chains are ordered into compact domains. The degree of crystallinity is 1.

Most often, polymers are semicrystalline containing regions of 3D ordering and amorphous regions without any order; the degree of crystallinity (weight fraction or volume fraction of crystalline material) ranges from near 0 up to near 1. For a given polymer, the degree of crystallinity depends on the previous thermal history.

The semicrystalline polymers are generally tougher than totally amorphous polymers but are opaque when some amorphous polymers are transparent. Semicrystalline TPs are, for example, PA except some amorphous grades, PE, polypropylene (PP), polyacetal (POM), TP polyester (polyethylene terephthalate (PET) or polybutylene terephthalate (PBT)), and most fluorinated polymers…

They differ from the amorphous polymers by the preservation of a notable percentage (35–50%) of their mechanical properties, beyond the glass transition temperature. The dimensional stability is maintained approximately up to the threshold of the crystalline melting point. Unlike amorphous polymers, the melting temperature is sharp. The glass transition of the amorphous domain leads to significant increases in the coefficient of thermal expansion (CTE), the permeability to oxygen (and others), and oxidation risks. Semicrystalline polymers cannot be transparent.

For a given semicrystalline TP, the crystallinity depends on processing and subsequent thermal conditions. An annealing treatment followed by a slow cooling leads to the increase in the degree of crystallinity that can vary widely for a defined plastic, for example:

• PA6	30–40%
• HDPE	40–70%
• PP	45–75%
• PTFE	50–90%

Generally, increasing crystallinity leads to:

- specific gravity increase
- stiffness increase
- slower modulus decrease when temperature increases
- impact resistance decrease
- impermeability and resistance to chemical product increase
- shrinkage increase.

The following examples of variation of properties with crystallinity relate to low crystalline polyphenylene sulfide (PPS) injected into a cold mold and highly crystalline PPS injected into a hot mold (135 °C).

Crystallinity	Low	High
Flex modulus, GPa	14	15
HDT 1.8 MPa, °C	<244	244
Notched impact	74	58

2.3.3.3 The Glass Transition Temperature (Tg)

For amorphous polymers or amorphous domains of semicrystalline polymers, the glass transition temperature (Tg) is a reversible transition from a hard and brittle state into a molten or rubber-like state. There are sudden and significant changes in the physical properties including the CTE and specific heat. The transition temperature value depends on the testing conditions, notably the cooling or heating rate and the frequency of the measured parameter.

The glass transition temperature is always lower than the melting temperature of the crystalline domains.

Figure 2.9 schematizes modulus variations versus temperature for, on the one hand, an amorphous TP with the drop down when temperature reaches Tg and, on the other hand, for a semicrystalline TP with an additional platen.

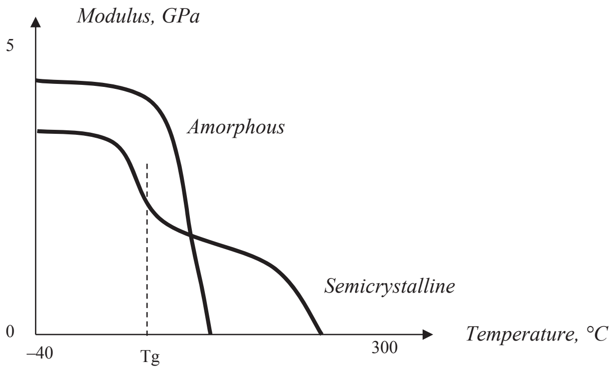


Figure 2.9 Examples of modulus variations versus temperature for an amorphous and a semicrystalline thermoplastics.

2.3.3.4 Crystallization Is Time- and Thermal-Dependent and Is not Homogeneous

Figure 2.10 shows different crystalline states for bulk (left) and skin (right) of an injected PP part:

- in cold mold: skin (right) is clearly amorphous when bulk (left) is slightly crystalline
- in hot mold: the skin (right) is slightly crystalline but less than the bulk (left).

2.4 Viscoelasticity, Time, and Temperature Dependency

Rearrangement of macromolecules in plastics, notably TPs, leads to significant viscoelastic properties that cannot be overlooked as far as temperature rises.

2.4.1 Time Dependency

Table 2.4 displays examples of yield strength, yield strain, and modulus dependence of the strain rate for several amorphous (sample A) or semicrystalline (samples B, C, D, E), neat (samples A, B, C, D), or filled (sample E) TPs. Generally speaking, when the strain rate increases, stress and modulus increase, and strain decreases. Tensile properties being tested at defined strain rates, and data can be different at service strain rate.

For longer load times, creep and relaxation must be taken into account.

Creep is the time-dependent strain induced by a constant mechanical loading. The strain evolves with the stress level, the time for which the stress is applied, and the temperature. The results can be presented graphically in various ways by combining these three parameters or in quantified forms: creep modulus and creep strength, for example. Creep can lead to breaking for levels of stress much lower than ultimate stresses measured by dynamometry. For example, to reach a breaking time superior to 8000 h, a defined glass fiber (GF)-reinforced polyolefin

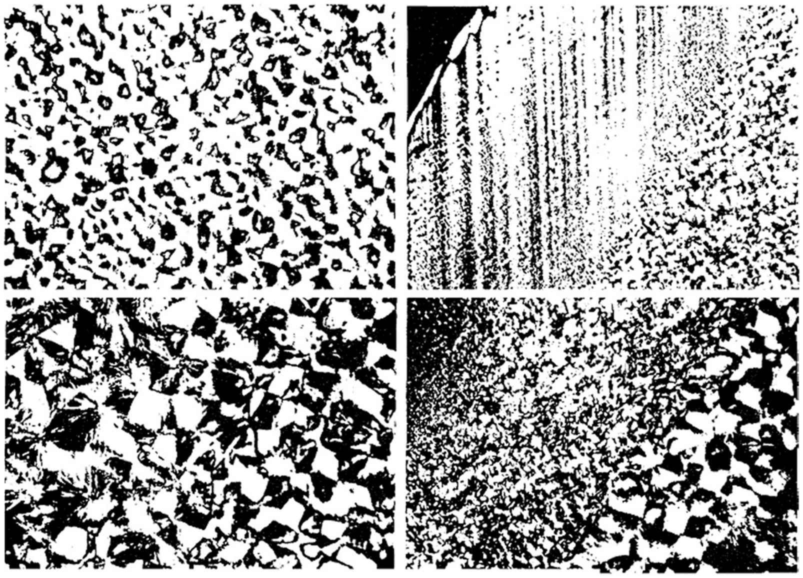


Figure 2.10 Micrographs of polypropylene injected in a cold and a hot mold. PP injected in a cold mold: core is slightly crystalline (left) when skin is amorphous (right). PP injected in a hot mold: core is highly crystalline (left) when skin is less crystalline (right).

cannot be loaded at more than 50% of the tensile strength measured by standardized dynamometry.

Relaxation is the time-dependent stress resulting from a constant strain. The stress evolves with the strain level, the application time, and the temperature. The results of tests at a defined temperature can be presented as a load versus time curve or a stress retention versus time curve. The stress retention for a defined time and temperature is the actual measured stress divided by the original stress at time zero. For example, for a polyolefin, under a 2% elongation at room temperature, the stress retention after 1000 h (42 days) is about 67%.

2.4.2 Temperature Dependency

Figure 2.9 shows evolutions of moduli for temperatures evolving from −40 °C up to more than 200 °C. Table 2.5 displays examples of yield strength, yield strain, and modulus dependence of temperature for several amorphous or semicrystalline, neat, or filled TPs. Generally speaking, when the temperature increases, stress and modulus decrease. Tensile properties being generally tested at room temperatures, and data can be very different at service temperature. It must be pointed out that significant property changes between 20 °C and temperature as low as 50 °C.

When temperature decreases below room temperature, tensile strength generally increases, elongation decreases, and the material becomes brittle.

For some materials, properties at 10 °C and 30 °C are significantly different from those tested at room temperature.

2.5 From Raw Polymers to Actual Grades: Upgrading and Customization

Each raw polymer has its set of interesting properties that can be modified in order to adapt to the requirements of each customer and application. Several routes are suitable:

- alloying of two compatible (or compatibilized) TPs
- compounding with additives.

The upgrading of service properties mainly concerns:

- reinforcement: strength and modulus improvement
- durability: stabilization, aging resistance, UV protection, hydrolysis…
- low-temperature behavior, flexibility…: plasticization
- toughening: impact strength improvement
- sensory properties: color, gloss, odor…
- cost
- possibly, some specific characteristics such as fire behavior, electrical or thermal characteristics, magnetic or tribological properties, biodegradability…

Figure 2.11 illustrates some examples of solutions to customize basic polymers.

Table 2.4 Tensile Properties at Room Temperature versus Strain Rate

	Strain Rate						
	mm/min	**min^{-1}**	**Yield Stress, MPa**	**Yield Strain, %**	**Stress at Break, MPa**	**Strain at Break, %**	**Modulus, GPa**
Amorphous A	5		49	Some %	51	175	
Amorphous A	200		52	Some %	49	120	
Amorphous A	1200		70	Some %	50	30	
Amorphous A	60,000		90	Some %	82	5	
SC B	5		70	15			
SC B	50		75	15			
SC C	5		63	11			
SC C	50		68	11			
SC D	30	5	35	13			1.6
SC D	300	50	38	10			1.8
SC D	3000	500	40	9			1.9
Filled SC E	30	5	27	2.3			7.7
Filled SC E	300	50	28	2.1			7.7
Filled SC E	3000	500	30	2			9
SC semicrystalline							

Table 2.5 Tensile Properties at Low Strain Rate versus Test Temperature

	Temperature, °C	Yield Stress, MPa	Yield Strain, %	Stress at Break, MPa	Strain at Break, %	Modulus, GPa
A	20	70	15	51	175	
A	50	63	11			
A	100	35	8			
F	20	35	13			1.6
F	50	26	16			0.8
F	75	18	17			0.4
F	100	15	15			0.2
G	20	27	2.3			7.7
G	50	20	2.6			5
G	75	15	3			3
G	100	12	10			0.5
H	20			85		3.8
H	100			51		3.1
H	150			25		2.5
H	200			8		0.6
H	250					0.3

For some specific TPs, cross-linking is used to improve some properties induced by the formation of the 3D network.

2.5.1 TP Alloying

TP families are diverse but their number is limited and often there are wide gaps between the properties of two basic polymer types. To bridge the gap, two polymer families can be mixed if they are compatible or if it is possible to compatibilize them with a third material.

Examples are numerous: ABS (the most widespread), ABS/PC, ABS/PA, acrylonitrile styrene acrylate (ASA)/PC, ASA/PVC, thermoplastic olefin (TPO), thermoplastic vulcanizate, PPE (marketed grades are actually alloys with PS or PA), PA/PP, and so on. Fossil plastics can also be allied with bioplastics to decrease the environmental footprint of fossil plastics or to enhance performance of bioplastics. For example, Fujitsu and Toray have developed an FR resin made of a blend of PC and polylactic acid (50/50) designed for notebook computers. This composition has the processability, heat resistance, and flame resistance required in larger IT devices.

For a suitable mixing of two components, the properties of an alloy, including the cost, are generally intermediate between those of each component, as we can see in Figure 2.12 for an ABS/PC:

- mechanical properties: tensile strength, elongation at break, and notched impact strength
- thermomechanical properties: HDT A
- thermal properties: continuous use temperature (CUT).

2.5.2 Filled and Reinforced TPs: Overview

The most used reinforcements are:

- short glass fibers randomly dispersed in the TP matrix.
- mineral fillers such as talc, calcium carbonate…
- glass microspheres…

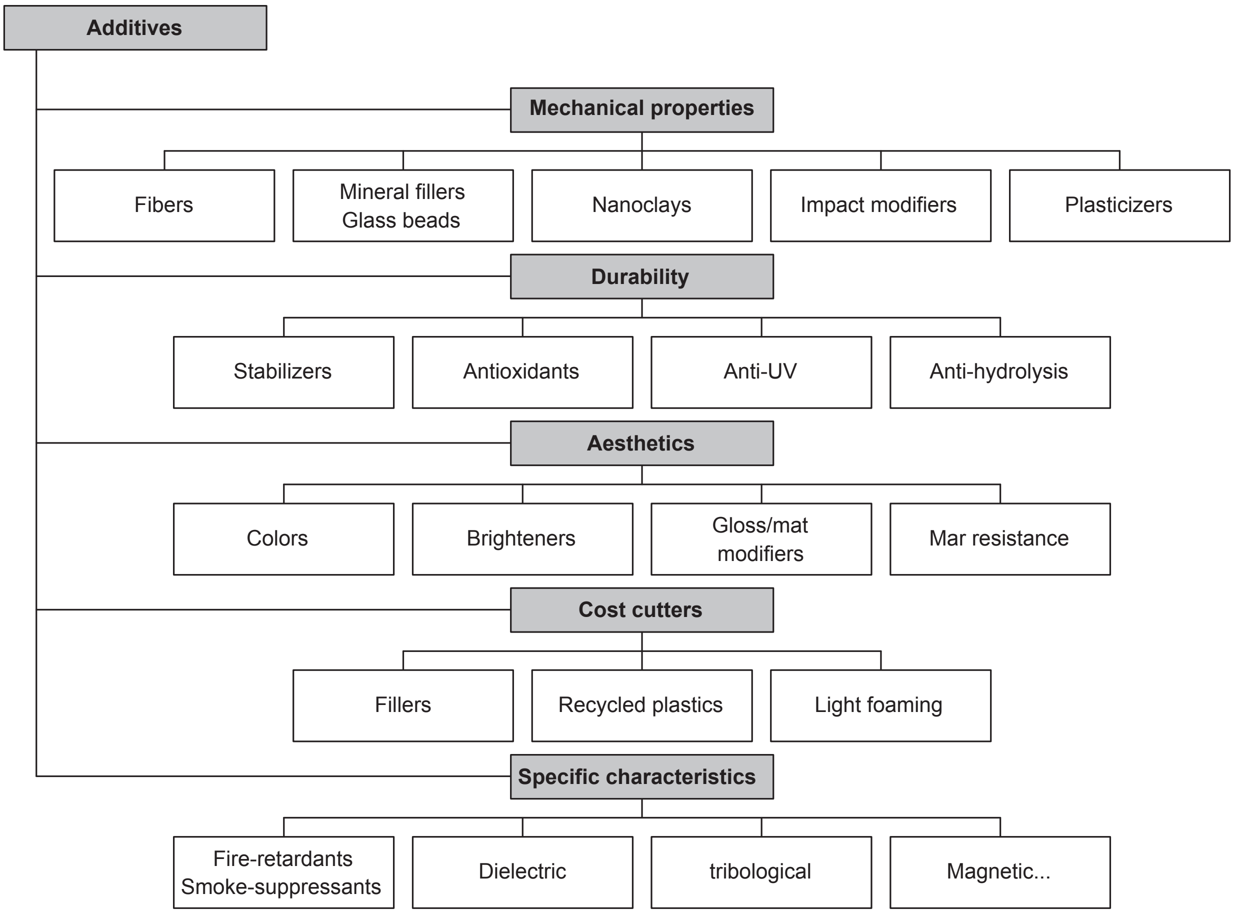


Figure 2.11 Examples of solutions to customize basic polymers.

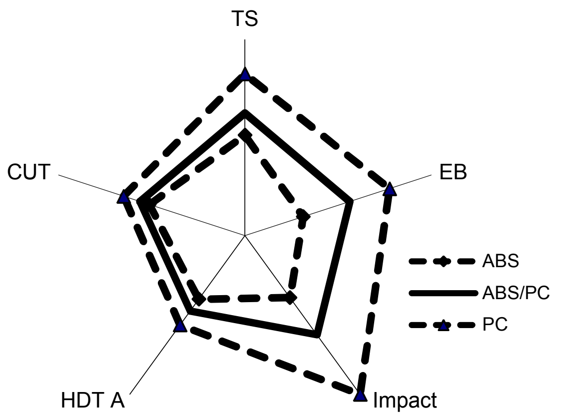


Figure 2.12 Property examples for acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and ABS/PC alloy.

Developing and most up-to-date reinforcements include:

- short carbon fibers
- glass and carbon "long" fibers
- assemblies containing fibers.

Environmental trends give new interest for natural fibers (NFs). Highly promising nanofillers, nanoclays, and carbon nanotubes are also developing well.

Depending on the reinforcement, the main difficulties are:

- achieving an excellent adhesion between matrix and reinforcement
- the risk of shortened fibers broken during processing
- anisotropy due to the filler or fiber orientation and settling. With some processes, this is an advantage: a correct placement of the fibers permits reinforcement at specific spots in the right direction.

2.5.2.1 Reinforcement with Fibers

The principle of reinforcement is to transfer a part of the structural role to fibers that have much higher modulus and strength than the matrix. Figure 2.13, which plots tensile strength versus modulus for some

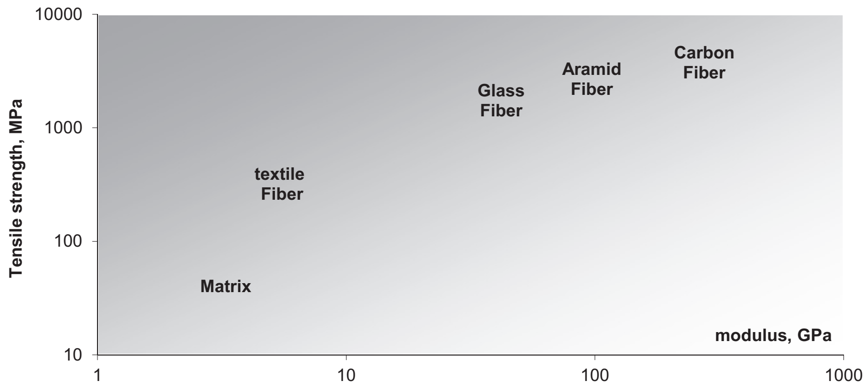


Figure 2.13 Fibers: Examples of tensile strength versus modulus.

typical fibers and matrices, clearly shows the gap between the performances of the matrix and GF or carbon fibers (CFs).

Note that injection molding limits the possibilities of reinforcement to injectable reinforced compounds and use of premanufactured reinforced inserts. Mechanical properties are not as high as data indicated in Figure 2.13 concerning all the forms of composites.

Currently, GFs are the most widely used, accounting for 95% of the reinforcement fibers consumed by plastics. Aramid and carbon fibers account for nearly all the remaining 5%.

NFs such as jute, flax, and so on are developing to satisfy environmental trends.

Textile fibers such as nylon and polyester are used to reinforce flexible materials such as soft PVC.

The properties of polymers reinforced with chopped GFs dispersed in the polymer matrix depend on:

- the nature of the fiber
- the fiber loading
- the fiber aspect ratio (length versus diameter of the fibers)
- the sizing of the fibers to enhance adhesion to the matrix
- the real length of the fibers in the final part
- the quality of the fiber dispersion
- the anisotropy in the final part.

The properties of polymers reinforced with continuous filaments, rovings, fabrics, and so on depend on:

- the fiber type
- the fiber loading

Table 2.6 Examples of Glass Fiber Reinforcement Ratios Based on Tensile Strength and Modulus

Glass Fiber	Strength	Modulus
None	1	1
Dispersed short GF	2.2	5
Dispersed long GF	3.3	6.7
Fabric reinforcement	5	5
Unidirectional reinforcement	20	20

- the form of the fiber reinforcement (filament, roving…)
- the orientation of the fibers
- the adhesion of the fibers to the matrix
- the anisotropy in the final part.

Table 2.6 shows some examples of the modulus and the strength reinforcement ratios for various reinforced TPs and thermosets. The reinforcement ratio is the performance of the reinforced polymer divided by the performance of the neat polymer.

Note that injection molding limits the possibilities of reinforcement to injectable reinforced compounds and use of premanufactured reinforced inserts. Reinforcement ratios are not as high as data indicated for fabric and unidirectional reinforcements.

2.5.2.2 Reinforcement and Filling with Mineral Fillers

The reinforcement effect with mineral fillers is not as evident as with fiber reinforcement. Often the cost

Table 2.7 Examples of the Effect of Mineral Fillers on Polypropylene Properties

	Effect Ratio		
	Talc	Mineral	Glass Fiber
Tensile strength	0.8	0.7	1.5
Tensile modulus	2.4	2.1	3.2
Notched impact strength	0.4	0.3	0.3
Thermal conductivity	1.9	1.9	1.4
Coefficient of thermal expansion	0.5	0.4	0.5
Density	1.2	1.2	1.1
Shrinkage	0.5	0.4	0.3

is significantly decreased but only a few properties are improved and others can be altered.

Table 2.7 shows some examples of the property effect ratios for mineral filler-reinforced PP. The effect ratio is the performance of the reinforced polymer divided by the performance of the neat polymer. Properties of low-level GF-reinforced PP are given for comparison.

Compared to neat and GF-reinforced polymers:

- tensile strength decreases compared to neat polymer
- elongation at break is intermediate between neat and GF-reinforced polymers
- modulus increases and becomes intermediate between neat and GF-reinforced polymers
- impact strength decreases compared to neat polymer
- HDT becomes intermediate between neat and GF-reinforced polymers
- CTE and shrinkage are reduced, while thermal conductivity increases
- price often decreases but density increases.

Table 2.8 Examples of the Effect of Glass Beads on Polyamide Properties

	Effect Ratio
Tensile strength	1
Tensile modulus	1.5
Notched impact strength	0.4
Hardness	1.2
HDT A	1.2
Thermal conductivity	1.7
Coefficient of thermal expansion	0.6
Density	1.2
Shrinkage	0.6
Water absorption	0.4

2.5.2.3 Filling with Glass Beads

Glass beads act as a mineral filler with an aspect ratio of 1. Table 2.8 displays results for glass bead-reinforced PA. The effect ratio is the performance of the reinforced polymer divided by the performance of the neat polymer.

These results are in the same order as those in Table 2.7 for mineral-filled PP. Against neat polymer:

- tensile strength is unchanged
- modulus increases and becomes intermediate between neat and GF-reinforced polymers
- impact strength decreases
- HDT slightly increases
- CTE and shrinkage are reduced, while thermal conductivity increases
- density increases
- water absorption decreases due to the specific hygroscopic character of PA, while glass beads are hydrophobic.

2.5.2.4 Nanofillers

Nanofillers are made up of:

- elementary particles in platelet form with thickness in the order of the nanometer and diameter in the order of 100 nm
- primary particles formed by stacking several elementary particles. The thickness is about 10 nm

Table 2.9 Property Examples for Polyamide Nanocomposites Processed by Various Methods

	Neat PA	PA Nanocomposites	
		Property	Reinforcement Ratios
Tensile modulus (GPa)	2.7	3.3–4.3	1.2–1.6
Tensile stress at yield (MPa)	64	69–85	1.1–1.3
Elongation at break (%)	40	8–60	–
Izod notched impact (J/m)	37	36–50	1–1.3

- aggregates of numerous elementary particles.

To exceed the typical filler reinforcement and to obtain a real nanocomposite, it is necessary to destroy the primary particle structure during processing:

- either completely, by dispersing the elementary particles in the macromolecules, which leads to delaminated nanocomposite; or
- partially, by intercalating macromolecules between the elementary particles, which leads to intercalated nanocomposite.

The most popular nanofiller is a natural layered silicate, montmorillonite, that is subjected to specific treatments. The properties of the final nanocomposite depend on these treatments and the mixing efficiency.

Table 2.9 displays property examples for PA nanocomposites processed by various methods.

Practically all the polymers can be processed to make nanocomposites. This emerging technology is developing into PA and TPO nanocomposites with applications in the automotive industry, and there are experiments with saturated polyesters, acrylics, and PSs.

The nanosilicates, because of their high aspect ratio, high surface area, and nanometric scale, are reinforcing at low incorporation levels.

The main nanocomposite properties are:

- mechanical performances between those of the neat polymer and short glass fiber-reinforced grades
- higher HDT than neat polymer but lower than short glass fiber-reinforced grades
- density much lower than reinforced grades
- lower gas permeability
- better fire behavior.

Table 2.10 Property Examples for a 2% Nanosilicate-Filled Polyamide

	Property Example	Reinforcement Ratio
Density (g/cm^3)	1.15	1
Tensile strength (MPa)	100	1.25
Flexural modulus (GPa)	3.9	1.3
HDT A (1.8 MPa) (°C)	140	1.9

For an industrial example (see Table 2.10), the reinforcement ratios obtained with a loading of nanosilicate as low as 2% are attractive. The reinforcement ratio is the ratio of the nanocomposite performance versus that of the neat polymer.

For a barely higher density, the nanocomposite has significantly better thermomechanical properties than the neat PA.

2.5.2.5 Continuous Fiber-Reinforced Sheet Overmolded by Injection

Continuous fibers in multiple layers of unidirectional tapes or sheets provide reinforcements that can be overmolded with a TP. The continuous fiber inserts improve reinforcement to a level above long glass fibers (LGFs).

For example:

- BASF offers commercial Ultracom product packages. For customer projects requiring parts of high stiffness, the package consists of an Ultralaminate™ based on PA 6 in combination with Ultramid G12 COM with 60% GF reinforcement as overmolding compound. For crash-loaded applications with a special need for impact strength, BASF offers a package which is optimized for high energy absorption.

- Lanxess introduced Tepex dynalite 102 RG 600, a nylon composite sheet of PA 6 reinforced with 47% continuous GFs by volume that can be back-injected with an impact-modified PA 6 copolymer. A car seat shell applying this technology is being used in the Opel Astra OPC. According to Lanxess, the seat shell combines impressive stiffness with exceptional strength. This enables it to absorb a great deal of energy in the event of a crash. To produce the seat shell, the semifinished composite in sheet form is heated and then placed in an injection mold. It is then molded into shape and immediately overmolded with PA 6 filled with short glass fibers to integrate reinforcing ribs and functions, such as mounts for fixing elements. This one-shot process helps to ensure cost-efficient production of the seat shell.

2.5.3 Formulation of Compounds

2.5.3.1 Improvement of General Behavior

Impact Modifiers

Impact modifiers enhance impact strength at ambient temperature and reduce embrittlement at subzero temperatures. The principle is to distribute and dampen the energy of an impact by adding an elastomer or a rubbery polymer, which also reduces rigidity and some other properties.

The impact modifier is finely dispersed in the TP to absorb the energy of the impact. Numerous polymers are used, for example, ABS, methyl methacrylate–butadiene–styrene, chlorinated polyethylene, styrene–butadiene–styrene (SBS), styrene–butadiene–styrene (SEBS), polyacrylate, polybutadiene, terpolymer ethylene, propylene, diene (EPDM), ethylene-acrylate, modified polyolefins, and so on. The selected impact modifier must be compatible with the polymer to be enhanced and must adhere strongly to it. It must have enough cohesive strength and a glass transition temperature low enough to maintain high impact strength at low temperature.

Impact enhancers modify the balance of properties, notably stiffness, hardness, heat deflection temperature (HDT) (see Table 2.11), as well as, possibly, weatherability and thermal stability.

Table 2.11 Examples of Toughening Effects on Properties of Polyamide and Polyacetal

	Ratios: Performance of Impact Grades Divided by the Same Performance of Unmodified Grade	
	PA66	**POM**
Impact strength	5	2
Hardness, Rockwell M	0.5	0.7
Tensile strength	0.6	0.8
Elongation at break	1	2.9
Tensile modulus	0.4	0.6
HDT B	0.9	0.9

Some inorganic impact modifiers are also marketed, such as amorphous silicon dioxide.

Plasticization

Plasticizers are mainly used to obtain a better flexibility at ambient and low temperature. However, they can also have other advantages, such as the possibility to increase the amount of filler, which leads to cost savings, or, with specific grades, the possibility to bring other characteristics such as FR or antistatic effect. Processing is generally enhanced, mixing and shaping being easier.

Unfortunately, they can have some drawbacks, such as decreased tensile strength and modulus, pollution, toxicity, migration, or environmental risks. The global requirements, local and professional regulations, standards, and specifications must be carefully studied.

For specific polymers, halogen and phosphorus-free plasticizers can reduce the oxygen index. The transparency can be altered if the compatibility is low and/or the refractive index is inadequate.

The plasticization benefits can be reduced or even suppressed if the plasticizers disappear during service life by:

- volatilization, the more so as the temperature rises
- migration by contact with other solid materials, the more so as the temperature rises
- extraction by contact with fluids

Table 2.12 Examples of PVC Properties According to the Degree of Plasticization

	Negligible Plasticization	Low Plasticization	High Plasticization
Density (g/cm^3)	1.35	1.35	1.15
Shrinkage (%)	0.3	0.8	5
Hardness, Shore D	75	70	15
Tensile strength (MPa)	45	25	10
Elongation at break (%)	40	200	500
Tensile modulus (GPa)	3	1	0.001
Notched impact strength (J/m)	20	NB	NB
HDT B (°C)	70	55	<30
Glass transition (°C)	60	–5	–50
Minimum service temperature (°C)	–5	–10	–40
Resistivity (ohm·cm)	10^{15}	10^{15}	10^{10}
Oxygen index (%)	40	40	20
NB: No break			

There are superabundant commercial products. Let us quote some of them:

- the esters:
  - the phthalates: diethylhexyl, also called dioctyl phthalate, is the most widely used; dimethyl, diethyl, dipropyl, dibutyl, dipentyl, dihexyl, diisoheptyl, dinonyl, diisononyl, butylbenzyl, dibenzyl
  - the phosphates
  - other esters are used to some degree, for example: sebacates, adipates, azelates, glutarates, formates, hexoates, caprates, caprylates, tallates, trimellitates, tricitrates…
- petroleum oils, including the three main categories: paraffinics, aromatics, naphthenics
- low-molecular-weight rubbers or plastics (PE, PPO), liquid rubbers
- chlorinated hydrocarbons
- epoxidized soya bean oil
- FR additives such as tricresylphosphates, chlorinated waxes, and others.

The choice of plasticizer types and levels is a subtle compromise between the bestowed advantages and drawbacks:

- compatibility with the polymer to be plasticized
- targeted processing and rheological properties
- specified thermal, electrical, and mechanical properties of the end product
- optical properties: light transmission, haze
- fire behavior: fire retardancy, smoke, toxicity, corrosivity…
- chemical resistance
- aging: resistance to heat, humidity, light, and UV
- volume and/or weight cost
- toxicity and environmental risks
- stress cracking of other polymers by plasticizer migration, discoloration of other plastics or rubbers by contact
- contact with food and medical articles.

Table 2.12 displays three examples of PVC properties according to the degree of plasticization.

Aging Protection: Additives, Films

Oxygen, heat, light and UV, and shear and dynamic stresses attack polymers, degrading performances and esthetics. Practical consequences of aging generally are:

- mechanical property degradation, weakening, embrittlement…
- esthetics degradation
- weight loss, shrinkage
- desorption and consumption of additives
- pollution of environment…

A durable protection is needed to avoid damage during processing, to satisfy the customer's specifications and requirements, and to give satisfaction during the complete service life of parts. Protective additives can be classified as follows:

- processing stabilizers: antioxidants incorporated into the polymer to avoid heat degradation during processing
- antioxidants: added to the polymer to decrease thermo-oxidation during service life, avoiding molecular weight changes and loss of mechanical, physical, and esthetic properties
- light stabilizers: decrease degradation initiated by sunlight or UV exposure. Certain fillers absorb UV and act as filters protecting the polymer
- hydrolysis stabilizers: chemicals added to the polymer to avoid hydrolysis degradation during service life.

Another route to protect polymers from oxygen, light, and UV is to encapsulate the part with a continuous film of another, more resistant polymer to provide a barrier to oxygen. This technology is also used for decoration of plastic parts (in-mold decoration or IMD, painting, multilayer sheets for thermoforming…). There is no protection against heat.

All these methods cannot totally inhibit polymer degradation. This is just a question of time, heat, and exposure to light, water, and other aggressive environments.

The efficiency of these additives depends on:

- the nature of the matrix
- the nature of the protective additive
- the actual level of additive in the part
- interactions with the other ingredients.

Table 2.13 shows examples of the very different efficiencies of eight antioxidants incorporated in the same polymer.

The other additives in the compound can also influence aging as we can see in Table 2.14, which displays the effect of silica in combination with two different protective agents. In one case, the silica degrades the aging resistance and in the others, silica enhances aging behavior.

Table 2.13 Examples of Antioxidant Efficiencies in Polypropylene Films

	Air Aging at 130 °C (Hours to Reach Brittleness)	Efficiency Ratio Linked to Control Performance
Without protective agent	5	1
Protective agent A	34	7
Protective agent B	89	18
Protective agent C	91	18
Protective agent D	264	53
Protective agent E	456	91
Protective agent E + D	456	91
Protective agent E + A	552	110
Protective agent E + B	576	115

High part thickness decreases oxygen diffusion in the core of the polymer and reduces degradation, as can be seen in Figure 2.14.

Weathering is difficult to quantify because of the variation of the parameters according to the local conditions:

- hours of sun per annum
- irradiation energy
- UV level
- average and extreme temperatures
- hygrometry, rain
- ozone
- pollution, acid rain

The technical consequences of weathering are similar to heat aging with more pronounced surface degradation and notably:

- discoloration, yellowing, gloss loss, decreased transparency for transparent polymers
- chalking, crazing, hardening.

Table 2.14 Examples of Interaction between Antioxidant and Silica in Polypropylene Films

	Air Aging at 130 °C (Hours to Reach Brittleness)
Without protective agent	5
Silica	3
Protective agent E	456
Protective agent E + silica	336
Protective agent B	34
Protective agent B + silica	91

Table 2.15 shows examples of the efficiencies of anti-UV stabilization.

The other additives in the compound can also influence weathering as we can see in Table 2.16, which displays the effect of colorants in combination with UV stabilization. Aging behavior depends on the nature of the colorant and the UV-filtering action of the filler. Black compound is by far the best choice but parts are black.

2.5.3.2 Improvement of Special Features

Important industrial applications of TPs need specific properties different from inherent features of polymers, for example, resistance to fire, electrical, and thermal conductivities; low coefficients of friction and wear resistance; magnetic properties, and so on. Specific additives can thoroughly modify the basic properties of the used polymers.

Fire-Retardant Thermoplastics

Generally, plastics are sensitive to fire, burning more, or less easily with fumes possibly toxic and corrosive.

Fire behavior is very complex for several reasons:

- technically: it is necessary to converge on a difficult balance of fire retardancy and low smoke emission with constraints concerning the opacity, toxicity, and corrosivity of fumes
- legally: standards, regulations, and specifications are complex and evolving, and vary according to country and industrial sector
- environmentally: many FRs are not environment-friendly
- FRs can modify mechanical properties and esthetics.

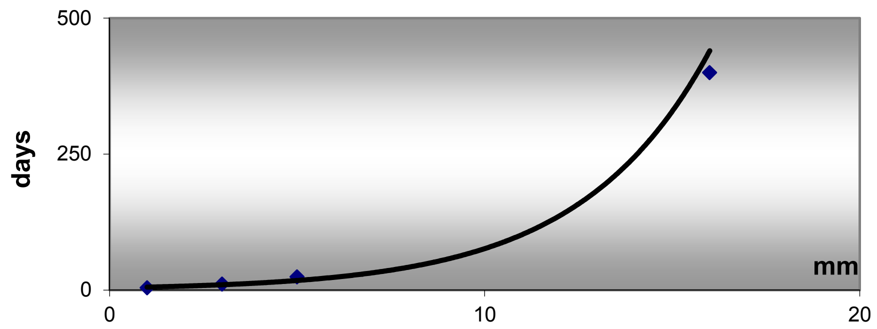


Figure 2.14 Days of aging leading to the same degradation level versus sample thickness.

Table 2.15 Examples of UV Degradation According to the Polymer and Exposure Location

Polymer	Location	Formulation	% Degradation		
			Tensile Strength	Elongation at Break	Impact
PC	Arizona	Unstabilized			93
		UV-stabilized			3
PC white	Florida	Unstabilized	4	78	9
		UV-stabilized	7	22	15
PE	Florida	Unstabilized	44	41	48
		UV-stabilized	24	22	5

Table 2.16 Examples of UV Exposure Time to Reach the Same Level of Degradation of Polypropylene According to the Colorant

	Exposure Time of Colored PP divided by Exposure Time of Pure PP
Pure PP	1
Red A	1
Magenta	1
Blue C	1.8
Yellow	2
White	2.3
Red B	2.8
Brick red	3.3
Blue D	3.5
Green	3.5
Black	12

When defining an FR system, one of the first questions is to decide between halogen-free and halogen-containing systems. The next question concerns the possible use of phosphorus additives. Some FRs are banned in some countries and the selected FR system must be free of ban in processing, marketing, service, and disposal countries.

Some FRs are, without claiming to be exhaustive:

- mineral fillers and additives: aluminum trihydrate (ATH), magnesium hydroxide, and boron derivatives are the best known but tin derivatives, ammonium salts, molybdenum derivatives, and magnesium sulfate heptahydrate are used to varying extents, and nanofillers are developing
- phosphorus additives: red phosphorus, phosphate esters, ammonium polyphosphate, melamine phosphates, melamine pyrophosphate. Some of them are halogenated
- halogenated derivatives: brominated organic compounds are the most used, often in combination with antimony trioxide to develop a synergistic effect. However, this generates a lot of smoke and toxic fumes, which is unacceptable for many regulations and standards
- brominated PS is marketed as an FR additive.

Conductive Polymers

Generally, polymers are insulating materials.

Two routes are suitable for producing conductive polymers:

- Extrinsic conductive polymers obtained by adding specific additives to naturally insulating polymers. At present, this is the easiest industrial method
- Intrinsic conductive polymers obtained by polymerization of conductive macromolecules. This is a difficult route for industrial applications.

According to the conductivity level, the main additives used are, for example:

- antistatic specialties: their action generally depends on the relative humidity. However, new generations are being marketed without this

drawback and are efficient at a relative humidity as low as 15%
- conductive carbon blacks but compounds are gray or black
- carbon or steel conductive fibers. Carbon fibers have a high reinforcing effect
- metal powders or flakes. Aluminum, copper, nickel, and silver powders or flakes are used to obtain electromagnetic interference (EMI) grades. The other properties—color, modulus, impact strength—are also modified.

Antifriction Polymers

Generally, polymers have high coefficients of friction and are sensitive to wear.

The most up-to-date additives for antifriction compounds are, without claiming to be exhaustive:

- specific fillers: MoS_2, graphite
- polymers: PTFE and silicone are efficient for providing antifriction properties but wear resistance falls.

More rarely used are:

- carbon or aramid fibers to simultaneously enhance mechanical properties and coefficient of friction and decrease the wear
- ceramics such as boron nitride or silicon carbide.

To enhance mechanical properties and decrease wear, GFs are added to polymers but they are abrasive and attack the opposing surface. According to the circumstances, they can also increase the coefficient of friction.

CFs are more satisfactory, simultaneously bringing a lower friction coefficient and lower wear. CFs are expensive.

Silicon carbide is marketed as a surface enhancer. At levels less than 10%, it significantly improves the coefficient of friction and the wear resistance.

Polymers with High Thermal Conductivity

General-purpose polymers, being thermal insulators, cannot dissipate heat generated by mechanical work or by electronic devices and so on. If the temperature rises, the mechanical properties of the polymer decrease and aging speeds up. Eventually, the temperature can reach the melting point.

To ease the dissipation of thermal flow, it is worthwhile to add dissipative additives such as ceramics, metal powders, or CFs that have a high thermal conductivity.

To provide some idea, thermal conductivities (W/mK) are roughly in the range of:

- 0.2–0.3 for neat polymers
- 10–170 for CFs
- 25–400 for ceramics, copper, or aluminum.

The cost and/or the toxicity may restrain the applications.

Magnetic Polymers

General-purpose plastics are not magnetic and cannot be used to produce magnets that generate permanent magnetic or electromagnetic fields for diverse applications, from domestic to high-performance devices: DC micromotors, telephones, coupling devices, toys, hardware, ore screening, and so on.

However, magnetic additives such as ferrites or rare earths can be added to plastics to produce polymer magnets.

Anisotropic powders of ferrites have excellent cost/performance ratio, limited service temperatures, and low electrical resistance.

Rare earths have higher magnetic performances, service temperatures, electrical resistance, and costs. The toxicity may restrain the applications.

2.5.4 Statistical Analysis of Some Properties of Marketed TP grades

Among other special features, TPs can lead to very broad ranges of properties from soft materials up to rigid ones, from impact resistant up to brittle grades, from heat-sensitive up to heat-resistant versions, from insulating to conductive grades, etc.

The following raw statistical results concern more than 200 TP grades, helping to understand the extent of this critical issue. Of course, these statistical data cannot be used for designing, computing, or to make economic predictions.

Table 2.17 shows properties of neat grades.

Table 2.18 shows properties of all the grades including neat, reinforced, modified, or conductive grades.

Table 2.17 Properties of Neat Grades

Neat Thermoplastics	Minimum	Mean	Maximum
Yield or ultimate tensile strength, MPa	9	59	195
Tensile modulus, GPa	0.1	2,4	21
Flex modulus, GPa	0.1	2,4	15
Hardness, Rockwell M	1	48	109
Notched Izod impact, J/m	5	290	Nonbreak
Strain at yield, %	0.7	8.1	100
Elongation at break, %	0.7	138	900
HDT B 0.46 MPa, °C	40	141	343
HDT A 1.85 MPa, °C	30	104	319
CUT, °C	50	125	300
Density	0.833	1.22	2.2
Shrinkage, %	0.01	1.3	6
Water uptake, %	0.005	0.6	4.8
Tg, °C	–110	95	315
CTE 10^{-5}/°C	–0.5	8.9	27
Minimum service temperature, °C	–269	–60	20
Volume resistivity, ohm·cm	10^{7}	10^{14}	10^{18}
Fire rating	1	2.6	5

Table 2.18 Properties of All Grades

	Minimum	Mean	Maximum
Yield or ultimate tensile strength, MPa	7	96	323
Tensile or flexural modulus, GPa	0.1	7.2	37
Notched Izod impact, J/m	5	182	Nonbreak
Hardness, Rockwell M	1	60	112
Strain at yield, %	0.25	4.6	100
Elongation at break, %	0.25	49	900
HDT B 0.46 MPa, °C	40	172	370
HDT A 1.85 MPa, °C	30	152	358
CUT, °C	50	127	300
Density	0.833	1.4	4
Shrinkage, %	0.01	0.8	6
Water uptake, %	0.005	0.5	5
Tg, °C	–110	80	315
CTE 10^{-5}/°C	–1	6	27
Minimum service temperature, °C	–269	–60	20
Volume resistivity, ohm·cm	10^{-1}	10^{12}	10^{18}
Oxygen index, %	16	29	96
Fire rating	1	2.5	5

Table 2.19 Property Comparison for Neat and Short Glass Fiber-Reinforced Thermoplastics

Plastic	Unreinforced Mean	GF Mean	% Variation GF/Unreinforced Positive	% Variation GF/Unreinforced Negative
Yield or ultimate tensile strength, MPa	58	121	108	
Tensile or flexural modulus, GPa	2.4	8.8	267	
Notched Izod impact, J/m	290	139		–52
Hardness, Rockwell M	48	65	36	
Strain at yield, %	8	2.9		–64
Elongation at break, %	138	4		–97
HDT B 0.46 MPa, °C	141	198	41	
HDT A 1.85 MPa, °C	104	189	81	
Density	1.22	1.44	17	
Shrinkage, %	1.3	0.5		–62
Water uptake, %	0.6	0.6	=	
CTE 10^{-5}/°C	8.9	3.5		–60
Volume resistivity, ohm·cm	10^{14}	10^{14}	=	
Fire rating	2.5	2.5	=	

For an in-depth understanding, the following statistical results are modeled according to normal (or Gaussian) distributions. Each grade is categorized according to its common designation (for example, glass fiber-reinforced or GF) without taking into account the level of filler or reinforcement, and possible alloying, heat or chemical stabilization, fire behavior improvement, impact modification, use of secondary filler, etc.

2.5.4.1 Short Glass Fiber-Reinforced TP Grades

Table 2.19 compares properties of neat and short glass fiber-reinforced TPs.

Ultimate tensile strength and yield strength are approximately doubled, mean data rising from 55/60 MPa up to 115/125 MPa. Standard deviation is also higher, the GF level being not taken into account.

Figure 2.15 shows examples of yield strengths for unreinforced and GF-reinforced grades.

The effect on tensile and flexural modulus is similar but amplified with mean values rising approximately threefold from about 2.4 GPa up to 8.7 GPa. Standard deviation is also higher, the GF level being not taken into account.

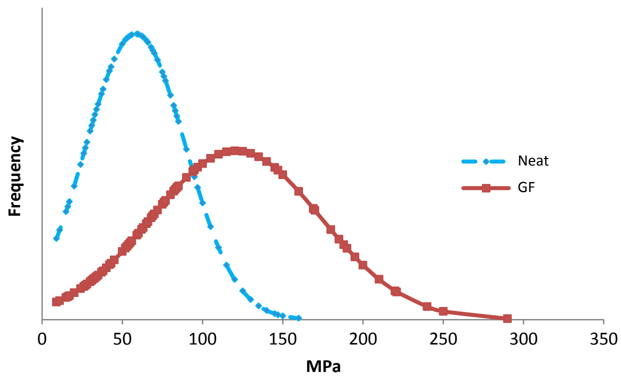


Figure 2.15 Yield stress of neat and glass fiber (GF) thermoplastics.

Figure 2.16 shows examples of tensile and flexural modulus for unreinforced and GF-reinforced grades.

The effect on notched impact strength is very different with mean values divided approximately by two, falling from 290 J/m down to 128 J/m. Standard deviation is also higher, the GF level being not taken into account. The frequency of low values is higher for reinforced grades and the frequency of values superior to 500 J/m is very low.

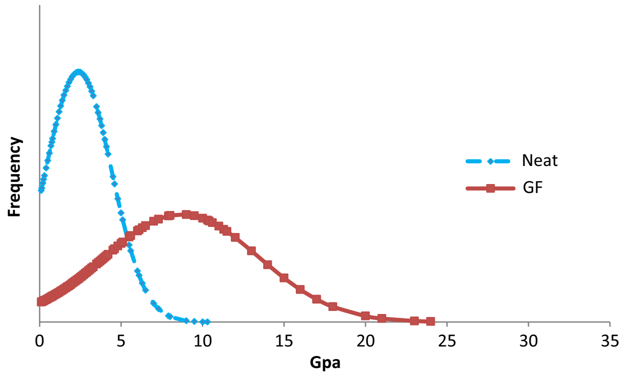


Figure 2.16 Tensile and flex modulus of neat and glass fiber (GF).

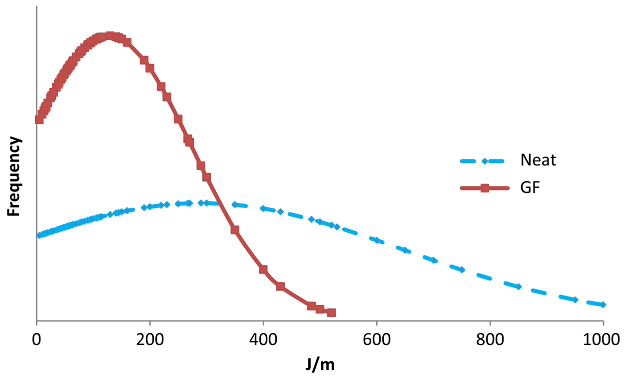


Figure 2.17 Notched impact strength of neat and glass fiber (GF) thermoplastics.

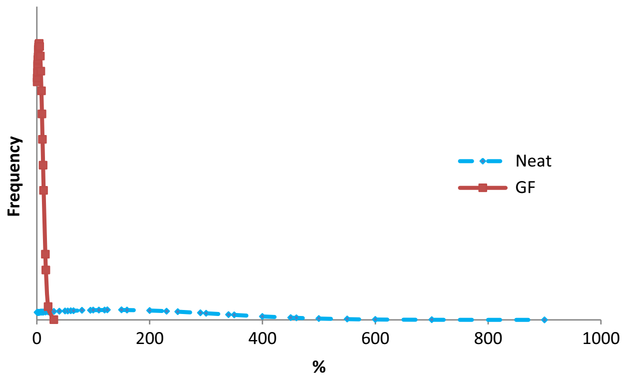


Figure 2.18 Elongation at break of neat and glass fiber (GF) thermoplastics.

Figure 2.17 shows examples of notched impact strength for unreinforced and GF-reinforced grades.

Elongation at break is sharply reduced with mean values divided by a factor superior to 20, falling from 130% down to 4%.

Figure 2.18 shows examples of elongation at break for unreinforced and GF-reinforced grades.

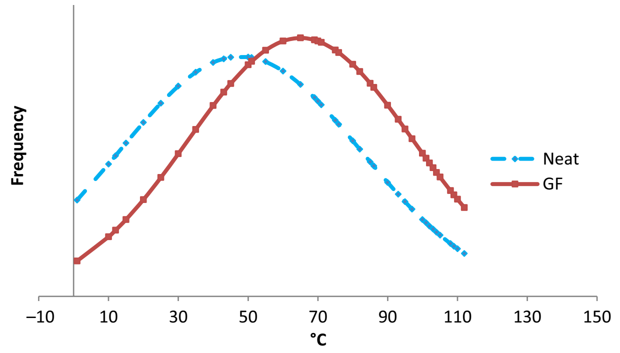


Figure 2.19 Rockwell M of neat and glass fiber (GF) thermoplastics.

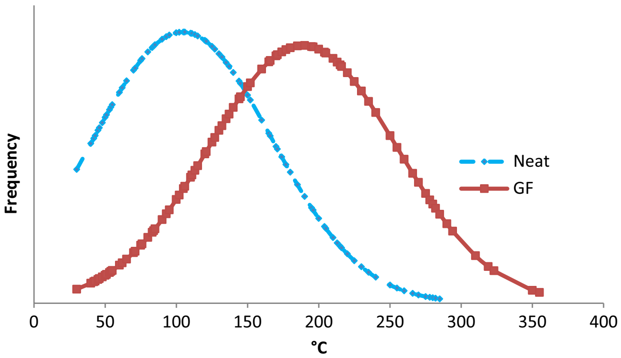


Figure 2.20 Heat deflection temperature (HDT) A of neat and glass fiber (GF) thermoplastics.

As for tensile and flexural modulus, Rockwell M hardness increases but more moderately with mean values rising approximately by 40% from about 48 up to 65.

Figure 2.19 shows examples of Rockwell M hardness for unreinforced and GF-reinforced grades.

Heat deflection temperatures (HDT A) increase, mean values rising from about 100 °C up to approximately 190 °C.

Figure 2.20 shows examples of HDT A for unreinforced and GF-reinforced grades.

Generally speaking, among the other properties:

- density increases with GF level as far as the plastic density is lower
- shrinkage is substantially reduced but beware of warpage
- CTE is substantially reduced but beware of anisotropy
- CUT under unstressed state is unchanged

Table 2.20 Property Means of Long Glass Fiber-Reinforced and Neat Grades

	Engineering Data		% Variation LGF/Neat	
	Neat	LGF	Positive	Negative
Yield or ultimate tensile strength, MPa	47	175	269	
Tensile modulus, GPa	1.85	15	706	
Flex modulus, GPa	1.85	14	653	
Hardness, Rockwell M	41	67	62	
Notched Izod impact, J/m	381	294		−23
Elongation at break, %	198	1.8		−99
Strain at yield, %	13	1.6		−87
HDT B 0.46 MPa, °C	128	218	71	
HDT A 1.85 MPa, °C	77	197	156	
Density	1.13	1.49	32	
Shrinkage, %	1.7	0.4		−77
CTE 10^{-5}/°C	10.2	2.9		−72

- minimum service temperature can increase (which is unwanted) if softness and brittleness are concerns
- fire rating depends on the formulation.

2.5.4.2 Long Glass Fiber-Reinforced TP Grades

Table 2.20 compares property means of LGF-reinforced grades and neat grades of the same polymers. These data are only examples and cannot be used for designing, computing, or to make economic predictions. Data evolve as for short glass fiber-reinforced TPs but variations are amplified as far as fiber level is often high, 60% for example.

Compared to neat polymers, properties of LGF composites evolve as follows:

- Ultimate tensile strength and yield strength are approximately tripled, mean data rising from 47 MPa up to 175 MPa.
- The effect on tensile and flexural modulus is similar but amplified with mean values rising approximately eightfold from about 1.85 GPa up to 14/15 GPa.
- As for tensile or flexural modulus, Rockwell M hardness increases with mean values rising approximately by 60% from about 41 up to 67.
- The effect on notched impact strength is very different with mean values slightly inferior for LGF grades, decreasing from 381 J/m down to 294 J/m.
- Elongation at break is widely reduced with mean values divided by a factor superior to 20, falling from more than 100% down to less than 2%.
- Heat deflection temperatures (HDT A) increase, mean values rising from about 77 °C up to approximately 197 °C.
- Of course, density increases with GF level as far as the plastic density is lower.
- Shrinkage is substantially reduced but beware of warpage.
- CTE is substantially reduced but beware of anisotropy.

Generally speaking, among the other properties:

- CUT under unstressed state is unchanged
- Resistivity is not significantly changed
- Minimum service temperature can increase (which is unwanted) if softness and brittleness are concerns
- Fire rating depends on the formulation.

Table 2.21 Property Means of Short Carbon Fiber-Reinforced and Neat Grades

Plastic	Engineering Data		% Variation CF/Neat	
	Mean Neat	Mean CF	Positive %	Negative %
Yield or ultimate tensile strength, MPa	72	157	118	
Tensile or flexural modulus, GPa	3.2	16	396	
Notched Izod impact, J/m	298	104		–65
Hardness, Rockwell M	59	76	29	
Strain at yield, %	6.5	1.6		–75
Elongation at break, %	97	22.5		–77
HDT B 0.46 MPa, °C	168	202	20	
HDT A 1.85 MPa, °C	134	211	58	
Density	1.33	1.39	4.6	
Shrinkage, %	1.2	0.4		–68
CTE 10^{-5}/°C	7.9	4.2		–47
Volume resistivity, ohm·cm	10^{14}	10^{4}		~–100

2.5.4.3 CF-Reinforced TP Grades

The following analysis relates to a few grades and other properties can be found elsewhere.

Short CFs lead to a higher reinforcement effect than short glass fibers with some distinctive features: high conductivity and high cost. For a same fiber level, CFs lead to lighter materials than GFs.

Table 2.21 compares property means of CF grades and neat grades based on the same polymers. These data are only examples and cannot be used for designing, computing, or to make economic predictions.

Properties evolve as for short glass fiber-reinforced TPs but reinforcement is amplified. CUT under unstressed state is unchanged and fire rating depends on the formulation.

For long CF-reinforced TP grades, data evolve as for short CFs but variations are amplified.

2.5.4.4 NFs and Wood Plastic Composites

The following analysis relates to a few grades and other properties can be found elsewhere. These data are only examples and cannot be used for designing, computing, or to make economic predictions.

Table 2.22 compares properties of NF-reinforced grades and wood plastic composites (WPC), on the one hand, and neat grades based on the same polymers, on the other hand. Properties evolve similarly to those of GF-reinforced TPs but the reinforcement is far lower.

Compared to neat polymers, properties of NF composites evolve as follows:

- Tensile strength is not significantly different
- Elongation at break is far lower
- Tensile and flexural modulus are approximately doubled
- Notched Izod impact strength decreases
- HDT A increases by 20 °C
- Density is slightly increased
- CTE decreases.

2.5.4.5 Mineral-Filled TP Grades

There are many mineral fillers leading to a broad range of properties. Table 2.23 relates to some mineral-filled grades and other properties can be found elsewhere. These data are only examples and cannot be used for designing, computing, or to make economic predictions.

Table 2.22 Properties of Natural Fiber Reinforced and Wood Plastic Composites Grades Compared to Neat Polymers

	Neat Thermoplastics			NF and WPC		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Tensile strength, MPa	18	40	83	10	36.5	102
Elongation at break, %	1	186	700	0.8	6.5	15
Tensile modulus, GPa	0.5	2.1	4	1.7	4.9	13.2
Flex modulus, GPa	0.5	2.1	3.9	1.1	4.1	8
Notched Izod impact, J/m	10	117	500	16	75.5	185
HDT A 1.85 MPa, °C	40	64	100	43	84	134
Density	0.9	1.09	1.5	0.95	1.12	1.4
CTE 10^{-5}/°C	5	11.2	22	3	7.4	12

Table 2.23 Property Means of Mineral-Filled and Neat Grades

	Engineering Data		% Variation Mineral/Neat	
	Neat	Mineral and GB	Positive	Negative
Yield strength or tensile strength, MPa	65	64		–0.1
Tensile or flexural modulus, GPa	2.8	4.8	65	
Notched Izod impact, J/m	309	85		–72
Hardness, Rockwell M	50	58	16	
Strain at yield, %	8	5		–37
Elongation at break, %	117	21		–82
HDT B 0.46 MPa, °C	156	162	4	
HDT A 1.85 MPa, °C	117	129	11	
Density	1.21	1.41	17	
Shrinkage, %	1.4	0.9		–36
CTE 10^{-5}/°C	8.7	5.5		–37
Volume resistivity, ohm·cm	10^{14}	10^{14}	=	

Compared to neat polymers, properties of mineral-filled grades evolve as follows:

- Tensile strength: mean is not significantly different but low values can be substantially affected
- Elongation at break is far lower
- Tensile and flexural modulus are significantly increased
- Notched Izod impact strength significantly decreases
- HDTs slightly increase
- Density is significantly increased
- CTE decreases
- Volume resistivity is unchanged if conductive fillers are excluded.

Table 2.24 Properties of Conductive and Neat Grades

	Neat Thermoplastics			Conductive Thermoplastics		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Yield or tensile strength, MPa	16	53	110	20	70	216
Strain at yield, %	0.7	12	100	0.5	4.4	20
Elongation at break, %	0.7	160	700	0.5	26	400
Tensile modulus, GPa	0.1	2.1	5	0.35	6	24
Notched Izod impact, J/m	5	294	Nonbreak	10	165	Nonbreak
HDT B 0.46 MPa, °C	57	127	240	50	135	275
HDT A 1.85 MPa, °C	40	92	200	40	114	268
Density	0.9	1.13	1.42	0.9	1.23	1.8
Shrinkage, %	0.2	1.3	4	0.1	0.8	3
Water uptake, %	<0.01	0.4	3	0.01	0.4	1.8
Hardness, Rockwell M	1	45	109	1	62	108
CTE 10^{-5}/°C	3	9.6	22	1	8.2	20
log(volume resistivity), ohm·cm	10^{8}	10^{14}	10^{18}	10^{-1}	10^{3}	10^{11}

2.5.4.6 Conductive TP Grades

As already said in Chapter 1, there are many designations for conductive TPs: conductive, electrostatic discharge, EMI/RFI, antistatic leading to a broad range of resistivity.

There are very different methods allowing to reduce the resistivity that leads to a broad range of properties. Table 2.24 relates to some conductive grades and other properties can be found elsewhere. These data are only examples and cannot be used for designing, computing, or to make economic predictions.

Compared to neat polymers, properties of conductive grades are scattered due to the very different ways leading to high conductivities. Mineral additives lead to reduced reinforcements when CFs lead to high reinforcements.

- Volume resistivity decreases.
- Tensile strength may be slightly changed or doubled.
- Elongation at break is far lower.
- Tensile and flexural modulus may be slightly changed or may be as high as 24 GPa.
- Notched Izod impact strength may significantly decreases but some grades do not break.
- HDTs may be unchanged or increased.
- Density may be unchanged or increased.
- CTE generally decreases.

2.6 Isotropy and Anisotropy

Polymer parts can be isotropic or, voluntarily or not, anisotropic.

Isotropic polymers have equal properties in all directions (X, Y, and Z). Carefully molded glass bead-filled TPs are isotropic.

A polymer or composite is anisotropic if its properties depend on the test direction. When measured along different axes (X, Y, and Z), physical and/or mechanical properties (modulus, aspect, refractive index, conductivity, etc.) are different. Unidirectional tapes are highly anisotropic. LGF-reinforced TPs are more or less anisotropic.

Oriented stretched films or fibers are voluntarily anisotropic aiming to better properties in the stretched direction that is not in the framework of this book.

Table 2.25 Examples of Anisotropy

Anisotropy of a Thermoplastic SBS Having a Low Hardness			
	EPa	**EPe**	**CA**
Direction versus flux	Parallel	Perpendicular	EPe/EPa
Strength at break, MPa	95	117	1.2
Elongation at break, %	691	866	1.3
Stress at yield, MPa	14.1	11.9	0.8
Strain at yield, %	22.1	24.9	1.1
Anisotropy of a Thermoplastic Polyetherester Having a Higher Hardness			
	EPa	**EPe**	**CA**
Direction versus flux	Parallel	Perpendicular	EPe/EPa
Strength at break, MPa	315	365	1.2
Elongation at break, %	507	658	1.3
Stress at yield, MPa	141	142.5	1
Strain at yield, %	28	26	0.9

For usual molded parts, anisotropy is an unintended and adverse collateral effect of compound formulation (fibers, for example) and/or processing conditions. Random sampling and use of the average of testing data hide this phenomenon as we can see according to the following trial.

2.6.1 Example of Tensile Property Anisotropy for Simple Regular Plates

Rectangular plates, 100×400 mm, are injected by their center and specimens are cut into two areas of sampling, symmetrical to the injection point. Test pieces are located quite far from the edges and from the injection point for a regular flow and a homogeneous cooling. The principle does not take into account the injection gate area.

On a series of plates test pieces EP are cut following two perpendicular directions:

- EPa specimens are cut in the direction of the flow of matter (parallel to the long side of the rectangle) and
- EPe specimens are cut in the direction perpendicular to the flow (perpendicular to the long side).

For a given property, the coefficient of anisotropy is calculated by dividing the average of the results of the measurements on EPe specimens, perpendicular to the stream by the average of the results obtained on the EPa test specimens, parallel to the flow.

The anisotropy coefficients in this trial are calculated on:

- strength and elongation at break
- stress and strain at yield.

Table 2.25 relates to two TPs and other properties can be found elsewhere. These data are only examples and cannot be used for designing, computing, or to make economic predictions.

For these two very different TPs, the anisotropy coefficients are 1.2–1.3 for tensile properties. On the other hand, for properties at yield, the anisotropy coefficients are lower and vary from 0.8 to 1.1.

Anisotropy coefficients are significant, depending on:

- the considered property
- the part geometry
- the location of sampling
- the formulation of the actual used grade.

Anisotropy cannot be neglected in designing and the safety factor should include it, taking into account the location of the point of injection, the geometry of the parts, and the formulation.

From a theoretical point of view, molecular orientation depends on the different flows of molten polymer. For a flat piece injected by its center, three types of flow come into play:

- A shear flow near the walls
- An extensional flow of fountain type on the flow front
- An extensional flow in the core of the piece.

Each flow type causes a different orientation of the molecules that can relax differently during cooling, which leads to a temperature gradient in the bulk of the part, skins cooling faster than the core.

The anisotropy of compounds can increase with:

- a higher viscosity of the molten flow
- a decrease in the elastic memory
- a faster cooling decreasing the time available for the relaxation
- an orientation of fillers and reinforcements

2.6.2 Special Behavior of Liquid Crystal Polymer

The mechanical properties are good but depend on the shear stresses during processing and consequently depend on the thickness of the part.

For similar samples differing by their thickness, which is 1 mm for one and 4 mm for the other:

- tensile strength is 26% higher for the thin sample
- modulus is 45% higher for the thin sample.

The parts are anisotropic in the bulk and according to the processing direction.

Thanks to special part and tool designs, and processing conditions, it is possible to take advantage of this behavior named self-reinforcement behavior of the liquid crystal polymers.

2.7 Dimensional Stability

Anybody has already seen too little (or too big) a polymer part disturbing a device made by assembling several parts of various materials. Sometimes, the dimension is fair but a more or less strong warpage prevents a correct assembly.

Dimensional variations are the consequences of:

- CTE
- external or internal stresses, pressure
- anisotropy of stresses or other polymer properties or orientation can lead to warpage
- shrinkage after demolding
- moisture and water uptake particularly known for PAs. Other chemicals can also swell polymers but they are rather relevant from chemical behavior
- desorption of humidity or additives such as plasticizers or other low-molecular-weight organic additives.

Plastics are often simultaneously used with conventional materials, notably metals whose CTEs may be 10–100 times lower. This can promote high stresses and failure of the device including these different materials.

Dimension variations can be immediate (thermal expansion) or time-dependent (water uptake) or delayed after a given time of aging:

- Thermal expansion or retraction is reversible.
- Water uptake and drying are almost reversible with a limited hysteresis.
- Releasing of additives is irreversible.
- Bulk compression is time-dependant: after a short time of compression and after a sufficient time of relaxation, the original geometry is recovered but for a sufficient time of compression there is a permanent set even after long times of relaxation.

2.7.1 The Coefficient of Thermal Expansion

CTE can be volumetric or more frequently linear. It is defined as the fractional variation of volume (volumetric coefficient) or length (linear coefficient) per unit change in temperature. Being thermal-dependant, the validity range of test temperatures must be indicated. The volumetric coefficient is roughly three times the linear one. The CTE is significantly changed by:

- the temperature, particularly if the glass transition temperature is reached
- the structure and morphology of the polymer
- the additives eventually used
- the degree of cross-linking for cross-linked TPs.

2.7.1.1 Deformation Due to Mechanical Stresses

For a sample free from stresses, the compression in one direction leads to an expansion in the other two free directions perpendicular to the direction of compression. Conversely, if the material is stretched in one direction, it tends to contract in the two free directions transverse to the direction of stretching.

2.7.1.2 Poisson's Ratio and Young's Modulus

The bulk modulus K is linked to Young's modulus (E) and Poisson's ratio (ν) by

$$K = E/\left(3*(1-2*\nu\right)$$

For a panel of 18 TP grades, minimum Poisson's ratio is 0.33, mean is 0.4, and max is 0.47.

These data are only examples and cannot be used for designing, computing, or to make economic predictions.

2.7.1.3 Residual Internal Stresses

TP injection moldings may contain residual stresses that are the consequence of differential cooling rates through the molded parts. They depend upon a wide range of variables including the mold design, material, and processing parameters. These stresses can significantly reduce the lifetime of parts and can reduce the dimensional stability by warpage. They also contribute to environment stress cracking damages.

2.7.1.4 Shrinkage

Shrinkage after molding is a universal problem depending on:

- the CTE: for given conditions, the shrinkage increases with the CTE
- the molding temperature: for given conditions, the shrinkage increases with the molding temperature
- the additives
- the orientation of the macromolecules
- the orientation of fibers or acicular fillers
- the crystallinity: a possible crystallization after molding leads to a volume increase that minimizes the total shrinkage.

2.7.1.5 Warpage

Warpage or distortion can be due to:

- anisotropy of internal stresses
- shrinkage variations induced by local changes of formulation or processing parameters.

Colorants, for example, can nucleate the polymer and locally favor shrinkage.

Fibers and acicular fillers can accumulate in certain spots of the mold leading to local decreases of CTE, shrinkage, and increases of moduli, leading to warpage.

Calcium carbonate ($CaCO_3$) fine powder and other spheroid fillers such as microballoons or glass beads decrease shrinkage and easily flow in the mold, reducing warpage.

2.7.1.6 Water Uptake

All the polymers absorb more or less humidity or water in quantities depending on:

- the form of the water: humid air, liquid water, pure or polluted water
- the temperature
- the recipe of the compound
- the crystallinity of the polymer

The volume of absorbed water causes a dimensional increase. Really, the absorption of water is very slow and, in the case of atmospheric changes, the equilibrium is not always reached damping the effects of humidity variations.

Anisotropic absorption of water can cause warpage the more so as the material modulus is low. For example, a membrane covering a water container can curve because of the swelling of the inner face.

2.7.1.7 Releasing of Organic Additives

Organic additives, particularly plasticizers, can degas the more so as the temperature and the airflow rise. Consequently, dimensions decrease.

High molecular weight or reactive additives minimize releasing.

2.8 Market Appeal: Sensory Properties Are of the Prime Importance

The market appeal of plastics is important for numerous applications such as packaging, automobile, appliances, and so on. Often, parts are used out of injection press without surface treatment, painting, machining, and so on.

Sensory properties depend on the general formulation and processing conditions. Specific additives can be needed to satisfy some of the sensory requirements. The choice of general additives depends on a subtle balance of numerous parameters concerning the nature of the polymer, the processing constraints (notably heat exposure, mixing technology), end-product esthetics requirements, and the durability under service conditions of the end product.

As mechanical or physical properties, sensory properties are sensitive to aging.

Color, transparency, gloss, touch, scratch resistance, acoustic properties, odor, taste, and fogging among others contribute to make a plastic part attractive, unappealing, or repulsive.

2.8.1 Optical Properties

Color can be obtained by adding colorants to compounds, or encapsulating the part with a continuous film of another colored or printed polymer: IMD, painting, multilayer sheets for thermoforming, and so on.

Colorants can be classified according to:

- their chemical structure: inorganic or organic
- their form: powders, masterbatches or concentrates in pellets, pastes, liquids, dustless powders, encapsulated
- their function: colorants, brighteners, phosphorescent colorants, pearlescent colorants, metallic colorants

Clarity and transparency can be enhanced by adding clarifiers.

Matting can be obtained by adding special mineral fillers, another secondary polymer that is miscible to a greater or lesser degree with the main polymer, or proprietary additives.

Glossy polymers can be obtained by polishing, postmolding into perfectly polished molds, lay out of films, IMD, film insert molding, in-mold coating, painting, and so on.

2.8.1.1 Touch

Touch can be as varied as rubber-like, metallic, or mimicking cloth, wood, leather. Now a soft touch is particularly in fashion thanks to soft and ultrasoft TPEs.

Touch can be tuned by modification of the used compound or by overmolding with a TPE or other soft compound.

There are crowds of soft-touch applications such as:

- soft-touch knobs, grips, handles for appliances, kitchenwares, housewares
- grips, feet, nonskid surfaces for hand and power tools, industry, lawn and garden equipment
- feet, impact cladding, soft-touch handles for mobile phones, game consoles, computer mouses, MP3 players, and other electronic/telecommunication equipment.
- grips and soft-touch buttons and panels, keypads, pencil grips for personal care applications and consumer goods.
- soft-touch panels, cup holders, console and tray liners, instrument panel covers, arm rests and steering wheels, pillars for automotive interior.
- soft-touch components for sports and leisure.

2.8.1.2 Scratch Resistance Improvement

Soft polymers are more sensitive to scratch than some harder plastics. The use of silicone helps reduce the coefficient of friction and correspondingly improves the scratch resistance. Surface treatments with hard resins are also used.

2.8.1.3 Acoustic Comfort

Generally speaking, conventional plastics have sound and vibration dampening properties that conventional metals have not. For example, polyetheretherketone, UHMWPE, and other ETPs are used to build silent gears.

But plastic parts can also initiate unwanted noises by vibration. For example, certain automotive parts can vibrate at frequencies of engine rotation. Plastics rubbing on other plastics or various materials can also emit annoying noises.

2.8.1.4 Odors

Some plastics can develop unpleasant odors during and after processing or after aging. To avoid or reduce that, it is possible:

- to choose odorless grades and additives
- to add deodorants or specific fragrances marketed for polymers
- to add bactericides or preservatives to avoid growth of microorganisms, fungi, and so on during service life.

Certain recycled plastics can smell bad.

Plastics can adsorb surrounding odors and then release unpleasant odors.

2.8.1.5 Taste

Some plastics can develop unpleasant taste during and after processing, use, or aging.

Plastics may also adsorb surrounding substances and take a bad taste.

2.8.1.6 Fogging

The word "fogging" relates to two different phenomena:

- One is the condensation of the air moisture on the cold plastic, formation of tiny droplets of water on the surface, light scattering, and obscuring of the polymer. This is an important problem for optical applications, packaging, horticulture, and so on. For a given difference of temperatures between the air and the plastic part, the duration of the fogging depends on the thermal conductivity of the polymer. Other materials as glass are subject to the same problem.
- Desorption of additives, oligomers, or low-molecular-weight polymers from the plastic parts and their condensation on other cold parts: glazing of cars and particularly windscreens, optical lenses, or electronic devices where the deposit of additives can also make electrical insulation. To avoid these troubles, two main ways are used: choice of low outgassing additives and polymers without monomers or oligo mers; spreading of a permanent barrier coating onto the surface of the plastic part.

Further Reading

Technical Guides, Newsletters, Websites

Matweb, Omnexus, Specialchem.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

Books & Papers

[6] M. Biron, Thermosets and Composites – Technical Information for Plastics Users, Elsevier Ltd, 2013.

3 Thermoplastics: Economic Overview

OUTLINE

The decision to use a new material is difficult and important. It has both technical and economic consequences, making it essential to consider:

- the abundance or scarcity of the material and the process targeted
- the cost
- the actual penetration of the material category in the industrial area.

The goal of the following facts and figures concerning thermoplastics and composites is to help quickly clarify the real applications and the relative importance of the various families and processes. The figures are roughly estimated from professional or governmental studies and papers or news from technical reviews. These sources can indicate significantly different figures according to the methodology used (applications, whether or not the captive industry is taken into account, etc.).

The reader must verify the economic figures and information and is solely responsible for the chosen solutions. The facts and figures herein are provided for information only, without any warranty.

3.1 Overview of the Global Plastics Industry Today and Tomorrow

The plastics industry has grown continuously for over 50 years. Production increased from 1.5 million tons in 1950 to 290 million tons in 2014. The annual growth was hit hard by the global economic crisis beginning in 2008. In the long term, the plastics success story is expected to continue. Per capita

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00003-9

Table 3.1 Global Plastics Consumption—2014

	Million Tons	%
Commodity	214	74
Engineering	13–15	5
Composites	9–12	3–4
Speciality	3	1
TPE	3–4	1
Environment-friendly	1	<1
Others	40–46	15
Total	~288	100

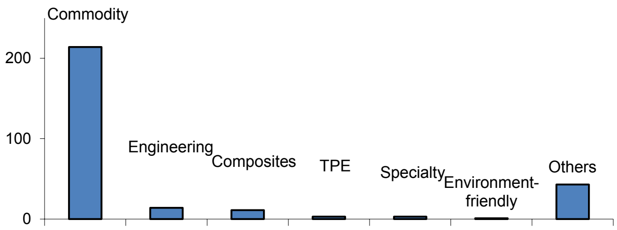


Figure 3.1 World plastic consumption—million tons.

consumption in Asia and Central Europe is significantly below the levels of mature industrial regions and global per capita demand is growing at a long-term trend of 4%. Mature industrial regions are also expected to see growth rates slightly above gross domestic product.

Worldwide plastics consumption is in the order of 290 million tons annually in round figures, with a turnover of US $1200 billion or more. Over the past recent years, global plastics consumption has grown consistently by an average annual rate of 5%, superior to steel and aluminum rates. Table 3.1 and Figure 3.1 display the orders of magnitude of global plastics consumption.

Worldwide plastic growth is estimated between 5% and 5.5% per annum for the next few years, leading to a worldwide consumption estimated to about 400 million tons by 2020.

Consumptions and growth rates broadly vary according to the area considered. China and other Asian countries excluding Japan are the leaders for commodity plastics consumption and growth rate, superseding North America and Western Europe, which in return are leaders for engineering and specialty plastics. Table 3.2 and Figure 3.2 display consumption data for 2014 and forecasts for 2020 according to a medium hypothesis of annual growth rate. Consumptions are uncertain and forecasts are

Table 3.2 Consumption and Growth Rate Forecasts for All Plastics

	Commodities (million tons)	Total Plastics (million tons)		Annual Growth Rate (%)
Year	2014	2014	2020	2020/2014
China	53	60	111	10
Rest of Asia excluding Japan	23	30	56	10
NAFTA	47	67	77	2.5
Western Europe	43	66	77	2.5
Japan	11	16	17	2
Latin America	14	17	21	4
Africa and Middle East	16	22	28	4.5
Eastern Europe/FSU[a]	7	10	13	5
	214	288	400	5.6

NAFTA: North American Free Trade Agreement (Canada, the USA, and Mexico).
[a]FSU: Former Soviet Union.

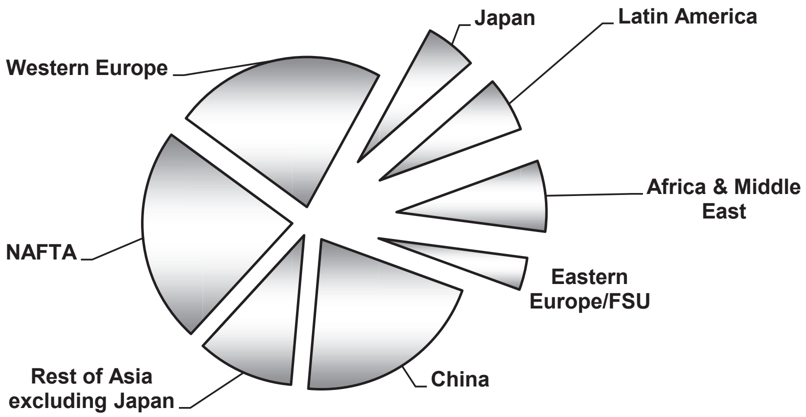


Figure 3.2 Consumptions in 2014 according to the areas.

Table 3.3 Market Shares by Weight for the Main Plastics

Thermoplastics	Thermosets	Market Share (%)
PE		27–33
PP		18–20
PVC		11–13
PET		8–10
PS		6–8
	PUR	5–7
	Amino resins	2–5
	Unsaturated polyesters	2–3
	Phenolic resins	1
PA		2–3
Other engineering		3–4
	Other engineering	1
TPEs		1
Total thermoplastics		83
	Total thermosets	14
Composites		3–4
Total		100

more or less subjective. Consequently, other estimations can be found in other sources.

The market shares for the major families of plastics are estimated in Table 3.3 for industrialized countries; however, other figures can be found in other sources according to the applications taken into account and the areas considered.

Thermoplastics represent more than 80% of overall plastic consumption.

The distribution between the families varies from one area to another mainly for polyethylene and thermoplastic polyesters.

The market shares by weight (order of magnitude only) for some engineering and specialty plastics were estimated as follows (see Table 3.4). Remark that market shares by cost are different because of the high cost of high-performing thermoplastics. So, for polyetheretherketone (PEEK), the market share estimated at some ‱ by weight may be estimated at some ‰ by cost.

3.2 Market Shares of the Various Thermoplastic Families

Table 3.5 and Figure 3.3 indicate the market shares by weight of the main thermoplastics versus total thermoplastics in the main industrialized countries.

3.3 Market Shares of Composites

In terms of weight, the share of composites in the total plastics consumption is relatively weak (4–5%), but the share in terms of value is higher: roughly 12%.

Table 3.4 Market Shares by Weight for Some Engineering and Speciality Plastics

Thermoplastics	Thermosets	Market Share (%)
PET		Several %
	Polyure-thanes	Several %
	Amino resins	Some %
	Unsaturated polyesters	Some %
	Phenolic resins	Some %
Polyamides		1% to some %
Polycarbonates		1% to some %
PMMA		1% to some %
Market shares <1%		
	Epoxies	Some ‰
Polyacetal		Some ‰
PBT		Some ‰
PPE		Some ‰
PC/ABS alloys		Some ‰
SAN		Some ‰
Cellulosics		Some ‰
Bioplastics		Several ‰
Market shares <1‰		
PTFE		Some ‱
PPS		Some ‱
PA/Polyolefin alloys		Some ‱
PSU, PESU		Some ‱
PEI		Some ‱
Market shares <1‱		
FEP		Some %ooo
LCP		Some %ooo
PEEK		Some %ooo
PFA		Some %ooo

Table 3.5 Market Shares by Weight for the Main Thermoplastics

Thermoplastics	Market Share (%)
PE	33–39
LDPE/LLDPE	18–22
HDPE	15–17
PP	21–23
PVC	13–15
PET	9–12
Styrenics: PS and others	7–11
PA	2–4
PC	1
PMMA	1
Aceta1	<1
Other engineering	6
TPEs	1
Bioplastics	<1
Total thermoplastics	100

The growth rate, 5–7% per year, is greater than that of the plastics industry as a whole.

Table 3.6 and Figure 3.4 show the consumption of composites in North America, Europe, and BRIC (Brazil, Russia, India, China).

Composite matrices may be thermoset or thermoplastic. The unsaturated polyester resins (thermosets) are the most used, followed by polypropylene (thermoplastic). The thermoplastic share is growing fast.

Asian consumption is specifically oriented to glass-reinforced plastics without a significant production of advanced composites.

Figure 3.5 shows the share for polypropylene matrices versus thermoset matrices.

3.4 Market Shares for the Main Application Sectors

Table 3.7 and Figure 3.6 indicate the approximate market shares consumed by different application sectors for plastics as a whole. The figures vary according to geographical regions and may evolve with time.

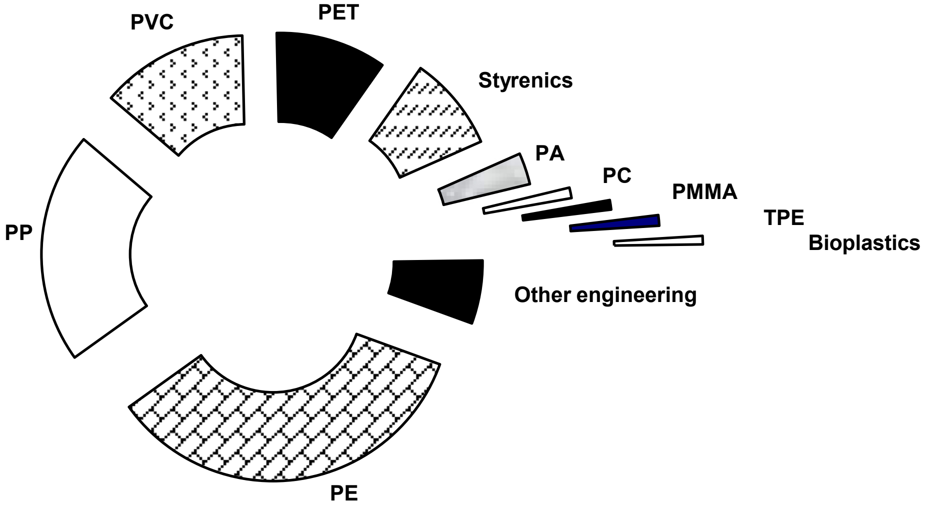


Figure 3.3 Market shares based on total thermoplastic consumption.

Table 3.6 Composite Consumption in North America, Europe, and Asia

	America	Europe	BRIC	Others
Composite consumption (million tons)	3.1	3.1	3.2	0.6
Share of world composite consumption (%)	31	31	32	6

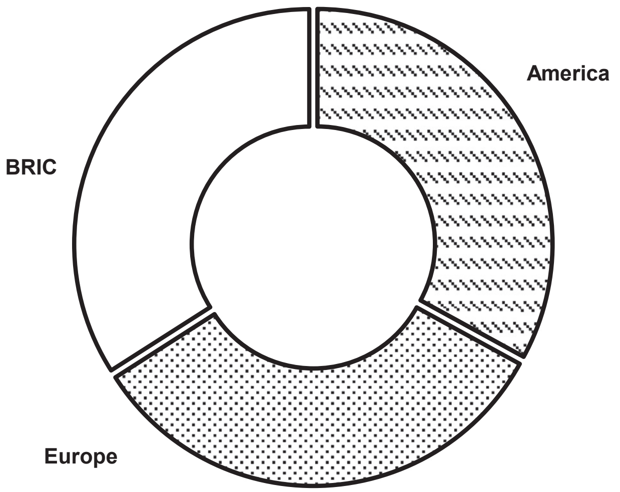


Figure 3.4 Market shares of the three main regions of composite consumption.

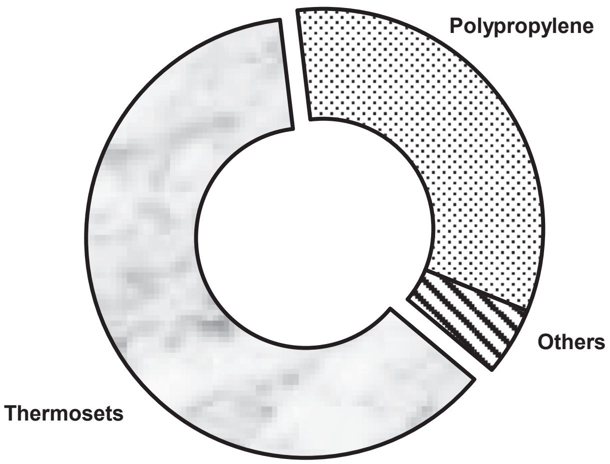


Figure 3.5 Market shares of the main composite matrices.

- Three application sectors—packaging, building and civil engineering, automotive, and transportation—consume 70% or more of all plastics.
- The eight application sectors that each consumes more than 1% of plastics together account for more than 90% of the total plastics consumption.

The consumption of thermoplastics predominates (as indicated by Table 3.3) but the market share distribution of the thermoplastic application sectors (see Table 3.8 and Figure 3.7) is nevertheless somewhat different from that of plastics as a whole. Figures vary broadly according to the geographical area.

Table 3.7 Market Shares for the Eight Main Plastic Application Sectors

Market	%
Packaging	37–39
Building and civil engineering	18–24
Automotive and transportation	8–13
Electrical and electronics	7–9
Sports and leisure	2–5
Furniture and bedding	2–4
Agriculture	2
Medical	1
Others	7–11
Total	100

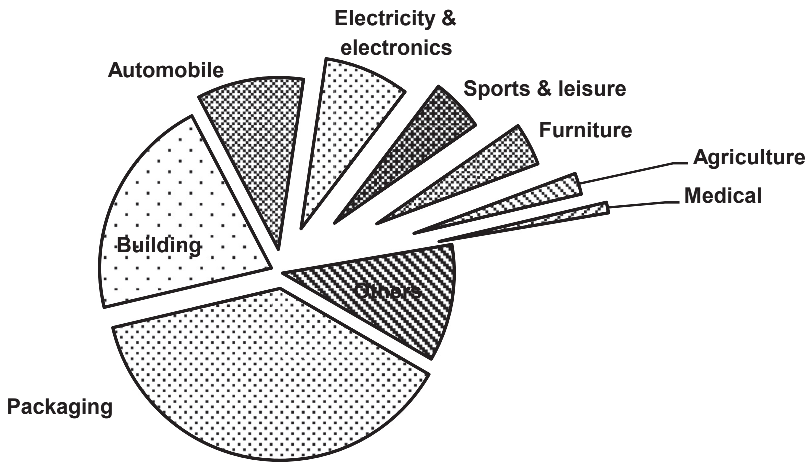


Figure 3.6 Market shares of the eight major plastic application sectors.

- The packaging sector, which is also a major application area for plastics as a whole, consumes 33% up to 48% of thermoplastics.
- The building and civil engineering sector is also the second largest market for thermoplastics.
- The consumer goods sector is the third largest market for thermoplastics. (This sector is somewhat ill-defined and in later sections is divided between the household, office, and entertainment appliances and sports and leisure sectors.)
- The shares consumed by the automotive and transportation, and electrical and electronics sectors vary substantially with the geographical area considered.

The consumption of composites (see Table 3.9 and Figure 3.8) is atypical:

- The building and civil engineering sector is the major consumer.
- The composite market shares taken by the automotive and transportation, electrical and electronics, and sports and leisure sectors are approximately twice the average for plastics as a whole.
- The shipbuilding sector consumes 6% of composites.
- The aeronautics sector is a significant composite consumer, particularly in terms of turnover, because of the high proportion of advanced composites used with matrices such as epoxies, polycyanates, polyimides, PEEK, and reinforcements such as carbon fibers.
- The packaging sector is absent.

3.5 Importance of the Various Processing Modes

For each type of polymer, there are several possible processing methods from which it will be necessary to choose to best suit the required geometries, production rates, targeted properties, and economic context.

Figure 3.9 gives some indications of the distribution of thermoplastic consumption according to processing method:

- Molding is the most used process for injection of small to large parts, from micro-switches up to fenders and pallets. Blow molding allows the manufacture of hollow parts, notably bottles.

Table 3.8 Market Shares for the Eight Main Thermoplastic Application Sectors

Market	%
Packaging	33–48
Building and civil engineering	19
Consumer goods	16
Automotive and transportation	5–13
Electrical and electronics	3–8
Furniture and bedding	1–4
Medical	2
Industrial	1
Others	4–6
Total	100

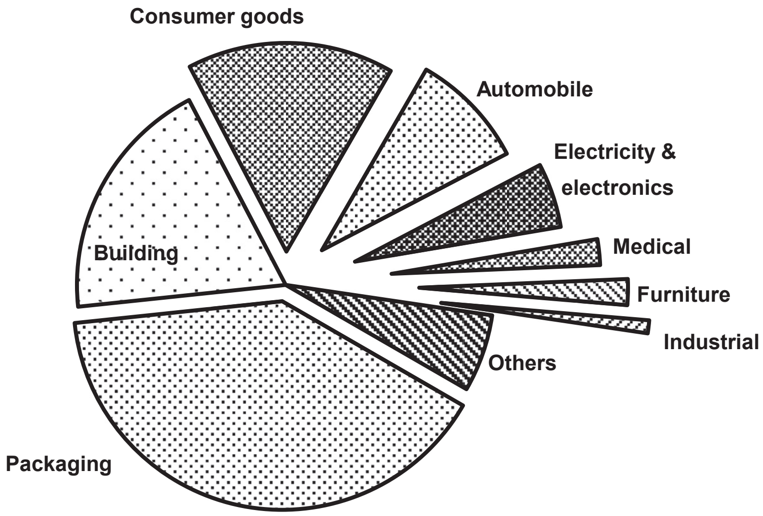


Figure 3.7 Market shares of the eight major thermoplastic application sectors.

- Extrusion is used for films and sheets, tubes and pipes, various profiles…
- Among the other processes, let us quote, for example:
  - calendaring, rotomolding, casting, slush molding, and powdering for primary processing
  - thermoforming, machining, and boiler-making for secondary processing.

Composite processing uses specialized methods. For thermoplastics, glass mat thermoplastic is the main method but prepreg, layup, tape winding, pultrusion are also used to produce thermoplastic composites. Sheet molding compound and bulk molding compound are the main processes for thermosets but layup is currently used for large parts and prepregs are used for high-tech parts.

Figure 3.10 displays examples of market shares for the main composite processing methods.

3.6 Consumption Trends

In 2014, China remains the leading plastics player.

3.6.1 Thermoplastics

Table 3.10 displays the expected consumption of the major thermoplastics in 2014 for the three main geographic areas. These identified thermoplastics represent roughly 76% of the overall global consumption of plastics. Data are of uncertain order of magnitude and other figures may be found elsewhere.

- Polyethylene is the most consumed thermoplastic—39% of the subtotal of the identified thermoplastics for the three main areas.
- The market share of polypropylene is lower but its annual growth rate is high.
- PVC, the third largest, is handicapped by environmental pressure. Its annual growth rate, mainly due to China, is the lowest.
- Thermoplastic polyesters are atypical with a low consumption in China but a high annual growth rate in Europe and America.
- Styrenics are fifth of commodities.

Table 3.9 Market Shares for the Nine Main Composite Application Sectors

Market	Composite Shares
Building and civil engineering	23–39
Automotive and transportation	25–31
Consumer goods	5–13
Electrical and electronics	3–14
Mechanical and industrial	10
Shipbuilding	6
Aeronautics	1–3
Medical	1
Railway	1
Others	3
Total	100

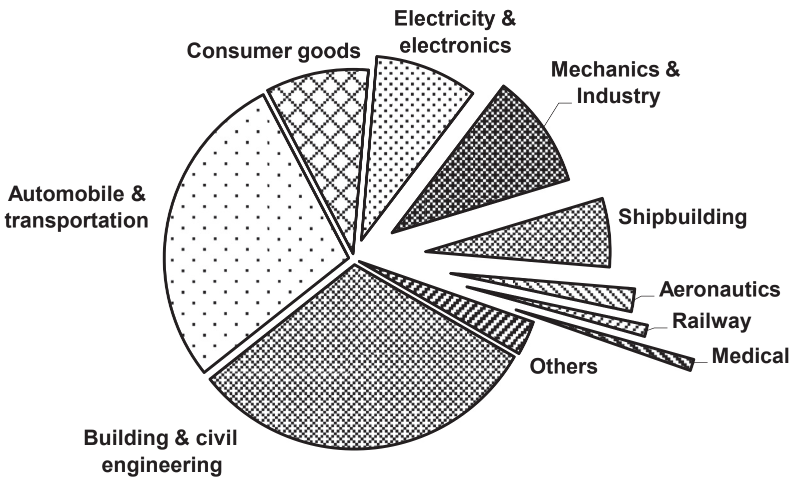


Figure 3.8 Market shares of the nine major composite application sectors.

Globalization promotes the transfer of general-purpose thermoplastic processing from Europe or America to Asia.

3.6.2 *Thermoplastic and Thermoset Composites*

The annual growth of composite consumption in industrialized countries is approximately estimated at a few percent. Table 3.11 shows some trends for the USA.

3.7 The North American Market

Table 3.12 (after statistics from the American Plastics Council) displays some estimations of US consumptions (2012, round figures) and 2012–2011 annual growth rates for thermoplastics and thermosets.

3.8 The Western European Market

Table 3.13 (after PlasticsEurope) displays the Western European consumption of thermoplastics for 2005 and 2012, with market shares and average annual growth rates. The European market shares are near the global ones with a slight increase coming from the global economic crisis and a shifting of polyethylene market toward China. Together, the big five thermoplastic families (polyethylene, including low density (PE-LD), linear low density (PE-LLD), and high density (PE-HD); polypropylene (PP), polyvinylchloride (PVC); styrenics; and polyethylene terephthalate (PET)) account for around 75% of all European plastics. PVC is the third family but declines for environmental issues. There is a slight slowdown of high-density polyethylene (HDPE) for economic issues leading to a shifting of production toward China.

3.9 The Asian Market

Statistics are rare and often differ. However, it is generally estimated that:

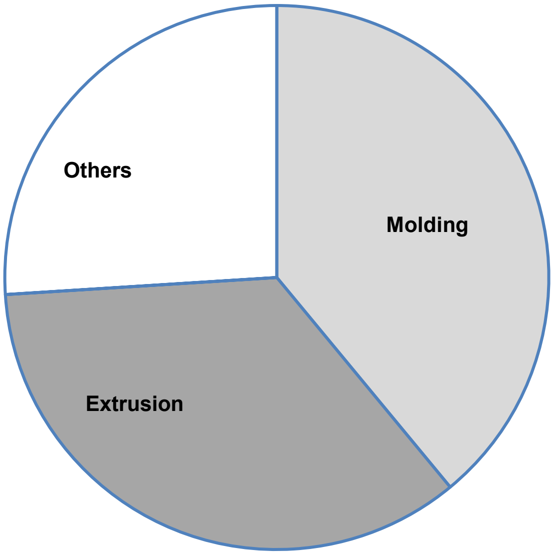


Figure 3.9 Market shares of the main thermoplastic processings.

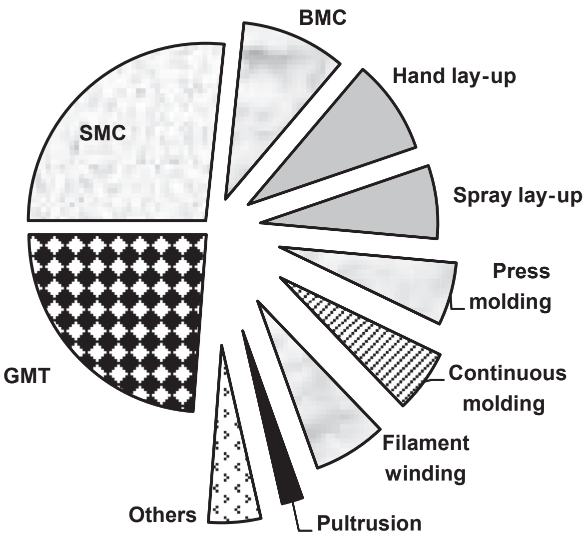


Figure 3.10 Market shares of the main composite processings.

- China is the main consumer among the Asian countries,
- the consumption of commodities is higher than in fully industrialized countries, and
- the annual growth rates are higher, ranging between 7% and 30% according to the material considered and the optimism of the source. China benefits from globalization, which leads to the transfer of commodity processing from industrialized countries.

Table 3.14 displays some estimations without any warranty.

We can observe that the market shares are atypical:

- the share for PVC is a lot higher than the worldwide consumption
- PET/PBT are marginal, far lower than the global consumption
- polyamides have lower consumption than in industrialized countries.

3.9.1 The Chinese Market

Statistics are rare and often differing. However, it is generally estimated that:

- China is the main consumer of the Asian countries,
- the commodities are more consumed than in industrialized countries, and
- the annual growth rates are higher ranging between 7% and 30% according to the considered material and the optimism of the source. China benefits from the globalization, which leads to the transfer of commodity processing from industrialized countries.

Table 3.10 2014 Consumption (million tons) of Major Thermoplastics for the Three Main Areas

	North America	Western Europe	China	Subtotal for the Three Areas
PE	17	13	21	51
PP	7	9	14	30
PVC	7	5	12	24
PS and other styrenics	2	4	8	14
PET/PBT	7	3	1	11
PA	1	1	1	3

Table 3.11 US Market Shares for the 10 Main Composite Application Sectors

	Share of Composite Consumption (%)	Annual Change (%)
Automotive and transportation	27–31	5
Building and civil engineering	20–24	2
Corrosion protection	10	4
Shipbuilding	10	4
Electrical and electronics	10	4
Aeronautics	7–10	5
Sports and leisure	6	3
Mechanics and Industry	4	2
Railway	1	4
Medical	1	4
Total	100	4

Table 3.12 American Market: Estimations of Consumption and Annual Growth Rates

	Consumption	2012–2011 AGR
LDPE	3	0.4
LLDPE	6	–1.7
HDPE	8	2.2
Subtotal PE	17	
PP	8	0.6
PVC	7	5.7
PS	2.5	–3.5
Nylon	0.5	7.7
Other thermoplastics	7	2.4
Total thermoplastics	42	1.6
Total thermosets	7	5.4
Grand total plastics	49	2.1

We can remark that the market shares are atypical:

- The consumption of commodities account for 95% of the total, higher than in fully industrialized countries.
- The consumption of engineering plastics is very low.
- The share of PVC is a lot higher than the worldwide consumption.
- PET/PBT are marginal, far lower than the global consumption.

3.9.2 The Japanese Market

The structure of the Japanese market is typical of an industrialized and mature market:

- Commodities account for 70% of the total
- PVC share is in the worldwide range
- PET/PBT consumption is in the range of other mature markets
- Polyamides are less consumed than in industrialized countries.

Total plastic consumption is slightly declining.

3.9.3 The Indian Market

The global economic crisis has not really hit the India's plastics industry. Growth rates for polyethylene, polypropylene, and other commodity resins should be in the high range of 15–30% annually for the next several years. The Indian plastics market is about 11–13 million tons of resin per year. That number is expected to double in the next five years reaching 19–23 million tons in 2017.

Table 3.13 Western European Market: Estimations of Consumption and Annual Growth Rates

	Total Sales and Captive Use (million ton)		2012 Market Shares Linked to Identified Thermoplastic Uses (%)	AAGR (% per Year)
Year	2005	2012		
LDPE/LLDPE	7.4	8	24	1
HDPE	5.2	5	15	–0.5
Subtotal PE	12.6	13	38	0.5
PP	7.9	9	26	2
PVC	6.2	5	15	–3
Thermoplastic polyester	2.2	3	9	5
Styrenics	2.3	4	12	8
Identified TP	31.2	34	100	1.3

Table 3.14 Asian Market in Recent Years: Estimations of Consumption and Average Annual Growth Rates

	Consumption (million tons)	Market Share (%)	Annual Change (%)
Chinese market			
PE	15	32	7–15
PP	12	25	7–15
PVC	10	21	7–15
PS and other styrenics	8	17	7–15
Subtotal of commodities	(45)	(95)	
PC	1.3	3	10–30
POM	0.4	<1	7–15
PA	0.4	<1	10–20
PET	0.3	<1	10–20
PPE	<0.1	<1	10–30
Subtotal of engineering TP	(2.5)	(5)	
Total Chinese TP market	47.5	100	7–15
Japanese Market, 2012			
PE	2.6	25	
PP	2.4	23	
PVC	1.3	12	
PS and other styrenics	1.1	10	
Subtotal of commodities	(7.4)	(70)	
PET—PBT	0.7	6.6	

Continued

Table 3.14 Asian Market in Recent Years: Estimations of Consumption and Average Annual Growth Rates—cont'd

	Consumption (million tons)	Market Share (%)	Annual Change (%)
PC	0.32	3	
PA	0.22	2.1	
POM	0.12	1.4	
Subtotal of engineering TP	(1.36)	(13.1)	
Others	1.7	16.2	
Total Japanese TP market	10.5	100	–1.6
Indian Market, 2012			
Total Indian market	11–13	100	15–30

Table 3.15 Structure of Plastics Processing Companies

Processing Company and Employment Statistics			
	No. of Companies	**No. of Employees**	**Ratio of Employees to Companies**
Europe	50,000	1,600,000	32
USA	18,000	1,000,000	56
Japan	20,000	450,000	23
Processing Turnover Statistics			
	Turnover (million €)	**Average Turnover (million €) per Company**	**Average Turnover (million €) per Employee**
Europe	280,000	5.6	0.2
USA	374,000	20	0.37
Japan	86,000	4.3	0.2

3.10 Structure of the Plastics Processing Industry

In Europe, there are approximately 50,000 companies specializing in processing plastics. Together, they employ about 1.6 million people and have sales superior to €280 billion. These figures do not represent the whole of plastics processing. A large number of enterprises are integrated into automotive, electrical/electronics, building, and toys and games firms and are not taken into account in these statistics.

SMEs employing more than 100 workers generate 75% of the plastics processing turnover. The general trend is toward alliances and mergers.

In the USA, there are approximately 18,000 companies specializing in processing plastics, less than half the European figure. They employ about 1,000,000 people and have sales around €374 billion. A large number of enterprises, integrated into other industries, are not included in these statistics.

In China, it is expected that companies are much smaller than in industrialized countries. For example, China is the leader for PE films but production is shared between about 10,000 companies. Probably, the given figures exclude the smallest companies.

Compared with the USA and Japan (Table 3.15), Europe appears to have smaller companies than the USA (a smaller ratio of employees versus the number of companies), but larger ones than Japan.

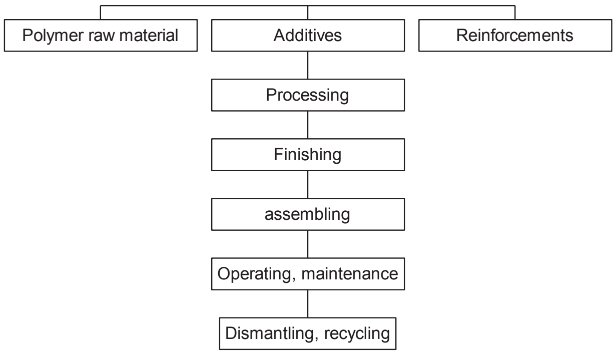


Figure 3.11 End-life cost of plastic parts.

3.11 Plastic Costs

Polymeric materials are intrinsically expensive, but their use becomes appealing if one takes into account the processing costs, the new technical possibilities that they permit, and the total cost at the end of their lifetime.

Figure 3.11 summarily analyzes the various cost components.

3.11.1 Raw Material Costs

The price per kilogram varies in round figures from about €1 to €100 according to the nature of the polymer itself, the formulation of the grades, and the inclusion of high-cost reinforcements including carbon fibers and so on.

The highest prices relate to the polymers with the highest performances, which are also the least used. Figure 3.12 illustrates this situation. Very broadly speaking, prices per kilogram increase from commodities up to specialty plastics as follows:

- Commodities: €1.2 ($1.4) up to €2.4 ($3)
- Engineering plastics: €2 ($2.3) up to €10 ($12)
- Specialty plastics: €6 ($8) up to €85 ($100).

3.11.2 Examples of Additive Costs

Apart from the reinforcements, the additives are numerous and some are more expensive than the raw polymer. Figure 3.13 displays the main additive categories.

Average prices for overall additives are roughly estimated from €1.6/kg ($2/kg) to €2/kg ($2.5/kg) with a broad range of individual prices from less than €1/kg ($1.2/kg) for cheap fillers up to tens of €/kg (or $/kg) for specialty additives.

To solve a same problem, it is sometimes possible to choose between very different economic routes. For example:

- compatibility between fillers and polymers can be obtained with silanes ranging from €10/kg ($12/kg) up to €20/kg ($24/kg) or with functionalized polymers ranging from €3/kg ($3.5/kg) up to €5/kg ($6/kg)
- UV protection can be obtained with cheap special carbon blacks (but color is gray to black) or with expensive photostabilizers.

The final choice depends on the specifications and the end-user's requirements.

3.11.3 Reinforcement Costs

For the global advanced composites market, the average cost of high-performance fiber reinforcements (carbon, aramid, high modulus polyethylene, boron, R/S/T-glass, and some E-glass) is estimated from €5 ($6) to €70 ($90). This moderate price is due to the decrease in the carbon fiber price. Some grades could fall to less than €20 ($24)/kg in the short or medium term.

The price of the fibrous reinforcements (Figure 3.14) depends on the nature of the fibers and the form of the reinforcement: continuous or chopped fibers, mats, rovings, 2D or 3D fabrics, or unidirectional.

The prices of fibers cover a large range, which partly explains the low consumption of fibers other than those of E-glass. For example, without any warranty:

• Carbon fiber sleeves	€70 ($85) up to €270 ($350)
• Carbon and aramid fiber sleeves	€70 ($85)–€90 ($110)
• Aramid fiber sleeves	€60 ($75) up to €73 ($95)
• Basalt fiber	€25 ($30)
• Glass fiber chopped strand mat	€0.9 ($1.1)
• Fiber glass woven rovings	€0.7 ($0.8) up to €7 ($9)

The prices of sandwich composite cores (Figure 3.15) range from 1 (reference) for balsa to 5 for the aramid honeycombs.

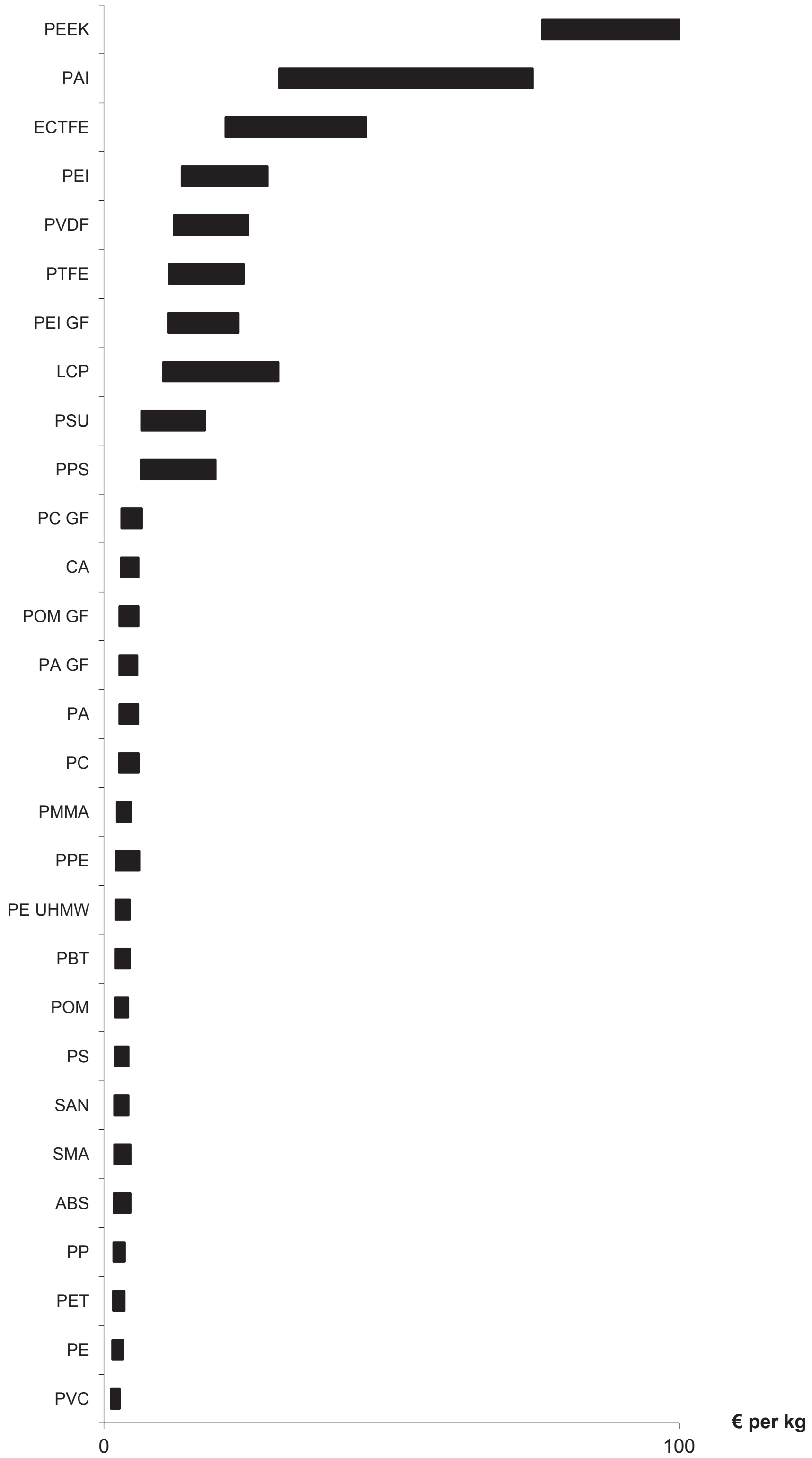


Figure 3.12 Approximate plastic raw materials costs, € per kg.

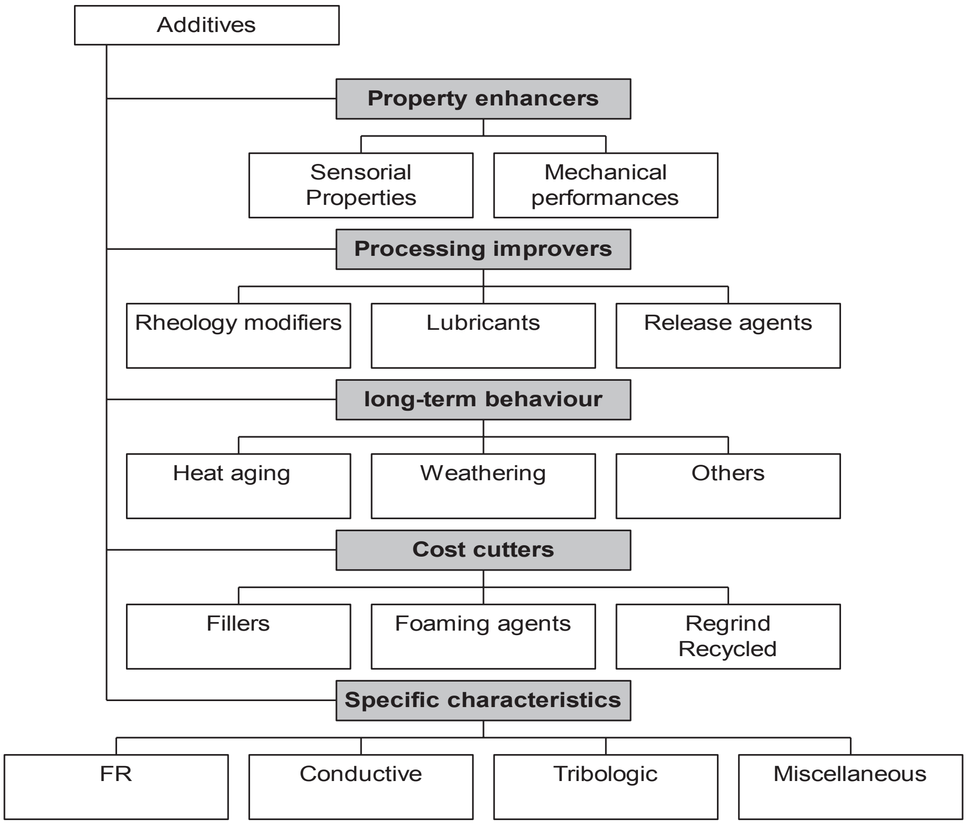


Figure 3.13 Examples of additives for thermoplastics.

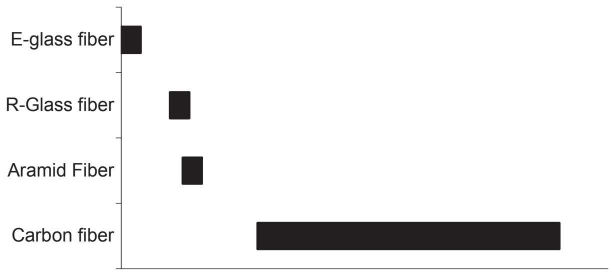


Figure 3.14 Relative costs of various fiber reinforcements.

3.11.4 Processing Costs

The following figures for processing costs are some examples of the orders of magnitude for specific cases; a different context can lead to a very different cost.

For the fully industrialized countries, the average cost of plastics is €5 ($6) in the range €3.3 ($4) up to 6.6 ($8) per kg.

For a given processing technology, the processing costs are highly dependent on:

- the annual production
- the size and shape of the parts
- the precision level
- the material cost
- the processing difficulties
- the recycling possibilities.

For extruded goods such as films, sheets, and tubes, the costs are of the order of:

- €3.3 ($4)–€4 ($5)/kg for commodities
- €6.6 ($8)/kg for high-performance films.

Each different design with a profile requiring the machining of a specific tool is charged with the tool cost.

The average cost for packaging is in the order of €4.5 ($5.5)–5.5 ($7)/kg.

The injection molding cost of a part is superior to the price of the raw polymer. The average selling prices are of the order of:

- €8 ($10)/kg for building purposes
- €12 ($15)/kg for consumer goods
- €14 ($17)/kg for technical parts.

Figure 3.15 Relative costs of various cores for sandwich composites.

Table 3.16 Examples of Average Selling Prices versus Market

Market	Average Prices € per kg ($/kg)
Miscellaneous	4.5 (5.5)
Building and civil engineering	4.5 (5.5)
Electricity and electronics	4.5 (5.5)
Mechanics and industry	5.5 (7)
Automotive and transportation	6.5 (8)
Shipbuilding	6.5 (8)
Sports and leisure	10 (12)
Medical	16.5 (20)
Aerospace	45 (550)

Each different design of parts requires the machining of a specific mold whose cost (for example, €55,000 ($70,000)) or much more, is charged to the series of parts manufactured.

The composites, even those that are mass-produced, always have a high added value, for example:

- €4.5 ($5.5)–€9 ($11)/kg for mass-produced parts
- €11 ($13)/kg up to €45 ($55)/kg for advanced composites.

Table 3.16 displays some approximate average selling prices of thermoplastics per kilogram.

Table 3.17 analyzes some examples of the relative processing cost versus the annual production in units. The various technologies listed are not suitable for all materials or parts:

- machining is used with numerous materials
- rotational molding uses liquid resins
- vacuum forming uses thermoplastic sheets
- blow molding uses special grades of thermoplastics
- injection molding is used with numerous thermoplastics, with a very few exceptions such as PTFE.

The costs shown in this table are index-linked and do not have intrinsic value. The reference (base 1) is the part cost for injection molding 1 million parts per year. The comparison is only valid for this table.

3.11.5 Some Good Reasons to Use Thermoplastics and a Few Examples of Success Stories

The cost of a plastic part is generally higher than that of its metal counterpart and the "overspend" must be compensated for by:

- the redesign of the parts, the integration of several functions
- the selection of innovative processing methods adapted to the number of parts to be produced
- the choice of new assembly technologies that save costs
- the decrease in operating costs. The automotive, aerospace, and railway sectors are excellent examples of the compensation of material overspend by operating cost savings. The weight savings from the use of polymers and composites offer higher performances, increased payload and/or speeds, and/or allow decreased fuel consumption. Consequently, the operating costs are reduced. The overspending allowed for a traditional solution compared with a polymer solution is roughly:
  - €300 ($350) per kg gained for a helicopter
  - €1200 ($1500) per kg gained for a satellite

Table 3.17 Examples of Processing Methods and Relative Costs per Unit[a]

	Processing Methods for Prototypes
Units per Annum	**Machining**
1	150
10	125

Processing Methods for Small and Medium Annual Production							
Units per Annum	**Hand Layup**	**Machining**	**Rotational Molding, Simple Tooling**	**Rotational Molding, Sophisticated Tooling**	**Vacuum Forming**	**Blow Molding**	**Injection**
100	25	110	35	60			
1000	15	100	10	40	15	80	200
10,000	7	7	7	10	20		

Processing Methods for High Annual Production			
Units per Annum	**Rotational Molding, Sophisticated Tooling**	**Blow Molding**	**Injection**
100,000	3	2.5	2.5
1,000,000	2.5	1.5	1

[a]*Relative to the part cost for injection molding 1 million parts per year.*

- maintenance cost savings, mainly due to corrosion resistance (but beware of aging).

A few examples illustrating these features have already been quoted (see Chapter 2) but there are many other cases including replacement of metals and other materials such as glass.

- Fabrication of single unit or short runs take advantage of innovative additive technology and new performing dedicated compound: CRP Technology has developed Windform XT 2.0, a carbon fiber-reinforced polyamide designed for processing by selective laser sintering technology. Applications may be fully functional such as the production of parts for the CubeSat, a GPS satellite.
- For the electricity and electronics markets, Table 3.18 displays the performances and costs of six engineering thermoplastics reinforced with glass fibers and UL94 V0 rated. The designer can choose between four levels of costs, five levels of water absorption, and several levels of mechanical and thermal properties according to the requirements.
- A panoramic roof system by Webasto uses a two-shot injection process. The first shot injection-compression molds the glazing in high-impact, tinted polycarbonate (PC), which weighs 40% less than a comparable-size panel in tempered glass. A second conventional injection shot backfills the large-area frame—which holds the glazing and is bonded to the vehicle's roof—in an opaque black grade of mineral-reinforced PC/acrylonitrile butadiene styrene (PC/ABS) blend. Last, both layers are protected from scratching, chemicals, and weathering by a silicone hardcoat supplied by Momentive Performance Materials. The tinted polycarbonate glazing is said to block 60% of incoming heat and 100% of incoming ultraviolet radiation, but the system also features a sliding sunshade of perforated fabric to cut glare and heat especially on sunny days.
- Evonik is supplying Plexiglas for the cockpits of the Eurocopter EC135. According to the company, it provides both excellent clarity and UV protection to pilots. Plexiglas is twice as light as traditional mineral glass. This reduces fuel usage and means that the Eurocopter EC135 can stay in the air for longer. If a bird strikes the cockpit, only the directly affected area is damaged.
- Sonoco delivers a durable, lightweight plastic option for replacement of 16-oz. and 20-oz. glass jars with an 84% glass saving.
- The Inrekor concept by JSP, a new technology for motor vehicle chassis, is claimed to have the potential to save 46% weight thanks to an ultralightweight sandwich structure technology using an Arpro expanded polypropylene core with bonded skins, to give exceptional strength-to-weight performance.
- Boeing's Dreamliner features a carbon fiber composite fuselage made of 50% carbon fiber composite material replacing traditional aluminum. The significant weight saving leads to a reported 20% saving in fuel with no compromise on speed.

Table 3.18 Examples of UL94 V0 Glass Fiber-Reinforced Engineering Thermoplastics

	PBT	PA66	PET	PPA	PPS	LCP
Density (g/cm^3)	1.65	1.45	1.67	1.68	1.65	1.65
Cost/liter (€/l)	6	6	8	11	11	34
Water absorption (%)	0.1	1	0.2	0.2	0.05	0.02
HDT (°C)	204	250	224	293	260	265
CUT (°C)	120	130	120	180	210	220
Modulus/cost	1.6	1.5	1.2	1.2	1.3	0.3
Impact/cost	13	51	10	6	8	3
HDT/cost	34	39	26	28	24	8

In addition, the carbon fiber composite fuselage requires far fewer parts compared with aluminum as there is less to bolt together. A one piece composite fuselage section saves a total 1500 aluminum sheets and 40,000 aluminum fasteners.

- Victrex has developed a polyaryletherketones (PAEK)-based polymer and an innovative hybrid molding technology allowing to overmold a PAEK-based composite with fiber-reinforced VICTREX® PEEK injection molding materials. That allows to design stronger, lower cost components that are up to 60% lighter than typical metal and thermoset systems.
- BASF and Faurecia have developed a new technology for replacing the existing metal structure of automotive seats by implementing a one-piece plastic part that minimizes needed foam and trim. The special features of the seat back are layers of continuous fiber-reinforced plastic which are overmolded with Ultramid® in a second step. The seat back weighs about 20% less than conventional car seats and is approximately 30 mm thinner saving useful space.
- For surgical parts, the ease of liquid crystal polymer (LCP) processing compared to metal results in cost savings of about 50% for some standard parts and up to 90% for high-tech parts.
- Material for endoscopic surgery: a high-fluidity glass fiber-reinforced LCP made it possible to mold long parts with thin walls in much shorter cycle times. The matrix is more expensive but with a 38% shorter cycle time, the overall cost saving is 42%.
- Framework of load compensator on plane wings: injection molding of a high-fluidity carbon fiber-reinforced PEEK allows the manufacture of parts with dimensions of 200 mm by 400 mm. This solution saves weight, finishing costs because the part is ready for use when it exits the press without finishing operations, in contrast to the aluminum part, and improves the behavior with the hydraulic fluids.
- Thermostat casing for automotive cooling system: a new design with 40% glass fiber-reinforced polyphenylene sulfide makes it possible to integrate 8 of the 12 components of the previous device. Benefits are weight, processing, finishing, and assembling cost savings thanks to the integration of functions and the ability to use the plastic part directly at the exit of the press without finishing operations, in contrast to the metal part.
- Replacement of metal bearings by a self-lubricating polymer: special self-lubricating grades of polyamide imide perform well and the overspending versus metal is compensated for by a lighter weight, and the maintenance cost savings in the case of a lubrication break.

3.12 The Future: Two Important Issues Linked to Crude Oil: Costs and Drying Up

Most polymers are made out of petroleum and the polymerization consumes energy. Consequently, their price and their availability are directly linked to the crude oil cost.

3.12.1 Polymer Cost Evolutions versus Crude Oil Price

Figures 3.16–3.21 display the price (cents per pound) of major commodity plastics versus the price ($) of crude oil barrel during the period 1990/2012.

For HDPE, LDPE, PP, polystyrene (PS), PVC, and ABS, modeling data thanks to linear equations lead to the following regression equations with very good correlation coefficients (R^2 is always higher than 0.9):

HDPE: $y = 1.1536x - 26.127$, $R^2 = 0.9332$

LDPE: $y = 0.9132x + 30.456$, $R^2 = 0.9432$

PP: $y = 1.3113x - 14.735$, $R^2 = 0.9651$

PS: $y = 0.7899x + 36.864$, $R^2 = 0.9444$

PVC: $y = 0.9445x - 0.0069$, $R^2 = 0.9224$

ABS: $y = 0.6238x + 58.402$, $R^2 = 0.912$

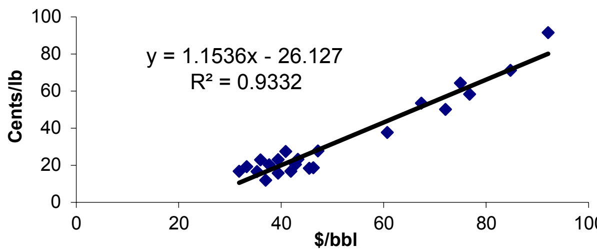


Figure 3.16 High-density polyethylene price versus crude oil price.

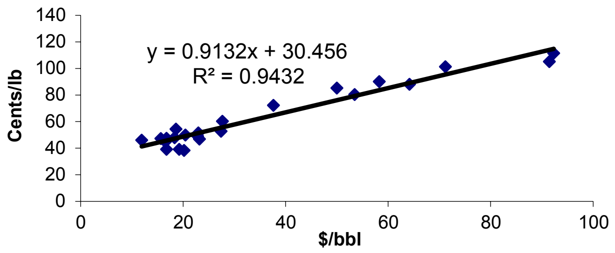


Figure 3.17 Low-density polyethylene price versus crude oil price.

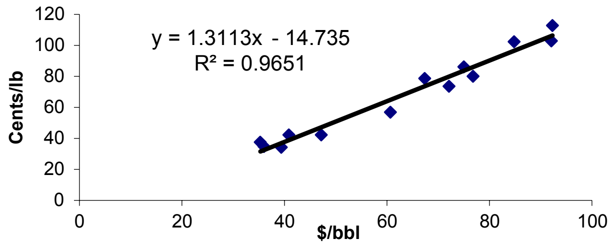


Figure 3.18 Polypropylene price versus crude oil price.

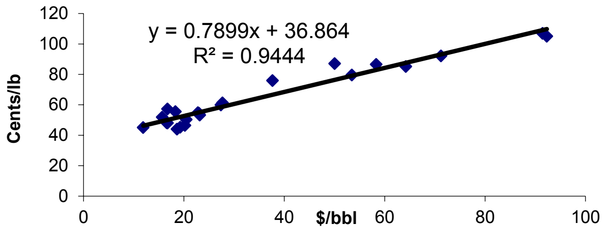


Figure 3.19 Polystyrene price versus crude oil price.

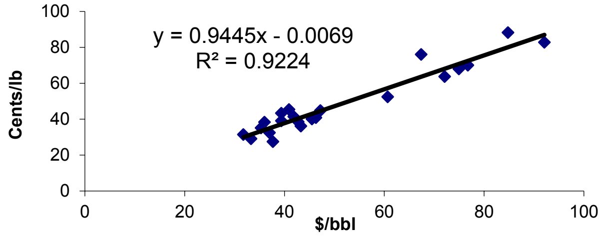


Figure 3.20 Polyvinylchloride price versus crude oil price.

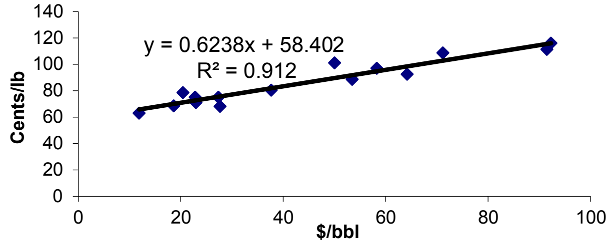


Figure 3.21 Acrylonitrile butadiene styrene price versus crude oil price.

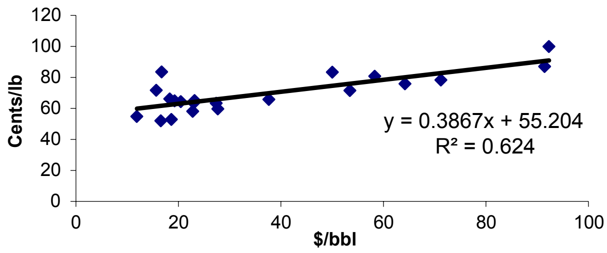


Figure 3.22 Polyethylene terephthalate (PET) price versus crude oil price.

Table 3.19 Plastics Price (cent/lb) Forecast versus Crude Oil Price ($)

	100	125	150	175	200
HDPE	89	118	147	176	205
LDPE	122	145	167	190	213
PP	116	149	182	215	248
PS	116	136	155	175	194
PVC	94	118	142	165	189
ABS	121	136	152	168	183
PET	94	104	113	123	133

For PET (see Figure 3.22), cost also increases with crude oil price but results are very different with a lower correlation coefficient and a lower slope. Linear regression equation is

$$\text{PET: } y=0.3867x+55.204,\ R^2=0.624$$

According to these models, Table 3.19 displays plastics price (cent/lb) forecast versus crude oil price ($).

3.12.2 New Raw Material Sources: Bio-Sourced Plastics

At current consumption levels, known recoverable crude oil reserves would be dried up in some tens of years for relatively easy extractable sources and 100 years or more if petroleum from sands is recovered. Potentially, this leads to a global energy crisis in a medium term.

As a result, it is essential to replace crude oil-sourced polymers with renewable ones. Now, in round figures, the global market for bioplastics (less than 1% of plastics as a whole) is set to grow by 8–10% annually.

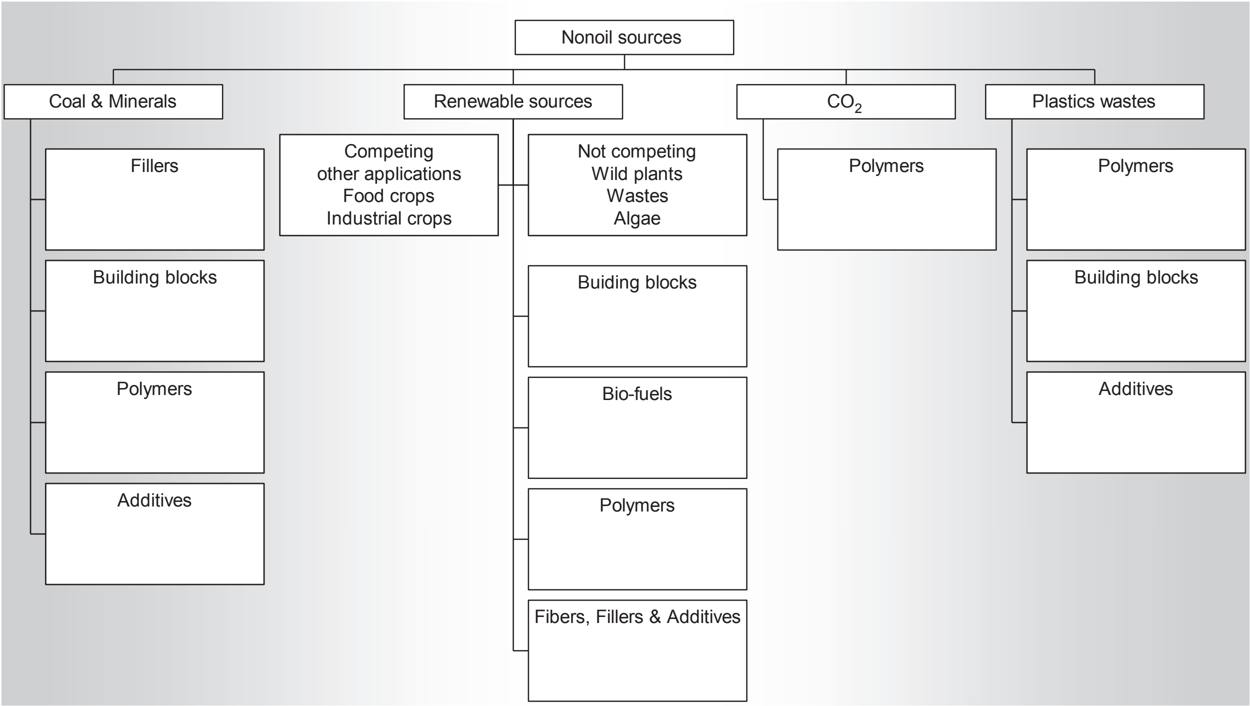


Figure 3.23 Nonoil alternatives.

Nonoil alternatives (see Figure 3.23) can be false or true solutions depending on the renewability of the source and the competition with existing uses:

- Replacement of crude oil by coal and minerals is not a true solution because the renewal of sources is far from the human scale
- Replacement by food crops-sourced polymers is not a good solution because of the global lack of food crops
- Replacement by plants used by the textile industry is not a good solution because of the competition with natural textile and the risk of replacement with synthetic textiles
- Wild plants, natural waste, and algae are really true solutions because they are not exploited
- Polymer synthesis from overabundant CO_2 consuming a harmful greenhouse gas (GHG) is a true solution
- Recycling and reuse of existing plastics wastes has several advantages such as to intelligently get rid of wastes, to decrease consumption of energy, and to reduce emissions of carbon dioxide (CO_2) and other GHG having a greenhouse effect.

Biopolymers derived from renewable biomass sources ensure the conservation of fossil resources, the utilization of renewable vegetal resources with its geopolitics involvements, the consumption of CO_2 instead of its emission. Several ways are exploited:

- Direct processing of natural polymers such as starch, polylactic acid (PLA), polyhydroxyalkanoate (PHA), and natural fibers. The bioplastics currently available contain more than 50% weight issued from renewable sources, reaching 100% for polymers such as PLA, PHA, and natural fibers.
- Use of biocomponents partly replacing petroleum-based components. The used level can vary from 20% up to more than 60%. Among the numerous examples are polyamide 11, thermoplastic elastomers (Hytrel, Pebax, Pearlthane, etc.), acrylics containing 20% renewable carbon or more.
- Natural scraps are a smart solution to avoid food crop competition. However, to be honest, it is possible that another competition appears between industrial uses of scraps, any industrial sector trying to value these cheap and limitless sources of

raw materials. The natural wastes are sources of a multitude of chemical bricks and molecules, for example, cellulose, starch, lignin, proteins, albumin, blood meal, casein, glycerin (a by-product of biodiesel), soaps and fatty acids, terpenes including limonene, citric, and succinic acids.

- CO_2 and CO-based polymers pump an abundant, undesirable, and cheap GHG to turn it into engineering thermoplastics. The general principle is to alternate oxygenated sequences and another monomer. Using CO_2 suffers from two drawbacks:
  - insufficiently efficient catalysts leading to expensive plastics
  - inadequate properties of the obtained products.

However, steady progresses lead to higher catalyst activities and more viable products.

- Recycling and reuse of commodity plastics such as polyethylene, PVC, styrenics, and engineering plastics lead to an average CO_2 saving of 50% with contrasted situations depending on the waste sources and reuse levels. Waste plastic recycling has several advantages such as to intelligently get rid of wastes, to decrease consumption of energy, and to reduce emissions of carbon dioxide (CO_2) and other GHG. One must consider recycled plastics in a completely new light. Wastes are an industrial feature to be considered as a valuable resource, a plastics mine needing new mining techniques and the adaptation of designing and processing. For example, upgrading of recycled products, adaptation to unusual rheologies, performance differences, and inherent coloration.
- The algae biofuel highway: During photosynthesis, algae capture carbon dioxide and sunlight and convert it into oxygen and biomass. Biomass can be turned into vegetable oil, biodiesel, biogasoline, and other biofuels that can generate the same hydrocarbons as crude oil. This so-called "drop-in" solution differs from conventional counterparts only in terms of the renewable raw material base.

  Several companies and government agencies are funding efforts to reduce capital and operating costs and make algae fuel production commercially viable. The United States Department of Energy estimates that if algae fuel replaced all the petroleum fuel in the USA, it would require 40,000 km^2. This is less than one-seventh the area of corn harvested in the USA in 2000.

  The main advantages of the biofuel way are:

  - the huge amounts of targeted biofuel and biogasoline (C6 up to C12) production, several times the tonnage of conventional plastics
  - the use of conventional processing methods of the petroleum industry such as refining, hydrocracking, or hydrogenation
  - the use of conventional polymerization methods and existing chemical plants to produce conventional plastics based on renewable sources.

  Today extraction costs (for example, $2 per gallon) and refining costs (for example, $3 per gallon) are too high but larger-scale refining operations would be competitive with fossil fuels. Projects run by the companies SAIC and General Atomics are expected to produce 1000 gallons of oil per acre per year from algal ponds at competitive costs.

- Use of bio-additives: there are two main reasons for developing and using bio-additives:
  - Produce 100% renewable compounds made out of renewable polymers (growing by 8–10% annually) and renewable additives
  - Replace oil-based additives with natural source additives. The global market for plastics additives was estimated $41 billion in 2013 and is expected to increase to $58 billion in 2020, for a compound annual growth rate of 4.9%.

  Processing renewable biomass according to more or less complex treatments can lead to nonoil additives, chemical blocks, and raw materials for additives. Uses with starch derivatives, PLA, PHA, polyhydroxybutyrate, green polyethylene, polypropylene, polystyrene, and PVC, bio-polyurethane allow to achieve a total 100% renewable strategy.

Bioplastics constitute an emerging niche market with a market share inferior to 1% of the plastics. Consumption data broadly vary with sources, depending on the concept of bioplastics, a certain confusion between consumption and production capacity, the retained data for partially biopolymers, the retained global economy hypotheses, and the optimism of the forecaster.

According to various market studies (Nova-Institut, BCC Research, Markets and Markets, European

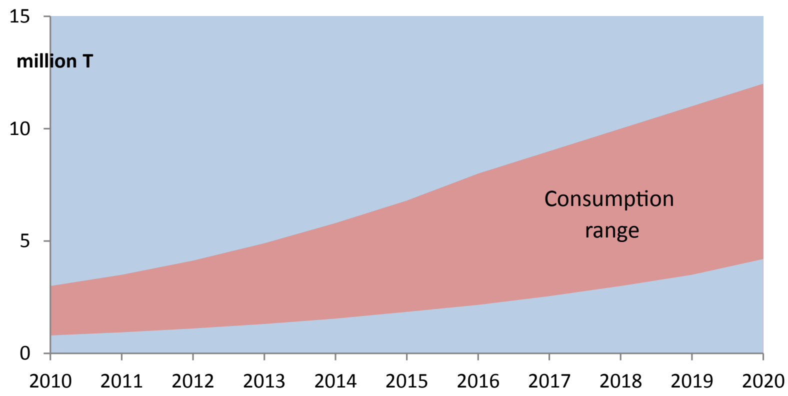


Figure 3.24 Consumption of bioplastics—2010/2020.

Table 3.20 Expected Raw Material Costs, $/kg

Bioplastics		Fossil Plastics		Bioplastics Additional Cost
SPI	2.39	PE	1.6	0.79
PLA	2.64	PS	1.8	0.84
TPS	4	ABS	3.1	0.9
PHA	4.9	PP	3.12	1.78
Mean	3.5		2.4	1.1

Bioplastics, etc.), Figure 3.24 shows the broad range of forecasts.

Bioplastic consumption must be sliced in more than five families and inevitably prices are those of niche plastics. Table 3.20 proposes expected prices for raw materials. Considered bioplastics are PLA, soy protein isolate, thermoplastic starch, and PHA. Fossil plastics include PE, PS, PP, ABS. Cost differences are of the order of $1/kg for the raw materials and the end products.

3.13 Price Index Hypotheses for 279 Plastics

The highest prices relate to the polymers with the highest performances, which are also the least used. Very broadly speaking, approximate prices per kilogram increase from commodities up to specialty plastics as follows:

- Commodities: €1.6 ($1.9) up to €3 ($3.6)
- Engineering plastics: €2 ($2.4) up to €10 ($12)
- Specialty plastics: €6 ($7) up to €76 ($100)
- Fluoroplastics: €13 ($16) up to €150 ($180).

In no instance, we do not guarantee the accuracy of those costs.

Obviously, upgraded or customized versions are more expensive than general-purpose grades. For example, carbon fiber-reinforced grades are generally more expensive than the neat polymer because of the high cost of carbon fibers. Recycled plastics are cheaper than virgin grades.

Prices are also linked to the annual volume depending on the plastic category. For example, may be considered as high annual volumes:

- greater than 10,000 tons for commodity thermoplastics
- 500 tons for engineering thermoplastics
- 100 tons for high-performance thermoplastics.

Table 3.21 displays, without any warranty, low and high hypotheses for price index concerning 279 plastics.

3.14 Useful Source Examples for Initiation of In-depth Studies

The economic conditions concerning plastics like the general economy are continually changing and it is necessary to refresh and often deepen the economic context. Table 3.22 suggests some examples of market study specialists, associations, and institutes that can be useful to initiate in-depth studies by the reader.

Table 3.21 Price Index Hypotheses for 279 Plastics

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
ABS	Low	Low	ABS	Low	Low
EVA	Low	Low	ABS GF	Rather low	Low
PE-HD	Low	Low	ABS GB	Rather low	Low
PE-LD	Low	Low	ABS CF	Medium	Medium
PET amorphous	Low	Low	ABS conductive	Medium	Medium
PMMA	Low	Low	ABS FR	Rather low	Low
PP impact	Low	Low	ABS/PA	Rather low	Rather low
PP Co	Low	Low	ABS/PA 20 GF	Medium	Rather low
PP Ho	Low	Low	ABS/PC	Rather low	Rather low
PP recycled	Low	Low	ABS/PC low-level long GF	Medium	Rather low
PP talc	Low	Low	ABS/PC medium-level long GF	Medium	Rather low
PP CaCO3	Low	Low	ABS/PC conductive	Medium	Rather low
PS	Low	Low	ABS/PC GF	Medium	Rather low
PS impact	Low	Low	ABS/PVC	Rather low	Rather low
PVC plasticized	Low	Low	Acrylique imide	Medium	Rather low
PVC unplasticized	Low	Low	ASA	Rather low	Rather low
ABS GF	Rather low	Low	ASA/PBT GF	Medium	Rather low
ABS GB	Rather low	Low	ASA/PC	Rather low	Rather low
ABS FR	Rather low	Low	ASA/PMMA	Rather low	Rather low
CA	Rather low	Low	ASA/PVC	Rather low	Rather low
CAB	Rather low	Low	CA	Rather low	Low
CP	Rather low	Low	CAB	Rather low	Low
CPE	Rather low	Low	COC	Medium	Rather low
EVOH	Rather low	Low	COPE high Shore D	Medium	Rather low
PA 6 recycled	Rather low	Low	COPE low Shore D	Medium	Rather low
PB	Rather low	Low	COPE Bio	Medium	Rather low
PE wood WPC	Rather low	Low	CP	Rather low	Low
PE-X cross-linked	Rather low	Low	CPE	Rather low	Low
PMI or PMMI	Rather low	Low	ECTFE	Very high	High
PMMA GF	Rather low	Low	EMA	Rather low	Rather low
PMMA impact	Rather low	Low	ETFE	Very high	High
POM	Rather low	Low	ETFE GF	Very high	High

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
POM GF	Rather low	Low	EVA	Low	Low
POM mineral	Rather low	Low	EVOH	Rather low	Low
PP low-level GF	Rather low	Low	FEP	High	High
PP medium-level GF	Rather low	Low	FEP GF	High	High
PP GB	Rather low	Low	LCP	High	Medium
PP mineral	Rather low	Low	LCP CF	Very high	Very high
PP cellulose fibers	Rather low	Low	LCP GF	High	Medium
PP wood WPC	Rather low	Low	LCP mineral	High	Medium
PP antistatic	Rather low	Low	MABS	Rather low	Rather low
PP natural fibers	Rather low	Low	MPR	Medium	Rather low
PP/EPDM-V	Rather low	Low	PA 10-10 high-level GF Bio	High	Medium
PPE	Rather low	Low	PA 10-10 Bio	High	Medium
PS GF	Rather low	Low	PA 11	Medium	Medium
PS 40% wood WPC	Rather low	Low	PA 11 GF	Medium	Medium
PVC GF	Rather low	Low	PA 11 or 12 plasticized	Medium	Medium
PVC wood WPC	Rather low	Low	PA 12	Medium	Medium
SAN	Rather low	Low	PA 12 CF	High	High
SMA	Rather low	Low	PA 12 GF	Medium	Medium
Starch/copolyester	Rather low	Low	PA 12 GB	Medium	Medium
Starch/PE	Rather low	Low	PA 12 conductive	High	Medium
Starch/PP	Rather low	Low	PA 12 friction	High	Medium
Starch/PS	Rather low	Low	PA CNT	High	High
TPE based on PVC	Rather low	Low	PA 4-10 GF Bio	High	Medium
TPO Shore D	Rather low	Low	PA 4-10 Bio	High	Medium
TPS Shore D	Rather low	Low	PA 4-6	Medium	Medium
TPV Shore D	Rather low	Low	PA 4-6 GF	Medium	Medium
ABS/PA	Rather low	Rather low	PA 4-6 mineral	Medium	Medium
ABS/PC	Rather low	Rather low	PA 6	Rather low	Rather low
ABS/PVC	Rather low	Rather low	PA 6 GB	Medium	Rather low
ASA	Rather low	Rather low	PA 6 medium-level GF	Medium	Rather low
ASA/PC	Rather low	Rather low	PA 6 medium-level long GF	Medium	Rather low

Continued

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
ASA/PMMA	Rather low	Rather low	PA 6 GF recycled	Rather low	Rather low
ASA/PVC	Rather low	Rather low	PA 6 high-level GF	Medium	Rather low
EMA	Rather low	Rather low	PA 6 high-level long GF	Medium	Rather low
MABS	Rather low	Rather low	PA 6 FR	Medium	Rather low
PA 6	Rather low	Rather low	PA 6 mineral FR	Medium	Rather low
PA 6 GF recycled	Rather low	Rather low	PA 6 recycled	Rather low	Low
PA 66	Rather low	Rather low	PA 6-10	High	Medium
PA castable	Rather low	Rather low	PA 6-10 CF	High	High
PBT	Rather low	Rather low	PA 6-12	Medium	Medium
PC	Rather low	Rather low	PA 6-12 GF	Medium	Medium
PE GF	Rather low	Rather low	PA 66	Rather low	Rather low
PE 60% long GF	Rather low	Rather low	PA 66 CF	High	Medium
PE-HD antistatic black	Rather low	Rather low	PA 66 GB	Medium	Rather low
PET	Rather low	Rather low	PA 66 medium-level GF	Medium	Rather low
PE-UHMW	Rather low	Rather low	PA 66 long CF	High	High
PK	Rather low	Rather low	PA 66 medium-level long GF	Medium	Medium
PLA	Rather low	Rather low	PA 66 mineral	Medium	Rather low
PLA/copolyester	Rather low	Rather low	PA 66 high-level GF	Medium	Rather low
PLA natural reinforcement	Rather low	Rather low	PA 66 high-level long GF	Medium	Medium
PLA wood WPC	Rather low	Rather low	PA 66 conductive	Medium	Medium
PLA/PBT GF	Rather low	Rather low	PA 66 impact medium-level GF	Medium	Rather low
PLA/PC	Rather low	Rather low	PA castable	Rather low	Rather low
PLA/PE	Rather low	Rather low	PA castable friction	Medium	Rather low
PLA/PMMA	Rather low	Rather low	PA far	Medium	Rather low
PLA/PP 30% GF	Rather low	Rather low	PA transparent	High	Medium
PMMA antistatic	Rather low	Rather low	PAA medium-level CF	High	High
PMP	Rather low	Rather low	PAA medium-level GF	High	Medium
PMP GF	Rather low	Rather low	PAA high-level GF	High	Medium
PMP mineral	Rather low	Rather low	PAA mineral	High	Medium
POM long GF	Rather low	Rather low	PEEK	Very high	Very high

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
POM GB	Rather low	Rather low	PEEK GF	Very high	Very high
PP long GF medium level	Rather low	Rather low	PEEK CF	Very high	Very high
PP long GF high level	Rather low	Rather low	PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	Very high	Very high
PP conductive	Rather low	Rather low	PAEK 30% GF	Very high	Very high
PP/PA	Rather low	Rather low	PAI	Very high	High
PP/PA GF	Rather low	Rather low	PAI GF	Very high	High
PPE GF	Rather low	Rather low	PAI CF	Very high	Very high
PPE mineral	Rather low	Rather low	PAI friction	Very high	Very high
PPE/PA	Rather low	Rather low	PAI mineral	Very high	High
PPE/PA GF	Rather low	Rather low	PB	Rather low	Low
PTT Bio	Rather low	Rather low	PBI	Very high	Very high
PTT Bio GF	Rather low	Rather low	PBT	Rather low	Rather low
PVCC	Rather low	Rather low	PBT medium-level GB	Medium	Rather low
SAN GF	Rather low	Rather low	PBT medium-level GF	Medium	Rather low
SMMA	Rather low	Rather low	PBT GF and mineral	Medium	Rather low
TPU GF	Rather low	Rather low	PBT long GF	Medium	Rather low
TPU Bio	Rather low	Rather low	PBT long CF	High	High
TPU Shore D	Rather low	Rather low	PBT CF	High	Medium
SMA GF	Medium	Low	PC	Rather low	Rather low
ABS/PA 20 GF	Medium	Rather low	PC GF	Medium	Rather low
ABS/PC low-level long GF	Medium	Rather low	PC CF	High	Medium
ABS/PC medium-level long GF	Medium	Rather low	PC CNT	High	Medium
ABS/PC conductive	Medium	Rather low	PC conductive	Medium	Medium
ABS/PC GF	Medium	Rather low	PC friction	Medium	Medium
Acrylique imide	Medium	Rather low	PC/PBT	Medium	Rather low
ASA/PBT GF	Medium	Rather low	PC/PBT GF	Medium	Rather low
COC	Medium	Rather low	PC/SAN GF	Medium	Rather low
COPE high Shore D	Medium	Rather low	PCT GF	Medium	Rather low
COPE low Shore D	Medium	Rather low	PCTFE	Very high	Very high

Continued

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
COPE Bio	Medium	Rather low	PE GF	Rather low	Rather low
MPR	Medium	Rather low	PE wood WPC	Rather low	Low
PA 6 GB	Medium	Rather low	PE 60% long GF	Rather low	Rather low
PA 6 medium-level GF	Medium	Rather low	PEBA 25–45 Shore D	Medium	Rather low
PA 6 medium-level long GF	Medium	Rather low	PEBA 50–72 Shore D	Medium	Rather low
PA 6 high-level GF	Medium	Rather low	PEBA Bio	Medium	Medium
PA 6 high-level long GF	Medium	Rather low	PEEK/PBI	Very high	Very high
PA 6 FR	Medium	Rather low	PEEK/PBI GF	Very high	Very high
PA 6 mineral FR	Medium	Rather low	PEEK/PBI CF	Very high	Very high
PA 66 GB	Medium	Rather low	PE-HD	Low	Low
PA 66 medium-level GF	Medium	Rather low	PE-HD antistatic black	Rather low	Rather low
PA 66 mineral	Medium	Rather low	PEI	High	Medium
PA 66 high-level GF	Medium	Rather low	PEI GF milled	High	Medium
PA 66 impact medium-level GF	Medium	Rather low	PEI GF	High	Medium
PA castable friction	Medium	Rather low	PEI CF	High	High
PA far	Medium	Rather low	PEI conductive	High	High
PBT medium-level GB	Medium	Rather low	PEI mineral	High	Medium
PBT medium-level GF	Medium	Rather low	PE-LD	Low	Low
PBT GF and mineral	Medium	Rather low	PES	High	Medium
PBT long GF	Medium	Rather low	PES GF	High	Medium
PC GF	Medium	Rather low	PES CF	High	High
PC/PBT	Medium	Rather low	PES friction	High	High
PC/PBT GF	Medium	Rather low	PET	Rather low	Rather low
PC/SAN GF	Medium	Rather low	PET GF	Medium	Rather low
PCT GF	Medium	Rather low	PET amorphous	Low	Low
PEBA 25–45 Shore D	Medium	Rather low	PET/PBT high-level GF	Medium	Rather low
PEBA 50–72 Shore D	Medium	Rather low	PET/PC	Medium	Rather low
PET GF	Medium	Rather low	PET/PC GF	Medium	Rather low
PET/PBT high-level GF	Medium	Rather low	PE-UHMW	Rather low	Rather low
PET/PC	Medium	Rather low	PE-X cross-linked	Rather low	Low

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
PET/PC GF	Medium	Rather low	PFA	Very high	Very high
PK GF	Medium	Rather low	PI TP	Very high	Very high
PLA GF	Medium	Rather low	PI TP CF	Very high	Very high
Polyarylate	Medium	Rather low	PI TP GF	High	Very high
Polyarylate GF	Medium	Rather low	PI TP friction	Very high	Very high
POM conductive	Medium	Rather low	PK	Rather low	Rather low
POM far	Medium	Rather low	PK GF	Medium	Rather low
POM friction	Medium	Rather low	PLA	Rather low	Rather low
PP low-level CNT	Medium	Rather low	PLA/Copolyester	Rather low	Rather low
PP medium CNT	Medium	Rather low	PLA GF	Medium	Rather low
PVDC	Medium	Rather low	PLA natural reinforcement	Rather low	Rather low
TPU long GF	Medium	Rather low	PLA wood WPC	Rather low	Rather low
ABS CF	Medium	Medium	PLA/PBT GF	Rather low	Rather low
ABS conductive	Medium	Medium	PLA/PC	Rather low	Rather low
PA 11	Medium	Medium	PLA/PE	Rather low	Rather low
PA 11 GF	Medium	Medium	PLA/PMMA	Rather low	Rather low
PA 11 or 12 plasticized	Medium	Medium	PLA/PP 30% GF	Rather low	Rather low
PA 12	Medium	Medium	PMI or PMMI	Rather low	Low
PA 12 GF	Medium	Medium	PMMA	Low	Low
PA 12 GB	Medium	Medium	PMMA GF	Rather low	Low
PA 4-6	Medium	Medium	PMMA antistatic	Rather low	Rather low
PA 4-6 GF	Medium	Medium	PMMA impact	Rather low	Low
PA 4-6 mineral	Medium	Medium	PMP	Rather low	Rather low
PA 6-12	Medium	Medium	PMP GF	Rather low	Rather low
PA 6-12 GF	Medium	Medium	PMP mineral	Rather low	Rather low
PA 66 medium-level long GF	Medium	Medium	Polyarylate	Medium	Rather low
PA 66 high-level long GF	Medium	Medium	Polyarylate GF	Medium	Rather low
PA 66 conductive	Medium	Medium	POM homo or copolymer	Rather low	Low
PC conductive	Medium	Medium	POM GF	Rather low	Low

Continued

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
PC friction	Medium	Medium	POM long GF	Rather low	Rather low
PEBA Bio	Medium	Medium	POM GB	Rather low	Rather low
PP CF	Medium	Medium	POM CF	High	Medium
PPA	Medium	Medium	POM conductive	Medium	Rather low
PPA GF	Medium	Medium	POM far	Medium	Rather low
PPA mineral	Medium	Medium	POM friction	Medium	Rather low
PSU	Medium	Medium	POM mineral	Rather low	Low
PSU GF	Medium	Medium	PP impact	Low	Low
PSU mineral	Medium	Medium	PP Co	Low	Low
PSU modified	Medium	Medium	PP Ho	Low	Low
PSU/ABS	Medium	Medium	PP recyclé	Low	Low
PSU/PBT GF	Medium	Medium	PP low-level GF	Rather low	Low
PSU/PC	Medium	Medium	PP medium-level GF	Rather low	Low
TPU conductive	Medium	Medium	PP GB	Rather low	Low
LCP	High	Medium	PP mineral	Rather low	Low
LCP GF	High	Medium	PP talc	Low	Low
LCP mineral	High	Medium	PP low-level CNT	Medium	Rather low
PA 10-10 high-level GF Bio	High	Medium	PP medium CNT	Medium	Rather low
PA 10-10 Bio	High	Medium	PP cellulose fibers	Rather low	Low
PA 12 conductive	High	Medium	PP long GF medium level	Rather low	Rather low
PA 12 friction	High	Medium	PP CaCO3	Low	Low
PA 4-10 GF Bio	High	Medium	PP wood WPC	Rather low	Low
PA 4-10 Bio	High	Medium	PP long GF high level	Rather low	Rather low
PA 6-10	High	Medium	PP antistat	Rather low	Low
PA 66 CF	High	Medium	PP CF	Medium	Medium
PA transparent	High	Medium	PP conductive	Rather low	Rather low
PAA medium-level GF	High	Medium	PP natural fibers	Rather low	Low
PAA high-level GF	High	Medium	PP/EPDM-V	Rather low	Low
PAA mineral	High	Medium	PP/PA	Rather low	Rather low
PBT CF	High	Medium	PP/PA GF	Rather low	Rather low
PC CF	High	Medium	PPA	Medium	Medium

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
PC CNT	High	Medium	PPA GF	Medium	Medium
PEI	High	Medium	PPA mineral	Medium	Medium
PEI GF milled	High	Medium	PPA long GF	High	Medium
PEI GF	High	Medium	PPA CF	High	High
PEI mineral	High	Medium	PPE	Rather low	Low
PES	High	Medium	PPE GF	Rather low	Rather low
PES GF	High	Medium	PPE CF	High	Medium
POM CF	High	Medium	PPE mineral	Rather low	Rather low
PPA long GF	High	Medium	PPE/PA	Rather low	Rather low
PPE CF	High	Medium	PPE/PA GF	Rather low	Rather low
PPS	High	Medium	PPS	High	Medium
PPS GF	High	Medium	PPS GF	High	Medium
PPS long GF medium level	High	Medium	PPS long GF medium level	High	Medium
PPS long GF high level	High	Medium	PPS long GF high level	High	Medium
PPS GF + mineral	High	Medium	PPS CF	Very high	High
PPSU	High	Medium	PPS CF + GF	High	High
PPSU GF	High	Medium	PPS conductive	High	High
PTFE	High	Medium	PPS far	High	High
PTFE GF	High	Medium	PPS GF + mineral	High	Medium
PVDF	High	Medium	PPSU	High	Medium
PVDF friction	High	Medium	PPSU GF	High	Medium
PVDF mica	High	Medium	PS	Low	Low
PVF	High	Medium	PS GF	Rather low	Low
FEP	High	High	PS 40% wood WPC	Rather low	Low
FEP GF	High	High	PS impact	Low	Low
PA 12 CF	High	High	PSU	Medium	Medium
PA CNT	High	High	PSU GF	Medium	Medium
PA 6-10 CF	High	High	PSU mineral	Medium	Medium
PA 66 long CF	High	High	PSU modified	Medium	Medium
PAA medium-level CF	High	High	PSU/ABS	Medium	Medium
PBT long CF	High	High	PSU/PBT GF	Medium	Medium

Continued

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
PEI CF	High	High	PSU/PC	Medium	Medium
PEI conductive	High	High	PTFE	High	Medium
PES CF	High	High	PTFE CF	Very high	High
PES friction	High	High	PTFE friction	High	High
PPA CF	High	High	PTFE GF	High	Medium
PPS CF + GF	High	High	PTT Bio	Rather low	Rather low
PPS conductive	High	High	PTT Bio GF	Rather low	Rather low
PPS far	High	High	PVC GF	Rather low	Low
PTFE friction	High	High	PVC plasticized	Low	Low
PI TP GF	High	Very high	PVC unplasticized	Low	Low
ECTFE	Very high	High	PVC wood WPC	Rather low	Low
ETFE	Very high	High	PVCC	Rather low	Rather low
ETFE GF	Very high	High	PVDC	Medium	Rather low
PAI	Very high	High	PVDF	High	Medium
PAI GF	Very high	High	PVDF CF	Very high	High
PAI mineral	Very high	High	PVDF friction	High	Medium
PPS CF	Very high	High	PVDF mica	High	Medium
PTFE CF	Very high	High	PVF	High	Medium
PVDF CF	Very high	High	SAN	Rather low	Low
LCP CF	Very high	Very high	SAN GF	Rather low	Rather low
PEEK	Very high	Very high	SMA	Rather low	Low
PEEK GF	Very high	Very high	SMA GF	Medium	Low
PEEK CF	Very high	Very high	SMMA	Rather low	Rather low
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	Very high	Very high	Starch/copolyester	Rather low	Low
PAEK 30% GF	Very high	Very high	Starch/PE	Rather low	Low
PAI CF	Very high	Very high	Starch/PP	Rather low	Low
PAI friction	Very high	Very high	Starch/PS	Rather low	Low
PBI	Very high	Very high	TPE based on PVC	Rather low	Low
PCTFE	Very high	Very high	TPO Shore D	Rather low	Low
PEEK/PBI	Very high	Very high	TPS Shore D	Rather low	Low
PEEK/PBI GF	Very high	Very high	TPU GF	Rather low	Rather low

Table 3.21 Price Index Hypotheses for 279 Plastics—cont'd

Rating by Prices			Alphabetical Rating		
Plastic	**Price Indexes**		**Plastic**	**Price Indexes**	
PEEK/PBI CF	Very high	Very high	TPU long GF	Medium	Rather low
PFA	Very high	Very high	TPU Bio	Rather low	Rather low
PI TP	Very high	very high	TPU conductive	Medium	Medium
PI TP CF	Very high	Very high	TPU Shore D	Rather low	Rather Low
PI TP friction	Very high	Very high	TPV Shore D	Rather low	Low

Table 3.22 Examples of sources for in-depth studies

Market Research Specialist Examples	Web Sites
AMI Consulting	http://www.amiplastics.com/
BCC Research	http://www.bccresearch.com/
Ceresana	http://www.ceresana.com/en/
CMAI—IHS	http://www.cmaiglobal.com/marketreports/
Freedonia	http://www.freedoniagroup.com/
Global Industry Analysts, Inc. (GIA)	http://www.strategyr.com/
IbisWorld	http://www.ibisworld.com/industry/global/
IHS	http://www.ihs.com/products/chemical/
Lux Research Company	http://www.luxresearchinc.com/
Market Research.com	http://www.marketresearch.com/
Markets and Markets	http://www.marketsandmarkets.com/
Research and markets	http://www.researchandmarkets.com/
Townsend solutions	http://www.townsendsolutions.com/
Transparency Market Research	http://www.transparencymarketresearch.com
Association and Institute Examples	
American Chemistry Council: Plastics Division	http://plastics.americanchemistry.com/
American Composites Manufacturers Association	http://www.acmanet.org/
Associação Brasileira da Indústria Química	http://www.abiquim.org.br/
Australian Plastics and Chemicals Industries Association	http://www.pacia.org.au/
Beijing Plastics Industry Association	http://www.bpia.cn/
Canadian Plastics Industry Association	http://www.plastics.ca/
China Die & Mould Industry Association	http://www.diemouldchina.com/en/
China Plastic Machine Industry Association	cdmia@cdmia.com.cn

Continued

Table 3.22 Examples of sources for in-depth studies—cont'd

Association and Institute Examples	Web Sites
China Plastics Processing Industry Association	http://www.cppia.com.cn
China Taizhou Plastics Industry Association (TZPIA)	http://www.cnpid.com/tzpia/en/
Composites Association of New Zealand Inc.	http://www.composites.org.nz/
Composites Australia Inc.	http://www.compositesaustralia.com.au/
Federation of Thai Industries	http://www.fti.or.th/2008/eng/
Hong Kong Plastics Industry Council of the Federation of Hong Kong Industries	http://www.industryhk.org/english/
Indian Plastics Institute	http://ipiindia.com/
Indian Society of Plastics (ISP)	http://www.plasticsindia.com/
Japan Chemical Industry Association	http://www.jcia-net.or.jp/
Japan Plastics Industry Federation (JPIF)	http://www.jpif.gr.jp/english/
Plastics Europe	http://www.plasteurope.com
Plastics & Rubber Institute of Singapore	http://www.pris.org.sg/
Plastics & Rubber Institute of Sri Lanka	http://www.prisrilanka.com/
Plastics New Zealand Inc.	http://www.plasticsnz.com/
Plastindia Foundation	http://plastindia.org/
Polymer Society of Thailand	http://thaipolymersociety.org/
Singapore Plastic Industry Association	http://www.spia.org.sg/link.htm
Society of Plastics Engineers—SPE	http://www.4spe.org
SPI	http://www.plasticsindustry.org
Taiwan Plastics Industry Association	http://www.ttpia.com.tw/
Thai Plastic Industries Association	http://www.tpia.org/
Vietnam-Saigon Plastic Association	http://www.vnplas.com

Further Reading

Technical guides, newsletters, websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie

GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

4 Elements for Analogical Selections: Survey of the 10 Top Markets

OUTLINE

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00004-0

As the trends toward miniaturization, portability, improved esthetics, cheaper products, and environmental responsibility drive change, selecting the right materials has become more critical. To achieve optimal product usability, appearance, endurance, and performance, designers must carefully consider all available materials but must exclude, as soon as possible, unsatisfactory solutions.

When product designers want to create a new product, they can use traditional computing methods to determine a material with sufficient performances, compute the right part geometry, and choose the right processing method.

They can also use an alternative approach based on analogy, called, for example, design-by-analogy method or something like that. The concept is to search analogies with existing solutions solving an analogous problem. Knowledge can be provided by the designer's experience and all readily available information sources. Analogies can concern the product itself, the domain, or the functionalities of more or less similar products of other domains. To ease the application of this method, this chapter is, in fact, a specialized database providing more than 1500 couples of parts or products, on the one hand, and the related used thermoplastic(s), on the other hand. Of course, this method leads to a preselection of a plastic family, not to a defined compound.

So, time and cost associated with final end-product development can be reduced, thereby speeding time to market.

Figure 4.1(a) and (b) schematizes the various steps of a preselection.

Figure 4.1(b) concerns more specifically the use of the lists of this chapter.

- Firstly, the designer must determine the function(s) of the product in the end application and minimum performance criteria for each critical material characteristic.
- Secondly, the designer must choose the application market in the list of applications.
- Thirdly, the designer must search in the listed end products those that are of interest.
- Fourthly, he must compare required critical material characteristics and characteristics of the selected end products.

At the opposite, this chapter has also another utility: if a plastic subfamily has been selected by traditional ways, it is also of interest to easily verify if similar applications are already listed for the selected plastic subfamily.

The main markets and market shares for thermoplastics from the breakdown in statistics from different countries are roughly:

- packaging, 33–48%
- building and civil engineering, 19%

(a)

(b)

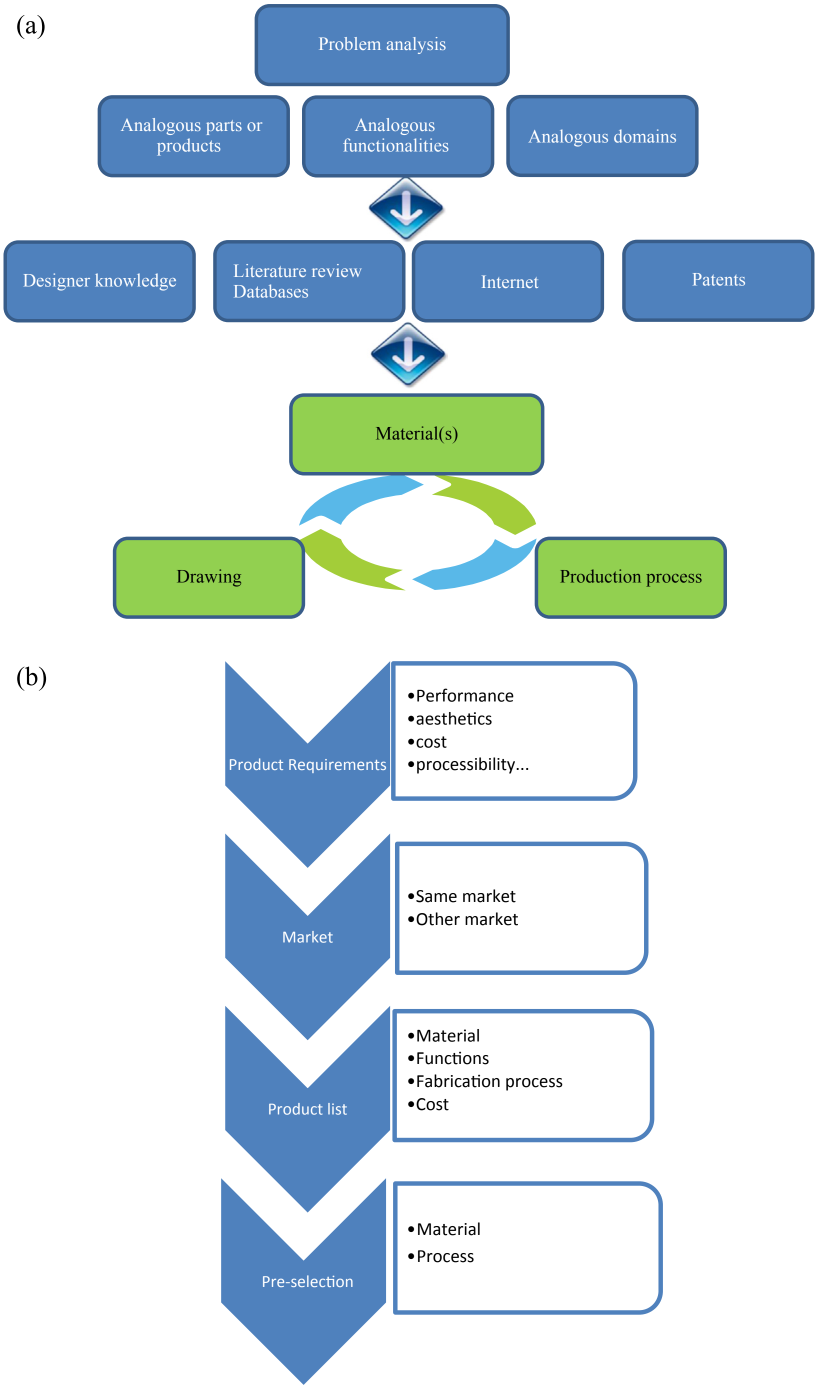


Figure 4.1 Diagrammatic material selection using listed products for main application markets. (a) General selection approach. (b) Detailed approach using the lists proposed in this book.

- automotive and transportation, 5–13%
- electricity and electronics, 3–8%
- household appliances, 3–6%
- miscellaneous appliances, 2–4%
- sports and leisure, 2–5%
- furniture and bedding, 1–4%
- agricultural, 2%
- medical, 2%.

4.1 Packaging

Packaging, the primary outlet for thermoplastics, consumes between 33% and 48% of all thermoplastics, depending on the country.

Several exceptional features explain the high level of thermoplastic use for packaging:

- Technical properties: thermoplastics offer an exceptional set of well-balanced properties, comprising low density, mechanical performances, physical characteristics, ease of processing, esthetics, and cost.
- Economical interest: thermoplastics are suitable for economical processing, from mass production down to low-output specific packaging or even household uses.
- Aesthetic properties: thermoplastics allow much more design freedom than paper, cardboard, wood, glass, metals, and other conventional materials.
- Environmental requirements: the lightweight, the high waterproofing, and damping properties compared to paper and cardboard make thermoplastics environment-friendly.

According to a report from the Packaging Science Department of Clemson University in the USA, packaging is essential for some basic reasons:

- Containment is the primary purpose of packaging—to carry food and water; industrial, agricultural, and domestic chemicals…
- Protection:
  - of the contents from the environment: despoiling, breakages, contamination, pollution or leakage, protection of food from bacteria…
  - of the environment from the contents: leakage of pollutants, poisons, toxic and aggressive products…
  - of people, thanks to the shatter resistance that avoids the cutting shreds of broken glass
  - of the enclosed atmosphere: oxygen barriers keep organic produces fresh…
  - against inopportune uses: safety caps, child-resistant caps…
- Information: thermoplastics can be directly printed to inform the prospective user, without the possibility to falsify use-by dates and other information.
- Aesthetics: thermoplastics can be transparent or opaque, colored, decorated, mimicking metal, wood… to appeal to prospective users and customers.
- Ease of use: extrusion and injection molding are mass-production processes. Thermoforming and welding are convenient for high, medium, and low outputs, with welding even being possible with household devices. Use of thermoplastics allows original applications and continuous innovation for the best known applications, resealable packaging; flexible, shrinkable, tear-proof, barrier films; inviolable packaging…

The commodity thermoplastics are the most used plastics in this sector, accounting for 95% of all thermoplastic packaging. Polyolefins are the most important, accounting for more than 65% of the total plastic weight. Polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC) are also commonly used.

Engineering thermoplastics such as acrylics (polymethylmethacrylate (PMMA)), polyamides (PAs), and polycarbonates are only used for specific properties.

Thermoplastic composites are not listed in packaging statistics. There are only specific applications in the transport of fragile and expensive goods.

Thermoplastic elastomers (TPEs) are not listed in packaging statistics: there are only specific uses for thermoplastic styrenics, copolyester TPEs (COPE), and polyether bloc amides in tear-proof films, and for thermoplastic olefins (TPOs) and thermoplastic vulcanizates (TPVs) in seals, etc.

Figure 4.2 shows the estimated shares of the most used thermoplastics. Very different figures can be found elsewhere according to the estimations, countries, types of packaging, etc. that are taken into account.

Environmental regulations and trends are leading to a decay in the consumption of PVC.

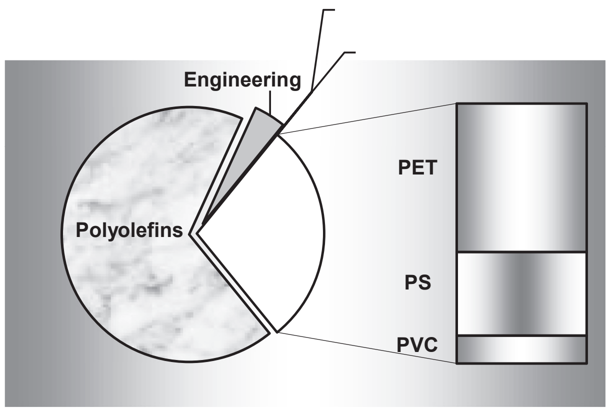


Figure 4.2 Thermoplastic shares in the packaging market.

Plastics comprise 17% of all materials used in packaging.

Thermoplastics can also lead to composites and hybrids including other conventional materials—such as paper, cardboard, metals, and glass—to integrate several functionalities thanks to the exceptional combination of properties: for example, multilayers of polyethylene (PE) (a water barrier) and polyvinyl alcohol (an oil barrier), shatterproofing of glass containers…

Polymers also have some general drawbacks:

- the environmental constraints and public image
- raw material costs (see Figure 4.3) considered as a function of volume (€/liter)
- the low modulus and strength
- the propensity to creep.

Figure 4.3 shows that the cost per volume of the commodity thermoplastics is intermediate between steel and aluminum, which explains their development in packaging and the poor penetration of the much more expensive engineering thermoplastics.

When they cannot directly compete with conventional materials, the versatility of thermoplastics easily allows for a partnership among them. Examples are numerous:

- multilayer films with paper
- spread papers and cardboards
- multilayer films with metal foils
- protective coatings for metals.

The versatility of plastics allows the industrialization of innovative solutions combining several functions such as, for example:

- packaging and display units for toys, knickknacks…

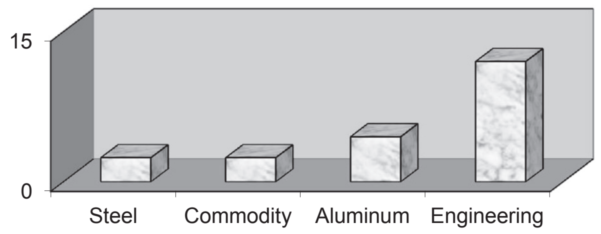


Figure 4.3 Cost per volume (€/l) of most used materials for packaging.

- packaging and support of fitting for fans, taps…
- esthetics and insulating housing for champagne bottles…

Packaging, the primary application of biodegradable plastics

Packaging is the primary application of biodegradable plastics for several reasons:

- Plastic bags have been restricted or taxed in Ireland, Germany, South Africa, Taiwan, and elsewhere due to concerns about disposal.
- Packaging often has a short lifetime.
- Packaging produces pronounced visible pollution.

Consequently, there is new interest in degradable polymers despite a general overspend. The natural and biodegradable thermoplastics are, for example:

- starch and other natural derivatives of uncertain formula…
- polylactic acid (PLA)
- polyglycolic acid
- polycaprolactone
- polyhydroxyalkanoate
- polyhydroxybutyrate.

These materials are of interest for packaging as shown by some examples:

- UK supermarket chains Co-op, Kwik Save, and Somerfield use degradable carrier bags. In Italy, the large supermarket chain IPER is using Cargill Dow's NatureWorks-brand resin in film to wrap fresh food and pasta at its 21 locations.
- Major UK supermarket Tesco will use PE carrier bags containing a degradable additive supplied by Canadian firm EPI following a 6-month trial.
- Cellulose hydrate is used with sweets and as artificial skin for sausages.
- Cellulose acetate has been used for dry food without fat.
- At the Olympic Winter Games in Lillehammer, biodegradable products were used for catering.
- Investigations for yoghurt cups are ongoing.

- Foil bags for the collection of biological waste and biodegradable loose-fill packaging materials are already in use.
- Cargill Dow's PLA has some commercial applications in Europe and Asia. A major market has been blister packaging used to wrap such products as Sony Walkman radios and digital versatile discs (DVDs).
- Milk bottles are now available in Europe.
- Transparent containers for olive oil and other cooking oils will be soon available.
- Cadbury will use a cornstarch polymer for the chocolate tray in its Milk Tray range.
- Sugar boxes are in biopolyethylene.

The use of thermoplastics, TPEs, and composites is growing in the various segments of packaging:

- films: PE, polyester, PVC
- bottles, cans, and other containers: PET, PE, PVC (declining)
- foams for damping and protective packaging: PS, PE, and others…
- rigid and transparent sheets of PVC, polycarbonate, PMMA for blisters and boxes…
- sealing against gas, liquids, dust, moisture, and air: TPEs and some soft thermoplastics
- structural packaging.

For the packaging market, the sector with the highest consumption of thermoplastics, recycling is, of course, of crucial importance. Unfortunately, plastic recycling presents technical and economic difficulties and is less advanced, industrially, than that of metals or glass.

Apart from consumption, packaging is also a crucial sector because:

- the products are of short lifetime
- polymers are very resistant to degradation, their natural elimination is often impossible, and the environment is polluted for a long time
- a high percentage of the packaging wastes, such as films, bags, and bottles, are very lightweight and lead to evident pollution:
  - visual: films, PE bags, PVC or polyester bottles…
  - physical: obstruction to water flow…
- end-of-life wastes are often domestic and the sources are very diffuse
- the wastes are often soiled with food, oils, chemicals…

The main methods for the recycling of polymer-based packaging wastes are:

- energy recovery by combustion
- mechanical recycling and reuse with virgin material in the same or another application.

Conversion into basic chemicals by chemolysis or thermolysis is a secondary method.

To ease recycling, some general rules, which of course suffer from exceptions, can be stated:

- mark parts to make the later identification of the materials easier
- avoid the use of incompatible polymers in the same part or subset
- standardize the polymers used
- preferably choose a material that can be recycled in the same fabrication.

4.1.1 Films

Typically, film usages can be divided into:

- packaging
  - food
  - nonfood
  - stretch and shrink wraps
- nonpackaging.

Food packaging film is used as, for example:

- in-store bags for produces such as vegetables, breads, and other bakery goods
- tray covers for institutional deliveries
- bags-in-a-box (for wine, for example)
- edible bags containing food directly reheated in boiling water
- candy and confection bags and wrappers
- carton liners
- poultry and seafood wraps…

Nonfood packaging film is used as, for example:

- industrial liners for shipments, shipping sacks, multiwall sack liners…
- bubble packing
- overwrap
- rack and counter bags
- envelopes.

Stretch wrap is a strong, flexible film that can be stretched to take the shape of the contained goods. It is used at home to overwrap fresh meat and other leftovers or industrially to secure shipping cartons to pallets. It is usually made of linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), or PVC.

Shrink wrap is a film that is applied loosely around products, then sealed and shrunk by heating to take the shape of the contained products. It can be used to bind multiple packages, or to secure an entire pallet of packages, to bundle magazines and papers, to protect and display albums, CDs, and so on. It is usually made of LLDPE, LDPE, or polypropylene (PP).

Let us remember that nonpackaging applications are numerous, for example:

- agricultural films
- construction films such as vapor and moisture barriers in walls, foundation, roofing
- protective cloths and drapes
- medical and health-care films
- garment bags, self-service bags, household wraps
- disposable diapers
- recording tapes
- dielectric films…

4.1.2 Bottles and Other Containers

Thermoplastic bottles and other containers are growing fast by replacing glass principally but also metals in the packaging of food, beverage, household and industrial chemicals, oils, drugs, cosmetics, toiletries…

Thermoplastics offer an exciting set of diversified characteristics:

- Technical: dramatic weight reduction versus glass leads to many energy savings, such as less energy and fuel used in packaging production, handling, transport of the product, and of the end-of-use wastes.
- Economical: plastics are the economical answer for mass production as well as for specific packaging.
- Aesthetics: plastics allow much more design freedom than glass or metals.
- Environmental: the reduction of weight compared to glass makes plastics environment-friendly.

Blow-molded containers have various and diversified applications from small bottles to drums for packaging of foods and beverages, chemicals, motor oils, cosmetics, toiletries, drugs, and pharmaceuticals.

The use of bottles and other containers depends on several growing markets, for example:

- water bottles
- juice and noncarbonated beverage bottles
- PET salad dressing and condiment containers replacing glass
- dry food containers
- milk packaging
- beer packaging, an enormously promising sector for PET.

The rapid growth of PET can be explained by:

- environmental pressure on PVC
- the suitability of PET for hot-filling
- possibility to carry PET packaging directly from freezers to ovens, including microwaves
- superiority of PET clarity versus that of PE
- better balance of gas permeabilities, combining the moisture impermeability of PE with a better oxygen and CO_2 impermeability than PVC.

4.1.3 Foams

Foams are efficient as:

- damping materials, providing an economic protection against vibrations and moderate impacts
- insulating materials, providing an economic protection against heat for fish, ice cream, and other refrigerated products.

Thermoplastic foams—mainly PS, PVC, PE, and PP—account for roughly 50% of all plastic foams, the other 50% being polyurethane, a thermoset material. For all uses added together, expanded polystyrene (EPS) accounts for more than 90% of all thermoplastic foams, followed by PVC with a few percent, and PE and PP.

Packaging is not the main market for foams.

Let us quote some examples of applications without claiming to be exhaustive:

- EPS: heat insulation, damping, structural functions:
  - boxes, crates, cases for cooled foodstuffs: fish, ice creams…
  - packaging of electrical household appliances, TVs, radios, office automation, electric tools…
  - structural industrial packaging: car engines…
  - packaging and display units
  - flakes, chips, sheets…
- PE: heat insulation, damping functions:
  - flakes, chips, sheets, blocks are used for impact protection and damping in the packaging of various products such as cameras, electronic devices…
  - antistatic, conductive foams for electronics packaging
  - isothermal packaging
  - cool bags…
- PP: damping and protection, thermal insulation, structural functions:
  - reusable packaging or shuttle packaging for heavy parts such as doors, windscreens, rear mirrors…
  - packaging of fragile parts: electronics, office automation devices, electric motors…
  - damping blocks, intermediate layers…
  - functional packaging useful for shipping and installation on site…
- PVC: packaging of fragile goods, warm or cold foods…

4.1.4 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.1, without claiming to be exhaustive, some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.2 Building and Civil Engineering

With a consumption of about 20% of all thermoplastics, the building and civil engineering market is the second largest outlet for thermoplastics.

Several exceptional features explain the high level of thermoplastic use for this engineering sector:

- Technical motivations: using thermoplastics is favored by:
  - design freedom, allowing a high level of function integration
  - ease of use: low density and attractive performance/weight ratio lead to weight reduction, providing easier handling and setting up
  - good thermal insulation…
  - ease of maintenance, but beware of the mar resistance
  - resistance to moisture, but beware of aging.
- Economical features: thermoplastics provide:
  - a favorable economical solution for mass production as well as “niche” production
  - higher productivity due to ease of handling and setting up…
- Aesthetics: thermoplastics allow:
  - much more design freedom than steel, concrete, and other conventional materials
  - decoration possibilities to mimic stone, marble, wood, metal…
  - pleasant finish.
- Environmental features: thermoplastics save energy throughout their lifetime because of their high thermal insulation properties…

Statistics differ according to the source and the country considered. For example, window frames can be mainly made of PVC in one country and of a composite in another. Thermoplastics are matching cheap conventional materials and, consequently, commodities

Table 4.1 More than 150 Examples of Thermoplastic Applications in Packaging

Aesthetic packaging…	Cellulosics
Airtight boxes with integrated TPV seal (bi-injection molding of PP and PP/EPDM-V)	TPE
Baby bottles, water dispensers, water bottles…	PC
Bags for collection of organic waste: Mater-Bi® (starch)	Bioplastics
Bags: Cereplast resins	Bioplastics
Barrier films for food, pharmaceuticals, chemicals…	PVDC
Basins, bottles, stoppers, hollow parts, pallets…	PE
Beverage bottles	PET
Biodegradable and compostable bags, shopping bags, separate waste collection: Mater-Bi® (starch)	Bioplastics
Biodegradable packaging for White Ballotins Chocolate Box: Plantic® (starch-derived)	Bioplastics
Blister packaging used to wrap such products as Sony Walkman radios and digital versatile discs (DVDs)	Bioplastics
Blisters and dosage packs for pharmaceuticals and medicines, single-dose medication packaging, shatterproof bottles and jars…	PVC
Blow-molded and sheet-thermoformed products for food, personal care, health, medical and lab ware applications, household chemicals and beauty aid products…	PP
Blow-molded chemicals bottles	PE
Blow-molded drugs, cosmetics, and toiletries packaging	PE
Blow-molded food bottles	PE
Blow-molded motor-oil bottles	PE
Blow-molded other items	PE
Blown and cast films, retail bags, organics and yard waste collection bags: Mirel & Mvera (PHA)	Bioplastics
Bottle, container: Bionolle™ (aliphatic polyester resin)	Bioplastics
Bottles and flasks by extrusion blow molding, translucent to opaque, flexible to rigid, small to large volumes. Stability in contact with shampoos, detergents, oils and fats, alcohols, etc. Gaialene	Bioplastics
Bottles, containers: Cardia Biohybrid™ resins for blow molding	Bioplastics
Boxes, crates, cases for cooled foodstuffs: Fish, ice creams… expanded PS	PS
Carry bag and trash bag applications: Cereplast compostable resins	Bioplastics
Chocolate tray: cornstarch polymer	Bioplastics
Clear and opaque bottles consume 1% of the PVC total…	PVC
Clear or drop impact-resistant containers, boxes, hot-filled bottles, dessert pots, horticultural pots, integrated hinge boxes, bottles and other cans up to several liters, caps and closures for beverage and cosmetic applications, medical disposable trays, containers for irrigation, parenteral, hemodialysis solutions…	PP

Continued

Table 4.1 More than 150 Examples of Thermoplastic Applications in Packaging—cont'd

Closures: Cardia Biohybrid™ resins	Bioplastics
Coat paper and cardboard for food wrapping paper, package for freshly cut products such as cheese, sliced meat, meat products, etc.: Mater-Bi® (starch)	Bioplastics
Coated cardboard to make cups for hot and cold drinks, plates, cups for ice cream, trays for food or containers for frozen food: Mater-Bi® (starch)	Bioplastics
Commercial food packaging: Plantic® material (starch-derived)	Bioplastics
Compostable plastic parts: Ecovio resins	Bioplastics
Containers for dry cosmetics such as face powders, eye shadow, lipstick, etc.: Mater-Bi® (starch)	Bioplastics
Containers, bottles, boxes, and tubing…	Cellulosics
Containers, trays…	ABS
Containers, trays…	PS
Cosmetics and pharmaceutical packaging	PET
Cosmetics packaging…	ABS
Cosmetics packaging…	PS
Crates and totes…	PE
Damping blocks, intermediate layers…	PP
Deli, fruit, and food containers can be made with Ingeo biopolymer (PLA)	Bioplastics
Disposable cups, plates, and cutlery that can be biodegraded and composted: Mater-Bi® (starch)	Bioplastics
Disposable cutlery: Vegemat (natural fibers, starch, proteins, lipids)	Bioplastics
Disposable food packaging, bowls, retail packs, plates, containers, lids, snack boxes, hamburger clams: Na:Pac (made of renewable plant materials)	Bioplastics
Disposable plastic cups, cutlery, and plates can be made with Ingeo biopolymer (PLA)	Bioplastics
Drugs, cosmetics, and toiletries containers…	PE
Drums	PE
Dry food without fat	CA
Environment-friendly food packaging: Plantic Technologies (starch-derived)	Bioplastics
Extruded and woven nets for packaging food products like citrus fruit and garlic: Mater-Bi® (starch)	Bioplastics
Fibers: BIOFRONT (stereocomplex PLA)	Bioplastics
Film and bottle blowing, cast film: BIOPAR®	Bioplastics
Film for packaging different types of nonfood products, such as toilet paper, kitchen roll, napkins and tissues, nappies, sanitary towels or magazines: Mater-Bi® (starch)	Bioplastics
Films and packaging with barrier properties, blister packaging, shrink caps, sleeves and stand-up pouches, co-extruded films…	COC
Films and sheets for packaging and thermoforming consume 7% of all PVC…	PVC

Table 4.1 More than 150 Examples of Thermoplastic Applications in Packaging—cont'd

Films and sheets with high clarity, puncture resistance, impact strength, low heat-seal temperature used for shrink wrap, heavy-duty shipping sacks, produce bags, bag-in-box food and technical packaging films…	EVA
Films, caps, containers, and bottles for cosmetics…	PMP
Films, packaging: BIOFRONT (stereocomplex PLA)	Bioplastics
Films, sheets, and plates for packaging and thermoforming, barrier layers of multilayer films…	PA
Films, shrink films…	PET
Films, transparent wrapping, blister packaging…	Cellulosics
Flakes, chips, sheets… expanded PS	PS
Flexible packaging for food, fruit and vegetables, frozen food, cheese, etc.: Mater-Bi® (starch)	Bioplastics
Foam packaging, as an environment-friendly alternative to polystyrene, polyurethane, and polyethylene: Mater-Bi® (starch)	Bioplastics
Foam packaging: Ecovio resins	Bioplastics
Foamed Gaialene for packaging	Bioplastics
Folded carton packaging laminates can be made with Ingeo biopolymer (PLA)	Bioplastics
Food and other packaging, e.g., blister packaging; shopping bags: Solanyl® (starch)	Bioplastics
Food and beverage bottling applications including water bottle: NatureWorks PLA	Bioplastics
Food and beverage containers…	PE
Food and beverage: capping for dairy products, fruit juices, sports drinks, beers, wines, and food…	TPE
Food and nonfood packaging, various containers for chemicals, clear blisters…	PVC
Food packaging	PET
Food packaging, cups, and dairy containers from thermoformed sheets, vacuum-formed packages…	ABS
Food packaging, cups, and dairy containers from thermoformed sheets, vacuum-formed packages…	PS
Food packaging, pharmaceutical packaging, industrial packaging…	ETFE
Food, pharmaceutical, health care, medical, industry, and chemical packaging…	PCTFE
Free-standing pouches…	EVOH
Functional packaging useful for shipping and installation on site	PP
Health care, cosmetics, perfumery, and personal care supply containers and packaging	Cellulosics
High-clarity parts for medical and food packaging…	PP
Housewares	PE
Industrial and shipping pails…	PE

Continued

Table 4.1 More than 150 Examples of Thermoplastic Applications in Packaging—cont'd

Injection-molded bucket (HDPE-like) for insecticide attractant to mosquitos laying eggs, and water-resistant but biodegrade: Plantic® material (starch-derived)	Bioplastics
Integrated circuit packaging (hard disk drive; HDD) trays…	PEEK
Jar lid gasketing…	PVC
Kitchen and household food storage, lids and seals, cookware, housewares and closures…	TPE
Laminated paper: Bionolle™ (aliphatic polyester resin)	Bioplastics
Large-sized objects: cisterns, tanks, septic tanks, industrial drums…	PE
Lids for thermoformed food packages…	EVOH
Liquid food bottles, household chemical bottles…	PE
Microwaveable food packaging…	PPE
Milk bottles	Bioplastics
Moisture-proof film packaging…	PCTFE
Mulch films: Ecovio resins	Bioplastics
Overwrap, shrink wrap, shopping bags, waste bags: Cardia Biohybrid™ resins	Bioplastics
Packaging and display units… expanded PS	PS
Packaging film in Gaialene compound	Bioplastics
Packaging films and sealants, puncture-resistant films for pouches and blister packs, glass coatings…	EMA
Packaging for organic solvents, agricultural pesticides, and all kinds of oils…	EVOH
Packaging for tablets, pills, capsules, suppositories; urine containers, sterilizable equipment…	PET
Packaging of cosmetics and health-care products…	PET
Packaging of electrical household and business appliances, TV, radio, office automation, printers, computers, electric tools… expanded PS	PS
Packaging of fragile parts: electronics, office automation devices, electric motors…	PP
Packaging of perishable food products or variable shelf life products such as prewashed salads, bakery goods, biscuits, snacks, cereals, croquettes, or coffee: Mater-Bi® (starch)	Bioplastics
Packaging small electrical items (mobile phones, razors, etc.): Mater-Bi® (starch)	Bioplastics
Packaging, food and nonfood, perfume bottle caps, shampoo bottles, various bottles and containers, glass product coatings…	EMA
Packaging, food services, biomedical, agriculture: Biomer (PHA)	Bioplastics
Packaging: PLA modified with Biomax® strong, an ethylene copolymer	Bioplastics
Paper coated with Mater-Bi® (starch) for bags for bread, chicken, flour, single-use packets for sugar, etc.	Bioplastics
Paper-coating: Ecovio resins	Bioplastics

Table 4.1 More than 150 Examples of Thermoplastic Applications in Packaging—cont'd

Pharmaceutical containers and packages, primary packaging of pharmaceuticals…	COC
Pharmaceutical packaging closures, seals and liners…	TPE
Plastic bags	Bioplastics
Pouches for sauces, coffee, tea, soup…	EVOH
Promotional articles, packing: TREEPLAST (wood chips with crushed corn and natural resins)	Bioplastics
Public catering: cutlery, plates, beakers, cups, even boxes for transporting prepared food: Mater-Bi® (starch)	Bioplastics
Refrigeration packaging…	ABS
Refrigeration packaging…	PS
Reusable packaging or shuttle packaging for heavy parts such as doors, windscreens, rear mirrors…	PP
Seals and closures for cosmetics and toiletries…	TPE
Shrink film: Ecovio resins	Bioplastics
Sterilizable pharmaceutical and industrial packaging…	ECTFE
Structural industrial packaging: engines of cars… expanded PS	PS
Tea packaging: NatureFlex (cellulose-based)	Bioplastics
Technical packaging, pouches for gas sampling…	ECTFE
Thermoformed applications, packing foods and goods: Plantic® HP1 (starch-derived)	Bioplastics
Thermoformed packaging: Ecovio resins	Bioplastics
Thermoformed trays for foodstuffs (fruit, vegetables, meat, etc.): Mater-Bi® (starch)	Bioplastics
Transparent containers for olive oil and other cooking oils	Bioplastics
Transparent film for packaging fruit and vegetables: Mater-Bi® (starch)	Bioplastics
Transparent packaging…	PS
Transparent packaging… transparent ABS	ABS
Trays and other rigid containers for various products such as cheese, fruit, etc.: Mater-Bi® (starch)	Bioplastics
Trays for food…	PET
Trays, foam sheet, sheet: Cardia Biohybrid™ resins	Bioplastics
Urns injected from Fasal® BIO 322	Bioplastics
Waste bags, shopping bags: Ecovio resins	Bioplastics
Water bottles	PVC
Wrap, films, labels, and laminates can be made with Ingeo biopolymer (PLA)	Bioplastics

are the most used with a preeminence of rigid and soft PVCs. However, some engineering plastics are used for specific applications such as glazing, for example.

Thermoplastics and TPEs are commonly used in elements and fittings that are not highly loaded. They allow innovative techniques, such as the rehabilitation of old mains without the opening of trenches that would be expensive, time-consuming, and disturbing for road traffic. Some examples are listed below without claiming to be exhaustive:

- Use of a PE liner folded into a "C" shape and held by taping (Subcoil by Wavin). After insertion into the existing mains to be rehabilitated, pressure is applied to tear up the tape and lay the liner onto the main inner wall. This wall ensures the structural function and the PE liner ensures water tightness and corrosion protection.
- Use of a PET liner (Neofit by Wavin) that is inserted into the pipe to be rehabilitated to form a close-fit liner.

4.2.1 Wood Thermoplastic Composites

The reinforcement of thermoplastics with wood fibers is relatively recent because of the weak compatibility of the two types of materials.

About 20 years ago, the first industrial development was launched with a PP filled with 50% wood flour.

Other developments followed a few years later:

- a PE filled with approximately 50% wood fiber for deck boards, landscape timbers, picnic tables, and industrial flooring
- a PVC filled with 40% wood for French doors and windows
- a composite with 70% wood.

More recently, about 10 years ago, the first wood composite was marketed in pellets.

The market is fast growing in the USA where there is a considerable amount of wood residues of low prices comparable with those of inorganic fillers such as talc and calcium carbonate.

The highest growth area for the wood plastic composite (WPC) industry is in decking and other elements for construction such as industrial flooring, window and door profiles, hot tub siding, office accessories, landscape timbers, railings, molding, fencing, and others.

Currently marketed wood composites are based on 30–70% natural fiber-filled PP, PE, PS, and PVC. Formulations have high performances and are more expensive than the virgin material.

It is necessary to divide the building and civil engineering market into several submarkets with differing functions, environmental stresses, and requirements.

4.2.2 Application Overview

In building, we can consider two broad subdivisions:

- exterior applications subjected to direct sunlight, rain, temperature variations…
- interior applications subjected to less harsh constraints: sunlight irradiation, for example, is less severe, but esthetics requirements are more stringent.

Figure 4.4 shows some applications.

Civil engineering applications can be divided into two broad families:

- piping for water, gas, and sewers
- installations using geomembranes, seals, and anticorrosion materials.

Figure 4.5 shows some applications.

Recycling is particularly important for the building and civil engineering market, the sector with the second largest consumption of thermoplastics. Unfortunately, plastics recycling presents technical and economic difficulties and is less advanced, industrially, than that of metals or glass.

From an environmental point of view, this poor recycling situation is compensated for by the improvement of energy efficiency in the home.

Thermal insulation made from expanded PS or other foams, thermoplastic window frames, etc. help to reduce heat loss. This is very important in cold countries because domestic heating can represent almost one-quarter of the total energy consumption. Consequently:

- fuel consumption is reduced
- natural resources are preserved
- CO_2 emission is highly reduced (by two to five times) even taking into account the CO_2 emissions from plastic production.

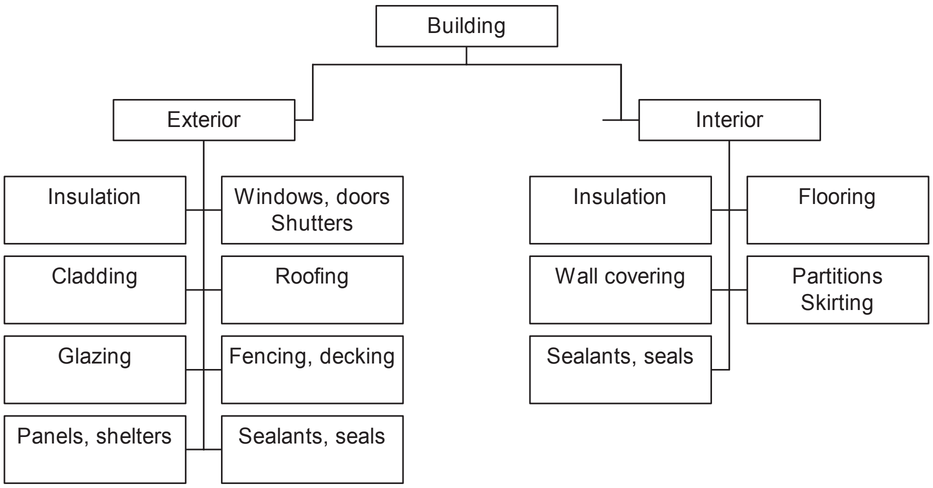


Figure 4.4 Thermoplastic application examples in building.

4.2.3 Building Exteriors

The main applications of thermoplastics are related to the following.

- Insulation
  - thermal insulation can be from the interior or the exterior of the building
  - acoustic insulation is developing
  - PS foam dominates the thermoplastic foams but is competing with polyurethane foam (thermoset).
- Windows are made of PVC or composites according to the country.
- Glazing can be:
  - sheets and plaques for domes, skylights…
  - glazing films.
- Cladding, fascias, shuttering, and panels can be interior/exterior items.
- Sealing can be ensured by:
  - seals and gaskets for windows, doors…
  - sealants for masonry…

Let us cite, without claiming to be exhaustive, some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his specific problem and must test the right grade in the real conditions of service life.

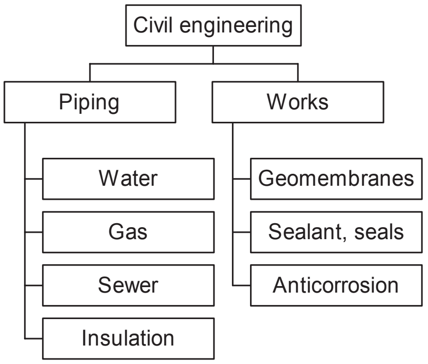


Figure 4.5 Thermoplastic application examples in civil engineering.

4.2.3.1 Insulation

PS and polyurethane (thermoset) foams dominate the market, with PVC and PE foams accounting for less than 1%. EPS used in building represents 18% of total PS consumption.

4.2.3.2 Light Structural Functions

- Framework: pultruded long glass fiber-reinforced plastics.
- Load-bearing panels for individual construction, Azurel by Dow made of wood and expanded PS hybrid.
- Windows and doors: extruded PVC is used for doors and windows for houses, buildings, and factories. Though the window and door market is fast growing (7.3% per year in the USA), the market share of plastics is only a few percent of the total US demand for windows and doors.

- Decking made out of PVC, WPC.
- Deck plank: vinyl profiles or composite boards are used to form the base of the walking surfaces or stairs.
- Railings including rail posts, cap rails, head rails, and balusters can be made out of PVC.
- Garden portals of plastic panels screwed on metal structures.
- Frontages in sandwich made of PVC foam core and skins of fire-resistant glass fiber-reinforced polyester. The panels are attached onto a steel framework.
- Panels in sandwich of expanded PS core with composite skins.

4.2.3.3 Transparency

Glazing, domes, skylights… consume 20% of all polycarbonate. Acrylic sheets account for 66% of total acrylics.

The main thermoplastic solutions for transparency in building are:

- PVC, the cheapest but it is necessary to carefully study the construction to avoid high temperatures exceeding the polymer continuous use temperature
- PMMA, the most naturally weather-resistant
- Polycarbonate, the best from the point of view of impact resistance.

The applications are, for example, skylights, domes, veranda roofs in simple or double-wall sheets of polycarbonate, exterior spotlights, waterproofed lights, globes.

4.2.3.4 Decoration

- Architectural panels made of PVC…
- Caps, end covers, fascias, fascia cover plugs, post caps, snap caps: vinyl parts or profiles placed along the tops of fences, open ends of planks, stairs and framing, screw heads… to conceal hardware, provide a finished look and prevent water penetration.
- Fill strips: vinyl strips fitted into the channels of deck planks to cover exposed hardware.
- Post base trim covers: vinyl trim pieces used to cover post-to-floor connections.
- Rail covers: vinyl trim that covers rail-to-post connections.

4.2.3.5 Waterproofing

Polymers provide several solutions for roofing and weatherboarding: flexible membranes, rigid sheets or plates, or tiles. Roofing membranes can differ by:

- raw material: PVC and alloys, TPO
- formulation and reinforcement with fibers, fabrics…
- seam type: solvent, welding, gluing, self-adhesive.

All these parameters influence the durability of the membrane. Durability also depends on the area of application.

For rigid roofing, it should also be remembered that PVC is the main thermoplastic for gutters.

4.2.3.6 Seals and Sealing

Prefabricated seals for windows, doors, etc. are made out of TPEs and TPVs competing with rubbers.

4.2.3.7 Flexible Structures

Canvas and other fabrics and films are used to realize structures. According to the usage, the materials are standard, such as PVC-coated fabrics, or sophisticated, such as polytetrafluoroethylene (PTFE)-coated glass fabrics…

Canvas coated with a polymer is used as a roofing material for applications such as industrial or storage buildings, garden canopies, exhibition halls, and so on.

Various stadiums and other large structures have an inflatable roof made of a volume of a coated fabric inflated by pneumatic pressure and attached to a concrete or concrete and steel building.

Portable temporary inflatable structures are designed for a huge variety of usages: emergency shelters, leisure marquees, decontamination or rescue units, urban rescue, personal protection, exhibitions, temporary warehousing, receptions, weddings, and so on. A reception structure 43 m long, 30 m wide, and 15 m high can be installed in 2 days and dismantled in 1 day.

4.2.4 Building Interiors

Figure 4.6 shows the versatility of thermoplastic applications by some examples for interior building use.

Apart from PVC and other commodity plastics, engineering plastics and WPCs are used for specific advantages corresponding to specific applications.

4.2.4.1 Styrenics, Possibly Foamed

Styrenics, approximately 18% of which (mainly EPS) are consumed in the Building and Construction sector, are used in building interiors for:

- interior heat insulation of buildings, prefabricated elements and partitions, window frames, expansion joints, conduits for air-conditioning, and cases for traveling shutters. EPS is the most important application of styrenics. The low thermal conductivity, compressive strength and mechanical resistance of extruded foams, and low moisture absorption properties provide excellent heat insulation, fair support, and long-term performance

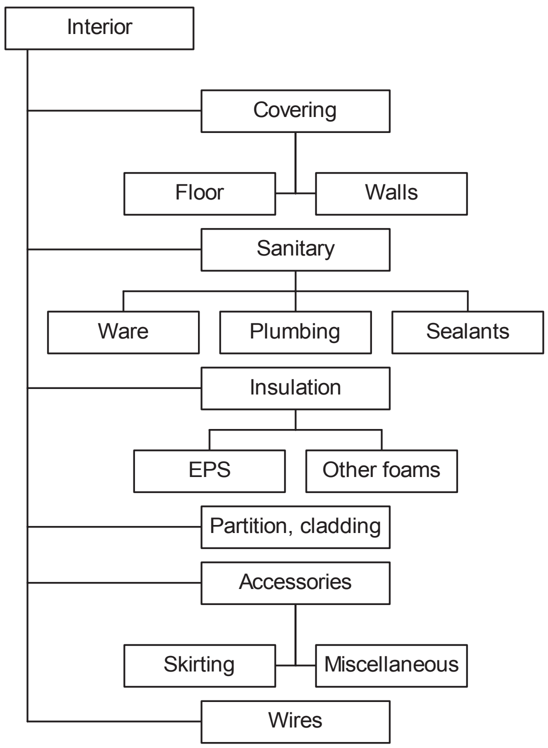


Figure 4.6 Building: interior elements.

- elements for decoration and furniture
- PS mirrors for interior decoration are composed of a flat sheet with a thin and flexible reflective top layer.

4.2.4.2 Soft and U-PVC, Possibly Foamed

PVCs are used in building interiors for:

- pipes for plumbing and other applications consume 43% of all PVC (including civil engineering)
- profiles for decoration, proofing, cladding, and other interior and exterior applications are the second outlet for PVC. Interior cladding made from unplasticized PVC (U-PVC) hollow panels improves insulation, and reduces condensation and mildew growth. For bathrooms, living rooms, bedrooms, and hobby rooms they can lead to high cost savings on conventional tiling
- floor covering, wallpapers: PVC is appreciated for its hygienic, easy to use, and economical properties
- insulation of electric wires
- heat insulation of buildings, but consumption is far below that of EPS.

4.2.4.3 Polyethylene

PE is used in building interiors for:

- pipes, tubes, and protective conduits
- vapor and moisture barrier films
- foams for insulation against heat, moisture, water, air, and noise: insulation of piping, walls, underlay for flooring, interior insulation of garage doors…
- insulation of electric wires
- furniture fittings.

4.2.4.4 Engineering Plastics

- Because of their pleasant aspect, lightweight, ease of working, and insensitivity to greasy fingers in sanded finishing, cast acrylic sheets are often used in building interiors. Sawing, milling, drilling, bending, thermoforming, welding, metallization, decoration mimicking stones and marble, graining, fire retardancy, impact-resistant grades, and alloys with PVC allow a multitude of applications, such as:

- washing tubs and washstands, worktops in kitchens, and bathroom fittings in residential and private home applications
- door coverings, furniture parts, and wall cladding for shops, hospitals, post offices, homes for the elderly, elevators, staircases; profiles such as handrails, angle protectors…
- flat and convex acrylic mirrors are 15 times more impact-resistant than glass for only one-third the weight.

- Acrylics and polycarbonates are used in glazing (doors and windows, fanlights, dormers, skylights…) and in lighting devices.
- Polyacetals are used for sanitary, plumbing, and furniture fittings.
- PAs are used for flooring (woven carpets and rugs) and furniture fittings.

4.2.4.5 Composites with Wood

- Decorative laminates made of particleboards with outer decorative plastic layers such as PVC and so on.
- WPCs based on 30–70% natural fiber-filled PP, PE, PS, and PVC.

4.2.5 Pipes and Tubing

Commodity thermoplastics are the most used, with rigid and soft PVCs dominating. However, some engineering thermoplastics are used for specific applications that justify their cost.

Typical materials are:

- commodity plastics: PVC, PE, PP, and their derivatives: cross-linked polyethylene (PEX), cellular PVC
- engineering plastics: chlorinated polyvinyl chloride, acrylonitrile butadiene styrene (ABS), PET for special purposes
- hybrids: metal/plastic, PEX-Al-PEX.

Let us quote some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his specific problem and must test the right grade in the real conditions of service life.

4.2.5.1 Rigid PVC

- General-purpose ducting systems.
- Drain-and-waste and vent lines for carrying cold water.
- Rainwater systems, channel drainage systems, land drainage systems (corrugated pipes).
- Water transportation (molecular orientated PVC).

4.2.5.2 Modified PVC

- Pressure pipes with higher impact resistance and greater ductility.
- Hot- or cold-water lines.

4.2.5.3 Polyethylene

- High-density PE (HDPE) is normally used for high-pressure pipes up to 20 bar for water and up to 7 bar for gas. LDPE is used for lower pressure applications mainly in agriculture. Examples of applications are potable water up to 20 bar, gas up to 7 bar, surface water drainage systems, stormwater drainage, cable ducting.

4.2.5.4 Flexible Polybutylene

- Hot- and cold-water lines.
- Underfloor heating.

4.2.5.5 Polypropylene

- High-temperature pipes.
- Surface water drainage systems.

4.2.5.6 ABS

- Food industry piping.
- Drain-and-waste and vent lines.

4.2.5.7 PET

- Liner into pipes to be rehabilitated.

4.2.6 Geomembranes, Geotextiles, and Geogrids

Geomembranes are giant impermeable membranes made of (un)reinforced polymeric materials and used to stabilize earth and to secure landfills ensuring containment of hazardous or municipal wastes and their leachates. Functionalities are varied:

- basal liners
- capping systems
- cushioning layers
- strengthening layers for soil reinforcement
- containment liners
- waterproofing membranes.

In many of these applications, geomembranes are associated with a geotextile or geogrid underliner that protects the geomembrane from direct contact with stones, gravel, and other damaging materials. In the case of landfills and other waste storage, the geotextile or geogrid can also drain gases and leachates generated by certain wastes.

Geomembranes and associated geotextiles are also used for the rehabilitation of channels, tunnels, reservoirs, and so on, economically providing complete reliability for waterproofing and avoiding liquid losses.

Geotextiles are fabrics used to:

- stabilize or reinforce soil for roads, railroads, airfields, embankments, retaining structures, reservoirs, canals, dams, bank protection, and coastal engineering
- protect geomembranes from direct contact with stones, gravel, and other damaging materials
- separate different layers of soil in civil engineering applications
- filter or drain soil in civil engineering applications, landfills, and so on.

Geomembranes must be resistant to:

- puncture, compression, tensile stress, tear, creep…
- long-term aging: oxidation, temperature, thermal cycling, UV, chemical attacks by the environment, contact with industrial pollutants or waste by-products, wet and dry cycles, stress cracking
- exchanges with the environment:
  - loss of additives to the environment through migration: plasticizers, antioxidants, UV stabilizers, low-molecular weight components…
  - absorption of elements from the environment: water, chemicals…

Let us quote some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his specific problem and must test the right grade in the real conditions of service life.

- channels and irrigation channels…
- dam, baffle, and levee covers…
- floating covers for canals, etc., fly ash covers, manure storage, coal-pile liners and covers, liners and caps…
- heap leach pads, filter beds, sludge drying beds…
- landfill lining and caps…
- reservoirs, tailing ponds, golf course ponds, decorative ponds and lakes, cooling ponds, fire ponds, farm ponds, aquaculture ponds, tanks for whales…
- stormwater runoff …
- municipal swimming pools, ice rinks…
- secondary containment, paper waste containment, industrial ponds for mining, brine, tank liners…
- solar evaporation ponds…
- tunnel waterproofing…
- waste treatment: wastewater, black liquor, wastewater treatment station, oxidation ponds, sewage lagoons…

The thermoplastics used—mainly PE (slightly more than 50%) and PVC (slightly less than 50%)—are necessarily flexible to allow their positioning, easy to seam and repair, puncture- and impact-resistant, long lasting, and cheap. For example, let us quote some applications without claiming to be exhaustive:

- PE and vinylacetate-ethylene or EBA copolymers such as LLDPE geomembrane pond liners, HDPE alloy geomembrane liners, lightweight tarps, and containment liners. Beware of low elongations at yield and the stress cracking sensitivity of certain PEs.

- Soft PVC, PVC-NBR such as containment liners, fish-safe grade pond liners, coated fabrics or laminates for tarps and shelters, landfills and canal linings (since the 1950s), decorative ponds, and lakes. Unfortunately, soft PVCs are subject to plasticizer desorption and extraction, becoming harder and brittle.
- PP is a material of choice for sewage lagoons. Long service lives (20 years) are claimed by certain processors.
- Ethylene interpolymer alloys are used for fuel, fertilizer, or transformer oil containment.

4.2.7 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.2, without claiming to be exhaustive, some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

The designer must check the possibility of using the proposed thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.3 Automotive and Transportation

The automotive and transportation market is the third outlet for thermoplastics. It is also an important sector for thermoplastic composites and TPEs.

4.3.1 Automotive Sector

The car industry is subject to many constraints:

- economic competition, worsened by production overcapacities
- margin reductions
- shortening of the development cycles especially for the small "niche" series
- strengthening of pollution, recycling, and energy regulations.

All these reasons persuade carmakers to lighten vehicles, improve their quality and performances, extend guarantees, reduce development and manufacturing times, and reduce costs and support materials that can be recycled.

Several exceptional features explain the high level of thermoplastics and thermoplastic composites used for the automotive and transportation market:

- Technical motivations: using thermoplastics is favored by:
  - ease and freedom of design (realization of forms impossible with metals)
  - integration of functionalities
  - ease of construction and assembly
  - reduction of design and manufacturing times. The vehicle models are refreshed and renewed more and more often. All these modifications require replacements and modifications of tools that are easier with plastics than with metals
  - low density and remarkable performance/weight ratios, leading to weight reduction and consequently better car performances and/or decreased fuel consumption and pollution
  - ease of maintenance, but beware of the mar resistance
  - nonrusting (but beware of aging)
  - acoustic damping (i.e., noise reduction).
- Aesthetics: thermoplastics allow:
  - much more design freedom than steel
  - decoration possibilities: bulk coloring, in-mold decoration…
  - pleasing finish.
- Economic features: thermoplastics provide:
  - a favorable economic solution for mass production as well as "niche" production
  - reduction of design and manufacturing times
  - reduction of finishing costs: plastics allow the integration of functions and, consequently, lead to the reduction of assembly costs
  - higher productivity due to adapted processes, integration of functions, fewer processing steps…
- Environmental features: thermoplastics save energy throughout their lifetime because of their lightweight…

Table 4.2 More than 150 Examples of Thermoplastic Applications in Building and Civil Engineering

Acoustic screens for civil engineering	PMMA
Anticorrosion components for cooling towers, laboratory sinks…	PVC
Anticorrosion components for cooling towers, laboratory sinks…	PVCC
Anticorrosion protection: lined pipes; buried gas pipelines; pipes co-extruded with MDPE and HDPE to increase their performance; dirty water and effluent pipes used in aggressive environments… PA11 or 12	PA
Architectural glass lamination…	TPU
Architectural panels made of PVC…	PVC
Ball cocks, faucets (taps), faucet cartridges, faucet underbodies, valve stems…	POM
Bitumen modification for roads, roofing, paving, impact-resistant shingles…	TPS
Breathable films for construction…	COPE
Breathable films for construction…	PEBA
Breeze blocks, prefabricated components, coatings, mortars and light concretes containing expanded beads… Expanded PS	PS
Brushes, honeycomb structures (tiles), level indicators (outer tubes for soil quality measurements): Solanyl® (starch)	Bioplastics
Building interiors	PMMA
Canvas and other fabrics and films are used to realize structures. According to the usage, the materials are standard, such as PVC-coated fabrics, or sophisticated, such as PTFE-coated glass fabrics… Canvas coated with a polymer is used as a roofing material for applications such as industrial or storage buildings, garden canopies, exhibition halls, and so on. Various stadiums and other large structures have an inflatable roof made of a volume of a coated fabric inflated by pneumatic pressure and attached to a concrete or concrete and steel building. Portable temporary inflatable structures are designed for a huge variety of usages: emergency shelters, leisure marquees, decontamination or rescue units, urban rescue, personal protection, exhibitions, temporary warehousing, receptions, weddings, and so on	PTFE
Canvas and other fabrics and films are used to realize structures. According to the usage, the materials are standard, such as PVC-coated fabrics, or sophisticated, such as PTFE-coated glass fabrics… Canvas coated with a polymer is used as a roofing material for applications such as industrial or storage buildings, garden canopies, exhibition halls, and so on. Various stadiums and other large structures have an inflatable roof made of a volume of a coated fabric inflated by pneumatic pressure and attached to a concrete or concrete and steel building. Portable temporary inflatable structures are designed for a huge variety of usages: emergency shelters, leisure marquees, decontamination or rescue units, urban rescue, personal protection, exhibitions, temporary warehousing, receptions, weddings, and so on	PVC
Caps, end covers, fascias, fascia cover plugs, post caps, snap caps parts or profiles placed along the tops of fences, open ends of planks, stairs and framing, screw heads… to conceal hardware, provide a finished look and prevent water penetration	PVC
Cast and extruded sheets, cell-cast sheets, stretched sheets, films down to 50 μm; laminated protective surfaces on ABS, PVC or other plastic sheets that are thermoformed into parts requiring resistance to outdoor weathering for residential siding and transformer housings…	PMMA

Continued

Table 4.2 More than 150 Examples of Thermoplastic Applications in Building and Civil Engineering—cont'd

Civil engineering and construction: BIOFRONT (stereocomplex PLA)	Bioplastics
Coated fabrics: extrusion of coated scrim for tarpaulins…	CPE
Conduits of cooling agents… Expanded PS	PS
Construction industry: ARBOFORM® (lignin)	Bioplastics
Containment liners, fish-safe grade pond liners, coated fabrics or laminates for tarps and shelters, landfills and canal linings (since the 1950s), decorative ponds and lakes. Unfortunately, soft PVCs are subject to plasticizer desorption and extraction, becoming harder and brittle: soft PVC, PVC-NBR	PVC
Damping mounts for noise and vibration…	MPR
Deck boards, landscape timbers, picnic tables, and industrial flooring: polyethylene highly filled with wood fiber	WPC
Deck plank used to form the base of the walking surfaces or stairs	PVC
Deck plank used to form the base of the walking surfaces or stairs	WPC
Decking	PVC
Decking	WPC
Decking and other elements for construction such as industrial flooring, window and door profiles, hot tub siding, office accessories, landscape timbers, railings, molding, fencing, and others	WPC
Disposable formworks… Expanded PS	PS
Docking, landfill liners, membranes, swimming pool liners…	PVC
Domes, skylights	PC
Door coverings, furniture parts, and wall cladding for shops, hospitals, post offices, homes for the elderly, elevators, staircases; profiles such as handrails, angle protectors…	PMMA
Doors and windows: PVC filled with wood	WPC
Drain-and-waste and vent lines for carrying cold water	PVC
Drain-and-waste and vent lines	ABS
Elements for decoration and furniture: expanded PS	PS
Expansion joints, water-stops…	TPV
External panels of house or building with glass fiber-reinforced plastic (GFRP) skins… Expanded PS	PS
Fencing, barriers, decking…	PVC
Fiber: removable protective panels…	PE
Filaments, fibers, and fabrics for indoor and outdoor carpeting, carpet backing, outdoor carpets around swimming pools or miniature golf courses…	PP
Fill strips: vinyl strips fitted into the channels of deck planks to cover exposed hardware	PVC
Film sandwich for bulletproof glazing…	EMA
Films…	PE

Table 4.2 More than 150 Examples of Thermoplastic Applications in Building and Civil Engineering—cont'd

Films, knitted, woven, braided, or sewn fibers for architectural fabrics…	FEP
Films, knitted, woven, braided, or sewn fibers for architectural fabrics…	PFA
Films, knitted, woven, braided, or sewn fibers for architectural fabrics…	PTFE
Fire-resistant wallpaper…	PI
Fittings, hinges, shower heads…	POM
Flat and convex acrylic mirrors are 15 times more impact resistant than glass for only one-third the weight	PMMA
Floating floors, reducing particularly the noise of impact… Expanded PS	PS
Floor covering, wallpapers: PVC is appreciated for its hygienic, easy to use, and economical properties	PVC
Flooring (woven carpets and rugs) and furniture fittings	PA
Flooring and wall coverings…	PVC
Flooring: TPE based on PVC	TPE
Foam for heat insulation of buildings (consumption is far below that of EPS)	PVC
Food industry piping	ABS
Frameworks for ventilation, fan blades, air filters…	PP
Furniture fittings	PE
Gas, water or sewer pipes, sheaths…	PE
Gasketing, tap washers, toilet buffers…	TPS
General-purpose ducting systems	PVC
Geomembrane pond liners, geomembrane liners, lightweight tarps, and containment liners. Beware of low elongations at yield and the stress cracking sensitivity of certain polyethylenes. HDPE, alloys, polyethylene, and VAE or EBA copolymers, LLDPE	PE
Geomembranes	TPV
Geomembranes	PE
Geomembranes	PP
Geomembranes	PVC
Glazing (doors and windows, fanlights, dormers, skylights…) and lighting devices	PC
Glazing (doors and windows, fanlights, dormers, skylights…) and lighting devices	PMMA
Glazing applications, shatter-resistant glazing, architectural and protective glazing, windows and skylights, sight glasses (e.g., observation windows), transparent thermoformed products…	PMMA
Glazing, architectural glazing, roofs of verandas, stations, stadiums, sheeting applications…	PC
Glazing, domes, skylights	PMMA
Glazing: PC is the best from the point of view of impact resistance	PC
Glazing: PVC is the cheapest but it is necessary to carefully study the construction to avoid high temperatures exceeding the polymer's continuous use temperature	PVC

Continued

Table 4.2 More than 150 Examples of Thermoplastic Applications in Building and Civil Engineering—cont'd

Gutters: PVC is the main used thermoplastic	PVC
Heat insulation of roofs, walls (insulation from the interior or exterior), floors of buildings, and hangars including heavy handling (aeronautical) and underfloor heating… Expanded PS	PS
High-pressure pipes up to 20 bar for water and up to 7 bar for gas: high-density PE (HDPE). Low-density PE is used for lower pressure applications mainly in agriculture. Examples of applications are potable water up to 20 bar, gas up to 7 bar, surface water drainage systems, stormwater drainage, cable ducting	PE
Hot- and cold-water lines	PB
Hot- or cold-water lines: modified PVC	PVC
Insulated panels for refrigerated warehouses and other cold storage… Expanded PS	PS
Insulation of electric wires	PVC
Insulation of electric wires	PE
Interior heat insulation of buildings, prefabricated elements and partitions, window frames, expansion joints, conduits for air-conditioning, cases for traveling shutters: expanded PS	PS
Internal and external cladding, roofing and ceiling systems…	PVC
Irrigation equipment and valves…	POM
Large-sized objects: cisterns, tanks, septic tanks…	PE
Lighting, light globes, lighting diffusers, outdoor lighting fixtures, traffic lights…	PC
Lighting, lights, lighting diffusers, light-control lenses in lighting fixtures…	PMMA
Lighting, signs, diffusers, lighting devices and accessories, profiles…	Cellulosics
Liner into pipes to be rehabilitated	PET
Linings and liquid surface coating systems for architectural fabrics…	PVDF
Mining screens…	TPU
Mirrors for interior decoration are composed of a flat sheet with a thin and flexible reflective top layer: expanded PS	PS
Monolayer tubes, corrugated or multilayer pipes, spiral wound, small or large diameter…	PVC
Multilayer pipes with polyethylene or polypropylene for underfloor heating systems in domestic and commercial buildings, preventing oxygen from dissolving in the hot water and avoiding metal corrosion of other parts in the heating device…	EVOH
Naturally weather-resistant glazing	PMMA
Nonflammable scenery, colored filter holders for studio and theater spotlights…	PI
Oil-resistant grades for seals, tubes, pipes, profiles for oil contact…	TPV
Pipe seals…	TPV
Pipes and fittings for potable water, sewers, irrigation, drain, rainwater, soil and waste systems, venting, ducting, fire sprinkler piping, chemical and food processing…	PVC
Pipes and conduits…	PE
Pipes and fittings for hot and corrosive environments…	PVCC

Table 4.2 More than 150 Examples of Thermoplastic Applications in Building and Civil Engineering—cont'd

Pipes for cold and hot pressurized water…	PB
Pipes for higher temperature than PE	PP
Pipes for paper and surface treatment sectors, electroplating plants, photographic, semiconductor, and chemical industries…	PVC
Pipes for paper and surface treatment sectors, electroplating plants, photographic, semiconductor, and chemical industries…	PVCC
Pipes for plumbing and other applications consume 43% of all PVC (including civil engineering)	PVC
Pipes, tubes, and protective conduits	PE
Pipes: metal/plastic hybrids, PEX-Al-PEX	PEX
Plumbing and installation sector, pump and filter housings, impellers, plumbing systems…	PPE
Plumbing and installation sector; small pressure vessels, sound-damping mountings for WCs and bathrooms, toilet cistern valves…	POM
Plumbing fixtures, faucet (tap) components…	PSU
Post base trim covers: vinyl trim pieces used to cover post-to-floor connections	PVC
Potable water fittings…	PSU
Potable water transportation equipment and water treatment plants: powder-coated metal parts… PA11 or 12	PA
Prefabricated seals for windows, doors, etc. are made out of TPEs and TPVs competing with rubbers	TPE
Prefabricated seals for windows, doors, etc. are made out of TPEs and TPVs competing with rubbers	TPV
Pressure pipes with higher impact resistance and greater ductility: modified PVC	PVC
Profiles for decoration, proofing, cladding, and other interior and exterior applications are the second outlet for PVC. Interior cladding made from U-PVC hollow panels improves insulation and reduces condensation and mildew growth. For bathrooms, living rooms, bedrooms, and hobby rooms, they can lead to high cost savings on conventional tiling	PVC
Protective glazing, vandal-proof windows, shatter-resistant glazing, windows and skylights…	PC
Public works: antifreeze bases of roads or railways… Expanded PS	PS
Pump and filter housings, impellers, plumbing systems…	POM
Rail covers: vinyl trim that covers rail-to-post connections	PVC
Railings including rail posts, cap rails, head rails, and balusters	PVC
Railway pads…	COPE
Rainwater systems, channel drainage systems, land drainage systems (corrugated pipes)	PVC
Residential and commercial carpets: Sorona® biopolymer	Bioplastics
Residential and nonresidential glazing, window and door weather seals…	TPV
Residential and nonresidential glazing, window and door weather seals… TPE based on PVC	TPE
Roofing…	TPO

Continued

Table 4.2 More than 150 Examples of Thermoplastic Applications in Building and Civil Engineering—cont'd

Roofing…	TPV
Roofing… TPE based on PVC	TPE
Roofing membranes	PVC
Roofing membranes	TPO
Sanitary, plumbing, and furniture fittings	POM
Sewage lagoons. Long service lives (20 years) are claimed by certain processors	PP
Siding consumes 15% of the PVC total, with gutters, downspouts, boardings…	PVC
Signs: internally illuminated outdoor signs, indoor and outdoor signs, diffusers, side-lit signs, very thin illuminated displays, fluorescent signs…	PMMA
Soft-touch overmolding…	TPO
Soundproofing of buildings… Expanded PS	PS
Structural insulated panels… Expanded PS	PS
Surface water drainage systems	PP
Tubes, pipes, conduits, and fittings	PE
Tubes, pipes, conduits, and fittings	PEX
Tubes, pipes, conduits, and fittings	PP
Tubes, pipes, conduits, and fittings	PVC
Tubes, pipes, conduits, and fittings for special purposes	ABS
Tubes, pipes, conduits, and fittings for special purposes	PET
Tubes, pipes, conduits, and fittings for special purposes	PVCC
Underfloor heating	PB
Vapor and moisture barrier films	PE
Washing tubs and washstands, worktops in kitchens, and bathroom fittings in residential and private home applications	PMMA
Water transportation (molecular orientated PVC)	PVC
Weather-resistant films, UV screening films for glazing panels, surface covering for PVC films, surface protection for sign industry…	PVF
Window and door weather stripping…	MPR
Window profiles…	PVCC
Window seals…	TPS
Windows and doors consume 4% of the PVC total in shutters, architectural glazing systems, conservatory devices…	PVC
Windows and doors for houses, buildings, factories	PVC
Woodlike profiles: Synthetic wood or wood plastic composites (WPC) made from rigid PVC heavily filled with wood flour, extruded in woodlike profiles that can be sawn, nailed, and screwed just like natural wood…	WPC

On the other hand, recycling brings some particular problems due to economic conditions, polymer modifications, and reinforcements.

To progress in the automotive industry, plastics must improve their performance characteristics, ease of processing, productivity, and recycling, for example:

- Better thermal resistance: under-the-hood applications are undergoing an increase in the service temperature. In the cockpit interior, temperatures are tending to increase due to increased use of glazed surfaces. The rise in lamp power and headlight miniaturization is leading to a temperature increase in the optical system and reflector. For the body, painting on line requires sufficient thermal resistance to tolerate the cooking temperature. Consequently, it is necessary to use new polymer grades or new, more thermally resistant families.
- Better low-temperature behavior: regulations tend toward an increase in low-temperature impact resistances and a more ductile behavior.
- Ease of processing: improved flow properties and processability lead to cycle time reductions and productivity gains.
- Low finishing costs: bulk coloring, in-mold decoration, an intelligent design, and an effective maintenance of the molds reduce or avoid painting and other finishing operations, cutting the finishing costs.
- Recycling: more effective solutions are sought. The development of the mono-material concept is favorable to thermoplastics and self-reinforcing thermoplastic composites such as self-reinforced PP (Curv™ from Propex Fabrics).

The use of thermoplastics and composites is growing in various segments of vehicles:

- bumpers
- body, external elements
- passenger compartment
- under-the-hood and other mechanical elements.

The automotive market must be segmented into several submarkets with differing functions, environmental stresses, and requirements. We can consider three major subdivisions (see Figure 4.7):

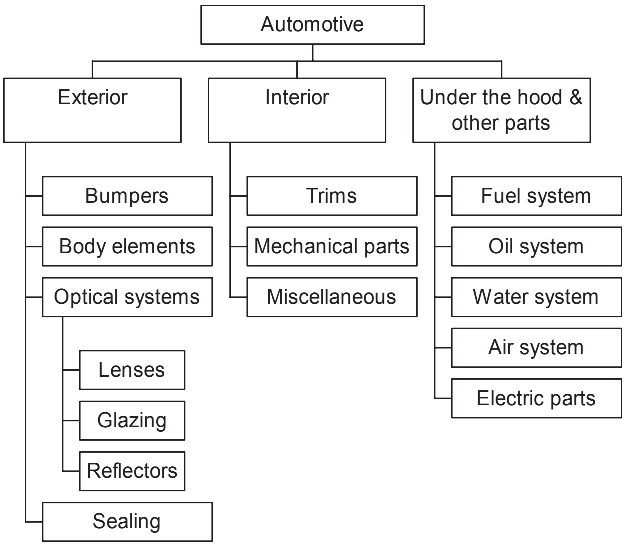


Figure 4.7 Market segmentation of the automotive sector.

- Exterior applications subjected to direct sunlight, rain, temperature variations, mechanical aggression (gravel splashing, scratches…), and increasing requirements related to styling, low cost, weight saving, ease of processing, safety, respect for the environment, and recycling.
- Interior applications subjected to temperature, sunlight irradiation through glazing and increasing requirements related to styling, comfort, low cost, ergonomics, weight saving, ease of processing, safety, respect for the environment, and recycling.
- Under-the-hood and other mechanical parts subjected to a harsh environment characterized by high temperatures, aggressive fluids (fuel, oils, coolant fluids, brake fluids, ozone…). On the other hand, there is no exposure to UV or light.

The penetration of thermoplastics and thermoplastic composites ranges from the totality of the considered parts—for example, bumpers or fuel tanks where metals are nearly ousted—down to applications that are widespread but with only a few consuming part types, such as wire supports, and promising outlets, for example, glazing or structural parts.

Well-established applications are, for example:

- bumpers
- fuel tanks

- lights: headlights, rear, and side lights
- ancillary equipment such as rear-view mirror housings, wheel trims, luggage boxes, bases for roof racks…

4.3.1.1 Developing Applications

- Sealing: weather strips, light seals made of TPEs
- Thermoplastic fenders
- Body elements such as panels, doors, spoilers…

4.3.1.2 Emerging Applications

- Glazing…

To favor the penetration of thermoplastics in the automotive industry, several concepts are being developed to ease assembly, stock control, and purchasing. The passenger compartment is a good example of two of these concepts:

- the mono-material concept and
- ready-to-install modules.

4.3.1.3 Mono-Material Concept

Some parts such as dashboards are an inextricable combination of various subparts of different materials making it impossible to dismantle. The choice of compatible materials is advised to allow recycling. For example, a part can be made out of several olefin subparts:

- long fiber-reinforced polypropylene (LFRT) for a structural subpart
- PP foam for a damping subpart
- thermoplastic polyolefin elastomer for the skin.

4.3.1.4 Ready-to-Install Modules

The automotive industry favors sets of parts assembled by the plastic furnisher and including nonplastic elements such as metal components, electronics… This simplifies purchasing and online operations. For example, a seat module includes the frame, cushioning, slide system, position control device…

Let us quote some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. As always, the designer must verify the possibility of using the quoted thermoplastic family for his specific problem and must test the right grade in the real conditions of service life.

4.3.1.5 Fuel Tanks

The first PE fuel tanks were used 40 years ago on Porsche rally cars and a few years later on special series of the VW Beetle. Weight savings were in the order of 30–50% versus the replaced metal tank. There are also other advantages such as:

- greater design freedom allowing optimization of free-space use and consequently of capacity
- better impact behavior
- better corrosion resistance
- lower cost due to the ease of manufacturing.

There is also a significant drawback: the inherently higher fuel permeability of polymers. The strengthening of environmental regulations (PZEV; partial zero emission vehicle) leads to severe requirements concerning fuel impermeability, needing modification of the techniques now in use. Moreover, some carmakers such as Ford and GM require higher mechanical and thermal resistance and conductive materials.

Here are a number of possibilities for improving fuel impermeability, including:

- thermoforming of six-layer HDPE/EVOH
- combination of PA/PO alloys and EVOH multilayer (Permblok by Atofina)
- fluorination of HDPE
- internal and/or external organic or organomineral coatings
- nanosilicate coatings, for example, SMA and silica nanoparticles with epoxy derivatives forming a cross-linked network
- redesign of the fuel line with capless fuel tanks (Velsatis and other Renault models).

4.3.1.6 Dashboards

A dashboard is a complex part with several subparts of very different functionalities:

- structural beam or substrate
- instrument panel with various dials and glazing
- cushioning

- skin
- grilles for heating and demisting
- glove boxes
- racks…

Polyolefins are well adapted to the mono-material concept: talc-filled PP and LFRT for structural parts, foamed PE and PP for damping, PP/terpolymer ethylene, propylene, diene (EPDM) alloys, or copolymers for skins. Some other functions need incompatible polymers with specific characteristics such as optical properties. Without claiming to be exhaustive, the other thermoplastic materials are:

- PVC and PVC/ABS, PVC/ASA alloys
- ABS, ASA, SMA
- polycarbonate and alloys with ABS
- PMMA
- PAs, polyphthalamides
- acetal
- polyphenylene oxide (PPO) or polyphenylene ether (PPE)
- glass mat-reinforced thermoplastics (GMTs)…

4.3.1.7 Bumpers

There are many solutions according to the materials, output, and processing methods, for example: rigid beam, damping foam, and skin with various thermoplastic versions such as:

- glass fiber-reinforced PP beam, PP foam, and TPO (PP/EPDM) skin: a big advantage is the mono-material solution, which eases recycling
- beam and foam with polycarbonate skin.

4.3.1.8 Interior Trims

Interior trim applications are decorative coverings with mechanical, safety, and aesthetic functions. They include:

- interior panels, doors, pillars…
- steering wheels, steering wheel covers, and airbag doors…
- glove box doors, consoles, package shelves…
- defroster/demister and loudspeaker grilles…

In these cases, polyolefins are also well adapted to the mono-material concept: talc-filled PP and LFRT for structural parts; foamed PE and PP for damping; PP/EPDM alloys or copolymers for skins. Some other functions need incompatible polymers with specific characteristics such as metallization possibilities. Without claiming to be exhaustive, the other thermoplastic materials used for these applications are:

- PVC and PVC/ABS, PVC/ASA alloys
- PS, ABS, ASA, AES
- polycarbonate and alloys with ABS
- PAs, polyphthalamides
- acetal
- double-wall panels made out of polycarbonate and PPO or PPE that can be shaped by thermoforming
- GMTs.

4.3.1.9 Airbag Systems

Cars are now equipped with several airbags to ensure safety when a crash occurs but there are some drawbacks such as the cost, the volume, which dictates the steering wheel design and limits the capacity of other storage boxes, and the weight.

The airbag system includes an ignition device that quickly generates a large volume of gas that inflates the airbag itself. The latter is a bag of synthetic textile possibly coated with silicone. Its properties are:

- controlled gas impermeability
- high tensile and tear strengths
- high pliability
- good durability.

To reduce weight, improve pliability and low-volume storage, and save costs, there are trends to reduce the fabric weight while preserving the properties.

4.3.1.10 Lenses

Lenses of headlights are often in polycarbonate and rear lights in co-molded acrylics.

4.3.1.11 Ancillary equipment

There are multiple parts with multiple functions as varied as:

- housing of rear-view mirrors
- grilles, back ventilation grids
- luggage boxes, in composites or thermoplastics
- wheel trims
- door handles
- accelerator pedals
- bases of cigar lighters
- seals
- safety transparent sandwich composites for glazing: polyvinyl butyrate or ionoplast core and two glass skins
- electrical wiring channels and pockets
- assembly aids, integral fasteners
- adhesive films…

All thermoplastics—commodity, engineering, or specialty—are used but in very small quantities for each specific function.

4.3.1.12 Under-the-Hood

The thermoplastics used are as diversified as the functionalities served. Table 4.3 displays examples of the choice of thermoplastics for different part types.

4.3.1.13 Engine Covers: Example of Competition between Nylon and BMC

Engine covers are generally made out of:

- glass-reinforced nylon by European carmakers
- bulk molding compounds (BMCs) and sheet molding compounds (SMCs) by American carmakers.

Certain groups manufacturing cars in both the USA and Europe use BMC in the USA and PA in Europe. Thermal behavior favors BMC but, on the other hand, nylon is advantageous for recycling. However, the situation is changing in the USA, where the Chrysler Group is adopting a mineral-reinforced nylon (Minlon by DuPont) for the rocker covers on the 2004 Chrysler Town & Country, Dodge Caravan, and Grand Caravan with 3.3 and 3.8-L V-6 engines. The weight gain is in the order of 30% versus aluminum.

4.3.1.14 Intake Manifold: PA Overview

Many automakers use reinforced nylon for air intake manifolds because of direct advantages, for example:

- weight saving because of the performance/weight ratios, which lead to fuel economy without sacrificing performances
- cost saving due to the ease of manufacturing
- design freedom allowing an improvement of the airflow boosting performances
- virtually unlimited possibilities of part integration
- rusting resistance compared to metals
- aesthetics…
- reduction of space used…

Plastic manifolds are not only used on mass-production cars, but also on sports cars such as Porsche models, the Chevrolet Camaro, and so on. For the intake manifolds used on the Camaro and Firebird, PPA is replacing PA because of several advantages:

- high-temperature resistance
- better moisture behavior
- higher resistance to tensile creep reducing leakage risks

On the other hand, the price is higher but there are also some running advantages:

- a significant weight reduction with a PPA part weighing 5 kg versus 12 kg for the aluminum counterpart, that is, a 58% weight saving
- 25% higher airflow and 20 HP extra power.

4.3.1.15 Radiator Fan: PA Instead of Steel

The first plastic automotive fan blades were made with glass-reinforced PA instead of steel for direct advantages such as:

- weight savings of 60% due to the low density and good mechanical performances
- a 50% cut in vertical stress on the water pump bearing at 5200 rpm because of the lightweight
- a higher flexibility.

Table 4.3 Examples of Choices of Thermoplastics versus Under-the-Hood Parts

Predominant Environment	Part Examples Selection Examples	Thermoplastic
Oil	Valve covers	PA 6
	Thrust washer for automatic transmission	PPA
	Oil supply components	PA 6
	Oil filter and oil filter casing	PA 66
	Pump paddle	Polyimide
Fuel	Fuel tank	PE
	Fuel pump	PBT
	Fuel supply component	PA 6, PBT
	Fuel manifold	Polyamide
	Gauge support, cap	POM
	Fuel line coupling	PPS
	Carburettor parts	PEI
	Fuel level sensor	POM
Water	Water tank	PE
	Water inlet and outlet housings	Composites
	Water supply components	PA 6, PPA
	Thermostat housing	PA 6
	Cooling system	PPO
Air	Air vent systems, air-conditioning, and climate control parts	PP, ABS, PA 6, PP/Talc, rotomolded PE
	Air supply components	ABS, PA 6, PBT
	Air intake manifold	PA, PA 66, PA 4.6
	Fans	PA 6
	Air sensors	PBT
	Filters	PBT
Electric parts	Electric or electronics components	PC, PC-HT, PA 6, PBT
	Bobbin frame	Polyimides
	Collector	Polyimides
	Ignition distributor	PBT
	Fuse, connector	PBT
	Wire support	PA 66/PPE, PA 6/PP
	Wire and cable coating	PVC, CPE, EVA, XLPE, TPE, PA 66/PPE, PA 6/PP
Miscellaneous	Silencer of turbocharger	PA, possibly semiaromatic
	Tension pulleys	PA 6
	Gear, stabilizer arm	POM

Moreover, there are indirect benefits, such as:

- improvement of the pump bearing durability because of the lower vertical loading
- fuel economy without sacrificing performances
- boosted performances
- improvement of worker and customer safety because of the flexibility and rusting resistance.

4.3.1.16 Body Elements

There are a multitude of solutions according to the material and processing methods. Without claiming to be exhaustive, thermoplastic solutions include:

- Structural foamed polycarbonate for roof of 4WD
- Nanocomposites: General Motors and Basell Polyolefins continue the development of nanocomposites for high-volume applications in external trim parts such as body panels. Three grades of TPO-based nanocomposites reinforced with 2.5% nanoclay have been commercialized by Basell Polyolefins. The first application of these nanocomposites was a low-volume minivan step option
- Thermoplastic composites: the production of GMTs and long fiber-reinforced thermoplastics demonstrates bright future prospects.

  Some examples are:

  - thermoplastic composites for the vertical body panels of General Motors' Saturne (1000 vehicles per day)
  - thermoplastic panels for the Smart ForFour
  - PC/PBT alloys for the Smart car
  - trunk lid of the Mercedes-Benz CL500 made out of PA blend allowing the integration of GPS and telephone antennae
  - fascia of the Dodge Neon made out of supergloss Surlyn alloy (DuPont)
  - PE rotomolded panels for the Think produced in Norway
  - hatchback doors in GMT
  - noise shields in GMT
  - underbody parts in self-reinforced PP (Curv) for the Audi A4
  - monocoque frames of special vehicles in composites.

4.3.1.17 Fenders

According to Bayer's forecasts, the demand for plastic fenders will double in the short term. Some current solutions are, for example:

- PPO/PA blend for passenger cars. A new conductive version of the online paintable Triax PA/ABS blend is proposed by Ineos. Heat deflection temperature is in the 180–200 °C range ensuring resistance to the temperatures encountered in the drying ovens during cathodic dip coating.
- Thermoplastic composites for the fenders of the Class A from Mercedes, and the Scenic and Laguna from Renault.

4.3.1.18 Sealing

Sealing is evolving from thermoset rubbers toward TPEs, particularly TPVs.

4.3.1.19 Glazing

Glazing applications are a significant prospect for polycarbonate but regulations can limit its use for windshield applications.

Exatec and Battenfeld are developing a 5-kg roof part that requires a subsequent antiscratch and UV protective coating.

4.3.1.20 Seating

- Frames and seat slides of front and back seats can be made out of GMTs. Long glass fiber-reinforced PAs are used for very light seats intended for sports cars.
- Polyamide is used for the swing arm of the seat-reclining mechanism.

4.3.1.21 Shields and Barriers: Damping, Sound, and Heat Absorbing Materials

There are myriad of such applications, for example:

- undercarpet heat and acoustic shields
- cabin-side barriers between the engine and the passenger compartment, made of sound-absorbing material, to prevent engine noise
- underlayers for interior trim panels, door panels, headliners, or package shelves
- cushioning and soundproofing of the dashboards, sun visors…

Foams and mats:

- Foams of PE are used for: insulation against moisture, water, temperature, and noise; for interior sealing of the doors; heat and phonic insulation of headliners; seals of air-conditioning systems; loudspeakers; cushioning of vanity mirrors; cushioning and soundproofing of dashboards; panels of doors; sun visors; undercarpet doubling; supports for adhesive tapes to smooth out unevennesses.
- Foams of PP are used for: side protection of doors, armrests with integrated baby seat, floor insulation, heat and phonic insulation of transmission tunnels, trunks, cushioning of sun visors, steering columns, knee bolsters, armrests, tool boxes, and racks…
- Lightweight mats of (natural) fibers, which can be die-cut and thermally molded, can be applied behind any interior trim panel, door panels, headliners, or package shelves as superior sound absorbers.

Some bioplastics are proposed for interior elements.

4.3.2 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.4, without claiming to be exhaustive, some automotive application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and test the right grade under real-service life conditions.

4.3.3 Aeronautics

Aeronautics is more demanding than automotive industry but accepts higher costs.

Aeronautics is subjected to the same requirements as the whole of the plastics industry with, in addition, specific requirements concerning specific standards and regulations, resistance to fire, durability, compatibility with specific fluids, lighter weights, more rigorous controls… The aeronautic industry offers new opportunities and challenges to the plastic suppliers. To reduce costs and to improve their competitiveness, manufacturers of materials work in partnership with producers to examine, among other things, the possibilities to improve the products, materials, equipment, and design methods.

Let us quote, Table 4.5, without claiming to be exhaustive, some aeronautic application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.4 Electrical and Electronics Market

The electrical and electronics market, with consumption estimated from 3% up to 8% of the thermoplastics total according to the region, is the fourth outlet for thermoplastics. It is also an important sector for thermoplastic composites and TPEs. The electrical and electronics industry is subject to many constraints:

- economic competition, worsened by production overcapacities
- margin reductions
- strengthening of safety, pollution, recycling, and energy regulations.

All these reasons persuade manufacturers to save costs, improve quality and performances, and support materials that can be recycled.

Several exceptional features explain the high level of thermoplastics and thermoplastic composites used for this sector:

- Technical motivations: the use of thermoplastics is favored by:
  - insulating properties with the possibility to make polymers conductive when necessary
  - choice between flexibility and rigidity
  - ease and freedom of design allowing a broad integration of functionalities
  - ease of processing and assembly
  - high-impact resistance versus glass and ceramics allowing miniaturization

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector

Air and water filter elements	PA
Airbag covers…	PEBA
Airbag covers, steering wheels…	COPE
Air ducts…	COPE
Air intake manifolds for top-of-the-range cars	PPA
Airbag canisters…	PA
Airbag covers, armrests, upholstery…	TPO
Airbag covers, armrests, upholstery…	TPS
Airbrake hose and tubing…	PEBA
Airbrake tubing…	COPE
Air-duct covers and hoses…	TPS
Airflow mass meter housings and sensors…	PBT
All-plastic deck lid for the Ford Mustang convertible	EMA
Apparel and automotive mats and carpets: Sorona® biopolymer	Bioplastics
Automobile parts: BIOFRONT (stereocomplex PLA)	Bioplastics
Automotive parts and other products: Sorona® EP	Bioplastics
Barrier layer in automotive plastic fuel tanks	EVOH
Base plates of cigar lighters, bases of car lamps	PI
Bearing retainers in engine compartments, gears, pivots… Aromatic PA	PA
Bearings…	PEEK
Bellows… PP/NBR-V	TPV
Belt covers	PP
Bezels and light bulb sockets…	PEI
Bobbins for electronically controlled automatic transmissions for trucks, solenoid coils in control modules for five-speed automatic truck transmissions: aromatic PA	PA
Brake and clutch system components…	PBT
Bumper: glass fiber-reinforced polypropylene beam, polypropylene foam, and PP/EPDM (TPO) skin	PP
Bumper: glass fiber-reinforced polypropylene beam, polypropylene foam, and PP/EPDM (TPO) skin	TPO
Bumper: polycarbonate skin	PC
Bumpers, bumper fascias	PP
Carburetor parts, fuel lines…	PPS
Card guides…	PC
Ceramic-coated pistons for 5-HP engine…	PAI
Clutch pedals	PA

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector—cont'd

Components for fuel handling, fuel or gas barrier structures…	LCP
Components for ignition systems…	LCP
Connectors, fuses…	PSU
Connectors, sensors, gear housings, brake booster valve bodies, tandem brake boosters	PBT
Console box lids… TPE/PVC	TPE
Consoles	ABS
Constant velocity boots…	TPU
Constant velocity joint (CVJ) boots, rack and pinion bellows…	COPE
Control cable sheathing…	TPV
Corrugated sheaths for wires and cables	PP
Damping mounts…	PEBA
Damping mounts for engine hoods…	COPE
Dashboard components	ABS
Dashboard components	ABS/PC
Dashboard components	ABS/PVC
Dashboard components	ASA
Dashboard components	ASA/PVC
Dashboard components	PA
Dashboard components	PC
Dashboard components	PMMA
Dashboard components	POM
Dashboard components	PPA
Dashboard components	PPE
Dashboard components	PVC
Dashboard components	SMA
Dashboards, instrument panel inserts, consoles, airbag system parts	PP
Decorative automotive trims…	EMA
Decorative parts	PA
Door handles, styling strips, housings and seat belt components, steering columns, window-support brackets, window cranks…	POM
Electronics, electronics boxes (E-boxes), fuse boxes, flex connectors, child-lock motor gear housings, ignition modules, ignition caps…	PBT
Engine control systems…	PEEK
Engine covers	PA
Engine covers are generally made out of glass-reinforced polyamide	PA

Continued

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector—cont'd

Exhaust gas return valves…	PPS
Exterior parts such as wiper arms, wiper blades, window wiper holders, exterior mirror housing, door handles…	PBT
Exterior parts, large parts, bumpers, body panels…	PC
Exterior side moldings, protective strips, window trims, body side moldings…	PVC
Exterior trims	PP
Exterior: spoilers, trims, lighting seals, mirror gaskets, dynamic and static weather seals…	TPV
Exterior: trims, seals, weather seals… TPE/PVC	TPE
External trim parts such as body panels: nanocomposites	TPO
Face shields…	Cellulosics
Fan blades, fan bases, fan shrouds	PP
Fascia of the Dodge Neon made out of supergloss Surlyn alloy (DuPont)	EMA
Fascias, front-ends, mudguards…	TPO
Fender liners…	PP
Fibers: removable protective panels for armored cars	PE
Filaments, fibers, fabrics for carpeting, carpet backing	PP
Film covering in aircraft interiors to reduce flammability…	PVF
Films for instrument panels, in-mold decoration…	PC
Films, laminated protective surfaces on ABS, PVC, or other plastic sheets that are thermoformed into parts requiring resistance to outdoor weathering: motorcycle shrouds, recreational vehicle panels…	PMMA
Flow control valves for heating systems, heat exchange elements…	PPS
Fluid containers	PE
Fuel pumps, cam covers, clutch parts, oil filter bodies… Aromatic PA	PA
Fuel tanks	PE
Fuel tanks for the automotive industry	PE
Furniture trims…	Cellulosics
Gear lever boots… TPE/PVC	TPE
Glazing applications are a significant prospect for polycarbonate but regulations can limit its use for windshield applications. Exatec and Battenfeld develop a 5-kg roof part that requires a subsequent antiscratch and UV protective coating	PC
Glazing applications, shatter-resistant glazing: aircraft, boats, mass transit…	PMMA
Glazing for automotive, aircraft, boats, mass transit…	PC
Glove box doors	ABS
Grilles	PA
Grilles, spoilers, exterior mirror housings, wheel trims…	PPE

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector—cont'd

Headlamp bezels, lighting, fog lamp reflector bodies, and brackets…	PBT
Headlight casings and rear light bases	PP
Headlight parabolas	PA
Heat shields, insulation shields for sparkplug heads in polyimide sheet	PI
Heater and air conditioner control system components, functional parts in the heating, ventilation, and coolant sectors…	POM
Heater and air conditioner control system components, functional parts in the heating, ventilation, and coolant sectors…	PPE
Heating device housings	PP
High performing seals, rings…	FEP
High performing seals, rings…	PFA
High performing seals, rings…	PTFE
Hook joints for transmission seal rings…	PAI
Housing of heating systems	ABS
Hydraulic, fuel and water hoses; truck airbrake hoses; monolayer and multilayer plastic fuel lines… PA 11 or 12	PA
Ignition components, sensors, and thermostat housings…	PEI
Ignition plates…	PPS
Instrument panels and associated moldings, dashboards, interior door panels and pockets, sun visors, security covers, headlining, floor coverings, floor mats, armrests, seat coverings…	PVC
Instrument panels, dials, indicators, tachometer covers…	PMMA
Instrument panels, interior mirror housings…	PPE
Instrument panels	ABS
Insulation of electric wires…	TPS
Intake manifolds	PA
Interconnection boxes	PA
Interior and exterior trims…	ABS
Interior automotive components: reSound biopolymer combining bio-derived resins with engineering thermoplastic resins	Bioplastics
Interior cladding, dashboards, instrument panel retainers, knee bolsters, glove box doors, steering column covers, defroster/demister grilles, speaker grilles…	PC
Interior door panels, scuff plates…	TPO
Interior elements: ARBOFORM® (lignin-based)	Bioplastics
Interior trims, door and quarter-panel trims, lift-gate trims…	PP
Interior: grips, knobs, mats, plugs, bumpers, grommets…	TPV
Interior: skins, grips, knobs, mats, plugs, bumpers… TPE/PVC	TPE

Continued

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector—cont'd

Lamp sockets…	LCP
Large parts such as body panels, fenders…	PPE
Lenses for taillights and parking lights, rear lights…	PMMA
Lenses of headlights are often in polycarbonate	PC
Light seats intended for sports cars: long glass fiber-reinforced polyamides	PA
Lighting, headlight reflectors, fog-light reflectors…	PEI
Lighting: head and fog lamp lenses, interior lighting covers, and exterior lighting applications…	PC
Linings…	PEEK
Lumbar supports…	TPU
Mechanisms of rear-view mirror, housings… Aromatic PA	PA
Molded-in-color film laminate technology for bumper fascias	EMA
Motorcycle fairings, bumpers and static structural components—Nissan X Trail front guards and Renault, Toyota side kit panels… PA/PPE	PPE
Mounts…	TPU
Mounts for damping noise and vibrations, shock absorbers… PP/NBR-V	TPV
Nameplates and bezels…	PC
Nameplates, medallions…	PMMA
Nonlubricated bearings, seals, bearing cages, rotating and sliding components	PAI
Paint-free applications	EMA
Panels for the Think produced in Norway: rotomolded PE	PE
Pipe covering… TPE/PVC	TPE
Piston components, seals, washers…	PEEK
Pump rotors…	PPS
Rack and pinion boots…	TPS
Radiator grilles	ABS
Radiator tank fittings, door handles, window winders	PA
Railway pads…	COPE
Rear lights are often made of co-molded acrylics	PMMA
Reflectors…	PPS
Reflectors…	SAN
Reinforced nylon for air intake manifolds	PA
Screenwash tubes…	PEBA
Seals for gas oil filters, carburetors, brake fluid tanks… PP/NBR-V	TPV
Seat backs…	PPE

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector—cont'd

Self-lubricated discs for windscreen wipers, synchronization rings of heavy lorry gearboxes	PI
Sensors…	LCP
Side moldings…	TPU
Skins for low-pressure injection molding…	TPO
Smart car elements: PC/PBT alloys	PC/PBT
Snap fittings and fixing parts for interior linings…	POM
Soft skins for interior and instrument panels, claddings, lower B pillar skins, soft-touch overmolding…	TPO
Spoilers	PA
Spoilers, step pads, body side moldings, wheel trims…	PP
Starting discs in bus gears…	PEEK
Steering column trim…	ABS
Steering wheels, gear lever knobs… TPE/PVC	TPE
Structural foamed polycarbonate for roof of 4WD	PC
Sun visors…	Cellulosics
Swing arms of seat-reclining mechanisms	PA
Tag axle assembly of cement trucks and heavy vehicles…	PAI
Taillights	SAN
Tailgate cap for the Hummer	EMA
Throttle bodies…	PEI
Transmission components…	PEI
Transmission components, transmission thrust washers, braking and air-conditioning systems, ABS brake systems…	PEEK
Transmission system components, pump components…	LCP
Transparent and decorative parts for automotive and transport applications…	PMMA
trap doors for gasoline (petrol) tanks	PA
Truck oil screens…	PEEK
Trunk lid of the Mercedes-Benz CL500 made out of polyamide blend allowing the integration of GPS and telephone antennae	PA
Trunk lid of the Mercedes-Benz CL500 made out of polyamide blend allowing the integration of GPS and telephone antennae	PA
Tubes and connectors for air induction systems… PP/NBR-V	TPV
Tubes for windscreen washers… TPE/PVC	TPE
Under the chassis: suspension parts, belly pans, plugs, bumpers, grommets…	TPV
Under the hood: tubes and connectors, plugs, bumpers, grommets for steering, air induction systems, fuel line systems…	TPV

Continued

Table 4.4 More than 150 Examples of Thermoplastic Applications in the Automotive Sector—cont'd

Underbody antiabrasion coating, mud flaps, antistone damage protection…	PVC
Under-the-bonnet parts…	PBT
Under-the-hood components, fuel pumps and other fuel system components, ball cocks and caps for gasoline systems, gears, cams, bushings, clips, lugs…	POM
Under-the-hood components, impellers for water pumps in engine cooling…	PPE
Under-the-hood components: PP/NBR-V	TPV
Under-the-hood parts, cases…	PPS
Under-the-hood parts, fasteners…	PSU
Under-the-hood parts, ventilation and air-conditioning units, battery boxes, air ducts, air vents, ventilation nozzles	PP
Vacuum nozzles…	PBT
Valve bodies…	PBT
Vandal-proof seats, seat adjustment parts… Aromatic PA	PA
Various products: Cereplast resins	Bioplastics
Warning triangles…	PMMA
Weathering protection for other thermoplastics…	PVDF
Weather stripping…	TPS
Wheel trims	PA
Window encapsulations… TPE/PVC	TPE
Window seals…	TPS
Windscreen washer parts, windscreen wipers…	POM
Windscreen washer parts…	PP
Wiper controls, headlamp controls and surrounds… Aromatic PA	PA
Wire harness grommets… TPE/PVC	TPE

- low density and attractive performance/weight ratio leading to weight reduction
- low or zero maintenance
- nonrusting (but beware of aging)
- acoustic damping (noise reduction)
- elasticity and sealing properties of TPEs and TPVs
- the replacement of conventional materials because of an exceptional combination of properties unattainable for ceramics and glass
- adaptation to mass production and small series
- cost cutting
- the possibility to associate several polymers to integrate several functionalities thanks to the exceptional combination of properties. For example, co-molding of hard plastic and soft TPE.

• Aesthetics: thermoplastics allow:
  - much more design freedom than conventional insulating materials
  - decoration possibilities: transparency, bulk coloring, printability, paintability, in-mold decoration
  - pleasing finish.

• Economic features: thermoplastics provide:
  - a favorable economic solution for mass production
  - reduction of manufacturing times

Table 4.5 Examples of Choices of Thermoplastics versus Types of Aeronautic Parts

Aeronautical and space: bearings, grooved couplings in self-lubricating polyimide	PI
Aeronautical and space: honeycombs	PI
Aeronautical and space: jet engine cones, hydraulic fluid tanks for jet engines, stiffeners of acoustic panels, spacers for engine acoustic panels, protection hoods, empennages, and supports for satellite antennas	PI
Visor of astronaut helmets…	PSU
Aeronautical and space: parts intended to function in space vacuum	PI
Aircraft: air and fuel valves…	PEI
Plane interior parts…	PSU
Aircraft: airbus interior components, bow-shaped luggage compartment retainers…	PEEK
Aircraft: cable conduits, cable clips, ventilation wheels inside aviation fans, suction manifold of aviation pumps…	PEEK
Aircraft: convoluted tubing…	PEEK
Aircraft: electrical wire harnesses isolated by monofilaments, sleeves…	PEEK
Aircraft: food tray containers, cooking utensils, and reusable airline casseroles…	PEI
Aircraft: interior cladding parts, structural components, semistructural components…	PEI
Aircraft: pump casings and impellers…	PEEK
Aircraft: steering wheels…	PEI
Aircraft: wire insulation…	PEEK

- reduction of the finishing costs: plastics allow the integration of functions and, consequently, lead to reduced assembly costs
- higher productivity due to adapted processes, integration of functions, fewer processing steps…

Polymers also have some general handicaps:

- high raw material cost (but attractive final cost)
- high voltage degradations
- recycling brings some particular problems due to economic conditions, polymer modifications, and reinforcements.

Certain thermoplastics are sensitive to ozone.

The electrical and electronics market dictates some specific regulations. Among them a typical example is the Underwriters Laboratories' (UL) requirements related to the long-term service temperature and the fire rating.

4.4.1 The UL Temperature Index

The temperature index is the maximum temperature that causes a 50% decay of the studied characteristics in the very long term. It is derived from long-term oven-aging test runs. The UL temperature index depends on:

- The targeted characteristics. There are three categories in the UL temperature indices according to the properties considered:
  - electrical only
  - electrical and mechanical, impact excluded
  - electrical and mechanical, impact included.

  For the same grade with the same thickness, the three indices can be identical (for example, a PE grade with a 50 °C UL index temperature) or different (for example, a PA grade with a temperature index varying from 75 °C for the electrical and mechanical properties, impact included, up to 105 °C for the electrical properties only).

- The thickness of the tested samples. The UL temperature indices increase with the thickness of the samples. For example, for a defined PA grade, the UL temperature indices for the same category are:
  - 75 °C for a 0.7-mm thickness
  - 95 °C for a 1.5-mm thickness
  - 105 °C for a 3-mm thickness.
- The formulation of the grade used.

Like all laboratory methods, the temperature index is an arbitrary measurement that must be interpreted and must constitute only one of the elements by which judgment is made.

4.4.2 The UL Fire Rating

The UL94 Fire Rating provides basic information on the material's ability to extinguish a flame, once ignited. The samples can be tested horizontally (H) or vertically (V) and the burning rate, the extinguishing time, and dripping are considered. The main categories are:

- V0: the most difficult to burn, extinguished after 10 s, neither dripping nor flaming particles.
- V1: extinguished after 30 s, neither dripping nor flaming particles.
- V2: extinguished after 30 s, flaming particles or drips permitted.
- 5V: extinguished after 60 s, flaming particles or drips permitted.
- HB: burning horizontally at a 76-mm/min maximum rate.

The UL rating depends on:

- The grade. An inherently flammable polymer can be V0 classified for a special fire-retardant grade or, vice versa, an inherently fire-resistant polymer can be HB classified for a special grade containing too high a level of flammable plasticizer.
- The sample thickness. For the same grade of PE, the UL ratings are:
  - V2 for a 1.6-mm thickness
  - V0 for a 6-mm thickness.

Smoke opacity is another increasingly important characteristic measured by optical density.

Fire-retardant additives can be halogenated or halogen-free, which reduces the corrosivity, toxicity, and pollution risks.

To progress in the electrical and electronics industry, plastics must improve their performance characteristics, ease of processing, productivity, and recycling, for example:

- Better thermal resistance in the long-term and better durability to favor long-term service without maintenance and miniaturization.
- Better fire behavior, lower smoke emission, and more widespread use of halogen-free grades.
- Ease of processing: improved flow properties and processability lead to cycle time reductions and productivity gains.
- Low finishing costs: bulk coloring, an intelligent design and an effective maintenance of the molds, dies, and other tools reduce or avoid finishing operations, cutting the finishing costs.
- Recycling: more effective solutions are sought.
- Development of highly conductive thermoplastics, cheaper and easy to process.
- Development of cheap thermoplastics with specific properties for solar cells, displays, and other high potential applications.

4.4.3 Application Overview

Thermoplastics are predominant among the plastics used in the electrical and electronics industry. PE is the most used followed by PVC and far behind PP and PA.

The electrical and electronics market can be divided into several submarkets differentiated by their functions and requirements. We can consider three large subdivisions:

- wire and cable coating
- electrical components
- electronics components.

Each category comprises both mass-production and high-tech products, with stringent economic requirements for the former and specific performances for the latter.

The penetration of thermoplastics and thermoplastic composites ranges from the totality of the considered parts, for example, housings and casings where metals are nearly ousted, down to areas where there are only a few applications, such as for highly conductive polymers.

Let us quote some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.4.3.1 Wire and Cable Coating

Wires and cables are universal and essential components of the electrical and electronics industry. Well known from simple building and automotive wiring, their complexity for energy cables is generally unsuspected. The properties are as diverse as the targeted functions:

- Building and automotive wiring is lightweight, mass-produced, and cheap with fair electrical and mechanical performances and long-term durability.
- Industrial wiring must have customized properties.
- Energy cables are high-tech goods.

General-purpose wires and cables are, for example:

- power transport and distribution networks: dry-insulated, armored, or unarmored cables for medium, high, and very high voltages
- low-voltage cables, aerial, or underground for distribution networks and connection
- domestic wires and cables and appliance cords for mobile apparatus with a 750V maximum rated voltage
- industrial cables, maximum rated voltage 1000V, for industrial equipment and power supply to mobile apparatus.

Special cables and wires for specific purposes:

- wires and cables intended for electrical equipment fitted in automobiles; aircraft; lifts; ships; machine tools; railway equipment, coaches, wagons, etc.; mines; handling equipment for transporting goods, conveyors, pumps, etc.; petrochemical industry; oil equipment; iron and steel industry; welding, etc.
- precision and data cables for computer equipment, electronics, automatic control instruments
- heating cables.

Telecommunications wires and cables:

- cables for aerial and underground medium- and long-distance lines
- cables for exchange area networks' underground and aerial junctions, subscribers' cables
- telephone cords
- cables for private installations.

Submarine and underwater cables:

- cables for power transport
- cables for telecommunications.

Connection accessories for power cables:

- low voltage: connections, branching
- medium voltage terminations
- medium voltage plug-in terminations: separable connectors, bushings…
- medium voltage connections and branching for dry or paper insulated cable, lapped, injected, heat-shrinkable…
- prefabricated medium voltage connections for dry-insulated cable
- high and very high voltage: terminations, connections.

Market shares are roughly estimated at:

- 65% for power cables (50% for low voltage and 15% for medium and high voltage)
- 25% for telecommunications
- 10% for other cables.

For Western Europe, the wire and cable market is estimated at roughly €18 billion.

PE has the highest consumption (nearly 60%) in both thermoplastic and thermoset (PEX) forms, and also foamed PE (2%). PVC is second (roughly 30%) and the others are PP, TPEs, PA, fluoropolymers…

Apart from PVC, PE, and its copolymers, other thermoplastics are used for special applications that justify their higher cost. They are, for example:

- fluoropolymers for high temperature and/or chemical resistance
- PA 11 or 12
- PEEK, PEI for high-temperature service
- TPEs: special grades are marketed, possibly cross-linked after extrusion.

4.4.3.2 Electric Components

Wires and cables just carry the electric current and the electric network needs a multitude of other electric equipment including:

- connectors, switches…
- electric power equipment
- motors and controls
- measuring and control equipment
- lighting and wiring equipment
- current-carrying equipment
- noncurrent-carrying wire devices
- pole line hardware.

These very dissimilar parts used for very different functions, from small parts without any special features up to electrical generators, consume significant shares of engineering plastics and composites.

Connectors, switches, electric distributors, fuse boxes, and other electric fittings need a subtle balance of electrical and mechanical properties, durability, cost, and esthetics. This broad field creates fierce competition not only between engineering thermoplastics and SMC/BMC for the main applications, but also with PP and PE or PVC for the lower performance parts and, at the opposite end of the scale, with high-tech plastics such as polyetherketone, polyetherimide, liquid crystal polymers… For example, without claiming to be exhaustive:

- polycarbonates and PPEs are used when chemical resistance is not necessary
- PA is commonly used but its applications are limited by sensitivity to moisture
- the aptitude for metallization of semicrystalline syndiotactic polystyrene filled with 30% glass fiber should open uses in the connector industry but, unfortunately, its marketing is uncertain in the near future
- thermoplastic polyesters PET and PBT are commonly used, but polyethylene naphthalate, which offers higher performance in certain characteristics, is still too expensive
- PEEK, PEI… are used for special purposes that justify their cost
- polyimides: terminal plates and terminals, connectors, and parts of circuit breakers.

4.4.3.3 Photovoltaic Solar Cells

Apart from plastic frames for solar cells, there is intensive development work to use polymer films as cheap and flexible photovoltaic materials.

At present, photovoltaic cells are made of thin, rigid sheets of silicon with other semiconducting materials. Standard commercial panels convert about one-tenth of the sunlight into electricity, that is, an efficiency of about 10%. The highest performance panels have an efficiency of roughly 20%.

The goal of polymers in photovoltaic cells is to make very cheap active materials even if their efficiency is very low. So, a cheap mass-production process could lead to domestic and industrial applications. Some research dates back 20 years and today several techniques are competing, with either hybrid or all-polymer systems. Among the various methods we can quote as examples:

- Deposition of a merocyanine-dye layer on a transparent electro-conducting film of polyester coated with indium-tin oxide (ITO). Two layered structures were studied:
    - aluminum/merocyanine/ITO
    - silver/merocyanine/ZnO/ITO—the most efficient.
- Production of a two-layer film made out of copper phthalocyanine and a perylene tetracarboxylic derivative. A power conversion efficiency of about 1% has been achieved.

- The Grätzel technology, consisting of a junction between a polymer and a liquid electrolyte, has a conversion efficiency higher than 10%. The photovoltaic generation is located in the polymer and the electrolyte ensures charge transfer. However, the liquid electrolyte evaporates over time as the operating temperature increases.
- Amorphous silicon can replace the expensive and more-efficient rigid monocrystalline and polycrystalline silicon sheets used in most common solar panels. Less efficient than crystalline silicon, it can be applied to a flexible plastic foil by plasma-enhanced chemical vapor deposition. It is expected that these amorphous silicon foils could be processed at low costs using the processing methods adopted for films.
- A hybrid, made of tiny nanorods dispersed in an organic polymer, can be easily sandwiched between electrodes and can produce, at present, about 0.7 V.
- An Austrian team boosts the performance of plastic cells by mixing a conducting polymer, MDMO-PPV (an asymmetrically substituted polyphenylenevinylene), with a molecule made from carbon fullerene…

Today, the best all-polymer solution achieves a conversion efficiency of a few percent.

4.4.3.4 Fuel Cells

There are many types of fuel cells, for example:

- proton exchange membrane (PEM) fuel cells
- phosphoric acid fuel cells
- direct methanol fuel cells
- alkaline fuel cells
- solid oxide fuel cells
- molten carbonate fuel cells (MCFC)
- regenerative fuel cells.

For cells working at low and moderate temperatures, thermoplastics could have openings for components such as membranes and plates. Polybenzimidazole (PBI), LCPs, and PPS could be suitable for these applications.

For cells working at high temperatures, plastics are candidates for:

- membranes: a sulfonated fluoropolymer manufactured by DuPont (Nafion®) is available, but at high temperatures its conductivity is greatly reduced
- binders for solid fuel (MCFC) such as PE, PP, and polybutylene.

4.4.3.5 Lighting

Lighting consumes transparent thermoplastics for light diffusion, and composites and other thermoplastics for boxes and housing. For example:

- polycarbonate: the lighting sector consumes roughly 3% of the polycarbonate total
- acrylics: transparent housing
- polyimides: lamp bases.

4.4.3.6 Polymer Light-Emitting Diodes

Polymer light-emitting diode or organic light-emitting diode (OLED) is a flat light-emitting technology, made by placing a series of organic thin films between two conductors acting as electrodes. One of these films is an electroluminescent conductive polymer film emitting light when connected to an external voltage.

One of the two electrodes needs to be transparent, so that the light which is created when applying a voltage can leave the layer stack.

Used plastics may be sliced in:

- traditional polymers such as PS, PET, PEN, PC, PMMA, PSU, LCP for general functionalities
- special electroluminescent conductive polymers such as, without claiming to be exhaustive, derivatives of poly(*p*-phenylene vinylene), polyfluorene, polypyrrole, poly(*n*-vinylcarbazole), polyhedral oligomeric silsesquioxanes for light emission.

All plastic lamps use a high-thermal-conductivity resin for the housing in place of aluminum. For example, the resin can be made by filling a polycarbonate resin with carbon fibers of Teijin (Raheama) having a high thermal conductivity.

OLEDs can be used to make rigid and flexible displays and lighting. Polymer OLEDs require a relatively small amount of power for the amount of light produced. Because OLEDs emit light, they do not require a backlight and so are thinner and more efficient than LCD displays (which do require a white backlight).

A disadvantage of the OLED technology is the sensitivity of the organic light-emitting materials to oxygen and water vapor. OLEDs must be protected using encapsulation with a polymer film that is the goal of intensive research.

4.4.3.7 Measuring and Control Equipment

Thermoplastics are used for insulation and housings, allowing a broad choice according to the technical and economic requirements, for example:

- ABS: housing of testers
- PP: housing of testers
- polycarbonate: transparent housing, magnifying windows
- PMMA: transparent housing, magnifying windows.

4.4.3.8 Wiring Equipment

PE, PVC, and composites are broadly consumed:

- PVC for cable shelves…
- PE for tubing…

4.4.3.9 Substrates for Electronic Equipment

For insulating substrates for electronic equipment, thermoplastic laminates are used:

- Commodity thermoplastics
  - PVC
  - PP
- Engineering thermoplastics
  - polycarbonate
  - PA
  - polyester
- Speciality thermoplastics
  - polyimide
  - PTFE.

4.4.4 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.6, without claiming to be exhaustive, some application examples for some thermoplastics. These examples may be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.5 Household, Entertainment, and Office Appliances

4.5.1 Overview

Technically, the household, entertainment, and office appliance market appears heterogeneous, including a variety of functionalities, shapes, forms, and properties. Table 4.7 proposes a classification method based on the lifetime and the main function but many other classifications are possible.

Most household and entertainment appliances are mass-production goods that are sold by the million. Production of business or office appliances varies from small series (shredders, for example) to medium or high series (PCs and other computers). Prices are spread from a few tens of euros up to thousands of euros and more.

Despite their apparent heterogeneity, these various appliances have several points of similarity:

- electrical properties
- esthetics and mar resistance
- impact resistance
- dimensional stability
- durability
- fire-resistant behavior for the large parts
- high performance/price ratio leading to a material choice according to the cost of the end product.

But there are also some differences between technical parts with specific functionalities and, consequently, specific material families and properties are utilized.

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications

Antenna covers…	COPE
Appliances: handles, cooking equipment…	PEEK
Battery components…	ETFE
Bobbins, coils…	LCP
Brush holders…	PPS
Burn-in sockets…	PAI
Cable shelves…	PVC
Card connector applications for mobile telephones, personal computers, and smart media. Used with lead-free solder	PPA
Cartridges of printers…	PSU
Chassis and housings for electrical and electronic equipment, sliding parts in video recorders, disk supports in CD players…	PPA
Chip carriers…	LCP
Coaxial cable connectors, terminal and high-voltage insulators; transformers, relays, antennae, power amplifier components…	FEP
Coaxial cable connectors, terminal and high-voltage insulators; transformers, relays, antennae, power amplifier components…	PFA
Coaxial cable connectors, terminal and high-voltage insulators; transformers, relays, antennae, power amplifier components…	PTFE
Coil formers, bobbins…	PPS
Coil forms…	ECTFE
Coil forms…	ETFE
Components in phone systems, power tools, refrigerators, washing machines, air conditioners, computers, keyboards, housings…	PVC
Computer components, mobile phone internal antennae…	PEI
Computer housings, transparent and translucent covers for PCs and copiers, keyboards, business machine equipment…	ABS
Connectors for electronic and electrical devices such as personal computers, digital cameras, and mobile telephones; safety switches, telecommunication parts…	PPA
Connectors, circuit breakers, switches…	PBT
Connectors, connectors for aircraft engines…	PBI
Connectors, high-heat connectors…	PEI
Connectors, switches, insulators, sockets…	PSU
Connectors, terminal blocks, relay components, switch components…	PPS
Consumer electronic equipment…	ABS
Consumer electronic equipment…	SAN
Consumer electronics products: PLA bioplastics compounds	Bioplastics

Continued

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Control dials	POM
Control panels, plates on terminals…	PPS
Damping mounts for noises and vibrations…	MPR
Displays and profiles…	Cellulosics
Drive wheels for microwave ovens, handles for electric ovens and other household appliances, parts for spit-roasters, air vents for slide projectors	PI
Dual-band hi-power passive circuits…	FEP
Dual-band hi-power passive circuits…	PFA
Dual-band hi-power passive circuits…	PTFE
E&E components: polyamide is commonly used but applications are limited by sensitivity to moisture	PA
E&E components: polycarbonates are used when chemical resistance is not necessary	PC
E&E components: polyimides: Terminal plates and terminals, connectors, parts of circuit breakers	PI
E&E components: polyphenylene ethers are used when chemical resistance is not necessary	PPE
Electric wire and cable sheathing…	EVA
Electrical and wire marking applications…	PVF
Electrical appliance and PC brackets, components for floppy disk drives…	PPS
Electrical components: sockets, connectors, switches, insulators, cable clamps…	ECTFE
Electrical components: sockets, connectors, switches, insulators, cable clamps…	ETFE
Electrical components: sockets, connectors, switches, insulators, cable clamps…	PVDF
Electrical control units…	PEI
Electrical engineering: lamp covers, switch parts, dials, control buttons, embedment of components…	PMMA
Electrical sleeving, wire and cable insulation and jacketing, appliance wires, motor lead wires, compact wire and cables, airframe wiring, extruded coatings…	ETFE
Electrical terminal housings, distributor cabinets, and large capacitor cases…	PPE
Electrical wire and cable insulation and jacketing, wire wraps, motor lead wires, compact wire and cables, airframe wiring, extruded coatings…	ECTFE
Electricity, electrical household appliances: cases and fuse holders, junction boxes, miniature junction boxes, inlet and outlet cable channels…	PA
Electricity, electrical household appliances: electrical cables, optical fibers, flexible telephone cables, inlet and outlet cable channels… PA 11, 12	PA
Electroluminescent display panels…	PCTFE
Electronic equipment: BIOFRONT (stereocomplex PLA)	Bioplastics
Electronics housings and equipment: reSound biopolymer combining bio-derived resins with engineering thermoplastic resins	Bioplastics

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Electronics: ARBOFORM® (lignin)	Bioplastics
Electronics: bi-oriented films, metallized films, light guides and diffusion plates for LCDs, semiconductor containers…	COC
ESD (electrostatic discharge) for integrated circuits, hard disk drives, circuit boards…	PAI
Fiber-optic connectors, optical transceivers…	PEI
Film capacitors for military and industrial AC applications…	PP
Films for capacitors…	PSU
Floppy disk jackets…	PVC
Frames of integrated circuits…	PSU
Fuel cell components such as membranes and plates	PPS
Fuel cell components such as membranes and plates	PBI
Fuel cells: sulfonated fluoropolymer manufactured by DuPont (Nafion®)	PTFE
Grips, buttons, bumpers, seals, feet, gaskets, spacers for electrical machines…	TPV
Grips, buttons, seals, feet, gaskets…	TPO
Grips, buttons, seals, feet, gaskets…	TPS
Grips, handles, feet, pads for small electrical machines…	TPU
Grips, handles, feet, pads for small electrical machines… TPE based on PVC	TPE
Guides…	LCP
Hard disk drive components…	LCP
Heating appliance insulation…	POM
High-temperature and/or chemical resistance wire and cables	PTFE
High tolerance electrical switch boxes and connectors…	PPE
High-performance motor components…	LCP
High-temperature service wire and cables	PEEK
High-temperature service wire and cables	PEI
Housing of testers	ABS
Housing of testers	PP
Housings of microscopes, connectors… PA 11, 12	PA
Housings of power tools, casing of projectors…	PA
Imaging devices…	LCP
Induction motor supports…	PPA
Insulating collars for chain saws, insulating elements and crossings for electric blowtorches	PI
Insulating elements and spacers for electron accelerators and cathode-ray tubes	PI
Insulating substrates for electronic equipment	PTFE

Continued

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Insulating substrates for electronic equipment	PVC
Insulating substrates for electronic equipment	PA
Insulating substrates for electronic equipment	PC
Insulating substrates for electronic equipment	PBT
Insulating substrates for electronic equipment	PI
Insulating substrates for electronic equipment	PP
Insulation of electric wires…	TPO
Insulation of electric wires…	TPS
Insulators…	PAI
Integrated circuit packaging (hard disk drive) trays…	PEEK
Integrated circuits…	PEI
Internal components and current-carrying devices, brush holders, coil bobbins and forms…	PC
Keypads…	COPE
Knobs, buttons…	PS
Knobs, small furniture…	PMMA
Laminates for critical microwave components, antennae and subassemblies, RF/microwave materials, hybrid RF multilayers, digital/microwave hybrid multilayer PCB assemblies, cellular base station antennae…	FEP
Laminates for critical microwave components, antennae and subassemblies, RF/microwave materials, hybrid RF multilayers, digital/microwave hybrid multilayer PCB assemblies, cellular base station antennae…	PFA
Laminates for critical microwave components, antennae and subassemblies, RF/microwave materials, hybrid RF multilayers, digital/microwave hybrid multilayer PCB assemblies, cellular base station antennae…	PTFE
Lamp bases	PI
Light globes, lighting diffusers, light-control lenses…	PC
Lighting and lamp fittings, lamp bases of energy saving lamps…	PBT
Lighting applications, reflectors, reflectors with dichroic coating without primer…	PEI
Lighting diffusers…	PS
Lighting sector consumes roughly 3% of the polycarbonate total	PC
Lighting, diffusers, lighting devices, and accessories…	Cellulosics
Lighting, lights, lighting diffusers, light-control lenses in lighting fixtures…	PMMA
Liquid crystal polymers could be suitable for fuel cell components such as membranes and plates	LCP
Low-noise gears…	COPE
Low-voltage switch gears, electric-motor parts…	PBT
Lowest loss applications…	FEP

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Lowest loss applications…	PFA
Lowest loss applications…	PTFE
Low-noise gears…	PEBA
Microphone boom on headset…	TPV
Millimeter wave components…	FEP
Millimeter wave components…	PFA
Millimeter wave components…	PTFE
Miniaturized electronic components…	PBT
Molded bulb sockets for electrical power stations, thermostat parts, halogen lamp housings…	PPS
Molded electrical accessories…	PP
Molded electrical accessories, electrical connectors…	COPE
Molded electrical accessories, electrical connectors…	PE
Molded electrical accessories, electrical connectors…	TPU
Molded electrical accessories, electrical connectors… TPE based on PVC	TPE
Molded electrical accessories, electrical connectors, shields, electrical connections…	TPV
Motor and vibration mounts…	TPU
Motor and vibration mounts… TPE based on PVC	TPE
Motor housings…	PPS
Optical media, computer and audio compact discs…	PC
Optoelectronics: covering of displays, from small LCDs in cellular phones to large rear-projection television sets or screens designed for audio-visual presentations…	PMMA
Outdoor lighting fixtures…	PC
Outer covers of printers, calculators, instruments, transparent covers for PCs and copiers, business machine equipment…	SAN
Overmolding of motor collectors, bodies of generator coils, overmolding of coils, coil frames, insulation of rotor axes	PI
Parts for heaters, grids of hair dryers, parts of domestic irons, coffee machines, microwave ovens, cooking appliances…	PPS
Parts for high-speed electronic printing and reproduction equipment…	PAI
Parts of alkaline batteries…	PSU
Piezoelectric films…	PVDF
Plates on terminals…	PSU
Plugs, pads, feet, damping mounts…	COPE
Plugs, pads, feet, damping mounts…	PEBA

Continued

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Power distribution and circuit protection…	PBT
Power distribution, connectors, insulators, relay components, meter housings and covers, casket hardware…	PC
Power tool housings…	ABS
Power transmission and distribution systems…	TPV
Printed circuit boards usable up to 300 °C	PI
Printed circuits, bobbins, connectors, ink cartridges for printers…	PMP
Printing circuit lamination, release film in the manufacture of PCBs…	PVF
Reels…	PEI
Reels…	PSU
Relay sockets, cable connectors, bulb sockets, coil formers…	PPE
RF-duplexers or micro-filters, EMI shielding…	PEI
Scroll wheel on Logitech mouse…	TPV
Seals, integrated seals…	TPU
Seals, integrated seals… TPE based on PVC	TPE
Semiconductor industry, vacuum chamber applications, clamp rings for gas plasma etching equipment, wafer retaining rings for gas plasma etching, vacuum tips…	PBI
Semiconductors…	PVDF
Sensors and circuits…	PPE
Sensors, LED housings…	LCP
Sign industry: surface protection…	PVF
Signs: internally illuminated outdoor signs, diffusers, side-lit signs, very thin illuminated displays, fluorescent signs…	PMMA
Sockets, switches, relays, electrical and electronic connectors, fuse holders, closures…	LCP
Soft handles and grips…	MPR
Special wire and cables	PA
Surface-mount devices, surface-mount interconnection devices, PCMCIA card frames…	LCP
Surface-mounted trimming potentiometers…	PEEK
Switches, contactors, socket-outlets, connectors, air resonators, washing machine pulleys	PA
Syntactic foams for microwave and RF applications	PI
Telecom and IT connectors, mobile phone casings, bobbins…	PBT
Telecommunication equipment…	ABS
Telecommunication equipment…	SAN
Telecommunication splice seals…	TPV

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Telecommunications…	FEP
Telecommunications…	PFA
Telecommunications…	PTFE
Telephone components…	POM
Terminal plates and terminals, lamp bases, connectors, and parts of circuit breakers	PI
Traffic lights…	PC
Transparent housing for lighting	PMMA
Transparent housing, magnifying windows	PC
Transparent housing, magnifying windows	PMMA
Transparent technical parts: indicators, dials, inspection holes, caps, casings, hoods and other electrical parts…	PMMA
Tubing…	PE
TV components…	PSU
TV tuner arms	POM
Vacuum cups, fingers, and holders for incandescent and fluorescent light bulbs…	PBI
Various products: Cereplast resins	Bioplastics
Wafer carriers…	PBI
Wafer wands, wafer transport carriers…	PEEK
Wire and cable insulation…	PE
Wire and cable insulation…	PMP
Wire and cable insulation and jacketing, telecommunication wires and cables, optical fiber coating, extruded coatings…	PVDF
Wire and cable insulation consumes 4% of all PVC with construction and automotive wires, electrical cord jacketing, fiber optic sheathing, heat-shrinkable sleeves…	PVC
Wire and cable jacketing (halogen-free flame retardant; HFFR)…	TPV
Wire and cable jacketing…	COPE
Wire and cable jacketing…	CPE
Wire and cable jacketing…	TPU
Wire and cable jacketing… TPE based on PVC	TPE
Wire and cable jacketing, electrical and communication cable jacketing, coil cables…	PEBA
Wire and cable or fiber optic applications, optical fiber tubing…	PBT
Wire and cables	PP
Wire and cables	TPE
Wire and cables: polyethylene is the most consumed (nearly 60%) in both thermoplastic and thermoset (PEX) forms, and also foamed PE	PE

Continued

Table 4.6 More than 150 Examples of Thermoplastic Applications in Electricity and Electronic Applications—cont'd

Wire and cables: PVC is second (roughly 30%)	PVC
Wire and electric cables for industry and robotics…	MPR
Wire insulation…	PEI
Wire insulation for extremely high-temperature applications, cable couplings and connectors, subsea connectors, coaxial connector jacks, subsea-controlled environment connectors…	PEEK
Wireless communications…	FEP
Wireless communications…	PFA
Wireless communications…	PTFE
Woven-glass/fluoropolymer composites…	FEP
Woven-glass/fluoropolymer composites…	PFA
Woven-glass/fluoropolymer composites…	PTFE

The household, entertainment, and office appliance market consumes an estimated 3% up to 6% of the thermoplastics total, according to the region, making it the fifth outlet for these materials.

The household, entertainment, and office appliance industry is subject to many constraints:

- economic competition, worsened by production overcapacities and market saturation for several products
- margin reductions
- strengthening of safety, recycling, environmental, and energy regulations.

All these reasons persuade manufacturers to save costs, improve quality and performances, and support materials that can be recycled.

Several exceptional features explain the high level of thermoplastics and TPEs used for the household, entertainment, and office appliance market:

- Technical motivations: use of thermoplastics is favored by:
  - insulating properties
  - ease and freedom of design allowing a broad integration of functionalities
  - ease of processing and assembly
  - impact resistance
  - low density and attractive performance/weight ratio leading to weight reduction
  - low or zero maintenance
  - nonrusting (but beware of aging)
  - acoustic damping (noise reduction)
  - elasticity and sealing properties of TPEs and particularly TPVs
  - the replacement of conventional materials because of an exceptional combination of properties unattainable for metals, ceramics, and glass
  - adaptation to mass production and small series
  - cost cutting
  - the possibility to associate several thermoplastics to integrate several functionalities thanks to the exceptional combination of properties, for example, co-molding of a hard thermoplastic and a soft TPE.
- Aesthetics: thermoplastics allow:
  - much more design freedom than conventional insulating materials
  - decoration possibilities: transparency, bulk coloring, printability, paintability, in-mold decoration
  - pleasing finish.
- Economical features: thermoplastics provide:
  - an economical response to mass production
  - reduction of manufacturing times

Table 4.7 Examples of Functionalities and Properties of Appliances

Estimated Average Lifetime (years)	Primary Functionality	Item Examples	Main Properties
Very Long Lifetime			
10+	Cooling	Refrigerators Freezers	Thermal insulation
			Cold impact
			Aesthetics
			Airtightness
			Ease of cleaning
			Microbial resistance
			Durability
			Cost
Long Lifetime			
10	Washing	Dishwashers Washing machines Dryers	Hydrolysis resistance
			Chemical behavior
			Heat resistance
			Durability
			Cost
10	Cooking	Ovens: Electric Gas Microwave	High-temperature resistance
			Fat, grease, oven-cleaner resistance
			Electrical insulation
			Durability
			Microwave transparency
10	Business or office appliances	PCs and other computers, printers, photocopiers, shredders…	Aesthetics
			Mar and scratch resistance
			Heat resistance
			Electrical insulation
			Durability
			Ease of cleaning
			Cost
10	Miscellaneous household appliances	Safety, alarm devices Waste compactors	Mechanical performance
			Aesthetics
			Durability

Continued

Table 4.7 Examples of Functionalities and Properties of Appliances—cont'd

Estimated Average Lifetime (years)	Primary Functionality	Item Examples	Main Properties
Medium Lifetime			
5–10	Entertainment appliances	Radios, Televisions, Audio systems, video systems, VCRs, Electronic video games…	Aesthetics
			Mar and scratch resistance
			Heat resistance
			Electrical insulation
			Durability
			Ease of cleaning
			Cost
5–10	Medium-sized household appliances	Vacuum cleaners Floor care devices Electrical insulation	Aesthetics
			Impact resistance
			Antistatic behavior
			Cost
			Resistance to floor care products
5–10	Small household appliances	Kitchen Personal care	Aesthetics
			Impact resistance
			Food and chemical resistance
			Heat resistance
			Ease of cleaning
			Microbial resistance

- reduction of the finishing costs: plastics allow the integration of functions and, consequently, lead to the reduction of assembly costs
- higher productivity due to adapted processes, integration of functions, fewer processing steps…

Thermoplastics also have some general handicaps:

- high raw material cost (but attractive final cost)
- recycling bringing some particular problems due to economic conditions, polymer modifications, and reinforcements…

The household, entertainment, and office appliance market is subjected to some specific regulations for specific parts, notably large ones. Moreover, standards and regulations depend on the country. Among them a typical example is the UL requirements related to the long-term service temperature and the fire rating.

4.5.1.1 The UL Temperature Index

As described in detail in Section 4.4, the UL temperature index is the maximum temperature that causes a 50% decay of the studied characteristics in the very long term.

Like all the laboratory methods, the temperature index is an arbitrary measurement that must be interpreted and must constitute only one of the elements of judgment.

4.5.1.2 The UL Fire Rating

As described in detail in Section 4.4, the UL94 Fire Rating provides basic information on the material's ability to extinguish a flame, once ignited.

Smoke opacity is another increasingly important characteristic measured by optical density. Fire-retardant additives can be halogenated or halogen-free, which reduces the corrosivity, toxicity, and pollution risks.

Thermoplastics are predominant among the plastics used for the household, entertainment, and office appliance industry with styrenics preeminent, including PS, high-impact PS, EPS, ABS, styrene acrylonitrile, acrylonitrile styrene acrylate (ASA)… followed by PP. Several engineering thermoplastics such as PA, polycarbonate (PC), polybutyleneterephthalate (PBT), PPO, and polyoxymethylene are also used.

The penetration of thermoplastics and thermoplastic composites ranges from the totality of the considered parts—for example, small household appliance housings and casings where metals are nearly ousted—down to areas where there are only a few applications, such as highly conductive polymers.

4.5.1.3 Bioplastics

Many development efforts concern compounds and composites for electronics. For example:

- A halogen- and phosphorus-free flame-retardant PLA/kenaf version using a metal hydroxide flame-retardant system has already been developed and will be used for personal computer housings.
- Fujitsu and Toray have developed an FR resin made of a blend of PC and PLA (50/50) designed for notebook computers. This composition has the processability, heat resistance, and flame resistance required in larger IT devices.
- Panasonic Electric Works has begun selling its MBA900H PLA molding compound for use in the housings of cell phones and other mobile devices and digital consumer electronics. The initial goal was 1000 tons of annual production. The bioplastic used in the MBA900H is Teijin's BIOFRONT™. It is claimed as a highly heat-resistant PLA with a melting point of at least 210 °C, which is significantly higher than that of conventional PLA.
- NEC uses kenaf as a natural fiber reinforcement providing enhanced stiffness for PLA. The impact strength of a 20% kenaf fiber-reinforced PLA composite is in the order of that of a 20% glass-reinforced ABS. Mass production of these bioplastic composites is expected for housings of electronic products.
- NEC develops a PLA-carbon fiber composite achieving high heat conductivity. Used in the housings of electronic products, the material releases the heat generated from electronic parts through whole housing surfaces. NEC says that with carbon fiber content of 10% the heat diffusion is comparable to stainless steel, and with 30% carbon fiber loading, heat diffusion is twice as important as that of stainless steel.

4.5.2 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.8, without claiming to be exhaustive, some application examples for some thermoplastics. These examples can be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility to use the quoted thermoplastic family for his/her specific problem and test the right grade under real-service life conditions.

4.6 Mechanical Engineering

4.6.1 Overview

The mechanical engineering sector is often omitted in statistics and its content is very unclear, overlapping other sectors such as electricity, appliances, and so on. When it is identified, it is evaluated as accounting for 2% up to 5% of overall thermoplastic consumption.

Technically, the mechanical engineering market is truly heterogeneous, putting all the properties of all thermoplastics to good use. Applications are very diverse, covering:

- all types of functionalities
- a broad diversity of shapes and forms, from miniaturized to giant parts
- mechanical, optical, physical, or chemical properties obtainable with either thermoplastics or thermoplastic composites.

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances

Air conditioner components…	PS
Air conditioner housings…	ABS
Air outlet grilles for microscopes…	PPS
Antenna covers…	COPE
Antifriction parts: bearings, rods…	PA
Automatic espresso machines, high-tech coffee machines…	PEEK
Bathroom fittings, electric toothbrushes, toothbrush handles, sanitary ware, soap dispensers, shower cubicle, shelves…	SAN
Battery components…	ETFE
Bearings, bushings…	FEP
Bearings, bushings…	PFA
Bearings, bushings…	PTFE
Bearings, plugs, pads, feet, damping mounts…	COPE
Bearings, plugs, pads, feet, damping mounts…	PEBA
Belting…	COPE
Blow-molded tanks for electric domestic heaters…	PB
Bumpers or edge accessories for vacuum cleaners, steam extractors, handheld vacuum cleaners…	TPV
Card connector applications for mobile telephones, PCs, and smart media… Aromatic PA	PA
Cartridges of printers…	PSU
Coffee machine capsules: Vegemat (natural fibers, starch, proteins, lipids)	Bioplastics
Coffee pots, drink vending machines, and washing machine parts…	PPE
Coils, rewind rollers for radio and videocassettes, stereo cassette parts, tape decks	POM
Components for cameras, projectors…	PSU
Components for humidifiers, cookers…	PSU
Components in phone systems, power tools, refrigerators, washing machines, air conditioners, computers, keyboards, housings…	PVC
Computer components, mobile phone internal antennae…	PEI
Computer housings, transparent and translucent covers for PCs and copiers, keyboards, business machine equipment…	ABS
Connectors for electronic and electrical devices such as personal computers, digital cameras, and mobile telephones; safety switches, telecommunications parts… Aromatic PA	PA
Consumer electronic equipment…	ABS
Consumer electronic equipment…	SAN
Control dials, pump and timer parts, valves, gears…	POM

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances—cont'd

Cord holders…	TPV
Cylindrical impellers for air conditioners…	SAN
Dishwasher parts, washing machine trims…	SAN
Domestic appliance housings, vacuum cleaners, small appliances, food mixers, electric shavers, electric toothbrushes…	ABS
Domestic appliances… Aromatic PA	PA
Door handles, curtain rings…	Cellulosics
Drive belts…	TPU
Drive wheels for microwave ovens, handles for electric ovens and other household appliances, parts for spit-roasters, air vents for slide projectors…	PI
Dual oven cookware, ovenware…	LCP
Electric household appliances: electrical cables, flexible telephone cables, inlet and outlet cable channels, connectors… PA 11 or 12	PA
Electric household appliances: inlet and outlet cable channels, housings of power tools, projector casings, air resonators, washing machine pulleys…	PA
Electric portable tool housings; computer and business machine parts…	PC
Electric razor heads, electric iron parts, vacuum cleaner motor supports, sewing machine parts… Aromatic PA	PA
Electric, commodity appliances: ECODEAR® (based on polylactic acid)	Bioplastics
Electrical appliance and PC brackets, components for floppy disk drives…	PPS
Electrical chargers, battery boxes…	PC
Electrical engineering: lamp covers, switch parts, dials, control buttons, embedment of components…	PMMA
Electroluminescent display panels…	PCTFE
Electroplated parts, handles…	ABS
Equipment housings…	PC
ESD for integrated circuits, hard disk drives, circuit boards…	PAI
Feet, pads for small appliances, dishwasher sump boots…	TPV
Fiber optics components, fiber optics connectors…	LCP
Floppy disk jackets…	PVC
Foamed PPE: computers, business equipment, electrical/electronic appliances, telecommunications…	PPE
Foamed seals for coolers, integrated seals…	TPV
Frames of integrated circuits…	PSU
Frames, ventilating parts…	PPE
Gasketing…	TPS
Gaskets and seals, hydraulic seals…	TPU

Continued

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances—cont'd

Gears…	PPE
Gears, sprocket wheels, gearwheels, cams, springs, clips…	POM
General business machine parts, brackets and structural components of office products, business machine chassis, frames and housings; large computer and printer housings (painted, foamed)…	PPE
General business machine parts, spring and screen parts…	POM
General-purpose parts…	PE
Gloves, combs, pegs: Bionolle™ (aliphatic polyester resin)	Bioplastics
Grips, buttons, bumpers, seals, feet, gaskets and spacers for computers, printers, copiers, scanners and fax machines, telecommunications, audio and video…	TPV
Grips, handles for irons, flatware, vacuum cleaners, steam extractors, handheld vacuums and other floor care items, colored utensil grips…	TPV
Grips, handles, feet and pads for office supply, personal care, sports and leisure, tool and garden devices…	TPV
Grips, handles, feet, pads for small appliances… TPE based on PVC	TPE
Grips, pencil grips…	PEBA
Hairdressing items…	Cellulosics
Hairdryer grilles and components, cutting head for electric shavers…	PPS
Handles, soft-touch overmolding…	TPO
Handles, soft-touch overmolding…	TPS
Hard disk drive components…	LCP
Headphones…	COPE
Heating appliance insulation…	POM
Hoses and tubing, flexible tubing…	TPU
Hoses and tubing, flexible tubing, hose jackets, convoluted tubing…	COPE
Hot water reservoirs, heat exchange systems…	PEI
Household appliance items…	Cellulosics
Housing parts, handles and knobs…	POM
Housing parts, handles and knobs…	PPE
Housings for the home appliance market… PBT or PET	PBT
Housings of cell phones and other mobile devices and digital consumer electronics. Panasonic Electric Works has begun selling its MBA900H PLA molding compound based on Teijin's BIOFRONT™	Bioplastics
Housings of electronic products: NEC develops a PLA-carbon fiber composite achieving high heat conductivity	Bioplastics
Housings of electronic products: NEC uses kenaf as a natural fiber reinforcement providing enhanced stiffness for PLA	Bioplastics
Housings of microscopes… PA 11 or 12	PA

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances—cont'd

Imaging devices…	LCP
Insulation of refrigerators… Expanded PS	PS
Internal appliance components, heating appliance insulation, insulators…	PPE
Keypads…	COPE
Kitchenware such as mixing bowls and basins; small appliances, food mixers, coffee filters, outer casings of thermally insulated jugs…	SAN
Knobs, buttons…	PS
Laundry system wheels…	PEEK
Lighting and lamp fittings, lamp bases of energy saving lamps… PBT or PET	PBT
Lighting applications, reflectors, reflectors with dichroic coatings without primer…	PEI
Lighting diffusers…	ABS
Lighting diffusers…	PS
Liquid dispensers…	COPE
Liquid dispensers…	PEBA
Low-voltage switch gear, electric-motor parts… PBT or PET	PBT
Low-noise gears, sprockets, caster wheels…	COPE
Low-noise gears, sprockets, caster wheels…	PEBA
Microfloppy diskettes…	PS
Microphone boom on headset…	TPV
Microwavable bowls, utensils…	PEI
Microwave components…	PPE
Mobile phone cases, appliances, cosmetics, laptops, and other durable goods: Ingeo biopolymer (PLA)	Bioplastics
Molded electrical accessories, electrical connectors…	COPE
Molded electrical accessories, electrical connectors…	TPU
Motor and vibration mounts…	TPU
Motor and vibration mounts…	TPV
Motor and vibration mounts… TPE based on PVC	TPE
Notebook computers: Fujitsu and Toray have developed a FR resin made of a blend of PC and PLA (50/50). This composition has the processability, heat resistance, and flame resistance required in larger IT devices	Bioplastics
Office automation components…	PI
Office automation equipment such as photocopiers, prisms, mirrors, polygon mirrors, optical films…	COC
Office equipment and supplies: PLA bioplastics compounds	Bioplastics
Office equipment: writing and drawing instruments, telephone dials…	PMMA

Continued

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances—cont'd

Optical applications: storage media, CD, CD-ROM, DVD, SACD (super audio compact disc); lenses for cameras on mobile phones, digital cameras, compact cameras, CD players, video recorders…	COC
Optical devices, optical lens components…	LCP
Optical fibers… PA 11 or 12	PA
Optical media, computer and audio compact discs…	PC
Optoelectronics: covering of displays from small LCDs in cellular phones up to large rear-projection television sets or screens designed for audio-visual presentations…	PMMA
Outer covers of printers, calculators, instruments, transparent covers for PCs and copiers, business machine equipment…	SAN
Parts for coffee machines, drinks dispensers, tubes, water tanks…	PSU
Parts for heaters, parts of domestic irons, coffee machines, microwave ovens, cooking appliances…	PPS
Parts for high-speed electronic printing and reproduction equipment…	PAI
Parts of alkaline batteries…	PSU
Parts of timers and slide projectors, housings of portable tools…	POM
Personal computer housings: a halogen- and phosphorus-free flame-retardant PLA/kenaf version using a metal hydroxide flame-retardant system	Bioplastics
Photocopier, printer and telephone parts…	PEBA
Plate bearings for printers, cable guides for printer heads; bearings and sockets for photocopiers; sliding parts and guiding rollers for high-speed printers and photocopiers…	PI
Portholes…	PSU
Power tool housings…	ABS
Power tools…	PC
Power tools, portable mixers, hairdryer housings…	PPE
Precision parts for measurement and control technology…	POM
Printer rollers…	TPV
Printers: print drum separation arms, drive wheels for photocopiers, drive rollers…	PI
Radio dials, TV set screens, hi-fi covers…	SAN
Refrigerator door linings…	PS
Refrigerator door linings, refrigerator inner liners, trays…	ABS
Refrigerator parts: trays, fittings, shelves…	SAN
RF-duplexers or micro-filters, EMI shieldings…	PEI
Roller coverings…	COPE
Scanner lids…	TPV

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances—cont'd

Scroll wheel on Logitech mouse…	TPV
Seals, integrated seals… TPE based on PVC	TPE
Self-lubricating components…	FEP
Self-lubricating components…	PFA
Self-lubricating components…	PTFE
Sensors, LED housings…	LCP
Shockproof, water-resistant shields, and other parts of webcams, cameras, personal digital assistants…	TPV
Shock-proofing casings…	COPE
Shock-proofing casings…	PEBA
Sliding parts in video recorders, disk supports in CD players… Aromatic PA	PA
Small appliances… PBT or PET	PBT
Small appliances, ovenware, kitchenware, microwave ovenware, tableware, cooking utensils, water tanks for coffee makers or electric irons…	PMP
Small appliances, service ware, cutlery, tumblers and thin-wall multicavity parts…	PS
Splash shields…	PS
Steam generator cover injected in Gaialene compound	Bioplastic
Structural and interior components…	PPE
Tableware, drinking tumblers, cutlery, jars and beakers, storage containers for foods	SAN
Technical parts: gears, screws and bolts, pulleys, collars, valve casings, rings, clips, ventilators, cooling fans…	PA
Telecom and IT connectors, mobile phone casings, bobbins… PBT or PET:	PBT
Telecommunication equipment…	ABS
Telecommunication equipment…	SAN
Telecommunications…	FEP
Telecommunications…	PFA
Telecommunications…	PTFE
Telecommunications frames and chassis, cell phone battery covers…	PPE
Telecommunications, mobile phones, housings for GSM phones…	PC
Telephone components…	POM
Telephone handsets…	ABS
Tool handles and grips for pliers, screwdrivers…	COPE
Transparent and decorative parts for vending machines, appliance panels, knobs and housings, housewares…	PC
Transparent technical parts: indicators, dials, inspection holes, caps, casings, hoods and electrical parts…	PMMA

Continued

Table 4.8 More than 150 Examples of Thermoplastic Applications in Household, Entertainment, and Office Appliances—cont'd

Transparent thermoformed products…	PMMA
Trims…	PVC
TV backplates and deflection yokes…	PPE
TV components…	PS
TV components…	PSU
TV components and housings, video and audio tape cassettes…	ABS
TV tuner arms…	POM
Utensils, pens: Cardia Biohybrid™ resins	Bioplastics
Vapor pumps and distributors for domestic irons, shock-proof kettles…	POM
Video and audio tape cassettes…	PS
Water purification equipment parts…	PPE
Wheel treads…	TPV
White goods connectors… PBT or PET	PBT
White goods, components for the "wet side" of domestic washing machines, dryers, and dishwashers; refrigerator parts, floor care, and small appliances, housewares, kitchenware, good clarity parts, jug kettles; toaster and iron parts…	PP
Wire and cable jacketing, electrical and communication cable jacketing, coil cables…	PEBA
Wireless communications…	PFA
Wireless communications…	FEP
Wireless communications…	PTFE
Workbench feet, appliance feet, supports, and pads…	TPO
Workbench feet, end caps, appliance feet, and pads…	TPS

Most mechanical engineering applications are produced in small or medium runs. Several exceptional features explain the high level of thermoplastics and TPEs used for the mechanical engineering market:

- Technical motivations: using thermoplastics is favored by:
  - ease and freedom of design allowing a broad integration of functionalities
  - ease of processing and assembly
  - impact resistance
  - low density and attractive performance/weight ratio leading to weight reduction
  - low or zero maintenance
  - nonrusting (but beware of aging)
  - insulating properties
  - transparency
  - mechanical and acoustic damping
  - elasticity and sealing properties of TPEs and particularly TPVs
  - the replacement of conventional materials because of an exceptional combination of properties unattainable for metals, wood, ceramics, and glass
  - adaptation to mass production and small series

  - weldability
  - cost cutting
  - the possibility to associate several thermoplastics to integrate several functionalities thanks to the exceptional combination of properties, for example, co-molding a hard thermoplastic and a soft TPE.
- Aesthetics: thermoplastics allow:
  - much more design freedom than conventional materials
  - decoration possibilities: transparency, bulk coloring, printability, paintability, in-mold decoration
  - pleasing finish.
- Economic features: thermoplastics provide:
  - an economical response to mass production
  - reduction of manufacturing times
  - reduction of finishing costs: plastics allow the integration of functions and, consequently, lead to reduction of assembly costs
  - higher productivity due to adapted processes, integration of functions, fewer processing steps…

Thermoplastics also have some general handicaps:

- high raw material cost (but attractive final cost)
- behavior differs significantly from that of steel
- susceptibility to fire of organic polymers
- recycling bringing some particular problems due to economic conditions, polymer modifications, and reinforcements.

4.6.2 Panel of Ideas for Application: 300 and More Examples

Let us quote, Table 4.9, without claiming to be exhaustive, some application examples. These examples can be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility to use the quoted thermoplastic family for his/her specific problem and test the right grade under real-service life conditions.

4.7 Sports and Leisure

4.7.1 Overview

The sports and leisure market consumes approximately 2% of all thermoplastics. It is sensitive to the economic situation, weather conditions, and the phenomenon of fashion and appears increasingly competitive. Nevertheless, the crises of growth that the sports industry encounters do not seem to weigh on the penetration of thermoplastics in this sector. The market analysis, however, emphasizes significant disparities of consumption according to the type of activity:

- football, rugby, basketball, tennis, golf, badminton: clothes, shoes, balls, protection, possibly flooring…
- diving: flippers, tubes, masks, wet suits…
- aquatic sports and sailing, sailing boards, dinghies, inflatable beach articles, paragliding: equipment, clothes, protection, footwear, boards of all kinds, paddles, hulls of canoes, helmets…
- hiking, cycling, mountain biking, horse riding, climbing: accessories, equipment, clothes, shoes and boots, protection…
- winter sports, ski, snowboard, toboggan: equipment, accessories, shoes, protection
- gymnastics, fitness: accessories, equipment, protection…

The broad range of applications shows that the thermoplastics are appreciated for general properties such as lightness, impact resistance, aesthetics, final cost and ease of processing, and for very versatile characteristics according to the grades or families, such as flexibility or rigidity, damping or elasticity, high friction or easy slip, and transparency. With the appearance of a broad choice of colors, fashion supports the use of thermoplastics of intense, well-defined, and varied colors.

Winter sports represent a significant share of the sports and leisure market where the majority of commodity and engineering thermoplastics are used.

4.7.2 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.10, without claiming to be exhaustive, some application examples for some thermoplastics in this sector. These examples can be

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering

Acoustic screens…	PMMA
Advertising elements… Expanded PS	PS
Aerosol components, aerosol valves, and heads…	POM
Air outlet grilles for microscopes…	PPS
Antiabrasion coating…	PVC
Anticorrosion, protection: offshore drilling, offshore oil and gas production and test lines, gas and water injection lines, gas lift lines, pipes, fittings, valves, lined pipes; powdering within the health-care equipment, oil industry; internal coating in new and refurbished injection tubing, production tubing and flow lines; production risers, choke and kill lines, nitrogen lines, hydraulic lines; buried gas pipelines; co-extruded pipes with MDPE and HDPE to increase their performances; dirty water and effluent pipes used in aggressive environments… PA 11 or 12	PA
Antifriction parts, bearings, bushings, rods, zippers…	POM
Antifriction parts: bearings, rods…	SAN
Antifriction parts: bearings, rods… PA 11 or 12	PA
Assemblies for piping systems, sprinklers, mixers…	FEP
Assemblies for piping systems, sprinklers, mixers…	PFA
Assemblies for piping systems, sprinklers, mixers…	PTFE
Ball cocks, faucets, faucet cartridges, faucet underbodies, valve stems…	POM
Bearings—sleeve and thrust	PCTFE
Bearings (PTFE lubricated)…	PPS
Bearings, plugs, pads, feet, damping mounts…	COPE
Bearings, plugs, pads, feet, damping mounts…	PEBA
Bearings, thrusts…	ECTFE
Bearings, thrusts…	ETFE
Bearings, thrusts…	PCTFE
Bearings, thrusts…	PVDF
Bellows	EVA
Bellows for glass columns, glass valves, pipelines…	FEP
Bellows for glass columns, glass valves, pipelines…	PFA
Bellows for glass columns, glass valves, pipelines…	PTFE
Belting…	COPE
Belting, conveyor belts…	PEBA
Boots and bellows…	TPV
Boots and bellows for oil contact… TPV PP/NBR-V	TPV
Brackets, structural parts, covers, handles, rollers, machine guards, fittings…	PC
Brakes on textile winding machine, pump pads, joint seatings, manipulator inserts for glass bottle demolding, gears of variable speed transmissions, toothed wheels…	PI

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Bumpers or edge accessories, cord holders…	TPV
Cable binders	EVA
Casings, caps	PP
Cast and extruded sheets, cell-cast sheets, stretched sheets, films down to 50 μm used in protection, communications…	PMMA
Caster wheels…	TPU
Caster wheels…	TPV
Ceramic-coated piston for 5-HP engine…	PAI
Chemical pipes…	PE
Chemical process equipment, semiconductor process equipment components…	PSU
Chip carriers…	LCP
Clips	EVA
Clips, lugs, conveyor components…	POM
Coated fabrics…	TPV
Coated fabrics, films and sheets…	MPR
Coated metal racks and shelving…	PVC
Cocks…	PVDF
Coffee spigots…	POM
Components for cooling towers, laboratory sinks, pumps…	PVCC
Components for fuel handling, fuel or gas barrier structures…	LCP
Compressors and pumps PCTFE Gaskets, pressure, diaphragm, liquid gauge seals, and fluid handling	PCTFE
Conductivity sensors…	PEEK
Containers, vessels, process vessels, tank construction and linings, columns…	ECTFE
Containers, vessels, process vessels, tank construction and linings, columns, elbows, tees…	ETFE
Containers, vessels, process vessels, tank construction and linings, columns, elbows, tees…	PVDF
Conveyor belts, food processing equipment, mining screens…	TPU
Couplings, pump impellers…	POM
Cross-linked foams, extruded and molded parts…	PE
Cryogenic applications, super-cold refrigeration components	PCTFE
Cryogenic applications, super-cold refrigeration components…	ECTFE
Cryogenic applications, super-cold refrigeration components…	ETFE
Cryogenic applications, super-cold refrigeration components…	PCTFE
Cryogenic insulation in PI foams…	PI

Continued

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Damping mounts for noise and vibration…	MPR
Detergent product vats	PP
Diffusers, luminaries…	Cellulosics
Drive belts…	TPU
Electrical components	PP
Encapsulated O-ring and other parts, lined products…	FEP
Encapsulated O-ring and other parts, lined products…	PFA
Encapsulated O-ring and other parts, lined products…	PTFE
Enclosures	ABS
Equipment housings…	PC
ESD trays…	PSU
Face shields, safety helmets…	PC
Fasteners…	ETFE
Fasteners…	PVDF
Feet, pads, mounts… TPE based on PVC	TPE
Fibers for heat and fire protection, clothing for fighter pilots, army and police forces; smoke filtration…	PAI
Fibers, screens…	PVDF
Filaments for fire-resistant padding…	PEI
Films and sheets…	TPU
Films for industrial applications…	PMP
Films for technical uses: keyboards, instrument panels, control boards, insulating layers and cards…	PC
Films, sheets, thin and flexible membranes, diaphragms…	COPE
Films, sheets, thin and flexible membranes, diaphragms…	PEBA
Filter technology… Aromatic PA	PA
Fire helmets…	PEI
Fittings, hinges, shower heads…	POM
Fluid handling, coupling and fitting applications…	PSU
Foam: damping and protection; air, water, and dust proofing, thermal insulation; soundproofing for industrial machinery…	PP
Foam: damping blocks, intermediate layers…	PP
Foam: impact and vibration damping…	PE
Foam: impact and vibration damping…	PVC
Foam: machine soundproofing…	PE
Foam: machine soundproofing…	PVC

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Foam: scale models…	PVC
Foamed seals, integrated seals…	TPV
Foamed tube: Bionolle™ (aliphatic polyester resin)	Bioplastics
Foams…	EVA
Frame of fan: Bionolle™ (aliphatic polyester resin)	Bioplastics
Frames, rollers of cables	PP
Frames, ventilating parts…	PPE
Framework of ventilation, fan blades, air filters, filters and pumps of industrial dishwashers, softeners, and washing machines	PP
Fuel tanks, oil field parts…	COPE
Gas sampling bags…	PVF
Gasketing, tubing… Extruded profiles	CPE
Gaskets and seals, hydraulic seals…	TPU
Gaskets, oil field pipe flanges and gaskets…	PEEK
Gaskets, seals, rings, O-rings, D-rings, U-seals, V-seals, cup seals…	FEP
Gaskets, seals, rings, O-rings, D-rings, U-seals, V-seals, cup seals…	PFA
Gaskets, seals, rings, O-rings, D-rings, U-seals, V-seals, cup seals…	PTFE
Gears…	PPE
Gears, bearings, antifriction parts for light loads… UHMWPE:	PE
Gears, screws and bolts, pulleys, collars, valve casings, rings, clips, ventilators, cooling fans, tanks and containers…	SAN
Gears, sprocket wheels, gearwheels, cams, springs…	POM
Gears, sprockets, caster wheels…	COPE
Gears, sprockets, caster wheels, low-noise gearwheels…	PEBA
Gears, valve plates, intake valves…	PAI
General-purpose boots and bellows…	TPS
General-purpose boots and bellows… TPE based on PVC	TPE
General-purpose gasketing, seals…	TPS
General-purpose profiles, tubes, pipes, sheathing…	TPO
Glazing applications, shatter-resistant glazing and protective glazing, windows and skylights, sight glasses, sight gauges…	PMMA
Glue-gun bushings…	PEEK
Goods with low permeability to moisture, air and oxygen for butyl rubber replacement… TPV PP/IIR-V	TPV
Grips, handles, feet, pads…	TPV
Grips, handles, overmolding… TPE based on PVC	TPE

Continued

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Guide rollers…	PBI
Guides…	LCP
Guiding rollers of grinder bands, sealing discs of valves in an industrial Freon compressor, segments of air compressors…	PI
Hairdryer grilles and components, cutting heads for electric shavers…	PPS
Hand tools, screwdriver handles, buttons, handles, hammer heads…	Cellulosics
Handcuff holders…	COPE
Handles…	ABS
Handles…	PS
Handles…	SAN
Handles, soft-touch overmolding…	TPO
Heat exchanger parts, flexible surface heaters…	PEEK
Heat insulation, soundproofing… Expanded PS	PS
Heat-shrinkable films, oriented films…	ETFE
Heavy wall tubing; plain, colored, striped tubing fabrications for instrumentation; automotive push–pull cables; industrial and process hydraulics, and other fluids…	FEP
Heavy wall tubing; plain, colored, striped tubing fabrications for instrumentation; automotive push–pull cables; industrial and process hydraulics and other fluids…	PFA
Heavy wall tubing; plain, colored, striped tubing fabrications for instrumentation; automotive push–pull cables; industrial and process hydraulics, and other fluids…	PTFE
High heat bushings, valve seats, ball valve seats, contact seals, insulator bushings…	PBI
High-performance motor components, transmission system components, pump components…	LCP
High-temperature labels…	PEEK
Hoses and tubing, flexible tubing, hose jackets, convoluted tubing, hydraulic hoses, pneumatic tubing…	COPE
Hoses and tubing, flexible tubing, hose jackets, convoluted tubing, hydraulic hoses, pneumatic tubing…	PEBA
Hoses and tubing, hydraulic hoses, fire hose liners, flexible tubing…	TPU
Hoses for chemical transfer and storage…	CPE
Hot water reservoirs, heat exchange systems…	PEI
Housing parts, handles and knobs…	POM
Housing parts, handles and knobs…	PPE
Housings…	ABS
Housings for airflow mass meter, connectors, gears, meters and sensors… Thermoplastic polyester	PBT
Impeller wheels for regenerative pumps, pump rotors, laundry system wheels, submersible pump insulation, dry transformer insulation…	PEEK

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Impellers, rotors…	PAI
Impermeable liners, protective sheets…	TPS
Industrial sheet goods…	TPV
Injection- and blow-molded articles…	ECTFE
Injection- and blow-molded articles…	ETFE
Injection- and blow-molded articles…	PVDF
Instrument components…	ETFE
Instrument components…	PVDF
Insulation, soundproofing	EVA
Insulators…	ABS
Insulators…	PAI
Insulators, cable separators…	PS
Irrigation equipment and valves…	POM
Jet pump impellers and diffusers…	PC
Joints and linings for vacuum pumps…	PI
Kneepads	EVA
Label materials for harsh environments…	PVF
Lantern rings for pumps, bellow-type seals for centrifugal pumps; hydraulic, pneumatic, earthmoving equipment; cylinder valves for O_2, CO_2, refined gases, chlorine, ammonia…	FEP
Lantern rings for pumps, bellow-type seals for centrifugal pumps; hydraulic, pneumatic, earthmoving equipment; cylinder valves for O_2, CO_2, refined gases, chlorine, ammonia…	PFA
Lantern rings for pumps, bellow-type seals for centrifugal pumps; hydraulic, pneumatic, earthmoving equipment; cylinder valves for O_2, CO_2, refined gases, chlorine, ammonia…	PTFE
Large-sized objects, tanks, cisterns: hydraulic tanks, septic tanks, chemical tanks…	PE
Leisure industry applications… Aromatic PA	PA
Lenses…	PS
Lenses…	SAN
Lids, all kinds of closures	EVA
Light globes, lighting diffusers, light-control lenses, outdoor lighting fixtures…	PC
Lighting and lamp fittings… Thermoplastic polyester	PBT
Lighting fixtures, portholes…	PSU
Linings of components used in chemical processing, pump housings, compressor linings and components…	PVDF
Linings of components used in chemical processing, sleeves…	ECTFE

Continued

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Linings of components used in chemical processing, sleeves…	ETFE
Machine housings, pump and filter housings, impellers, fluid and material handling components, water pump housings and impellers in machinery and engineering, impellers, plumbing systems…	PPE
Machine tools… Aromatic PA	PA
Magnetic media…	TPU
Manifolds, distributor valves…	PSU
Material handling components…	PAI
Membranes, filter media, filter bags, cartridges, microfiltration membranes, vents, and adsorbent products…	FEP
Membranes, filter media, filter bags, cartridges, microfiltration membranes, vents, and adsorbent products…	PFA
Membranes, filter media, filter bags, cartridges, microfiltration membranes, vents, and adsorbent products…	PTFE
Metallized parts, vacuum metallized parts, reflectors…	Cellulosics
Miniature gears…	LCP
Models and mock-ups… Expanded PS	PS
Molded shapes: pipe fittings…	CPE
Motor and vibration mounts…	TPU
Motor parts… Thermoplastic polyester	PBT
Mounts for damping noise and vibration, shock absorbers… TPV PP/NBR-V	TPV
Nameplates, medallions…	PMMA
Nonlubricated bearings, seals, bearing cages, rotating and sliding components, bushings, seal rings, wear pads, piston rings, hook joints for transmission seal rings…	PAI
Nuclear engineering components, gears, cams…	POM
Outer covers for instruments, machines and lamps…	SAN
Packaging machinery star wheels…	POM
Padding…	PVC
Paper for fire-resistant uses…	PI
Parts of pumps used for handling chemicals	PP
Parts with film hinge	PP
Photography, camera lenses, binoculars, magnifying glasses…	PC
Pipe seals…	TPV
Pipes…	PCTFE
Pipes…	PP
Pipes for paper and surface treatment sectors, electroplating plants, photographic, semiconductor, and chemical industries…	PVCC

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Pipes, parts, containers for contact with chemicals…	PVC
Piping liners for glass-lined reactors, stainless steel reactors, glass equipment and mixers…	FEP
Piping liners for glass-lined reactors, stainless steel reactors, glass equipment and mixers…	PFA
Piping liners for glass-lined reactors, stainless steel reactors, glass equipment and mixers…	PTFE
Piston rings of ethylene compressors, dry bearings, sliding plates, guides for cast solid films in self-lubricated PI…	PI
Plastic parts in central heating systems…	PPE
Plumbing fixtures, faucet components…	PSU
Pneumatic and hydraulic hoses; petrochemical, fuel handling and hydraulic applications; gears, collars, valve casings, rings, clips… PA 11 or 12	PA
Poultry processing parts, valve stems, food conveyors…	POM
Powdering… PA 11 or 12	PA
Power tools…	PC
Precision parts for mechanical and regulation components…	PPS
Profiles…	COPE
Profiles…	PEBA
Protective clothing, weatherproof clothing…	TPU
Protective glazing, vandal-proof windows, shatter-resistant glazing, windows and skylights, sight glasses, sight gauges, portholes, high temperature and pressure windows, portholes in pressure chambers…	PC
Protective strips, trims…	PVC
Pump and filter housings, milk pump impellers, plumbing systems…	POM
Pump housings, compressor linings and components…	ECTFE
Pump housings, compressor linings and components…	ETFE
PVC foam: insulation of tanks, pipes…	PVC
Quick coupling systems…	PEEK
Racks and handling cases for PCB treatment…	PI
Rail pads	EVA
Railway pads…	COPE
Reciprocating compressor parts…	PAI
Reusable packaging or shuttle packaging for heavy parts such as doors, windscreens, rear mirrors…	PP
Ring seals, O-rings, and protective caps	EVA
Roller covering…	COPE
Rollers, bearings, bushings, conveyor plates, wear pads…	POM

Continued

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Seals—lips, O-rings, V-rings, and special construction seals	PCTFE
Seals…	MPR
Seals for glazing… TPE based on PVC	TPE
Seals for oil filters; seals, tubes, pipes, profiles for oil contact… TPV PP/NBR-V:	TPV
Seals, compressor valve plates…	PEEK
Seals, gaskets, packing…	COPE
Seals, integrated seals, window encapsulations… TPE based on PVC	TPE
Self-lubricating components, bearings, bushings…	FEP
Self-lubricating components, bearings, bushings…	PFA
Self-lubricating components, bearings, bushings…	PTFE
Semiconductor industry, vacuum chamber applications; clamp rings for gas plasma etching equipment, wafer retaining rings for gas plasma etching, wafer carriers, vacuum tips…	PBI
Sensors…	LCP
Shock-proofing casings…	COPE
Shock-proofing casings…	PEBA
Shock-proofing casings…	TPU
Shock-proofing casings… TPE based on PVC	TPE
Sign panels…	PS
Signs: internally illuminated outdoor signs, indoor and outdoor signs, diffusers, side-lit signs, very thin illuminated displays, fluorescent signs…	PMMA
Small pressure vessels, coil formers…	POM
Soft handles and grips…	MPR
Sound-damping mountings…	POM
Static dissipative grades: covers, guards, access panels, machine windows and doors, static control shields, glove boxes, electronic equipment, process instrumentation, conveyor line covers, clean room windows and doors, partitions and pass through modules…	PC
Sterilizable laboratory equipment…	PPS
Sterilizable trays and equipment…	LCP
Studs, heels…	PS
Systems for glass production… Aromatic PA	PA
Tableware and catering, reusable food service, food trays, soup mugs, steam insert pans or gastronome containers, cloches, microwavable bowls, utensils, oven-ware, cooking utensils and reusable airline casseroles…	PEI
Tag axle assembly of cement trucks and heavy vehicles…	PAI
Tank covers…	PS
Terminal strips…	PAI

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Textile bobbins… Thermoplastic polyester	PBT
Thermal isolators, high heat insulator bushings for hot runner plastic injection molds	PBI
Thrusters of pumps, hot water pumps…	PPS
Timing screws…	POM
Tool handles and grips for pliers, screwdrivers…	COPE
Tool handles, screwdriver handles…	EMA
Translucent parts and cases	PP
Transparent and decorative parts for vending machines, machinery panels, knobs and housings, housewares…	PC
Transparent moldings, sensors…	COC
Transparent pipelines, molds, models, gauges, product prototypes, demonstration models…	PMMA
Transparent technical and decorative parts for lights, instrument panels, dials, indicators, tachometer covers, inspection holes, peepholes, portholes, domes, panes, caps, casings, hoods and electrical parts…	PMMA
Transparent technical parts: indicators, dials, inspection holes, peepholes, domes, panes, caps, casings, hoods and electrical parts…	PC
Trays for chemical treatments, floating balls for chemical bath insulation…	PMP
Trims…	Cellulosics
Trims… TPE based on PVC	TPE
Tubes… TPE based on PVC	TPE
Tubing…	TPV
Tubing for corrosive liquids…	PS
Tubing, pipes and fittings for aggressive environments and corrosive liquids…	ABS
Tubing, pipes, hoses, fittings, fluid handling, profiles… Extruded profiles	ECTFE
Tubing, pipes, hoses, fittings, fluid handling, profiles… Extruded profiles	ETFE
Tubing, pipes, hoses, fittings, fluid handling, profiles… Extruded profiles	PVDF
Tires (light uses)	EVA
UV screening films, surface covering for PVC film, surface protection of signs…	PVF
Vacuum nozzles… Thermoplastic polyester	PBT
Valve and pump components, balls for nonreturn valves…	FEP
Valve and pump components, balls for nonreturn valves…	PFA
Valve and pump components, balls for nonreturn valves…	PTFE
Valve bodies… Thermoplastic polyester	PBT
Valve seats, piston rings for hydraulic installations for the chemical industry, seals, and other parts for high-vacuum installations usable up to 300 °C without lubrication…	PI

Continued

Table 4.9 More than 300 Examples of Thermoplastics Applications in Mechanical Engineering—cont'd

Valves, seats, stems, seals	PCTFE
Valves, seats, seals, gaskets, diaphragms…	ECTFE
Valves, seats, seals, gaskets, diaphragms…	PCTFE
Valves, seats, seals, gaskets, diaphragms, liquid gauge seals…	ETFE
Valves, seats, seals, gaskets, diaphragms, liquid gauge seals…	PVDF
Vanes in air motor…	PAI
Vibration mounts…	TPV
Washers…	POM
Washers, flanges, baffles…	FEP
Washers, flanges, baffles…	PFA
Washers, flanges, baffles…	PTFE
Water purification equipment parts…	PPE
Water-pump impellers, expansion valves…	PEI
Weather-resistant film for glazing panels, glazing for solar panels……	PVF
Wheel treads…	TPV
Workbench feet, appliance feet, supports and pads…	TPO
Workbench feet, end caps, feet and pads for light loads…	TPS
Woven-glass/fluoroplastic composites…	PTFE

commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.8 Medical Market

4.8.1 Overview

The medical market consumes roughly 2% of all thermoplastics. It is subjected to the same requirements as the whole of the health industry: evolution of health services, compliance with specific standards and regulations, resistance to sterilization, biocompatibility, more rigorous cost controls, aging of the population, and increased resistance of pathogenic agents. The globalization of the medical industry offers new opportunities and challenges to the plastic suppliers. To reduce costs and to improve their competitiveness, manufacturers of medical materials work in partnership with producers to examine, among other things, the possibilities to improve the products, materials, equipment, and design methods.

Thermoplastics are used in very diverse products, some being specific to medical applications, whereas others being general-purpose parts and components as for other machinery or electric devices. Let us mention for example:

- flexible tubing for solutions
- pouches for blood and various liquids
- permeable membranes
- implants, prostheses
- pharmaceutical packaging: blisters, tubes, boxes…
- bottles, tanks, bulbs
- films, shrinkable films, gloves
- transdermal patches
- semirigid connectors
- various parts and plastic components, machine housings…

Table 4.10 More than 150 Examples of Thermoplastics Applications in Sports and Leisure Sector

Aesthetic applications…	PC
Architectural glazing, roofs of verandas, stadiums; aircraft, boat, mass transit glazing	PC
Arts and fashion: embedment of items, sculptures, decorative inclusions, jewels, knickknacks…	PMMA
Athletic footwear components…	PEBA
Ball bearings for America's Cup yachts…	PAI
Ballpoint pens: Cornpole (biodegradable bioplastic based on cornstarch)	Bioplastics
Beach shoes…	PE
Bike mudguard: Gaialene	Bioplastics
Buoys	EVA
Buoys and life jackets… Expanded PS	PS
Caterpillars for snowmobiles…	COPE
Christmas trees and Easter made with Fasal®	Bioplastics
Clock and watch parts, watch gears…	POM
Coated fabrics for clothing, leather working, opaque curtains, tarpaulins…	PVC
Combs made from Mater-Bi® (starch) have the additional advantage of being antistatic, avoiding the inconvenient buildup of static electricity experienced when using normal combs	Bioplastics
Consumer articles, jewellery, toys: ARBOFORM® (lignin)	Bioplastics
Consumer goods requiring low permeability to moisture, air, and oxygen, competing with butyl rubber: for example, inner tubes for bikes, bladders for balloons. PP/IIR-V	TPV
Cores of sea sailboards, surfboards, or beach boards with GFRP skins… Expanded PS	PS
Costume jewelry…	Cellulosics
Damping mounts for noise and vibration…	MPR
Damping systems, vibration and shock absorption in sports equipment, damping of tennis rackets…	PEBA
Deeply formed components subsequently backed with glass fiber-reinforced polyester: camper tops, furniture, and recreational vehicle bodies	PMMA
Disposable cutlery, dog treats, golf tees: Vegemat (natural fibers, starch, proteins, lipids)	Bioplastics
Face shields, safety helmets…	PC
Feet, pads, mounts… TPE based on PVC	TPE
Filaments for fishing…	PA
Films and sheets for adhesive tapes, translucent curtains, school and office stationery…	PVC
Films laminated on ABS, PVC, or other plastic sheets that are thermoformed into parts requiring resistance to outdoor weathering: motorcycle shrouds, recreational vehicle panels…	PMMA
Flexible toys	EVA
Floats of boards…	PP

Continued

Table 4.10 More than 150 Examples of Thermoplastics Applications in Sports and Leisure Sector—cont'd

Flooring for badminton and other specialized courts/playrooms…	PVC
Foam: buoys…	PE
Foam: buoys	PVC
Foam: gym mats, padding, damping, and insulating mats…	PE
Foam: gym mats, safety padding, damping, and insulating mats…	PVC
Foam: life jackets, life suits…	PE
Foam: life jackets, life suits	PVC
Foam: padding of helmets and seats for babies and children…	PP
Foam: padding of helmets and seats for babies and children…	PVC
Foam: protective devices for various sports such as hockey, basketball, soccer, boxing…	PVC
Foam: safety padding…	PE
Foam: safety padding…	PP
Foam: safety padding	PVC
Foam: stuffing of rucksack in foam-coated textile…	PE
Footwear components: thermoformed shoe inserts, football boot soles, protective pads for shoes and boots…	EMA
Footwear, soles, sports, and technical items	EVA
Front straps for ski boots…	COPE
Furniture, office, and institutional furniture…	PC
Fuselage of recreational plane…	ABS
Games made from colored Fasal® wood-based thermoplastic	Bioplastics
Garden equipment…	PC
Garden hoses…	PVC
Garden sprayers…	POM
Gaskets and seals…	TPU
Gift cards, hotel key cards, loyalty and transactional cards: Ingeo biopolymer (PLA)	Bioplastics
Glazing applications, shatter-resistant glazing for aircraft, boats, protective glazing…	PMMA
Gloves, golf tees: Bionolle™ (aliphatic polyester resin)	Bioplastics
Goggles…	TPU
Goggles, glass frames…	PEBA
Golf tees use Fasal. The parts are paintable and dyeable	Bioplastics
Grass and leaf blower parts and housings…	PA
Grips, buttons, bumpers, seals, feet, gaskets…	TPV
Grips, handles, overmolding… TPE based on PVC	TPE
Grips, pencil grips…	COPE

Table 4.10 More than 150 Examples of Thermoplastics Applications in Sports and Leisure Sector—cont'd

Grips, pencil grips…	PEBA
Handles, soft-touch overmolding…	TPO
Headphones…	COPE
Hovercraft propellers…	PA
Hulls of boats, canoes, buoys, sailboards, fun boards…	PE
Impermeable liners, protective sheets…	TPS
Inflatable covers, structures, and devices…	PVC
Inflatable rafts…	TPU
Injected parts: transparent, filled to a greater or lesser degree, possibly cross-linked and/or foamed in microcellular form	EVA
Injection- and blow-molded parts, seals and gaskets resisting oils, handles of motorbikes, cable guides…	MPR
In-line skates…	TPU
Kneepads	EVA
Lawn furniture, lawn products, garden furniture, garden tools…	PP
Leather-like goods… TPE based on PVC	TPE
Leisure industry applications… PA 11 or 12	PA
Lenses…	PS
Life vests…	TPU
Luges, ski pads…	PE
Luggage, suitcases, vanity cases…	PP
Magnetic media…	TPU
Mechanical pen and pencil parts…	POM
Miniature gears for watches…	LCP
Mosaic jigsaw puzzle, promotional articles, packing: TREEPLAST (wood chips with crushed corn and natural resins)	Bioplastics
Multiuse laptop stand, brush handle, Christmas tree decoration, golf tees, ice-drink holder: TREEPLAST (wood chips with crushed corn and natural resins)	Bioplastics
Musical instruments: ARBOFORM® (lignin based)	Bioplastics
Musical instruments: Fasal® wood-based thermoplastic	Bioplastics
Nonflammable scenery, colored filter holders for studios and theaters…	PI
Oam: toys: 2D and 3D puzzles, floating toys…	PE
Optical components for sunglasses, watch glasses, lenses, magnifying glasses, camera lenses…	PMMA
Parachute links: Vegemat (natural fibers, starch, proteins, lipids)	Bioplastics
Pen/stationery supplies, pen barrels, writing instruments, squares…	Cellulosics
Pens, pencil sharpeners, rulers, children's toys: Mater-Bi® (starch)	Bioplastics

Continued

Table 4.10 More than 150 Examples of Thermoplastics Applications in Sports and Leisure Sector—cont'd

Piano keys…	PMMA
Protective caps…	EVA
Protective films for boards and sailing boards…	PC
Puzzles… Expanded PS	PS
Quality toys…	POM
Recreational parts…	Cellulosics
Recreational vehicles, boats…	ABS
Rigid shells of snow boots…	PP
Roller skates, toys…	PA
Seals, integrated seals… TPE based on PVC	TPE
Shells of helmets…	ABS
Shockproof, water-resistant shields…	TPV
Shock-proofing casings…	COPE
Shock-proofing casings…	PEBA
Shock-proofing casings…	TPU
Shock-proofing casings… TPE based on PVC	TPE
Shoe binding system components, tensioner ski binding…	COPE
Shoe soles…	PVC
Shoe soles…	TPS
Shoe soles… TPE based on PVC	TPE
Ski bindings, shoe components, sole plates for golf shoes…	POM
Ski boots…	PA
Ski boots, sports shoe soles…	TPU
Ski boots, toys, snowmobile parts… PA 11 or 12	PA
Ski parts, ski boots components…	PEBA
Snowboard cover laminates…	COPE
Snowmobile bumpers…	PA
Snowshoe decking, athletics shoes and equipment…	PEBA
Soft handles and grips…	MPR
Soling…	COPE
Soling, outsoles for American football, soccer, rugby, baseball footwear…	PEBA
Sport balls, golf balls…	PEBA
Sporting goods, and toys: PLA bioplastics compounds	Bioplastics
Sporting goods, scratch-resistant golf balls, skittle and bowling pin covers, ski boots	EMA
Studs, heels…	PS

Table 4.10 More than 150 Examples of Thermoplastics Applications in Sports and Leisure Sector—cont'd

Suitcase handles…	COPE
Sunglasses: bridges for lenses, rear frames and arms, goggles…	COPE
Swim fins…	TPU
Swimming pool covers…	PE
Swimming pool hoses…	EVA
Toys…	PE
Toys…	PMMA
Toys…	PP
Toys…	TPO
Toys…	TPS
Toys…	TPU
Toys… TPE based on PVC	TPE
Toys and leisure; e.g., Airsoft bullets, golf balls and tees, hunting cassettes	Bioplastics
Toys and sporting goods…	Cellulosics
Toys, dolls, fishing lures, fancy goods…	PVC
Toys, tires for scale models…	MPR
Transparent thermoformed products…	PMMA
Tires (light uses)	EVA
Upholstery, covering, padding…	PVC
Weathering protection for other thermoplastics and metals…	PVDF
Weatherproof clothing…	TPU
Wheels, saddle stems, crank gears for bicycles…	PA
Workbench feet, appliance feet, supports and pads…	TPO
Workbench feet, end caps, appliance feet and pads…	TPS
Writing and drawing equipment…	SAN
Writing and drawing instruments…	PMMA

An example of the possibilities for plastics to respond to a specific problem is the replacement of almost 100% of the stoppers, capsules, joints, and other closure systems used for pharmaceutical products. The replacement of glass is the most significant opportunity for the development of thermoplastics but new possibilities could appear in medical self-care systems and blood sample tubes. A 50–70% increase in the use of plastics should come from existing mass-produced and low-cost products. Let us quote, for example:

- PVC for tubes and pouches for blood, but PVC is handicapped by environmental regulations and trends
- PP for pharmaceutical and medical packaging
- PS for tubes and other test and laboratory equipment

- thermoplastic polyester for bacteriology equipment
- PE foam for the waterproof layers of sanitary towels and nappies
- gloves and general-purpose films.

It has taken the surgery sector a long time to adopt plastic products. Engineering thermoplastics with high impact resistance, ultrahigh molecular weight polyethylene (UHMWPE), and some fiber-reinforced grades are starting to be used in applications where conventional materials are predominant, for example, implants, the instruments used to insert suture clips, and the casings of various apparatus. Thus, UHMWPE is used for internal prostheses and a blood pump used during open-heart operations includes several plastic parts—polycarbonate for the pump barrel and PP for the permeable membranes.

One factor in the reduction of health-care expenditure is home medical care, which involves adaptations of the methods of care. These uses dictate particular requirements for sterility, safety, reliability, weight, and ease of use. Plastics can bring solutions in the fields of single-use products, unbreakable equipment, and weight reduction, for example, in the syringes, tubes, and pumps for drug injections and apparatus for ambulatory dialysis.

The launch of new resins being rare, progress on materials intended for medical applications is by way of formulation, alloys, and modifications of existing resins. Thus, new radiation-stable PP grades are available for the manufacture of cups, boxes, baskets, mixers, etc. that are radiation sterilized. And polyesters with better environmental stress cracking resistance are extending their potential in the area of medical testing.

In less-specialized areas:

- Films of polyester for blisters and containers can be thinner without harming the integrity of the packed products.
- Co-extruded films of PP or other polyolefins and a flexible polyester are solutions for pouches for intravenous drug-delivery systems.
- Medical equipment and its packaging are undergoing significant evolution with regard to their design, which is being re-examined to reinforce the advantages of plastics:
  - economical production of structures with thin walls and reinforcement ribs—these measures have, moreover, the advantage of reducing the weight of waste to be eliminated after use
  - function integration—the elimination of a part brings significant economies by the reduction of tooling and assembly steps.
- Processing is also evolving to contribute to cost and waste savings without heavy investments:
  - multiplication of the number of cavities in a mold
  - improvement of mold cooling
  - reduction of cycle times
  - better control of processes by statistical processing of recorded parameters.
- The use of recycled materials, confined to parts without contact with medical components, is possible thanks to co-injection or co-extrusion.

Plastics also make it possible to reexamine the policy of medical wastes. The incineration of plastics, provided these resins are incinerated with negligible impact on the environment, poses fewer problems than the incineration of glass, which leaves significant residues.

The reuse of equipment is the subject of controversy because of the risks of contamination. Reuse limited to the treatment of only one patient is a solution under consideration. The economic advantages of this procedure are accompanied by a reduction in final waste. For its application, it is necessary to use thermoplastics with sufficiently high performance to withstand several sterilizations and uses. The polyetherimides, LCPs, polyetheretherketones, and polysulfones could be appropriate. The use of biodegradable thermoplastics is under evaluation.

TPEs have lower consumption in medical applications in Europe compared to the USA where they progress more quickly.

In addition to the functional tests common to any application, the TPEs that are proposed for medical applications must satisfy certain specific tests of biocompatibility and aptitude for sterilization.

4.8.2 Panel of Ideas for Application: 150 and More Examples

Let us quote, Table 4.11, without claiming to be exhaustive, some application examples for some thermoplastics. These examples can be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility

Table 4.11 More than 150 Examples of Thermoplastics Applications in the Medical Sector

Applications relating to low gas permeability, pharmacopoeia compliance, damping properties. TPV PP/IIR-V	TPV
Artificial skin for emergency burns treatment…	PVC
Autoclave- or radiation-sterilizable parts in the presence of aqueous solutions	PP
Bacteriology equipment: thermoplastic polyesters	PBT
Barrier films for food, pharmaceuticals, chemicals…	PVDC
Biomedical apparatus components…	TPU
Blisters and dosage packs for pharmaceuticals and medicines, single-dose medication packaging, shatterproof bottles and jars…	PVC
Blood vessels for artificial kidneys, heart and lung bypass sets…	PVC
Blow-molded and sheet-thermoformed products for personal care, health, medical, and lab ware applications…	PP
Blow-molded containers, bottles for drugs…	PE
Breathable films for medical disposables…	COPE
Breathable films for medical disposables…	PEBA
Cells for blood tests, centrifugation tubes	PMP
Clear polypropylene for packaging and casting cup applications, hospital disposables, and other bedside applications	PP
Composite cements for orthopedic surgery…	PMMA
Cups, boxes, baskets, mixers, etc. that are radiation sterilized: radiation-stable polypropylene grades	PP
Delivery catheters…	PEBA
Dentistry devices…	PEI
Dialysis equipment parts, compact heart-lung systems…	PC
Drip chamber components…	PVC
Drug-delivery systems and diagnostics…	LCP
Endoscope components…	PEEK
Endoscopic camera holders, epidural needle fixation devices…	TPO
Endoscopic probe positioning ferrules…	PSU
Eyeglass frames, medical care: BIOFRONT (stereocomplex PLA)	Bioplastics
Film, moisture barrier, food packaging, pharmaceutical packaging	PCTFE
Films and sheets…	PE
Films of polyester for blisters and containers can be thinner without harming the integrity of the packed products	PET
Fluid bags and containers for blood, plasma, intravenous solutions, urine incontinence	PVC
Foam for the waterproof layers of sanitary towels and nappies	PE
Foam: electrode pads for electrocardiogram testers	PE

Continued

Table 4.11 More than 150 Examples of Thermoplastics Applications in the Medical Sector—cont'd

Foam: waterproofing layers for sanitary towels and disposable nappies	PE
Foams: Core for composites used for X-ray tables… rigid polymethacrylimide (PMI) foam	PMI
Gamma-ray sterilizable reusables…	PC
Glazing…	PC
Hemodialyzers, dialysis machine components…	PEEK
Hemodialysis equipment parts, membranes for artificial kidneys, blood purification…	PSU
High-clarity parts for medical and food applications…	PP
Hip prostheses…	PMMA
Implants…	PMMA
Implants, the instruments used to insert suture clips, and the casings of apparatus of paramount importance: UHMWPE	PE
Inflatable splints, prosthetics…	PVC
Instrument covers, handles, machine guards, fittings…	PC
Intraocular lenses…	PMMA
Knitted, woven, braided, or sewn fibers: compression packing, sewing thread, membranes, filter media, filter bags, cartridges, microfiltration membranes, vents, and adsorbent products…	FEP
Knitted, woven, braided or sewn fibers: compression packing, sewing thread, membranes, filter media, filter bags, cartridges, microfiltration membranes, vents, and adsorbent products…	PFA
Knitted, woven, braided, or sewn fibers: compression packing, sewing thread, membranes, filter media, filter bags, cartridges, microfiltration membranes, vents, and adsorbent products…	PTFE
Laboratory ware: trays for chemical treatments, animal cages…	PMP
Laboratory wares, blood and centrifuge tubes, test tubes, beakers and pipette tips…	PP
Lenses…	PS
Medical and laboratory parts…	PS
Medical bandages…	PEBA
Medical clogs…	TPO
Medical devices and equipment: reSound biopolymer combining bio-derived resins with engineering thermoplastic resins	Bioplastics
Medical devices: PLA bioplastics compounds	Bioplastics
Medical disposable trays, containers for irrigation, parenteral, hemodialysis solutions	PP
Medical equipment components, homeopathic drug dispensers…	TPO
Medical instruments…	PEBA
Medical technology… Aromatic PA	PA
Medical tubing…	PC
Medical tubing…	TPO
Medical tubing…	TPU
Medical, laboratory, and care applications: transparent prefilled syringes, pharmaceutical containers, and packages	COC

Table 4.11 More than 150 Examples of Thermoplastics Applications in the Medical Sector—cont'd

Membranes for continuous hemodiafiltration…	PMMA
Miniature hearing aid parts…	LCP
Multiple sterilization components	LCP
Multiple sterilization components	PEEK
Multiple sterilization components	PEI
Multiple sterilization components	PSU
Nappies, sanitary towels, and panty liners: Mater-Bi® (starch)	Bioplastics
Nonwovens…	PP
Ophthalmic, optical safety frames, spectacles, sunglasses…	Cellulosics
Optical components, sunglasses, lenses, magnifying glasses…	PMMA
Optical recording, electroluminescent display panel packaging	PCTFE
Oriented, bi-oriented and cast films and foils for medical packaging…	PP
Orthopedic implant trails…	PSU
Oxygen tents…	PCTFE
Packaging for tablets, pills, capsules, suppositories, urine containers, sterilizable equipment…	PMMA
Packaging, containers for health care, cosmetics, perfumery, and personal care supplies	Cellulosics
Percutaneous polymethylmethacrylate vertebroplasty…	PMMA
Permeable membranes	PP
Pharmaceutical and medical packaging	PP
Pharmaceutical packaging…	PCTFE
Pipettes…	PEI
Port access systems…	PEEK
Pouches for gas sampling…	PCTFE
Pouches for intravenous drug-delivery systems: Co-extruded films of polypropylene or other polyolefins and a flexible polyester	PP
Primary packaging of pharmaceuticals, medical devices, diagnostic disposables, laboratory ware…	COC
Prostheses…UHMWPE	PE
Prosthesis…	PCTFE
Prosthetics…	PEEK
Pump barrel of a blood pump used during open-heart	PC
Reusable medical devices, sterilization trays…	PEI
Safety syringes, prefilled syringes, general-purpose syringes	PP
Seals, gaskets and diaphragms, blood filter seals overmolded on a PC base…	TPO
Sterilizable containers, steam-cleaning equipment components…	PSU

Continued

Table 4.11 More than 150 Examples of Thermoplastics Applications in the Medical Sector—cont'd

Sterilizable trays and equipment…	LCP
Stopcocks…	PEI
Sunglasses, magnifying glasses, lenses, lenses for eyeglasses…	PC
Surgical and dental instruments (up to 3000 autoclave sterilization cycles)…	PEEK
Surgical and examination gloves, inhalation masks, overshoes, protective sheeting and tailored covers, mattress and bedding covers, anti-bump protection bars…	PVC
Surgical garments, sheeting, mattress covers…	PEBA
Surgical instrument handles…	PSU
Surgical instruments, dental tools…	LCP
Synthetic blood vessels and patches for soft tissue regeneration; surgical sutures for use in vascular, cardiac, general surgery, and orthopedic procedures…	FEP
Synthetic blood vessels and patches for soft tissue regeneration; surgical sutures for use in vascular, cardiac, general surgery, and orthopedic procedures…	PFA
Synthetic blood vessels and patches for soft tissue regeneration; surgical sutures for use in vascular, cardiac, general surgery, and orthopedic procedures…	PTFE
Syringe plunger tips, epidural syringe plungers…	TPO
Syringes, needle hubs	PMP
Syringes, sterilizable packaging; membranes, tubes…	PCTFE
Transparent tubes and pipes…	PMP
Transparent tubes and tubing connectors, nebulizer parts, urine samplers…	PMP
Tubes and other test and laboratory equipment	PS
Tubes and pouches for blood	PVC
Tubing, catheters, cannulas, endotracheal tubing, feeding and pressure monitoring tubing…	PVC
Vials and bottles; contact lens casting cups and packaging…	PP

of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

4.9 Furniture and Bedding

4.9.1 Overview

The furniture and bedding sector consumes approximately 1–4% of the thermoplastics total. Thermoplastics find outlets in various categories of furniture:

- outdoor furniture: garden and street furniture
- storage units and small furniture
- kitchen and bathroom furniture
- movable furniture
- institutional and professional furniture
- fittings, accessories, supplies, and hardware for furniture.

4.9.1.1 Outdoor Furniture

Thermoplastics can offer:

- low or reasonable cost
- weather resistance adapted to lifetime
- mechanical performances and aesthetics
- design freedom
- adaptation to mass production

- lightness and ease of assembly of the delivery kits
- minimum or zero maintenance.

For street furniture, it is necessary to provide a greater mechanical resistance (vandalism, intensive use, safety of fixings) and, possibly, fire resistance.

The seats, tables, loungers, and other pieces of garden furniture are currently the prerogative of PPs.

The seats of bus shelters can be made out of PP, HDPE, PVC, or PA.

The structures of play areas (ladders, stationary motorbikes, labyrinths, huts…) can be in highly colored HDPE or PP.

4.9.1.2 Indoor Furniture

The main reasons to use thermoplastics are the same as for outdoor furniture, with some differences:

- Higher costs are acceptable if particular properties are obtained. For example, engineering thermoplastics such as modified and reinforced PAs can be used for demanding and top-of-the-range applications.
- Durability of coloring and appearance requirements are more stringent.
- Processes for small series or large parts are appreciated.
- Good resistance to moisture, greases, and healthcare products are required for kitchen and bathroom furniture.

Coffee tables, traveling tables, and modular storage elements can be made out of ABS, PMMA (when transparency is sought), and PVC.

Small storage units and medicine chests can be made out of HIPS, ABS, possibly PE for bottom-of-the-range articles.

Bathroom stools are often in HDPE.

Newspaper racks, CD racks, bedside units, and valet stands… can be made out of transparent or smoked PMMA, ABS, polycarbonate.

Lighting devices and accessories can be made out of PMMA and polycarbonate.

Certain beds are made out of thermoformed ABS or are covered with a PVC film or sheet mimicking wood.

Chairs, backrests, seats, and armchairs can be made out of PP, PMMA, ABS, possibly combined with a metal structure.

Decorative profiles can be made out of PVC, PS, or ABS.

Some inflatable furniture uses sheets or films of PVC or PE.

The penetration of thermoplastics in contemporary furniture remains limited by preconceived ideas on prohibitive costs and the difficulty of convincing both the profession and the public. Present in contemporary furniture at the end of the 1930s, plastics made their first breakthrough in the 1960s with German products and under the influence of Italian design. About the middle of the 1970s, the tendency was reversed, involving a rejection of plastics, which were labeled as bottom-of-the-range materials. Today, designers are again turning to these materials, which can represent 30% of the furniture of certain resolutely contemporary stores. Stools, seats, mobile pieces of furniture, nested tables, as well as dustbins, vases, lamps… can be made out of plastic, possibly combined with a more traditional material such as metal.

To reduce the costs of the small series, it is necessary to seek, as in other industries, new methods of design with integration of functions, simplification of assemblies and finishing operations, and a judicious choice of processing method. For example, the assembly of plastic panels on a metal structure makes it possible to obtain bulky objects with very low investments. The use of thermoforming or other techniques existing in packaging (the principle of blister packaging) makes it possible to achieve large parts (e.g., a seat made out of thermoformed PP) or double-shells at moderate prices.

The use of waste and recycled materials is also a route to be exploited and already allows for the realization of low-cost tiles by simple compression of wastes.

4.9.2 Panel of Ideas for Application: 100 and More Examples

Let us quote, Table 4.12 without claiming to be exhaustive, some application examples for some thermoplastics. These examples can be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility to use the quoted thermoplastic family for his specific problem and test the right grade under real-service life conditions.

Table 4.12 More than 100 Examples of Thermoplastics Applications in the Furniture and Bedding Market

Accessories: pegs, dowels, nuts, spacers, inserts, plate bearings, casters…	PE
Accessories: table feet, hinges, lighting brackets…	PP
Antifriction parts: bearings, rods…	PA
Armchair frames…	PA
Bathroom fittings, sanitary ware, soap dispensers, shower cubicles, shelves…	SAN
Bathroom stools are often in HDPE	PE
Bearings, bushings, wear pads…	POM
Beds are made out of thermoformed ABS	ABS
Bedsprings…	COPE
Bedsprings…	PEBA
Ceiling boxes from Fasal® for different lights	Bioplastics
Chairs, backrests, seats, and armchairs can be made out of ABS possibly combined with a metal structure	ABS
Chairs, backrests, seats, and armchairs can be made out of PMMA possibly combined with a metal structure	PMMA
Chairs, backrests, seats, and armchairs can be made out of polypropylene possibly combined with a metal structure	PP
City furniture, picnic tables, and parking poles made of Enviroplast	Bioplastics
Clips, wardrobe bars, drawers…	ABS
Clips, wardrobe bars, drawers… Styrenics, PS, HIPS	PS
Clothes hangers…	EMA
Coated metal racks and shelving…	PVC
Coffee tables, traveling tables, and modular storage elements	ABS
Coffee tables, traveling tables, and modular storage elements	PVC
Coffee tables, traveling tables, modular storage elements, small storage units, medicine chests… Styrenics, PS, HIPS	PS
Components for furniture…	SAN
Decorative profiles	ABS
Decorative profiles	PS
Decorative profiles	PVC
Decorative rods, bands, profiles…	ABS
Decorative rods, bands, profiles…	Cellulosics
Decorative rods, bands, profiles… Styrenics, PS, HIPS	PS
Demanding and top-of-the-range outdoor furniture: modified and reinforced polyamides	PA
Feet, end caps, pads…	TPS
Feet, pads…	TPV
Feet, pads… TPE based on PVC	TPE

Table 4.12 More than 100 Examples of Thermoplastics Applications in the Furniture and Bedding Market—cont'd

Feet, supports and pads…	TPO
Fittings, hinges, shower heads…	POM
Foam: panels for showrooms……	PVC
Foam: scenery…	PVC
Foam: shop fittings…	PVC
Furniture industry: ARBOFORM® (lignin-based)	Bioplastics
Furniture legs for bathroom furnishings: Fasal® wood-based thermoplastic	Bioplastics
Furniture, office, and institutional furniture…	PC
Garden equipment…	PC
Garden furniture…	PP
Grips, handles…	TPV
Grips, handles… TPE based on PVC	TPE
Handles, soft-touch overmolding…	TPO
Hinges, slides…	PA
Indoor and outdoor carpeting, carpet backing…	PP
Inflatable furniture…	PE
Inflatable furniture…	PVC
Inflatable furniture using sheets or films of polyethylene	PE
Inflatable furniture using sheets or films of PVC	PVC
Knobs, small furniture…	PMMA
Leather-like goods… TPE based on PVC	TPE
Lighting devices and accessories	PMMA
Lighting devices and accessories	PC
Newspaper racks, CD racks, bedside units, and valet stands	ABS
Newspaper racks, CD racks, bedside units, and valet stands	PC
Newspaper racks, CD racks, bedside units, and valet stands	PMMA
Patio furniture…	PVC
Seats of bus shelters	PA
Seats of bus shelters	PP
Seats of bus shelters	PVC
Seats of bus shelters: HDPE	PE
Small storage units and medicine chests	PS
Small storage units and medicine chests	ABS
Storage units and medicine chests (bottom-of-the-range small items)	PE
Street and bathroom furniture, seats…	PE

Continued

Table 4.12 More than 100 Examples of Thermoplastics Applications in the Furniture and Bedding Market—cont'd

Structures of play areas (ladders, stationary motorbikes, labyrinths, huts…) made out of highly colored HDPE	PE
Structures of play areas (ladders, stationary motorbikes, labyrinths, huts…) made out of highly colored PP	PP
Thrusts, slides, handles of doors and drawers, bolts…	ABS
Thrusts, slides, handles of doors and drawers, bolts… Styrenics, PS, HIPS	PS
Transparent coffee tables, traveling tables and modular storage elements	PMMA
Transparent furniture…	PMMA
Upholstery, coverings, padding…	PVC
Woodlike profiles: WPC or "synthetic wood" can be sawn, nailed, and screwed just like natural wood	PVC

4.10 Agriculture

4.10.1 Overview

The agricultural market consumes approximately 2–4% of all thermoplastics and, apart from packaging, can be divided into three main types of uses:

- plasticulture: films, pots, and other accessories
- pipes
- machinery.

4.10.1.1 Plasticulture

Thermoplastics make it possible to satisfy various functions of agriculture and plant breeding:

- Mulching: transparent or black LDPE, double-layered white and black LDPE for reflective purposes, photodegradable LDPE.
- Tunnels: plasticized PVC, LDPE, EVA.
- Flat covers: nonwoven PP, punched LDPE films.
- Greenhouses with simple walls: LDPE, EVA, PVC, multilayer LDPE/EVA, LDPE/recyclate.
- Greenhouses with multiple walls: PMMA, PC.
- Membranes for water reserves, geomembranes: PVC, PE, EVA.
- Ensilage films: LDPE, plasticized PVC.
- Cups, pots: PS, PP, bioplastics.
- Artificial soils: EPS.
- Mulching of radiant tubes for heating by warm water: PP.

4.10.1.2 Pipes

- Watering: PE, flexible PVC tube possibly reinforced with polyester yarn.
- Drainage: rigid PVC.
- Agricultural pulverization of weed killers, insecticides, fertilizers: reinforced PVC, PE, EVA, COPE.
- High-pressure couplings: reinforced PVC.
- Pneumatic control: PA, PE.

4.10.1.3 Machinery

Machinery is a heterogeneous sector that uses wisely all the properties of all thermoplastics. Applications are very diverse, covering all types of functionalities and a broad diversity of shapes and forms, from miniaturized (nozzle of atomizer) to giant parts (combine harvester). Requirements can be severe needing high-performance mechanical, thermal, optical, physical, or chemical properties obtainable with certain thermoplastics and thermoplastic composites.

4.10.2 Panel of Ideas for Application: 100 and More Examples

Let us quote, Table 4.13, without claiming to be exhaustive, some application examples for some thermoplastics. These examples can be commercialized, in development, potential, or related to very specific uses. The designer must verify the possibility of using the quoted thermoplastic family for his/her specific problem and must test the right grade in the real conditions of service life.

Table 4.13 More than 100 Examples of Thermoplastics Applications in the Agriculture Sector

Advertising product in the form of plant seeds packaged in a compostable blister: Plantic® material (starch-derived)	Bioplastics
Aerosol components, aerosol valves and heads…	POM
Agricultural paints: Cornpole (biodegradable bioplastic based on cornstarch)	Bioplastics
Agricultural pulverization of weed killers, insecticides, fertilizers: reinforced PVC tubes	PVC
Antifriction parts, bearings, bushings, rods, zippers…	POM
Antifriction parts: bearings, rods…	PA
Antifriction parts: bearings, rods… PA 11, 12	PA
Artificial soils: expanded PS	PS
Bearings (PTFE lubricated)…	PPS
Bearings, plugs, pads, feet, damping mounts…	PEBA
Casings, caps, framework of ventilation, fan blades, air filters, filters and pumps of agricultural machines, pipes…	PP
Cast and extruded sheets, cell-cast sheets for greenhouses…	PMMA
Caterpillars…	COPE
Cattle tags…	TPU
Clips, lugs, conveyor components…	POM
Co-extrusion with polyamides, polypropylene, polyethylene, EVA, thermoplastic polyester, polycarbonate, polystyrene, ionomers for packaging of fertilizers, herbicides, and other chemicals	EVOH
Constant velocity boots…	TPU
Constant velocity joint (CVJ) boots, rack and pinion bellows…	COPE
Conveyor belts…	TPU
Couplings, pump impellers…	POM
Cups, pots	PP
Cups, pots	PS
Cups, plant pot, tray: Bionolle™ (aliphatic polyester resin)	Bioplastics
Cups, plant pots, bindings, clips, and devices for the controlled release of pheromones: Mater-Bi® (starch)	Bioplastics
Damping mounts for noise and vibration…	MPR
Drive belts…	TPU
Ensilage films: LDPE	PE
Ensilage films: plasticized PVC	PVC
Artificial soil for horticulture…	PS
Heat insulation, soundproofing… Expanded PS	PS
Extruded and woven nets for potatoes, onions, etc.: Mater-Bi® (starch)	Bioplastics
Feet, end caps, pads…	TPS

Continued

Table 4.13 More than 100 Examples of Thermoplastics Applications in the Agriculture Sector—cont'd

Feet, pads…	TPV
Feet, pads… TPE based on PVC	TPE
Feet, supports, and pads…	TPO
Fibers: ropes for fish-farming, anchorage…	PE
Filaments, fibers, fabrics, partially and fully oriented yarns perform well in cordage, netting, woven bags…	PP
Films for tunnels and other agricultural applications…	PE
Filter housings…	POM
Fishing lures…	PVC
Flat covers: nonwoven PP	PP
Flat covers: punched LDPE films	PE
Tube: flexible PVC reinforced with polyester yarn	PVC
Fluid handling, coupling and fitting applications, potable water fittings…	PSU
Foam: Damping and protection; air, water and dust proofing, thermal insulation, soundproofing…	PP
Foam: impact and vibration damping…	PE
Foam: impact and vibration damping…	PVC
Foam: machine soundproofing…	PE
Foam: machine soundproofing…	PVC
Foamed seals…	TPV
Frames, ventilating parts…	PPE
Garden equipment…	PC
Garden hoses and pipes…	PVC
Garden sprayers…	POM
Garden supplies: ARBOFORM® (lignin)	Bioplastics
Garden, landscape gardening, and agriculture parts: BIOPAR®	Bioplastics
Gaskets and seals, hydraulic seals…	TPU
Gears, sprocket wheels, gearwheels, cams, springs…	POM
Glazing for greenhouses…	PC
Greenhouses with multiple walls	PC
Greenhouses with multiple walls	PMMA
Greenhouses with simple wall	PVC
Greenhouses with simple wall: EVA, multilayer LDPE/EVA	EVA
Greenhouses with simple wall: LDPE, multilayer LDPE/EVA, LDPE/recyclate	PE
Grips, handles… TPE based on PVC	TPE
Grips, handles, feet, pads for garden devices…	TPV

Table 4.13 More than 100 Examples of Thermoplastics Applications in the Agriculture Sector—cont'd

Handles…	ABS
Handles, soft-touch overmolding…	TPO
High-pressure couplings: reinforced PVC	PVC
Hoses and tubing, flexible tubing, hose jackets, convoluted tubing, hydraulic hoses, pneumatic tubing…	PEBA
Hoses and tubing, hydraulic hoses, flexible tubing…	TPU
Housing parts, handles and knobs…	POM
Housing parts, handles and knobs…	PPE
Housings…	ABS
Hydraulic, fuel and water hoses; airbrake hoses; monolayer and multilayer plastic fuel lines… PA 11, 12	PA
Insulation of tanks, pipes… PVC foam	PVC
Inflatable covers, structures, and devices…	PVC
Instrument panels, dials, indicators, tachometer covers…	PMMA
Irrigation equipment and valves…	POM
Large-sized objects: cisterns, tanks…	PE
Lawn and garden products: PLA bioplastics compounds	Bioplastics
Lenses for lights…	PMMA
Lighting fixtures, portholes…	PSU
Machine housings, pump housings and impellers, fluid and material handling components, water pump housings and impellers in machinery…	PPE
Machine lighting: lenses…	PC
Manifolds, distributor valves…	PSU
Membranes for water reserves	EVA
Membranes for water reserves	PE
Membranes for water reserves	PVC
Milk pumps…	POM
Motor and vibration mounts…	TPU
Motor and vibration mounts…	TPV
Motor and vibration mounts… TPE based on PVC	TPE
Mounts…	TPU
Mulching film, trash bag: Bionolle™ (aliphatic polyester resin)	Bioplastics
Mulching film: Mater-Bi®'s (starch)	Bioplastics
Mulching films: Cornpole (biodegradable bioplastic based on cornstarch)	Bioplastics
Mulching of radiant tubes for heating by warm water	PP

Continued

Table 4.13 More than 100 Examples of Thermoplastics Applications in the Agriculture Sector—cont'd

Mulching: transparent or black LDPE, double-layered white and black LDPE for reflective purposes, photodegradable LDPE	PE
Nameplates and bezels…	PC
Nameplates, medallions…	PMMA
Net, filament, yarn: Bionolle™ (aliphatic polyester resin)	Bioplastics
Overmolding… TPE based on PVC	TPE
Plant pot, tray: Bionolle™ (aliphatic polyester resin)	Bioplastics
Plant pots, bindings, clips and devices for the controlled release of pheromones: Mater-Bi® (starch)	Bioplastics
Porous filaments or membranes for micro- and ultrafiltration and reverse osmosis, membranes for wastewater recovery…	PSU
Poultry processing parts, food conveyors…	POM
Rack and pinion boots…	TPS
Rollers, bearings, bushings, conveyor plates, wear pads…	POM
Seals, gaskets, packing…	COPE
Seals, integrated seals… TPE based on PVC	TPE
Seedling and planter pots: Plantic® material (starch-derived)	Bioplastics
Soft handles and grips…	MPR
Technical parts: gears, screws and bolts, pulleys, collars, valve casings, rings, clips, ventilators, cooling fans, tanks, and containers…	PA
Technical parts: pneumatic and hydraulic hoses; fuel handling and hydraulic applications; gears, collars, valve casings, rings, clips… PA 11, 12	PA
Thrusters of pumps, hot water pumps…	PPS
Transparent and decorative parts for agricultural machines…	PC
Transparent and decorative parts for agricultural machines…	PMMA
Tree nursery (e.g., clips, tree protection spirals), pots, trays: Solanyl® (starch)	Bioplastics
Tubes for drainage: rigid PVC	PVC
Tubes for pneumatic control	PE
Tubes for pneumatic control	PA
Tubing for agricultural pulverization of weed killers, insecticides, fertilizers	COPE
Tubing for agricultural pulverization of weed killers, insecticides, fertilizers	EVA
Tubing for agricultural pulverization of weed killers, insecticides, fertilizers	PE
Tubing, pipes and fittings for aggressive environments and corrosive liquids…	ABS
Tunnels	EVA
Tunnels: LDPE	PE
Tunnels: plasticized PVC	PVC

Table 4.13 More than 100 Examples of Thermoplastics Applications in the Agriculture Sector—cont'd

Vineyard fasteners: Vegemat (natural fibers, starch, proteins, lipids)	Bioplastics
Water or sewer pipes, sheaths…	PE
Watering: polyethylene	PE
Weather stripping, window seals…	TPS

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

5 Avoid Some Pitfalls

OUTLINE

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00005-2

Polymers have some specific properties due to their organic nature. Thermoplastics, as seen in Chapter 2, are independent organic macromolecules with some sensitivity to environmental parameters: temperature, moisture, oxidation, deleterious solids, liquids, gases, and other chemical products. They are also sensitive to mechanical loading, especially cyclic loading. Their specific properties, such as electrical, optical, or esthetic properties, are also important for their applications.

All the properties are influenced by the additives used with the thermoplastic matrices, notably the reinforcements but also stabilizers, plasticizers, colorants, and others.

In addition, properties are affected by the processing method and possible finishing operations.

Properties including esthetics evolve more or less quickly during storage and use, which can lead to premature failure.

A common and important point of lack of understanding or misinterpretation is the nature of published data:

- Standard tests are rarely representative of the defined property required for the defined part to be studied. For a very simple example, an actual impact is rarely reproduced by a standard impact test. More surprising for many people, a tensile test result may be different from actual engineering data because of the differences concerning the shape of the part, the actual rate of loading, and small differences of temperature.
- Durability data often result from short tests that are not representative of conditions of use.
- Some results concerning chemical resistance are general assessments of behavior after "prolonged" immersions in a range of more or less pure chemicals at ambient temperature. Tested grades are not necessarily representative of all the polymer families. These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions.
- Combinations of aggressive parameters are rarely studied for practical reasons.
- Confusion of terms: for example, sometimes ultimate tensile strength at break and tensile stress at yield are confused making a huge difference for certain polymers. Same observations can be made for elongation at break and deformation at yield.
- Often tests are run under unknown conditions or, for some materials, certain properties are not directly measured but are deduced by analogy with other similar materials. It is often the case for thermal and electrical properties.
- Published data are often averages or high values, resulting from tests on specimen produced in the best conditions. Statistical results are rare and, unfortunately, weak points are potentially failure initiators. The numerous parameters involved during the development, production, processing, and use of plastics parts and products lead to a broad statistical distribution of the properties as far as the material is complex.
- When the lowest and highest values of a property are displayed, often more in-depth studies show that it is possible to find even lower figures coming from specific grades having some specific properties. Designers are often optimistic and they must be informed that these lower data are not errors and really exist.

In no case, collected data provide ready-to-use figures. The values used for computing must result from tests on the grade of material to be really used, processed in the conditions of the part to be designed. The collected figures give only ways for a better reflection. In the end, the designer is responsible for its choices and must assume data used for designing, taking the responsibility to use low, average, or high figures related to any suitable properties.

5.1 Balance Well-Estimated Part Requirements and Properties of the Used Compound: Objectively Fill Out Your Checklist

Defining objectively required part features may seem obvious but sometimes some aspects of functionalities are forgotten or are not fully evaluated. It would be advisable to remember that the first step is to prescribe specifications in an objective way:

- An undervaluation of the constraints leads to problems during use.
- An overvaluation of the requirements involves an overcharge due to the selection of materials that have unnecessarily high performance levels and are often more difficult to process and more expansive.

- Part oversizing causes useless expenditures because of excess of used material and higher processing difficulties.
- Part downsizing may lead to problems during use.
- An overvaluation of the compound properties leads to problems during use.
- Selection of an outperforming polymer generally leads to higher costs except if material overcharges are compensated for by processing or finishing or running cost savings.
- Do not forget weak points initiating failures.
- Do not forget aging, wear, and degradation by normal use.
- Remember that plastics properties are time-dependent, and cyclic stresses are more damaging than static ones.
- Remember that the combination of several factors often has a synergistic effect: a plastic resistant to a chemical in the absence of mechanical stress at ambient temperature can quickly crack when exposed to a certain load and may be degraded more or less quickly in the event of a temperature rise. However, when a combination of factors is effective, the highest value of each factor must not be systematically retained but the highest couple really reached must be studied.

The criteria to be examined are, among others, without claiming to be exhaustive:

- targeted lifespan, end of life criteria
- temperature: extremes and average
- environment: outdoor exposure, light, moisture, ozone, corrosion, radiation…
- physical properties: transparency, thermal and electrical conductivity, gas permeability, tribological properties…
- mechanical properties: instantaneous, permanent or cyclic stresses, impact…
- chemical properties: risks of polymer corrosion, risks of environmental pollution by the plastic, food contact, desorption of ingredients in space vacuum, pollution of chemical and electrochemical baths, migration…
- electrical properties: influence of moisture, temperature, and aging
- dimensional tolerances
- weight
- esthetics, color, gloss…
- environmental requirements
- price: has not only to be considered per kilogram, but also according to the fundamental properties. The total lifetime cost, taking account of the expenses of assembly, maintenance, disposal, etc., is the true criterion.

5.1.1 Failure Onset: Weak Points and Average Properties

For unused parts, the localized values of a property at any point of the part are subjected to a dispersion in the bulk of the part and to another dispersion between different parts. Moreover, this double dispersion is enlarged by aging and service life.

According to the material and the process, macromolecular and reinforcement orientations can dramatically change the properties depending on the direction of constraints versus that of processing.

Consequently, an actual property at a spot of a part can be far from the property measured on laboratory samples.

Weakest values, lower than the average value, generally provided by producers are initiators of failure. Figure 5.1 schematizes an example of a theoretical property. The onset of satisfaction (200 in this theoretical example) is totally satisfied at the initial stage. After aging, the average value is good enough (240) but there is a lot of data lower than the satisfaction onset, which leads to potential risks of failure. It is necessary to improve the aging resistance or the average initial property and its dispersion, to enhance the values after aging. Theoretically, it may also be possible to lower the acceptable aggressive constraints during the service life if the customer agrees. If not, it is possible to shorten the predicted lifetime with possible marketing consequences.

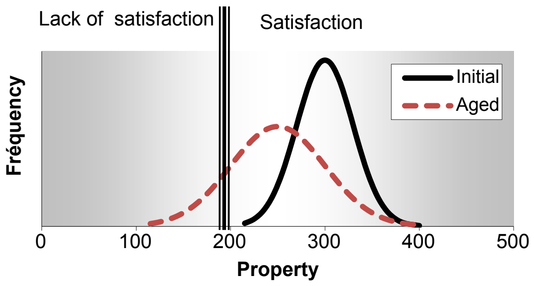


Figure 5.1 Weak points and user's dissatisfaction.

Weak points are often located at interfaces between reinforcements and matrix, joining between two different subparts, weldlines, sharp angles, voids…

5.1.2 Alternative Polymers Possibly More Expensive Can Lead to Cheaper Solutions

The set of properties and cost of each raw polymer is specific but many engineering applications can be satisfied, thanks to several raw polymers. The selection will depend on a suitable ratio of durability and final cost including part price, service life, operating costs, and collateral damages linked to repairing and change of the failed part. These latter can be out of all proportion compared to the part cost and there are many examples as varied as hot water pipes, rings for aeronautics, hoses for automobile cooling system, timing belts for automotive engines, seals for ship power systems, etc.

For example, Figure 5.2 shows examples of stresses at yield and continuous use temperatures (CUT) for an array of neat thermoplastics. If the onset of satisfaction is:

- about 100 °C for the CUT, stress at yield ranges from 20 up to 80 MPa. Higher yield strength can lead to thinner parts less costly.
- about 60 MPa or more for the stress at yield, CUT ranges from about 80 °C up to 425 °C. Higher CUT may lead to more durable parts, which reduces end part cost.

Please remember that according to Chapter 2, ultimate tensile strength and yield strength may be approximately doubled, thanks to glass fiber reinforcement, mean data rising from 55/60 MPa up to 115/125 MPa.

For example, Table 5.1 displays three examples of the tensile strength range obtained per 1 €/l (high values are the most interesting).

- Specialty grades are less interesting from this point of view but they have other high-tech performance such as high temperature or chemical resistance, for instance.
- Commodity plastics are the most interesting, thanks to fair engineering tensile strength and low material cost but some performances are limited.
- Engineering plastics have a middle position with intermediate cost and intermediate or good tensile strength. They have other interesting characteristics either mechanical, chemical, electrical and/or specific properties, for example tribological, magnetic, FR, etc.

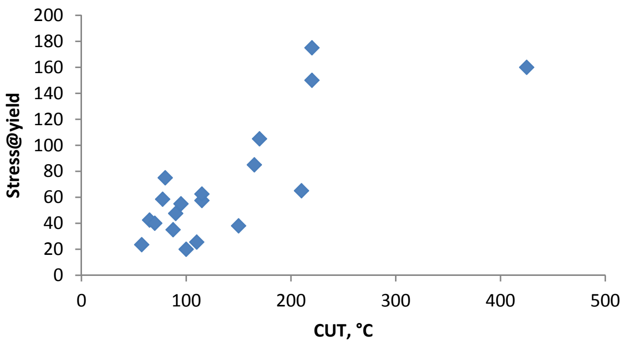


Figure 5.2 Stress at yield versus continuous use temperatures (CUT).

Table 5.1 Examples of (Tensile Strength/Raw Material Cost) Ratios, MPa/€/l

	Low	High Value
Specialty	<1	3
Engineering	<1	10
Commodity	<1	20

The cost of the used resin is only one element among others such as manufacturing costs and possibly running costs, disposal cost including waste collection and, if appropriate, recycling costs. In that case the recycled polymer value must be deduced from the recycling cost. Consequently, this rating can be turned upside down by other costs. For example, carbon fiber-reinforced thermoplastics despite their high cost find growing applications.

5.1.3 Downsizing Thanks to Expensive Performing Resins Can Save End Costs

Obviously, for a given compound, thickness reduction saves material weight and related cost. In addition, cooling and cycle times are reduced saving processing costs. However, strength is reduced in proportion of the affected dimensions.

For a given injected part, a thickness lowering of 10% can lead to:

- 27% weight saving for a 3D reduction or 19% for a 2D reduction or 10% for a 1D reduction
- 7–10% injection cycle time reduction (see Table 5.2)

Table 5.2 Examples of Cycle Time Reductions versus Wall Thickness Reduction

	Cycle Time Variation (s) for 10% Wall Thickness Reduction
POM	–8.8
PP	–8.5
PA	–9
PBT	–8.7
PC/ABS	–8

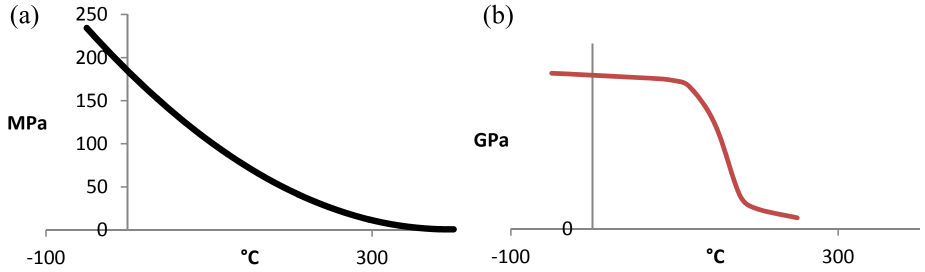


Figure 5.3 (a) High-tech thermoplastic: flex strength versus temperature. (b) High-tech thermoplastic: flex modulus versus temperature.

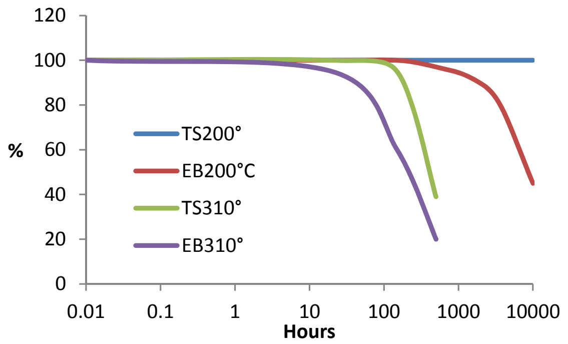


Figure 5.4 High-tech thermoplastic: tensile strength and elongation at break retentions versus time.

- 5–15% total cost saving for 1D to 3D reduction
- 19% tensile property reduction for a 2D reduction or 10% for a 1D reduction

To compensate for, it may be possible to select a more performing material. If tensile behavior must be kept at the same level, the new material must offer:

- at least 10–19% higher tensile performance
- a cost inferior to 1.05–1.15 times the cost of the material to be replaced.

These results relate to a few grades only processed in specific conditions and cannot be generalized.

It is imperative that the final selection is made by a skilled team or with the assistance of a polymer specialist.

5.1.4 Examples of Usual Combinations of Aggressive Factors

Most common cases combine heat, time on the one hand, and mechanical or chemical stresses on the other hand. The following of the book details those problems but we remind some brief facts to quickly give rough ideas of their extent. Without claiming to be exhaustive, let us quote some examples that are not rules.

- Heat and mechanical loading: Figure 5.3(a) and (b) shows examples of a high-tech thermoplastic. For a commodity thermoplastic, variations have the same general appearance but curves are much lower. We can remark the regular decrease in the tensile strength and the huge drop of the modulus.
- Time and heat: heat aging. Figure 5.4 shows the tensile strength and elongation at break retentions for a high-tech thermoplastic. Please note the logarithmic scale for time. For a commodity thermoplastic, variations have the same general appearance but are faster. We can remark the fast drop of elongation at break compared to the slower decrease in the tensile strength for a same temperature.
- Time and permanent stresses: creep, relaxation. Figure 5.5 shows the percentage of creep deformation for a high-tech thermoplastic at 23 °C under loads of 10, 30, and 50 MPa. Please note the logarithmic scale for time. For a commodity thermoplastic, deformations have the same general appearance but are much higher.

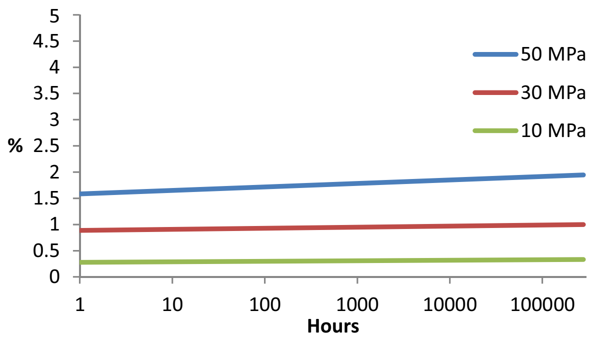


Figure 5.5 High-tech thermoplastic: creep deformation versus time.

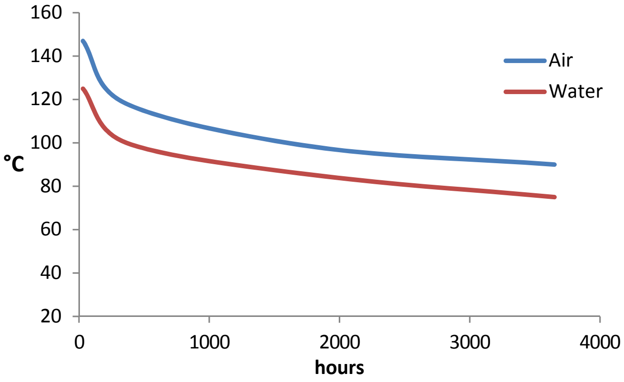


Figure 5.6 Engineering thermoplastic: examples of half-life temperatures for air and water aging.

- Water and heat aging: Figure 5.6 compares half-life temperatures for air and water aging of a moderately hydrolysis sensitive thermoplastic. In this case, water speeds up the degradation.
- Time and UV exposition: Figure 5.7(a) and (b) shows, for an engineering thermoplastic, variations of elongation at break, modulus, and yellowing index during an artificial exposition to UV (Xenotest 1200). We can remark the erratic and drastic variation of elongation at break divided by a factor higher than 10. Modulus is divided by 3.
- Stress, time, and chemicals: Table 5.3 displays some examples of critical stresses initiating cracks after 1 or 24 h of immersion in various fluids. Critical stresses at 24 h are several times lower than the tensile strength in air and water. For liquids leading to a limited behavior of unstressed polystyrene, critical stresses are even lower.
- Heat and chemicals: For a panel of polymers and chemicals, a rather low temperature increase of 40 °C leads, after 37 days (a rather short duration), to an increase of swelling

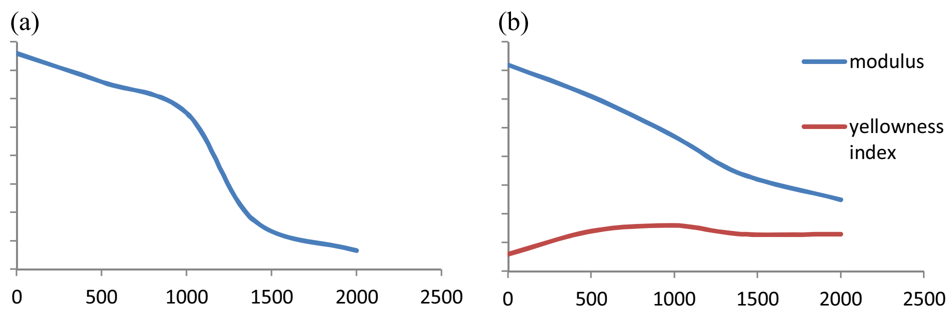


Figure 5.7 (a) Engineering thermoplastic: UV aging, elongation at break. (b) Engineering thermoplastic: UV aging, modulus, and yellowing index.

Table 5.3 Polystyrene: Example of Critical Stresses

	Critical Stress 1 h (MPa)	Critical Stress 24 h (MPa)	Unstressed Behavior
Heptane	<2		Nonsatisfying
Mix 50/50 olive oil/oleic acid	10	3	Limited
Methanol	10	8	Limited
Air	20	17	Good
Detergent		10	Limited
Acid for accumulator		17	Limited
Water		17	Good

and loss of tensile strength (TS). Elongation at break (EB) is doubled. Those average data cover very diverse situations ranging from no significant change up to failure with loss of tensile strength and high gain or loss of elongation at break.

Temperature, °C	Days	Swelling, %	TS Loss, %	EB Gain %
20	37	3	14	31
62	37	5	19	68

5.2 Mechanical Properties: At Break, at Elastic Limit, at Yield, after Creep

A lot of current mechanical characteristics are deduced from the stress–strain curves.

It must be noted that mechanical behavior is time-dependent and temperature-dependent resulting in the need to simultaneously consider the three-pillar system: load–time–temperature. In addition, some thermoplastics such as polyamides are plasticized by moisture absorption (see subchapter below).

Figure 5.8 shows the case of two tensile behaviors:

- One for a brittle polymer, when the break arises immediately after the yield point or coincides with it.
- The other for a ductile polymer, when the break point is far from the yield point. Other behaviors may be observed between yield point and break.

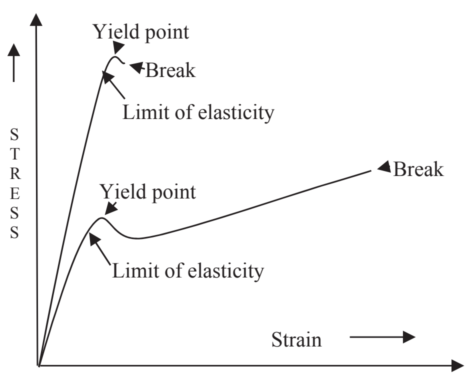


Figure 5.8 Examples of tensile behavior of polymers.

Although resulting from low-speed tests, these curves give results only under "instantaneous" loads, whereas in real life the parts are often exposed to long-term stresses or strains. For this, it is necessary to refer to the long-term mechanical properties.

Main conventional mechanical measurements are:

- Limit of elasticity
- Yield point
- Stress and strain at yield
- Break
- Ultimate stress and strain
- Modulus (see various readings).

The loading types generally used are:

- Tensile: it is generally a unidirectional loading. Bidirectional tensile properties are measured for modeling.
- Flexural: it is generally a unidirectional loading.
- Compression: it is generally a unidirectional compression. Bulk compression is rarely measured, except for modeling.

Obviously, the performance level is highly linked to the use of reinforcing materials.

Designer is cautioned that the product data sheets do not always clarify whether the supplier is providing:

- Ultimate tensile strength or strength at yield
- Elongation at break or strain at yield
- Young's modulus, initial modulus, or a secant modulus.

Please note that provided data are generally:

- Average data that hide low values
- Results of standard tests on well-processed test pieces in defined conditions that are different of application conditions
- Results on well-conditioned samples of a compound different of that used
- Quoted examples are not rules and cannot be used for computing and designing. Only results obtained with the used compound processed by a method similar to that used for real part production are convenient.

5.2.1 Elastic Limit or Proportional Limit

The elastic or proportional limit is the greatest stress at which the stress is proportional to strain. Note that some materials maintain this proportionality for large stresses and strains, while others show proportionality for very low strains. For some materials, there is not proportionality.

5.2.2 Yield Point

The yield point is the first point of the stress–strain curve for which one notes an increase in the strain without an increase in the stress. Parts must always operate well below this point during service. Note that some materials have not a yield point.

5.2.3 Stress and Strain at Yield

Stress and strain at yield are the values of the stress and strain corresponding to the yield point. Strain at yield is always inferior to elongation at break. Strain at yield may be slightly (one or some percent) or highly (up to more than 100%) different from elongation at break.

5.2.4 Ultimate Stress and Strain

Ultimate stress and strain, or stress and strain at break, are the values corresponding to the breaking of the samples.

5.2.5 Elastic Modulus

The elastic modulus is the slope of the tangent at the origin of the stress–strain curve. The tensile or compression modulus is often called Young's modulus, whereas the torsion modulus is often called shear modulus or Coulomb's modulus.

For some plastic materials, the elastic modulus can be misleading due to the material nonlinear elasticity leading to a flattening of the stress–strain curve.

5.2.6 Initial Modulus

If the rectilinear region at the start of the stress–strain curve is too difficult to locate, the tangent to the initial portion of the curve must be constructed to obtain the initial modulus. For some plastic materials, the initial modulus can be misleading due to the material nonlinear elasticity leading to a flattening of the stress–strain curve.

5.2.7 Secant Modulus

The secant modulus is the ratio of stress to corresponding strain at any point on the stress–strain curve. For example, the 1% secant modulus sometimes provided by producers or compounders is the stress at 1% strain. For a defined material, the secant modulus is lower than the initial modulus.

Apart from these characteristics measured at low speeds, creep characteristics are measured under static conditions, mainly creep modulus and creep strength.

5.2.8 Creep Modulus

The creep modulus for a specified stress, time, and temperature is the value of the stress divided by the strain measured after the creep time under consideration.

5.2.9 Creep Strength

The creep strength for a specified time and temperature is the value of the stress leading to failure after the creep time under consideration.

Creep modulus and strength values are broadly inferior to their counterparts measured by dynamometry. For instance, Table 5.4 displays tensile modulus and creep modulus for four engineering thermoplastics. Creep modulus at 1 h is 13–40% lower than elastic modulus, and creep modulus at 1000 h is 29–56% lower than elastic modulus.

5.3 Do not Confuse Local and Bulk Properties: Take into Account the Statistical Distribution of Properties

The numerous parameters involved during the development of polymers and additives, plastics processing, use of parts, and products lead to a statistical distribution of the properties as far as the material and the part geometry are complex.

5.3.1 Means Are False Friends

The common characterization of properties by their average value hides the weak points and leads

Table 5.4 Tensile Modulus and Creep Modulus Examples

	PBT		POM		PA66 Wet		PC	
	MPa	%	MPa	%	MPa	%	MPa	%
Elastic modulus	2500		2600		1300		2400	
Creep modulus 1 h	1500	60	1800	69	1000	77	2100	87
Creep modulus 1000 h	1100	44	1300	50	700	54	1700	71

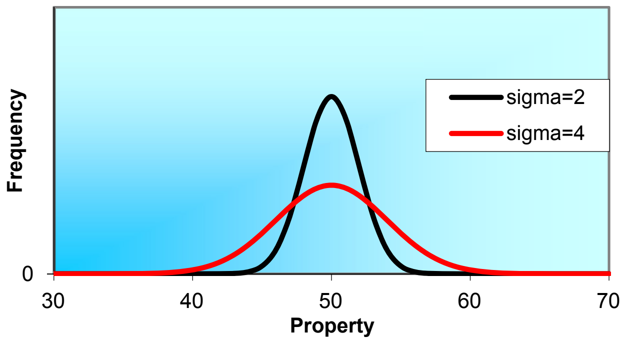


Figure 5.9 Normal distribution and standard deviation.

to a false safe feeling. The statistical treatment of experiments allows computing the lowest properties of weak points that are not visible.

Figure 5.9 displays the frequency versus the values of a theoretical property for two materials having the same mean property (50) with a standard deviation respectively of 2 and 4.

To have less than 1/10,000 failure, it is necessary to limit the service stress to 42 in one case and 35 in the other case.

Table 5.5 compares the statistical distribution of the results of strength at break of a steel and two thermoplastic materials:

- average, μ
- standard deviation, σ
- coefficient of variation, Cv, defined as the ratio between the standard deviation (σ) and average (μ): $Cv = \sigma/\mu$
- 95% confidence interval: two standard deviations on both sides of the average value.

Quoted examples are not rules and cannot be used for computing and designing. Only results obtained with the used compound processed by a method similar to that used for real part production are convenient.

5.3.2 Standard Deviation Depends on Multiple Factors

For laboratories trained in characterization of plastics, the distribution of the results depends, among other things of the nature of the measured characteristic, the history of the samples and the preparation of test specimens.

Table 5.6 displays examples of statistical results of stress and strain measured under tensile, compression, and shear loads for 26 different samples. Coefficients of variation are in a broad range from 0.5% up to 18.3%:

- 0.54% up to 3.4% for medium tensile strengths and 9% and 10.4% for high values of tensile strength related to composites (samples E and F)
- 9.3% and 11.6% for compression strength
- 3.9–8.3% for shear strength
- 0.7–7.1% for tensile modulus
- 3.3% and 6.2% for compression modulus
- 5.6–12.5% for shear modulus
- 9.5–18.3% for deformations.

Quoted examples are not rules and cannot be used for computing and designing. Only results obtained with the used compound processed by a method similar to that used for real part production are convenient.

5.3.3 A Thorny Example: Notched Izod Impact Resistance

Although apparently well defined, the Notched Izod impact test includes several methods and is

Table 5.5 Tensile Strength of Various Materials

Material	μ (MPa)	σ (MPa)	C_v (%)	95% Confidence Interval
Steel	527.9	1.161	0.2	526–530
Polycarbonate	59.18	0.3217	0.54	58.5–59.8
PMMA	77.62	2.606	3.4	72.4–82.8

Table 5.6 Statistical Distributions of the Results of Different Mechanical Tests

	Average	Standard Deviation	Coefficient of Variation	95% Confidence Interval	
Strength (MPa)					
Tensile strength					
Sample A	23.8	0.4	1.7	23	24.6
Sample B	26.9	0.8	3	25.3	28.5
Sample C	59.2	0.32	0.54	58.5	59.8
Sample D	77.6	2.6	3.4	72.4	82.8
Sample E	288	30	10.4	228	348
Sample F	266	24	9	218	314
Compression strength					
Sample G	155	18	11.6	119	191
Sample H	150	14	9.3	122	178
Shear strength					
Sample I	19	1.5	7.9	16	22
Sample J	18	0.70	3.9	16.6	19.4
Sample K	14	1	7.1	12	16
Sample L	12	1	8.3	10	14
Modulus (GPa)					
Tensile modulus					
Sample M	0.274	0.017	6.2	0.240	0.308
Sample N	0.295	0.021	7.1	0.253	0.337
Sample O	14	0.1	0.7	13.8	14.2
Sample P	13	0.7	5.4	11.6	14.4
Compression modulus Compression					
Sample Q	16	1	6.2	14	18
Sample R	15	0.5	3.3	14	16

Table 5.6 Statistical Distributions of the Results of Different Mechanical Tests—cont'd

	Average	Standard Deviation	Coefficient of Variation	95% Confidence Interval	
Shear modulus					
Sample S	1.70	0.2	11.8	1.3	2.1
Sample T	1.6	0.2	12.5	1.2	2
Sample U	1.8	0.1	5.6	1.6	2
Poisson's ratio					
Sample V	0.10	0.01	10	0.08	0.12
Deformation (%)					
Strain at yield					
Sample W	26.5	3.4	12.8	19.7	33.3
Sample X	34.3	5.7	16.6	22.9	45.7
Elongation at break					
Sample Y	409	39	9.5	331	487
Sample Z	311	57	18.3	197	425

difficult to run, leading to a large range of averages and standard deviations.

Among various standards, the ASTM D 256 shows the difficulty and diversity of the tests.

ASTM D 256-02 "Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics" includes four test methods A, C, D, and E differing by the specimen and the procedure. Apart from the used test method, this standard specifies "Caution must be exercised in interpreting the results of these standard test methods." The following testing parameters may affect test results significantly:

- Method of fabrication, including but not limited to processing technology, molding conditions, mold design, and thermal treatments;
- Method of notching;
- Speed of notching tool;
- Design of notching apparatus;
- Quality of the notch;
- Time between notching and test;
- Test specimen thickness;
- Test specimen width under notch; and
- Environmental conditioning.

Table 5.7, based on a round robin in accordance with Practice E 691, displays test results according to Method A, C, or E. Values are expressed in ft·lbf/in. of width (J/m of width).

- Test methods A and C: For each material, all the test bars were prepared at one source, except for notching. Each participating laboratory notched the bars that they tested. The basis of a test result is the average for five specimens. In the round robin, each laboratory tested, on average, nine specimens of each material.

  For a same test method, A, polycarbonate is the most resistant.

  For a same material, phenolic and two test methods, A and C, data are different. Compared to method C, method A leads to a higher average (+27%) and a lower standard deviation (−37%).
- Test method E is based on a round robin involving five materials tested by seven laboratories. For each material, all the samples were prepared at one source, and the individual specimens were all notched at the same laboratory. Test results are the average for five specimens. In the round robin, each laboratory tested 10 specimens of each material.

Table 5.7 Round Robin Results, Test Methods A, C, or E—Values in ft·lbf/in. of Width (J/m of Width)

Material	Method	Average	Sr[a]	SR[b]	Ir[c]	IR[d]	Number of Laboratories
Thermoplastics							
Acetal	A	1.45 (77.4)	0.075 (4.0)	0.604 (32.3)	0.21 (11.2)	1.70 (90.8)	9
Reinforced Polyamide	A	1.98 (105.7)	0.083 (4.4)	0.245 (13.1)	0.23 (12.3)	0.69 (36.8)	15
Polypropylene	A	2.66 (142.0)	0.154 (8.2)	0.573 (30.6)	0.43 (23.0)	1.62 (86.5)	24
ABS	A	10.80 (576.7)	0.136 (7.3)	0.585 (31.2)	0.38 (20.3)	1.65 (88.1)	25
Polycarbonate	A	16.40 (875.8)	0.295 (15.8)	1.056 (56.4)	0.83 (44.3)	2.98 (159.1)	25
Acrylic, injection molded	E	10.33 (551.6)	0.878 (46.9)	1.276 (68.1)	2.49 (133.0)	3.61 (192.8)	7
Acrylic sheet	E	3.02 (161.3)	0.243 (13.0)	0.525 (28.0)	0.68 (36.3)	0.71 (37.9)	7
Thermosets and composites							
Phenolic	A	0.57 (30.4)	0.024 (1.3)	0.076 (4.1)	0.06 (3.2)	0.21 (11.2)	19
Phenolic	C	0.45 (24.0)	0.038 (2.0)	0.129 (6.9)	0.10 (5.3)	0.36 (19.2)	15
Premix molding compounds laminate	E	6.11 (326.3)	0.767 (41.0)	0.786 (42.0)	2.17 (115.9)	2.22 (118.5)	7
Compound (SMC) laminate	E	11.00 (587.4)	0.719 (38.4)	0.785 (41.9)	2.03 (108.4)	2.22 (118.5)	7
Preformed mat laminate	E	19.43 (1037.6)	0.960 (51.3)	1.618 (86.4)	2.72 (145.2)	4.58 (244.6)	7

[a] *Sr = within-laboratory standard deviation of the average.*
[b] *SR = between-laboratories standard deviation of the average.*
[c] *Ir = repeatability = 2.83 Sr.*
[d] *IR = reproducibility = 2.83 SR.*

5.3.3.1 Concept of Repeatability (Ir) and Reproducibility (IR)

Sr being within-laboratory standard deviation of the average.

SR being between-laboratories standard deviation of the average.

Repeatability (Ir) = 2.83 Sr.

Reproducibility (IR) = 2.83 SR.

If Sr and SR have been calculated from a large enough body of data, and for test results that were averages from testing five specimens:

Ir = 2.83 Sr.

IR = 2.83 SR.

Repeatability, Ir

Repeatability, Ir compares two test results:

- for the same material, obtained by
- the same operator
- using the same equipment
- on the same day.

The two test results should be judged not equivalent if they differ by more than the Ir value for that material.

Reproducibility, IR

Reproducibility, IR, compares two test results:

- for the same material, obtained by
- different operators
- using different equipment
- on different days.

The two test results should be judged not equivalent if they differ by more than the IR value for that material.

Any judgment in accordance with previous information would have an approximate 95% (0.95) probability of being correct.

Table 5.7 displays averages, standard deviations, repeatability, Ir, and reproducibility, IR for various thermoplastics, thermosets, and composites. We can note the high values and the broad range of repeatability (Ir) and reproducibility (IR) leading to be cautious when reading impact test results.

Figure 5.10 shows repeatability (Ir) and reproducibility (IR) ranked by increasing values.

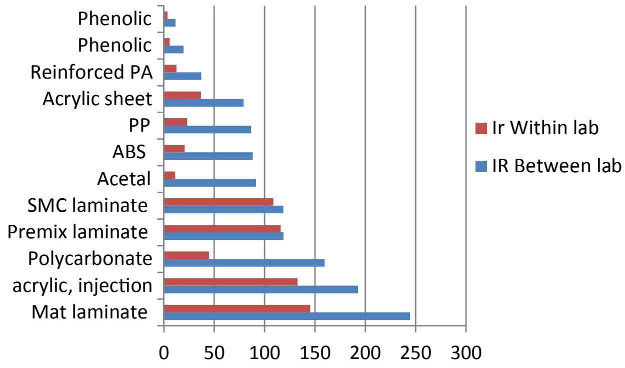


Figure 5.10 Notched Izod impact: repeatability, Ir and reproducibility, IR.

5.4 Chemical Behavior: Nature of Chemicals, Time, Temperature, Environmental Stress Cracking

5.4.1 Chemical Resistance of Unstressed Samples by Immersion or Contact

The action of a chemical on a plastic can induce three concomitant phenomena:

- Absorption of the fluid by the plastic, which leads to a swelling of the part.
- Extraction by the fluid of some material components (plasticizers, in particular, antidegradants, monomers and oligomers, colorants). This extraction can reduce the apparent swelling of the part, or even lead to a retraction.
- Pollution of the fluid by the immersed polymer: desorption of particles and ingredients.

The tests themselves consist in immersing the unstressed sample in the fluid under consideration for a given time at a given temperature.

The generated effects can be highlighted in several manners:

- Evaluation of the volume, weight, or dimension swelling of the sample.
- Percentage of extracted materials.
- Degradation of the mechanical characteristics, either immediately, or after drying.

For these tests, the service liquids (solvent, oil, hydraulic fluid, acid, base…) can be used but, to ease the establishment of specifications and comparative tests, one often uses reference solvents, oils, fuels. The most current are IRM 901, 902, or 903 oils (which replace ASTM 1, 2, and 3 oils), fuels, or solvents ASTM A, B, C.

One of the traps is the short duration of tests, often 7 days when parts are used during several years. If results of short duration tests are:

- unsatisfying, the material may be rejected without doubt nor regret if there is other satisfying material(s)
- satisfying, it is not possible to forecast behaviors during months or years.

Other traps, without claiming to be exhaustive, include:

- the precise nature of the chemical: raw or technical species may be more aggressive than pure chemical
- cycles alternating immersion and emersion, which may lead to higher degradation that continuous immersion
- Actual temperatures.

5.4.2 Chemical Resistance of Stressed Samples: Combination of Mechanical Loading and Contact with Chemicals—Environmental Stress Cracking

When a plastic exposed to air is subjected to a stress or a strain below its yield point, cracking can occur after a very long duration. The simultaneous exposure to the chemical environment under the same stress or strain can lead to a dramatic reduction of the failure time. The accelerated cracking in this way corresponds to the "environmental stress cracking" (ESC).

Table 5.3 displays, for polystyrene, some examples of critical stresses initiating cracks after 1 or 24 h of immersion in various fluids. Critical stresses at 24 h are several times lower than tensile strength in air and water. For liquids leading to a limited behavior of unstressed polystyrene, critical stresses are even lower.

Chemical behavior study of an unstressed compound is not representative of its ESC behavior that must be studied in representative conditions.

5.5 Ambient Humidity Can Plasticize Polymers and Change Their Properties Including Electrical Properties

Ambient humidity can plasticize polymers and change their electrical properties. In particular, polyamides are more or less hygroscopic according to their chemical formula. Table 5.8 displays examples of moisture absorption at 50% RH and saturation at 23 °C. Other data may be found elsewhere according to the formulation and test method.

For a defined polymer, the amount and rate of moisture absorbed from the atmosphere depends on the ambient humidity and temperature.

For polyamide, published mechanical and electrical data relate to dry material, on the one hand, and conventional wet material (50% relative humidity (RH) at 20 °C), on the other hand.

The time it takes for polyamide to come to equilibrium depends on the thickness. Figure 5.11 shows some

Table 5.8 Examples of Moisture Absorption at 50% RH and Saturation at 23 °C

PA	50% RH	Saturation
6	2.7	9.5
6/6	2.5	8.0
6/10	1.5	3.5
6/12	1.3	3.0
11	0.8	1.9
12	0.7	1.4

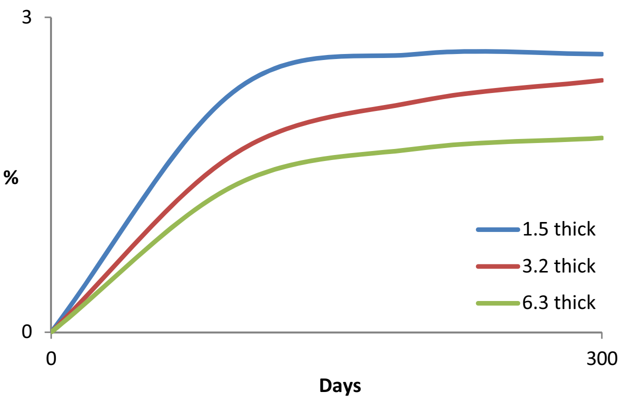


Figure 5.11 PA66: Moisture content versus time at 50% RH, 23 °C.

examples for samples of PA66 1.5-, 3-, and 6.3-mm thick. After 300 days, equilibrium is not reached for thickest samples.

Polyamide parts expand with exposure to moisture. These changes are small but must be considered in particular for very large dimensions or very tight tolerances.

Polyamides increase in impact resistance and toughness, while their strength and stiffness properties decrease as they absorb moisture.

Table 5.9 displays some examples of mechanical properties of dry and conditioned (50% RH, 23 °C) polyamides. Tensile modulus and yield strength or tensile strength at break are strongly decreased by conditioning, while strain at yield or elongation at break is more or less increased. Quoted examples are not rules and cannot be used for computing and designing. Only results obtained with the used compound processed by a method similar to that used for real part production are convenient.

Table 5.10 displays examples of Izod impact strength of dry or conditioned (50% RH, 23 °C) PA66. Conditioned samples are systematically tougher than dry samples but there is not an exact correlation between the two properties.

Table 5.11 displays examples of electrical properties of dry or conditioned (50% RH, 23 °C) polyamides. Conditioned samples are systematically more conductive than dry samples.

Quoted examples are not rules and cannot be used for computing and designing. Only results obtained with the used compound processed by a method similar to that used for real part production are convenient.

5.6 Often Properties Evolve Abruptly: Glass Transition, Yield, Knees, Frequency-Dependent Properties

Kinetics of polymer properties are rarely of the first order and are often more complex with abrupt and surprising evolutions.

Earlier we have seen examples of:

- glass transition with the sudden variation of modulus,
- yield point of mechanical properties with the change of strength evolution.

Table 5.9 Examples of Dry and Wet Properties of Various Polyamides

Polyamide	Glass Fiber		Tensile Modulus (GPa)	Yield Strength (MPa)	Yield Strain (%)	Tensile Strength (MPa)	Elongation at Break (%)
PA66		Dry	3.2	85	4		
		Conditioned	1.6	50	10		
PA6.66		Dry	3.0	85	3.6		
		Conditioned	1.1	50	25		
PA1010		Dry	0.8	40			
		Conditioned	0.6	35	30		
PA12		Dry	1.8	50	5		
		Conditioned	1.3	45	20		
PA66	25	Dry	6.4			85	2
	25	Conditioned	4.9			70	3
PA6	30	Dry	10			170	3.5
	30	Conditioned	5.8			100	6
PA6.66	30	Dry	9.8				
	30	Conditioned	6.5				

Table 5.10 Examples of Impact Strength of Dry and Conditioned Polyamides

Examples of Izod Impact of PA66 23 °C, J/m		
Polyamide	**Dry as Molded**	**Conditioned**
A	43	69
B	43	107
C	53	75
D	53	112
E	69	134
F	166	240
G	No break	800
H	910	910–1330
Unnotched Charpy impact, kJ/m^2		
Average	78	91
Standard deviation	10	10.5
Minimum	45	70
Maximum	95	110
Notched impact Charpy, kJ/m^2		
Average	12	17
Standard deviation	2.3	2.9
Minimum	6	14
Maximum	20	25

Table 5.11 Examples of Electrical Properties of Dry or Conditioned (50% RH, 23 °C) Polyamides

Electrical Properties	Dry	Conditioned
Volume resistivity (PA)	1.00E + 14 ohm-cm	1.00E + 10 ohm-cm
Surface resistance (PA)	1.00E + 12 ohm	1.00E + 10 ohm
Relative permittivity at 100 Hz (PA66)	4.1	6
Relative permittivity at 100 Hz (PA6.66)	4.3	9
Relative permittivity at 100 Hz (PA6.66 30 GF)	4	9.5

For long-term aging and periodic phenomena, beware of abrupt changes, thresholds, knees or sudden failure, and so on.

Among other examples, without claiming to be exhaustive, we can quote:

- aging degradation
- Transparency and wavelength.

5.6.1 Kinetics Changes during Long-term Tests in Steady Conditions

Figure 5.12 displays the hoop stress curve of a polyethylene pipe with the stage I concerning a first kinetics leading to a slow decrease of the property, then a stage II with a faster second

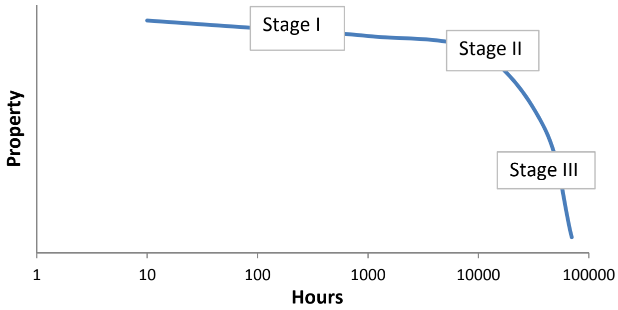


Figure 5.12 Aging example: property decay versus time.

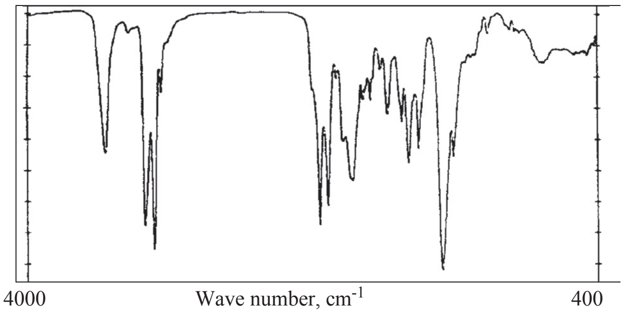


Figure 5.13 Theoretical absorbance spectra.

kinetics, and at the end a third kinetics leading to failure.

Figure 5.13 shows a theoretical absorbance spectrum with sudden sharp absorption variations versus wave numbers (or wavelength).

5.7 Modeling and Predictions of Lifetimes: Very Useful if Carefully Used; Very Hazardous in Other Cases

Modeling for lifetime forecasting: Modeling is a purely mathematical exercise providing a result when the formula or the software is supplied with (suitable or not) data. So the user takes a risk, the more so as the real conditions get far from the experimental context needed for the modeling basis. Certain predictions can be disastrous leading to completely false estimations. In the optimistic cases, modeling can save time and money by reducing trials and property testing.

The mathematical laws linking the effect of one property and a parameter such as time or temperature assume that the property continuously evolves without abrupt changes. These laws cannot predict thresholds or knees or sudden failure and so on.

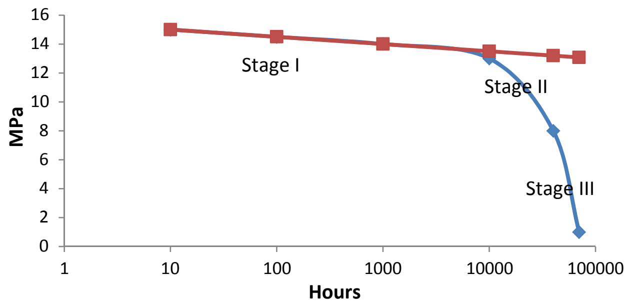


Figure 5.14 Hoop stress: modeling stage I and forecasting.

These phenomena must be specifically modeled. Being conscious of these features, modeling is very useful to give an idea of a property and to decide if it is opportune to further investigate a way.

Temperature is often increased for heat aging acceleration: Be careful on the aging temperatures. High temperatures can activate chemical reactions different from those observed at service temperatures, which can lead to false predictions. For example, degradation at 150 °C of commodity plastics is not of the same nature as the degradation at room temperature.

Thin samples age faster than thick ones: it is true, but it is also true that they age differently and can lead to false predictions. Thin samples oxidize rapidly by contact with atmospheric oxygen, whereas thick samples oxidize rapidly by their surfaces but diffusion of oxygen in depth being slow, they oxidize slowly in depth.

For complex and long-term aging, it may be necessary to slice the study into several stages. For example, in the case of the hoop stress curve of a polyethylene pipe (Figure 5.12), it is essential to study the three stages:

- stage I concerning the first kinetics leading to a slow decrease in the property up to 5000 h.
- stage II with a faster second kinetics.
- stage III with a third kinetics leading to failure.

The modeled curve (Figure 5.14) of the first stage leads to 13.5 MPa after 10,000 h with an error of 4% but after 40,000 h (about 5 years) the error is about 65%, and after 70,000 h (about 8 years) the huge error is superior to 1000%.

That forecast points out the increase in risks as far as test time is far from the prediction time. Certain sources suggest an empirical rule limiting the ratio [forecast lifetime/test duration] to a maximum of one decade.

Enhancing forecast needs to study one at a time the three stages. For example, we quote the **Study of 100-Year Service Life for Corrugated HDPE Drainage Pipe**.

Michael Pluimer—Technical and Engineering Manager, Plastics Pipe Institute—presents a method (Establishing 100-Year Service Life for Corrugated HDPE Drainage Pipe) for determination of long-term service life of corrugated HDPE pipes by modifying current, widely accepted methods employed by the plastic pipe industry to take into account the unique geometry and installation conditions of buried corrugated pipes.

Figure 5.15 briefly resumes the method principle.

First, the anticipated service conditions of the drainage pipes are assessed, including environmental conditions, soil and traffic loads, and the resulting long-term stresses and strains in the pipe. While deep installations may result in large compressive stresses on the pipe, shallow installations are more subject to bending and tensile stresses. Tensile stress is the most damaging parameter and leads to a limitation concerning installation conditions.

Second, the capacity of the material and the manufactured pipe product are assessed by Dr Hsuan by running elevated temperature testing at multiple stresses and applying the rate process method to forecast stage II performance at the design service temperature and stress level limits.

Third, appropriate antioxidant performance tests (OIT—oxygen induction time) deduced from previous studies ensure that stage III failures will not occur prior to 100 years (McGrath and Hsuan, 2005).

In conclusion, HDPE corrugated pipe can be evaluated for a 100-year service life.

Other traps, without claiming to be exhaustive, include:

- Ease the degradation study choosing a property seeming similar to functional properties but basically different. It is essential to verify that the testing methods apply physical and chemical principles of the same nature as the functional properties. For example don't study fatigue at given strain instead of fatigue at given stress.

  Don't systematically compare mechanical degradation and chemical structural changes. For erosion behavior of polymers, attention must be paid to the effects of testing variables such as erosion particle type and shape, impact velocity, impact angle.
- Beware of the risk to compute one property from the value of another: Don't study tensile strength instead of tensile modulus and conversely. Generally speaking, tensile strength decreases when modulus increases or decreases.

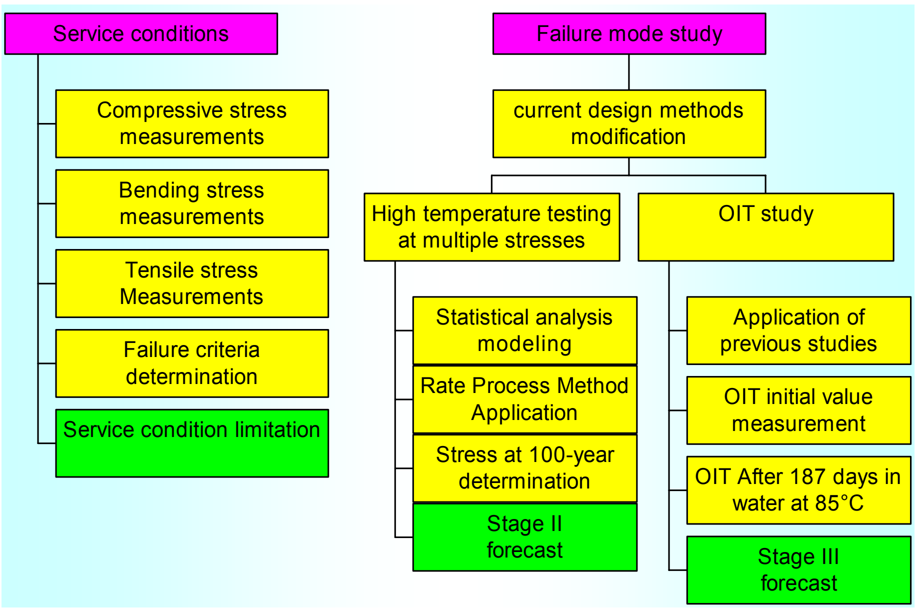


Figure 5.15 Corrugated pipes 100-year service life.

5.8 Helpful, Hazardous, and False Comparisons

First and foremost, helpful comparisons allow at best having a fair idea of a property but are too inaccurate to certify the compliance to a specification.

Property testing of materials is time-consuming and expensive and sometimes the engineers wonder about the possible reuse of known results by comparison between several methods or property characterizations to avoid making again new trials.

Another method to save time and money is to search a model linking a property and a parameter to reduce the number of trials. For example, if the tensile strength is known at 20, 50, 80, and 100 °C, is it unavoidable to test the compound at 70 °C or is it possible to apply a mathematical law to compute that data at that temperature? There is no universal response but each case must be examined with the experience of in-house technicians and with a sound good sense. In that very simple case, the response is probably yes because the property is well known and varies continuously. If the compound is the same and is processed by the same method, it is easier to apply a mathematical law (already known) to compute that data at that temperature. If the processing methods are different, or if the compounds are slightly different, the response is not so evident. For example, a colorant can change the crystallinity of the molded parts.

The user takes a risk with modeling, a purely mathematical exercise, the more so as the real conditions of use get far away, the experimental context needed to build the modeling basis.

5.8.1 Some Suggestions to Minimize Risks

- Compare only comparable characteristics and do not compare tensile strength and tear strength, for example, or modulus and hardness.
- Be careful on the suitability of the scales concerning the two characteristics to be compared. For example, IRHD hardness is only accurate between 30 and 94.
- Beware of long-term aging, periodic phenomena, abrupt changes, thresholds, knees or sudden failure, and so on.
- Compare only homogeneous families of samples: neat polymers, crystalline, amorphous, etc. Heterogeneity of sampling is a significant cause of distortion. If we study the Rockwell M/Shore D comparison with all the polymers in the suitable ranges of the two hardness scales, a trinomial law models the relation of Rockwell M (RM) in function of Shore D (D) data.
  - $RM = 0.33 * D^2 - 56 * D + 2396$
  - $R^2 = 0.76$

  If we study neat polymers only, it is possible to express Rockwell M by a first- or second-degree law with a far better value of R^2 (0.9).
- Make sure that all the other parameters are identical. For example:
  - do not include in a same group impact strength of dry and wet polyamides,
  - do not consider that properties of injection-molded samples and rotomolded compounds are identical,
  - do not consider that properties measured on samples of very different thickness are identical. Thickness can affect, for example, aging or fire behavior or even tensile strength as molded.
- Do not compare chemical and physical methods. For example, do not compare oxidation rate and mechanical properties during weathering or thermal aging.
- Verify that the testing methods apply physical principles of the same nature. For example, do not compare fatigue at given stress with fatigue at given strain.
- Be careful on the boundary temperatures that can lead to sudden changes of properties.

5.8.2 Examples of Hazardous Comparison: Flexural Modulus and Hardness

Comparisons of properties of different natures are hazardous or false comparisons.

For example: Modulus (bulk property) versus hardness (surface property).

Table 5.12 displays the results of a statistical analysis of hardness and flexural modulus.

- coefficient of variation C_v defined as the ratio between the standard deviation (σ) and average (μ): $C_v = \sigma/\mu$

Table 5.12 Statistical Analysis of Hardness and Flexural Modulus

	Hardness	Modulus
Mean	51	2.6
Median	50	2.5
Standard deviation	30	1.57
C_v	0.6	0.6
Minimum	1	0.01
Maximum	110	10

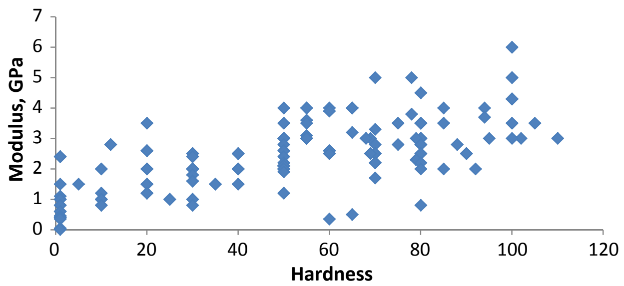


Figure 5.16 Flex modulus versus hardness.

It seems that the two properties are linked but, really, Figure 5.16 shows the spreading of results and the excessive risks of the comparison:

- For a hardness of 50 (about the average), modulus varies between 1 and 4 GPa.
- For a modulus of 2.5 (about the average), hardness varies between 1 and 90.

Although they seem of similar nature, notched impacts tested by different methods are another example of hazardous comparison as we can see in Figure 5.17 showing the dispersion of results:

- For an average value of Izod impact, Charpy value varies approximately between 3 and 17.
- For an average value of Charpy impact, Izod value varies approximately between 5 and 100.

5.8.3 Examples of Helpful Comparisons if Subject to Special Cautions

Some comparisons may be of interest if subjected to special cautions.

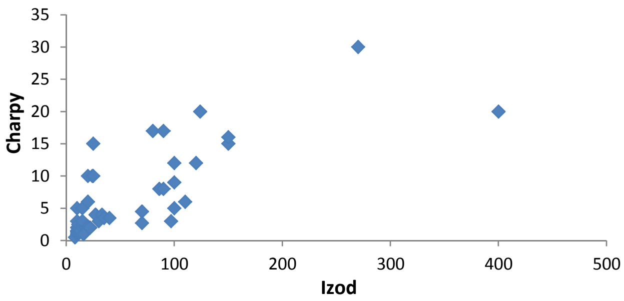


Figure 5.17 Charpy and Izod notched impacts.

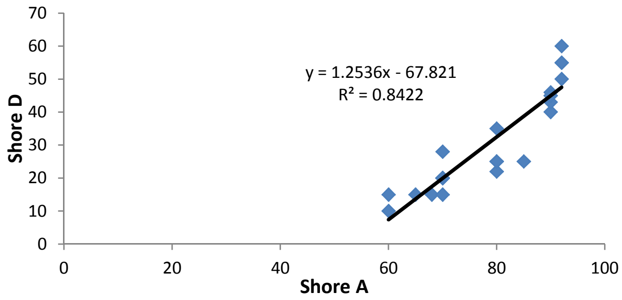


Figure 5.18 Comparison Shore D versus Shore A.

As already seen, properties must be of similar nature but in addition, it is essential that both properties are in the validity range of the two methods. For example, high hardness Shore D being out of the useful scale of Shore A cannot be measured in Shore A. For the same reason, a low Shore A cannot be measured in Shore D.

Figure 5.18 shows the dispersion of results for samples being in the useful scale of both methods:

- For an 80 Shore A hardness, Shore D value varies approximately between 22 and 35.
- For an average value of Shore D hardness, Shore A value varies approximately between 80 and 90.
- For a low Shore A, Shore D is not in the range of validity.
- For a high Shore D, Shore A is not in the range of validity.

Another helpful comparison: Flexural and tensile modulus if molded thermoplastics are isotropic. After the following graph, for **isotropic** plastics, there is a good correlation between flexural and tensile modulus (coefficient $R^2 = 0.96$).

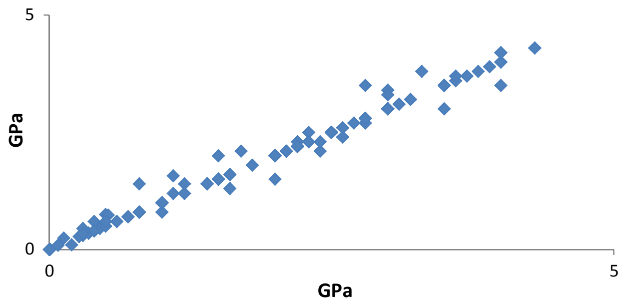


Figure 5.19 Tensile modulus versus flexural modulus.

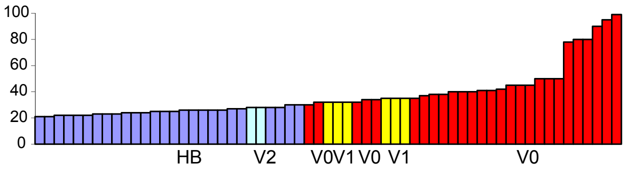


Figure 5.20 LOI (oxygen index) versus UL94 rating.

As we can see in Figure 5.19 showing the dispersion of results, it may be helpful to compare flexural modulus and tensile modulus for isotropic thermoplastics:

- For an average value of tensile modulus, flexural modulus value varies approximately between 2.1 and 2.5.
- For an average value of flexural modulus, tensile modulus value varies approximately between 2.2 and 2.6.

5.8.4 Example of Comparisons for Information Purposes Only: Oxygen Index and UL94 Rating

Oxygen index (LOI) is easy to measure and can give indications on the possible UL94 fire rating or the inability of a compound to satisfy high UL94 ratings. Figure 5.20 displays three zones:

- For an LOI ranging from 21 up to 27, all ratings are HB
- For an LOI ranging from 28 up to 36, ratings are mixed and can be HB, V2, V1, or even V0
- For an LOI superior to 36, all ratings are V0.

(Remember that the UL94 test depends on the sample thickness.)

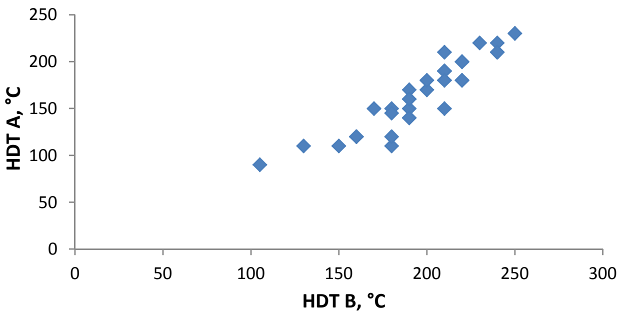


Figure 5.21 HDT A versus HDT B.

Those examples are not a rule and every one must make his own experience. At the end, it is essential to run the right UL tests on the selected materials.

5.8.5 Examples of Unexpected and Questionable Comparisons

5.8.5.1 Prediction of HDT A from HDT B Data

Heat deflection temperature (HDT) is the temperature at which a standard deflection occurs for defined test samples subjected to a given bending load and a linear increase in temperature. The stresses usually selected are 0.45 MPa (HDT B) or 1.8 MPa (HDT A).

HDT A and HDT B are similar procedures differing by the applied load. A priori, one can think that the comparison is easy but there are some traps:

- The short overlapping of suitable temperature scales
- The viscoelasticity varying with the crystallinity of the polymers
- The level of the melting temperature.

Figure 5.21 displays 34 examples concerning neat polymers excluding liquid crystal polymers (highly anisotropic) but including amorphous and crystalline polymers.

The dispersion of results is, for example:

- For an average value of HDT B, HDT A value varies approximately between 150 and 210.
- For an average value of HDT A, HDT B value varies approximately between 190 and 220.

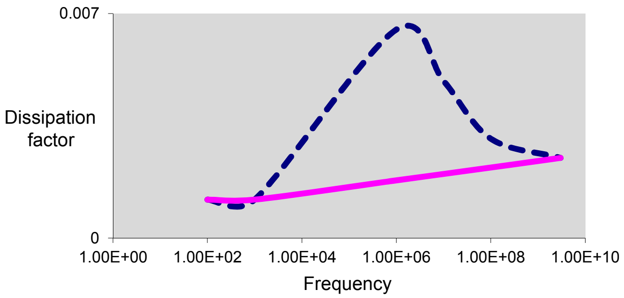


Figure 5.22 Example of dissipation factor versus frequency.

5.8.5.2 Prediction through a Process of Deduction for a Frequency- Dependent Property

Frequency-dependent properties must be considered with a special care because the evolutions are not monotonous. Figure 5.22 displays:

- A solid line: the model of the dissipation factor of a polymer computed after data at low (1 kHz) and high (1 GHz) frequencies.
- A broken line: the actual curve of the dissipation factor of the same polymer with a peak at 1 MHz.

If the dissipation factor is predicted from the model, the relative error is –72% at 1 MHz.

Further Reading

Technical Guides, Newsletters, Websites

Grace Hsuan, Y., McGrath, T., 2005. Protocol for predicting long-term service of corrugated high density polyethylene pipes, Ph.D., P.E., July 29.
3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, Fiber-Cote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
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6 Density, Actual Weight Savings, Cost, and Property per Volume Advantages

OUTLINE

Density is a basic characteristic of thermoplastics, decisive for engineering, economic, and structural reasons:

- Weight saving is one of the reasons leading to polymer choice. It depends on density and mechanical properties
- Of course, density is a leading player in specific properties taken as [performance/density] ratio
- Density is a consequence of the structure and allows one to distinguish low-, medium-, and high-density polyethylene materials
- Prices are based on weight and, often, the part design is based on volume, taking the density into account.

For dense thermoplastics, densities are in the range of 0.8 g/cm^3 to more than 2.0 g/cm^3. For cellular materials such as foams, densities can be as low as 10 kg/m^3.

Computing properties and cost versus volume changes the ranking of thermoplastics and traditional materials, as far as metals are taken into account.

6.1 Density of 280 Thermoplastics, Statistical Analysis, and Modeling

Table 6.1 displays the expected minimum and maximum values of density for 280 subfamilies of thermoplastics classified as follows:

- Expected neat grades: those compounds are claimed "neat" but some are probably more or less modified and may include secondary polymers and/or recycled materials
- Special grades reinforced with fibers or CNTs (carbon nanotubes), filled with minerals or glass beads (GB), flame retardant (FR), conductive, "antistat" (antistatic applications), WPCs (wood plastic composites), "friction" (low friction for bearings)…

Obviously, filled and reinforced grades have higher density than their unfilled counterparts.

There are many sources of monomers, polymerization methods, formulae, processing methods, recycling routes, levels of recycled and virgin materials leading to a wide range of properties. These data are only examples providing a rough idea of the significant differences between subfamilies. Actually, other higher or lower figures can be found elsewhere

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00006-4

Table 6.1 Density Examples

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PMP	0.833	0.84		
PP impact	0.88	0.91		
PP Ho	0.9	0.91		
PB	0.9	0.94		
PE-LD	0.917	0.94		
PE-UHMW	0.92	0.955		
PP low-level CNT			0.93	0.95
PP recycled	0.9	1		
PP/EPDM-V	0.9	1		
TPV Shore D	0.9	1		
EMA	0.93	0.97		
PP medium CNT			0.94	0.97
PP antistat			0.9	1.01
PE-HD	0.94	0.98		
PE-HD antistat black			0.95	0.97
PP Co	0.9	1.04		
COC	0.95	1.02		
EVA	0.92	1.07		
TPO Shore D	0.9	1.1		
PMP GF			0.96	1.05
Starch/PE	1.01	1.01		
PA 11 or 12 plasticized	1	1.03		
PP CF			0.95	1.1
PP conductive			0.95	1.1
PA 10-10 Bio	1.01	1.05		
PLA/PE	1.03	1.03		
PP low-level GF			0.97	1.1
PA 12	1.01	1.06		
PS	1.02	1.05		
Starch/PP	0.995	1.1		
PEBA 50 to 72 Shore D	1	1.1		
PLA wood WPC			1	1.1
PA 11	1.01	1.09		
PP/PA	1.03	1.07		

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PP natural fibers			0.99	1.13
ASA	1.05	1.07		
PA 6-12	1.06	1.06		
ABS/PA	1.06	1.07		
PEBA 25 to 45 Shore D	1	1.14		
PEBA Bio	1	1.14		
PPE	1.04	1.1		
PP wood WPC			0.95	1.2
ABS	1	1.15		
PMP mineral			1	1.15
PP cellulose fibers			1.02	1.13
SMMA	1.03	1.13		
PA 6 recycled	1.06	1.1		
SAN	1.06	1.1		
PA 6-10	1.07	1.1		
PA 4-10 Bio	1.08	1.09		
MABS	1.08	1.1		
TPS Shore D	0.9	1.3		
PA Transparent	1	1.2		
PS impact	1.03	1.17		
PA 6	1.05	1.15		
PP Talc			0.97	1.25
PPE/PA	1.1	1.12		
PS 40% wood WPC			1.07	1.16
PE wood WPC			0.994	1.24
PA 66	1.04	1.2		
SMA	1.05	1.2		
ABS CF			1.1	1.15
PP GB			1.1	1.15
PMMA antistatic			1.13	1.15
Starch/PS	1.1	1.18		
PA castable	1.13	1.16		
ABS/PC	1.1	1.2		

Continued

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
ASA/PMMA	1.1	1.2		
EVOH	1.1	1.2		
PA 12 CF			1.1	1.2
PMMA impact	1.1	1.2		
PPA	1.1	1.2		
TPU Bio	1.1	1.2		
PA CNT			1.13	1.17
PE-X cross-linked	0.915	1.4		
PA 12 friction			1.03	1.3
PP medium-level GF			1.1	1.23
PP long GF medium level			1.1	1.23
PC CNT			1.12	1.21
CPE	1.13	1.2		
PSU/ABS	1.13	1.2		
PA 12 conductive			1.04	1.3
PC	1.15	1.2		
PMMA	1.15	1.2		
PA 6 FR			1.16	1.2
ABS GF			1.17	1.19
PA 4-6			1.17	1.19
PA Far			1.15	1.22
TPE based on PVC	1.1	1.28		
ABS/PA 20 GF			1.15	1.23
PLA/PMMA	1.17	1.21		
PP $CaCO_3$			1.14	1.25
ABS FR			1.15	1.25
PA castable friction			1.15	1.25
Acrylique imide	1.2	1.2		
ASA/PVC	1.2	1.2		
TPU Shore D	1.2	1.2		
COPE Bio	1.1	1.3		
PE GF			1.1	1.3
MPR	1.06	1.35		
CP	1.17	1.24		

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PPE CF			1.18	1.23
ASA/PC	1.12	1.3		
PMI or PMMI	1.2	1.22		
PET/PC	1.2	1.23		
PP/PA GF			1.12	1.31
PP mineral			0.97	1.48
Starch/copolyester	1.13	1.32		
CAB	1.15	1.3		
PPE mineral			1.2	1.25
PSU/PC	1.22	1.23		
Polyarylate	1.2	1.26		
ABS conductive			1.15	1.32
PLA/PC	1.18	1.3		
PK	1.24	1.24		
ABS/PVC	1.13	1.36		
COPE low Shore D	1.1	1.4		
ABS/PC conductive			1.2	1.3
COPE high Shore D	1.2	1.3		
PC/PBT	1.2	1.3		
PPA CF			1.19	1.32
ABS GB			1.24	1.27
PLA/copolyester	1.24	1.27		
PA 12 GF			1.22	1.3
PSU	1.23	1.29		
PA 66 CF			1.2	1.33
PTT Bio	1.2	1.33		
PA 6-10 CF			1.1	1.44
PLA	1.21	1.33		
PSU modified	1.23	1.31		
PPE GF			1.26	1.28
SMA GF			1.2	1.35
SAN GF			1.15	1.41
CA	1.22	1.34		

Continued

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PPE/PA GF			1.2	1.37
PA 66 long CF			1.27	1.3
PEI	1.27	1.3		
PC CF			1.25	1.33
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	1.26	1.32		
PC conductive			1.24	1.35
PP long GF high level			1.24	1.35
PEEK	1.27	1.32		
TPU conductive			1.28	1.31
PA 66 conductive			1.2	1.4
PA 66 impact medium-level GF			1.2	1.4
PC/SAN GF			1.2	1.4
PVC wood WPC			1.2	1.4
PLA/PP 30% GF			1.1	1.5
PBI	1.3	1.3		
PAA medium-level CF			1.28	1.33
PLA natural reinforcement			1.28	1.33
ABS/PC GF			1.22	1.4
PA 11 GF			1.22	1.4
PPSU	1.29	1.35		
PA 4-10 GF Bio			1.3	1.35
PA 12 GB			1.22	1.44
PA 6 GF recycled			1.3	1.37
POM homo- or copolymer	1.26	1.42		
PA 6 medium-level GF			1.2	1.5
PA 6 medium-level long GF			1.25	1.45
PA 6-12 GF			1.3	1.4
PC friction			1.3	1.4
PEEK/PBI	1.3	1.4		
PEI conductive			1.3	1.4
PES	1.3	1.4		
PET	1.3	1.4		

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PET Amorphous	1.3	1.4		
PPS	1.3	1.4		
PS GF			1.3	1.4
PMMA GF			1.3	1.42
ABS/PC low-level long GF			1.36	1.36
PPS Far			1.35	1.38
PA 6 GB			1.35	1.4
PA 66 GB			1.35	1.4
PI TP	1.33	1.43		
PA 66 medium-level long GF			1.36	1.4
PEEK CF			1.33	1.44
PBT CF			1.34	1.44
PEI CF			1.31	1.48
PLA/PBT GF			1.2	1.6
ASA/PBT GF			1.3	1.5
PBT	1.3	1.5		
PC GF			1.3	1.5
PC/PBT GF			1.3	1.5
PEEK/PBI CF			1.4	1.41
PAI	1.4	1.42		
PI TP CF			1.4	1.43
PES CF			1.38	1.47
PAA medium-level GF			1.4	1.45
PA 4-6 GF			1.41	1.44
POM Far			1.35	1.5
PVC unplasticized	1.35	1.5		
PAI friction			1.4	1.5
PBT long CF			1.4	1.5
PEI mineral			1.4	1.5
Polyarylate GF			1.4	1.5
PPS CF			1.4	1.5
POM CF			1.42	1.48

Continued

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PET/PC GF			1.3	1.6
POM friction			1.4	1.54
PA 66 mineral			1.35	1.6
POM GF			1.35	1.6
PA 66 medium-level GF			1.36	1.6
POM conductive			1.42	1.54
PAI CF			1.48	1.5
PI TP GF			1.43	1.56
PSU/PBT GF			1.47	1.52
TPU GF			1.3	1.7
LCP CF			1.4	1.6
PCT GF			1.4	1.6
PPSU GF			1.4	1.6
PSU GF			1.4	1.6
PTT Bio GF			1.4	1.6
PVC GF			1.43	1.57
PBT medium-level GB			1.45	1.55
ABS/PC medium-level long GF			1.5	1.5
PE 60% long GF			1.5	1.51
PK GF			1.46	1.56
PVCC	1.47	1.55		
PA 10-10 high-level GF Bio			1.5	1.52
PA 4-6 mineral			1.51	1.51
PEEK GF			1.49	1.54
PAEK 30% GF			1.49	1.54
PVC plasticized	1.15	1.9		
PSU mineral			1.45	1.6
PVF	1.37	1.71		
PEI GF			1.48	1.6
PA 6 mineral FR			1.4	1.7
PI TP friction			1.4	1.7
PPS GF			1.4	1.7

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
TPU long GF			1.4	1.7
PA 66 high-level GF			1.5	1.6
PBT medium-level GF			1.5	1.6
PBT long GF			1.5	1.6
PEEK/PBI GF			1.5	1.6
PEI GF milled			1.5	1.6
PET GF			1.5	1.6
PLA GF			1.5	1.6
PPA mineral			1.5	1.6
PAI mineral			1.5	1.61
POM GB			1.5	1.62
PPA GF			1.43	1.7
PAA mineral			1.45	1.7
PES friction			1.45	1.7
PPS CF + GF			1.45	1.7
POM mineral			1.47	1.7
LCP	1.4	1.8		
PPS conductive			1.4	1.8
PA 6 high-level GF			1.5	1.7
PES GF			1.5	1.7
PAI GF			1.6	1.61
PPS long GF medium level			1.52	1.7
PPA long GF			1.59	1.65
LCP GF			1.5	1.8
PA 6 high-level long GF			1.6	1.7
PA 66 high-level long GF			1.6	1.7
PBT GF & mineral			1.6	1.7
PVDC	1.6	1.75		
LCP mineral			1.5	1.9
POM long GF			1.7	1.72
PPS long GF high level			1.72	1.73
PAA high-level GF			1.7	1.77
ECTFE	1.6	1.9		

Continued

Table 6.1 Density Examples—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
ETFE	1.6	1.9		
PET/PBT high-level GF			1.7	1.8
PVDF	1.7	1.8		
PVDF CF			1.7	1.8
PVDF friction			1.7	1.8
ETFE GF			1.7	2
PVDF Mica			1.8	1.9
PPS GF + Mineral			1.8	2
PTFE CF			2.05	2.22
FEP	2.1	2.2		
PCTFE	2.1	2.2		
PFA	2.1	2.2		
PTFE	2.1	2.2		
FEP GF			2.2	2.2
PTFE GF			2.2	2.3
PTFE friction			3.5	4

in the literature. These theoretical data cannot be used for designing, computing, or to make economic predictions. Only properties measured on the actually used compound must be considered.

Figure 6.1(a) and (b) displays the overall results in the form of graphs pointing out the wide range of data and the difference between neat and filled grades.

Table 6.2 displays statistical analysis of densities, confirming the significant differences between neat and special grades.

For comparison, density of traditional materials is in the order of:

Balsa	0.14
Wood	0.4 to ~1
Magnesium	1.75
Glass	2.5
Aluminum	2.8
Titanium	4.5
Steel	7.8

6.1.1 For Dense and Homogeneous Materials, Density of a Reinforced or Filled Grade Obeys a Simple Law of Mixture

If D_m and D_a are respectively the densities of the matrix and the additive,

If W_m and W_a are respectively the weights of the matrix and the additive,

Then the volume of the compound is $V_c = W_m/D_m + W_a/D_a$

The total weight of the compound is $W_c = W_m + W_a = 100$

and

The density of the end compound is $D_c = W_c/V_c = (W_m + W_a)/(W_m/D_m + W_a/D_a)$.

The application to a polyamide (density = 1.14) filled with various amounts of a short glass fiber (density = 2.6) gives excellent results.

Table 6.3 compares experimental and predicted data and the relative errors (%) inferior to 1%.

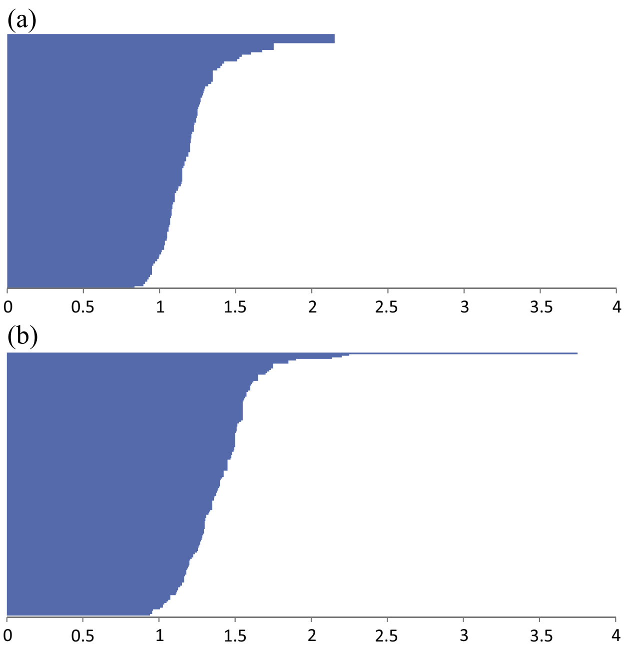

Figure 6.1 Density examples: (a) neat thermoplastic and (b) special grades.

Table 6.2 Density of Thermoplastics: Statistical Analysis

	Expected Neat Grades	Special Grades
Mean	1.22	1.41
Median	1.18	1.4
Standard deviation	0.26	0.30
Minimum	0.833	0.9
Maximum	2.2	4

6.2 Specific Yield Strength and Specific Modulus

Table 6.4 displays the differences between average specific modulus and yield strength, on the one hand, and average engineering modulus and yield strength on the other hand. The specific mechanical properties take account of the density and consider the performance to density ratio: [performance/density]. Moduli are ranged in an ascending order. We can remark on the significant changes of ranking and the differences between homologous property values.

These data are only examples providing a rough idea of the significant differences between subfamilies, and other data can be found elsewhere. These theoretical data cannot be used for designing, computing, or to make economic predictions. Only properties measured on the actually used compound must be considered.

For comparison, Table 6.5 displays some examples on the properties of traditional materials. High density of steel reduces its specific properties but they are still at the top of the range versus reinforced thermoplastics.

6.3 Cost per Volume Examples

Prices of plastics depend on the actual grade, the purchased volume per year, the volume per delivery, the country, the acumen of the buyer, and many other factors. In addition, actual costs are carefully concealed making that published prices are very approximate and imprecise. The following data are only examples without warranty, providing a rough idea of the significant differences between subfamilies. Of course, other data can be found elsewhere and these theoretical data cannot be used for designing, computing, or to make economic predictions. Only actual costs of the used compound must be considered.

Table 6.3 Density of Glass Fiber-Reinforced Polyamide

	Glass Fiber Level (%)					
Density g/cm^3	0	10	20	30	40	50
Experimental	1.14	1.21	1.29	1.37	1.46	1.57
Predicted (rounded)	1.14	1.21	1.28	1.37	1.47	1.585
Error %	0	–0.2	–0.4	0.1	0.7	1

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
CPE	<0.1	7.7	CPE	<0.1	9
COPE low Shore D	0.1	15.6	COPE low Shore D	<0.1	19.5
COPE Bio	0.2	19.2	EVA	0.155	21
EVA	0.2	21.1	PB	0.175	11
PB	0.2	12.0	COPE Bio	0.185	23
PVDC	0.3	14.9	EMA	0.26	20
EMA	0.3	21.1	PE-LD	0.315	19.5
PE-LD	0.3	21.0	PVDC	0.425	25
PTFE	0.4	13.5	PA 11 or 12 plasticized	0.45	27
PTFE CF	0.4	10.5	PEBA 50 to 72 Shore D	0.48	22.5
PA 11 or 12 plasticized	0.4	26.6	COPE high Shore D	0.7	34.5
PEBA 50 to 72 Shore D	0.5	21.4	PE-HD antistat black	0.75	20
ETFE	0.5	22.0	PE-UHMW	0.8	33
COPE high Shore D	0.6	27.6	PP impact	0.85	19.5
PTFE GF	0.6	6.0	PTFE CF	0.9	22.5
PCTFE	0.7	18.6	PTFE	0.9	29
PVC plasticized	0.7	19.7	PE-HD	0.95	24
PE-HD antistat black	0.8	20.8	ETFE	0.95	38.5
PE-UHMW	0.9	35.2	PMP	1.05	19.5
PVDF	0.9	21.7	PVC plasticized	1.10	30
PP impact	0.9	21.8	CP	1.175	36.5
PLA/copolyester	1.0	25.5	TPO Shore D	1.2	16
ECTFE	1.0	28.3	PP recycled	1.2	20
CP	1.0	30.3	CAB	1.2	30
CAB	1.0	24.5	PLA/copolyester	1.2	32
PE-HD	1.0	25.0	PA 12	1.2	47.5
PA 12 friction	1.1	32.2	PA 11	1.2	55
PA 11	1.1	52.4	PA 12 friction	1.25	37.5

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
PA 6 recycled	1.2	46.3	PA 6 recycled	1.25	50
PA 12	1.2	45.9	PP/PA	1.3	35
TPO Shore D	1.2	16.0	PTFE GF	1.35	13.5
PK	1.2	48.0	PP Co	1.35	26
PP/PA	1.2	33.3	PP Ho	1.45	37.5
PMP	1.3	23.3	ABS/PA	1.5	37.5
PC friction	1.3	35.2	PK	1.5	59.5
PP recycled	1.3	21.1	PMMA antistatic	1.55	40
CA	1.3	27.3	PVDF	1.55	38
PMMA antistatic	1.4	35.1	PCTFE	1.55	40
PVDF friction	1.4	30.9	PA 6-12	1.65	48
PP Co	1.4	26.8	PA 10-10 Bio	1.65	50
ABS/PA	1.4	35.2	CA	1.7	35
PET Amorphous	1.5	29.6	PC friction	1.7	47.5
PVF	1.5	24.4	ECTFE	1.7	49.5
PA 6-12	1.6	45.3	PA 6-10	1.7	60
PC/PBT	1.6	36.0	PP $CaCO_3$	1.9	20.5
PET/PC	1.6	41.2	PA 6	1.9	62.5
PA 6-10	1.6	55.3	PET/PC	1.9	50
PP $CaCO_3$	1.6	17.2	PP low-level CNT	1.915	37.5
PA 10-10 Bio	1.6	48.5	PE-X cross-linked	1.925	23
PP Ho	1.6	41.4	PC/PBT	1.95	45
PTT Bio	1.6	45.5	MABS	1.95	45.5
TPU conductive	1.6	40.9	PP antistat	2	27.5
PE-X cross-linked	1.7	19.9	ABS	2	40
POM friction	1.7	34.0	PET Amorphous	2	40
PA 6	1.7	56.8	PA 4-10 Bio	2	67.5
Polyarylate	1.7	56.5	PTT Bio	2.05	57.5
ASA/PVC	1.8	39.6	PA Transparent	2.05	71
POM homo- or copolymer	1.8	41.0	PP medium CNT	2.075	44
PPSU	1.8	62.1	ASA/PVC	2.1	47.5

Continued

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
MABS	1.8	41.7	ASA/PMMA	2.1	52.5
ABS/PC conductive	1.8	47.2	TPU conductive	2.1	53
PSU modified	1.8	48.4	PA castable	2.15	64.5
ASA/PC	1.8	43.4	Polyarylate	2.15	69.5
PVCC	1.8	33.1	PA 4-6	2.15	70
PA 4-6	1.8	59.3	PSU/ABS	2.15	46.5
ASA/PMMA	1.8	45.7	PS impact	2.2	27.5
PA 4-10 Bio	1.8	62.2	ASA/PC	2.2	52.5
PSU/ABS	1.8	39.9	ABS/PC conductive	2.25	59
PES	1.9	59.3	PA 66	2.25	60
PBT	1.9	35.7	ASA	2.3	40.5
ABS	1.9	37.2	PSU modified	2.3	61.5
PA Transparent	1.9	64.5	PC	2.3	62.5
PA castable	1.9	56.3	PPA	2.3	69
PSU	1.9	61.5	PVF	2.35	37.5
ABS/PVC	1.9	30.5	ABS/PC	2.35	55
PC	2.0	53.2	POM homo- or copolymer	2.35	55
PET	2.0	42.6	PPSU	2.35	82
PA 12 GB	2.0	34.2	PPE	2.4	55.5
PS impact	2.0	25.0	ABS/PVC	2.4	38
PSU/PC	2.0	49.8	PVDF friction	2.4	54
PPA	2.0	60.0	PC CNT	2.4	57.5
PA 66	2.0	53.6	PA 6 FR	2.4	64
PI TP	2.0	76.1	PSU	2.4	77.5
PA 6 FR	2.0	54.2	POM friction	2.45	50
PP low-level CNT	2.0	39.9	PSU/PC	2.45	61
ABS/PC	2.0	47.8	ABS FR	2.5	42.5
FEP GF	2.0	15.9	PMMA impact	2.5	50
PC conductive	2.0	44.4	COC	2.5	56.5
PC CNT	2.1	49.4	PPE/PA	2.5	57
ABS FR	2.1	35.4	PES	2.5	80

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
PP antistat	2.1	28.8	PP GB	2.6	22.5
PP mineral	2.1	20.4	PMP mineral	2.6	19
ASA	2.2	38.2	PP mineral	2.6	25
PP medium CNT	2.2	46.1	PBT	2.6	50
PMMA impact	2.2	43.5	SMA	2.65	35
PVC unplasticized	2.2	31.6	PA 12 GB	2.65	45.5
PVDF Mica	2.2	26.2	PC conductive	2.65	57.5
PPE	2.2	51.9	PET	2.65	57.5
PPE/PA	2.3	51.4	PP Talc	2.75	28
ABS conductive	2.3	34.8	PS	2.75	37.5
PA 6 GB	2.3	47.3	PVCC	2.75	50
POM GB	2.3	35.6	ABS conductive	2.8	43
PP GB	2.3	20.0	PI TP	2.8	105
SMA	2.4	31.1	PPE mineral	2.9	70
PBT medium-level GB	2.4	33.3	SMMA	2.9	67.5
PPE mineral	2.4	57.1	PVC unplasticized	3.1	45
PMP mineral	2.4	17.7	ABS GB	3.15	35.5
PP Talc	2.5	25.2	PA 6 GB	3.15	65
ABS GB	2.5	28.3	PA 12 conductive	3.175	57.5
PLA	2.5	33.9	PLA	3.2	43
COC	2.5	57.4	PA castable friction	3.2	75
PA 66 GB	2.5	58.2	PE wood WPC	3.35	24.5
PPS	2.6	45.6	SAN	3.4	72
PA 4-6 mineral	2.6	51.7	PPS	3.5	61.5
PS	2.7	36.2	PA 66 GB	3.5	80
PA castable friction	2.7	62.5	PEI	3.5	105
SMMA	2.7	62.5	PBT medium-level GB	3.55	50
PA 12 conductive	2.7	49.1	POM GB	3.6	55.5
PEI	2.7	81.7	PMMA	3.75	59
PEEK	2.9	71.4	PEEK	3.75	92.5

Continued

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	3.0	71.7	PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	3.85	92.5
PE wood WPC	3.0	21.9	PP low-level GF	3.9	51.5
SAN	3.1	66.7	Acrylique imide	3.95	78
PMMA	3.2	50.2	PA 4-6 mineral	4	78
PAI	3.2	99.3	EVOH	4.05	57
Acrylique imide	3.3	65.0	PMI or PMMI	4.05	78.5
PMI or PMMI	3.3	64.9	PVDF Mica	4.1	48.5
POM Far	3.4	61.8	PP wood WPC	4.25	26.5
EVOH	3.5	49.6	FEP GF	4.5	35
PP low-level GF	3.8	49.8	PLA wood WPC	4.5	35
PSU mineral	3.8	44.3	PAI	4.5	140
PET/PC GF	3.8	65.5	PMP GF	4.75	51
PVC wood WPC	3.8	28.5	PE GF	4.75	57.5
PA 66 impact medium-level GF	3.8	75.0	PS 40% wood WPC	4.9	25.5
POM mineral	3.8	39.4	POM Far	4.9	88
PP wood WPC	4.0	24.7	PVC wood WPC	5	37
PE GF	4.0	47.9	ABS/PA 20 GF	5	61
PEEK/PBI	4.0	66.7	PA 66 impact medium-level GF	5	97.5
PEI mineral	4.1	65.5	PP natural fibers	5.05	46
PAI friction	4.1	101.7	ABS GF	5.3	62.5
PEI GF milled	4.2	54.8	PA 12 GF	5.3	97.5
ABS/PA 20 GF	4.2	51.3	PEEK/PBI	5.35	90
PA 12 GF	4.2	77.4	PET/PC GF	5.5	95
PBI	4.2	115.4	PBI	5.5	150
PLA wood WPC	4.3	33.3	PSU mineral	5.75	67.5
PVC GF	4.3	52.3	PLA/PP 30% GF	6	72.5
PPSU GF	4.3	63.3	ABS/PC GF	6	77.5
PS 40% wood WPC	4.4	22.9	PEI mineral	6	95
TPU GF	4.4	70.0	PAI friction	6	147.5

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
ABS GF	4.5	53.0	POM mineral	6.1	62.5
PA 6 mineral FR	4.5	56.5	PA Far	6.3	115.5
PES GF	4.5	76.3	PP medium-level GF	6.5	78.5
ABS/PC GF	4.6	59.2	PVC GF	6.5	78.5
PLA/PP 30% GF	4.6	55.8	PEI GF milled	6.5	85
PMP GF	4.7	50.7	PP long GF medium level	6.5	85.5
POM conductive	4.7	39.5	PPSU GF	6.5	95
PA 66 mineral	4.7	47.5	PA 11 GF	6.5	107.5
PP natural fibers	4.8	43.4	TPU GF	6.65	105
Polyarylate GF	4.8	84.5	PP/PA GF	6.65	125
PI TP friction	4.8	35.5	POM conductive	7	58.5
PA 11 GF	5.0	82.1	PA 66 mineral	7	70
ASA/PBT GF	5.0	72.5	PA 6 mineral FR	7	87.5
PC/PBT GF	5.0	78.6	PC/SAN GF	7	97.5
PSU/PBT GF	5.0	73.6	ASA/PBT GF	7	101.5
PA 66 medium-level GF	5.1	89.5	PC/PBT GF	7	110
PA 4–6 GF	5.1	117.5	PA 6 GF recycled	7	112.5
PPA mineral	5.2	69.0	Polyarylate GF	7	122.5
PA 6 GF recycled	5.2	84.3	PES GF	7.25	122
PA Far	5.3	97.5	PA 4-6 GF	7.25	167.5
PC/SAN GF	5.4	75.0	PI TP friction	7.5	55
PP/PA GF	5.5	102.9	PS GF	7.5	77.5
PEI GF	5.5	100.6	PPE GF	7.5	110
PS GF	5.6	57.4	PSU/PBT GF	7.5	110
PP medium-level GF	5.6	67.4	SAN GF	7.5	110
PP long GF medium level	5.6	73.4	PA 66 medium-level GF	7.5	132.5
PVDF CF	5.7	48.9	SMA GF	7.8	65.5
PAI mineral	5.8	94.9	PPS Far	8	88.5
PK GF	5.8	79.5	PA 6 medium-level GF	8	100

Continued

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
PTT Bio GF	5.8	76.7	PPA mineral	8	107
SAN GF	5.9	85.9	PA 4-10 GF Bio	8	140
PPS Far	5.9	64.8	ABS/PC low-level long GF	8.5	125
PPE GF	5.9	86.6	PC GF	8.5	125
PA 6 medium-level GF	5.9	74.1	PEI GF	8.5	155
PCT GF	6.0	73.3	PMMA GF	8.7	97.5
PSU GF	6.0	75.0	PA 6-12 GF	8.7	135
PA 4-10 GF Bio	6.0	105.7	PTT Bio GF	8.75	115
PC GF	6.1	89.3	PPE CF	8.8	97.5
SMA GF	6.1	51.4	PK GF	8.8	120
PET GF	6.1	87.1	PCT GF	9	110
POM GF	6.2	80.3	PLA/PBT GF	9	112.5
ETFE GF	6.2	41.4	PSU GF	9	112.5
ABS/PC low-level long GF	6.3	91.9	PAI mineral	9	147.5
PES friction	6.3	84.1	PPE/PA GF	9	162.5
PAA mineral	6.3	90.5	POM GF	9.15	118.5
PMMA GF	6.4	71.7	ABS CF	9.5	92
PLA/PBT GF	6.4	80.4	PET GF	9.5	135
PA 6-12 GF	6.4	100.0	PVDF CF	10	85.5
PBT medium-level GF	6.6	87.1	PES friction	10	132.5
PBT GF & mineral	6.7	67.3	PC CF	10	136.5
PEEK GF	6.9	108.9	PAA mineral	10	142.5
PAEK 30% GF	6.9	108.9	PA 66 medium-level long GF	10	192.5
PPE/PA GF	7.0	126.5	PP conductive	10.2	34.5
PPS GF	7.1	101.6	PBT medium level GF	10.25	135
TPU long GF	7.1	138.7	PAA medium-level GF	10.5	147.5
PA 66 medium-level long GF	7.2	139.5	PEEK GF	10.5	165
PPE CF	7.3	80.9	PAEK 30% GF	10.5	165

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
PAA medium-level GF	7.4	103.5	PA 6 medium-level long GF	10.5	183.5
POM long GF	7.6	71.1	PP long GF high level	10.9	113.5
PLA GF	7.7	67.7	PP CF	11	41.5
PEEK/PBI GF	7.7	106.5	PBT GF & mineral	11	111
PC CF	7.8	105.8	PPS GF	11	157.5
PA 6 medium-level long GF	7.8	135.9	TPU long GF	11	215
PE 60% long GF	8.0	68.4	ETFE GF	11.5	76.5
PPA GF	8.0	141.2	PE 60% long GF	12	103
PA 66 high-level GF	8.1	125.8	PLA GF	12	105
PAI GF	8.1	99.7	PEEK/PBI GF	12	165
PBT long GF	8.3	106.5	POM CF	12.5	115
PA 10-10 high-level GF Bio	8.3	119.2	ABS/PC medium-level long GF	12.5	151
ABS/PC medium-level long GF	8.3	100.7	PA 10-10 high-level GF Bio	12.5	180
PP long GF high level	8.4	87.6	PA 66 high-level GF	12.5	195
ABS CF	8.4	81.8	PEI conductive	12.5	200
PPS GF + Mineral	8.6	55.3	PPA GF	12.5	221
POM CF	8.6	79.3	PBT long GF	12.8	165
LCP mineral	8.7	87.1	POM long GF	13	121.5
PA 6 high level GF	8.8	95.3	PAI GF	13	160
PEI conductive	9.3	148.1	PA 66 conductive	13.25	97.5
PPS long GF medium level	9.3	104.0	PA 6 high-level GF	14	152.5
LCP	9.4	93.1	PES CF	14.5	166.5
PP conductive	10.0	33.7	LCP mineral	14.75	148
PI TP GF	10.0	110.4	LCP	15	149
PES CF	10.2	116.8	PI TP GF	15	165
PA 66 conductive	10.2	75.0	PPS long GF medium level	15	167.5

Continued

Table 6.4 Examples of Specific and Engineering Moduli and Yield Strengths—cont'd

Thermoplastic	Specific Modulus	Specific Yield Strength (MPa)	Thermoplastic	Engineering Modulus	Engineering Yield Strength (MPa)
PET/PBT high-level GF	10.6	94.3	PBT CF	15.5	150
PP CF	10.7	40.5	PA 12 CF	15.5	211.5
PPA long GF	11.1	161.7	PPS GF + Mineral	16.3	105
PBT CF	11.2	107.9	PA 6-10 CF	16.5	121.5
PPS long GF high level	11.3	95.7	PPA CF	16.5	266.5
PPS conductive	11.9	62.5	PEI CF	18	196
PAA high-level GF	12.1	141.2	PPA long GF	18	262
LCP GF	12.1	100.0	PET/PBT high-level GF	18.5	165
PA 6 high-level long GF	12.4	160.6	PEEK CF	18.5	200
PEI CF	12.9	140.5	PPS conductive	19	100
PA 6-10 CF	13.0	95.7	PPS long GF high level	19.5	165
PA 66 high level long GF	13.0	167.6	LCP GF	20	165
PPA CF	13.1	212.4	PAI CF	20.5	201.5
PEEK CF	13.4	144.4	PA 6 high-level long GF	20.5	265
PA 12 CF	13.5	183.9	PAA high-level GF	21	245
PAI CF	13.8	135.2	PA 66 high-level long GF	21.5	276.5
PPS CF + GF	14.6	80.0	PPS CF + GF	23	126
LCP CF	17.0	129.7	PA 66 CF	23	230
PI TP CF	17.3	159.0	PAA medium-level CF	23.5	292.5
PEEK/PBI CF	17.4	167.3	PI TP CF	24.5	225
PPS CF	17.9	127.6	PEEK/PBI CF	24.5	235
PAA medium-level CF	18.0	224.1	LCP CF	25.5	194.5
PA 66 CF	18.2	181.8	PPS CF	26	185
PBT long CF	20.7	137.9	PBT long CF	30	200

Table 6.5 Examples of Specific Tensile Properties for Traditional Materials

	Specific Tensile Modulus (GPa)	Specific Yield Strength (MPa)		Engineering Tensile Modulus (GPa)	Engineering Yield Strength (MPa)	
		Minimum	Maximum		Minimum	Maximum
Steel	27	25	220	210	200	1700
Titanium	23	80	200	109	370	890
Aluminum	27	11	200	75	30	550
Magnesium	25	25	110	44	43	190
		Specific tensile strength			Engineering tensile strength	
Glass		16	120		40	300
Wood	13–27	12	21			

Thermoplastics are paid in cost per weight but are often used in a defined volume. So it is of interest to examine the cost per volume. The price per liter varies in round figures from about €1 to €100 according to the nature of the polymer itself, the formulation of the grades, and the inclusion of high-cost reinforcements including carbon fibers, and so on. The highest prices relate to the polymers with the highest performances, which are also the least used. Table 6.6 and Figure 6.2 illustrate this situation. Very broadly speaking, prices per liter increase from commodities up to specialty plastics as follows:

- Commodities: €1.4 ($1.8) up to €2.5 ($3.3)
- Engineering plastics: €2 ($2.6) up to €10 ($13)
- Specialty plastics: €8 ($10) up to €100 ($130)

Densities of plastics range from about 0.8 up to more than 2, which leads to changes in the ranking of plastics costs per liter versus ranking of costs per kilogram. For example, PVC is the cheaper commodity per kilogram but is more expensive than polyethylene and polypropylene per liter.

That is even truer for metals having higher densities, for instance, 7.8 for steel.

For comparison, costs per volume (€/l) of metals are expected to be:

- Some €/l for carbon steel, aluminum
- 10 €/l and more for special steel, titanium, copper
- More than 100 €/l for nickel.

6.4 Actual Weight Savings

Generally, the raw material cost of the part to be manufactured is the first examined parameter but one must keep in mind that it is only one element among others such as processing costs and possibly running costs, disposal cost including waste collection and, if appropriate, recycling costs. In that case the recycled polymer value must be deduced from the recycling cost. There are many ways leading to cost and weight savings, for example:

- The most used is, perhaps, the thickness lowering thanks to more performing resins or reinforced compounds.
- Apart from the direct weight and cost savings linked to thickness lowering, there are also cooling and cycle time savings, which reduce processing costs.
- For automotive and aerospace industries, weight savings lead to lower running cost thanks to fuel economy.
- For some applications, construction, for example, a better durability leads to long lasting parts saving operating costs and reducing recycling, pollution, carbon footprint, etc., in proportion of the extra lifetime. One way uses expensive protective agents extending the lifetime of parts for a modest compound overspent.

More generally, plastic resin use leads to a broad range of weight savings depending on the features taken into account including:

Table 6.6 Examples of Costs per Volume (€/l) for Some Thermoplastics

	Minimum	Maximum
PE	1.4	1.7
PP	1.6	1.8
PVC	1.8	2.1
ABS	1.9	3.1
PE UHMW	1.9	2.4
PS	1.9	2.5
SAN	2.0	2.6
SMA	2.0	3.1
PET	2.2	2.6
PPE	2.2	4.3
POM	2.5	3.1
PMMA	2.7	2.9
PBT	2.8	3.5
PA	3.0	3.6
PC	3.1	4.0
CA	3.8	3.9
POM GF	3.8	4.7
PA GF	4.1	4.7
PC GF	4.3	4.9
PSU	8.2	13.8
PPS	9.0	18.1
LCP	16.5	32.0
PEI GF	16.8	18.3
PEI	17.4	19.1
PVDF	21.3	22.5
PTFE	24.4	27.9
ECTFE	37.1	42.7
PAI	43.0	62.1
PEEK	90.0	99.1

- Design freedom allowing all shapes and all sizes, multiple function integrations, which is unfeasible with metals or wood
- Versatility of flow and processing features
- Ease of adaptation of manufacturing methods to small quantities or large series of parts
- Reduction of finishing, construction, assembling, and handling costs
- Aesthetics, possibilities of bulk coloring, or in-mold decoration to take the aspect of wood, metal, or stone, which removes or reduces the finishing operations
- Durability, absence of rust, and corrosion (but beware of aging), reduction of maintenance operations
- Transparency, insulation, and other collateral properties inaccessible for metals
- Adaptation to miniaturization…

Figure 6.3 proposes various routes to cost and weight savings.

Taking into account these various elements, actual cost savings range from levels as high as 95% down to 0% or even, in exceptional cases, a higher weight if other properties of prime importance are reached. Figure 6.4 shows the statistical analysis of actual weight savings.

6.5 Density Reduction Using Structural Foam Techniques and Hollow Parts

Structural foams are made of a cellular core with a denser skin. Density of final parts can be, to a certain extent, tuned by a limited foaming of the thermoplastic leading to structural foams. Of course, the density is lowered but some properties are reduced as far as the foaming rate is higher.

The technique is used for industrial and aesthetic goods such as automotive, electronics, household appliances, aeronautics… such as housings of machines, TV cabinets, computer housings, roofs for caravans or ships, hard tops of 4WD (Jeep), luggage boxes, parts for washing machines…

Table 6.7 displays a detailed example of dense and foamed polycarbonate properties. One property or the other of physical, mechanical, electrical, and thermal are more or less affected. These data are only examples providing a rough idea of the significant differences between foamed and dense polycarbonates and other data can be found elsewhere. These theoretical data cannot be used for designing, computing, or to make

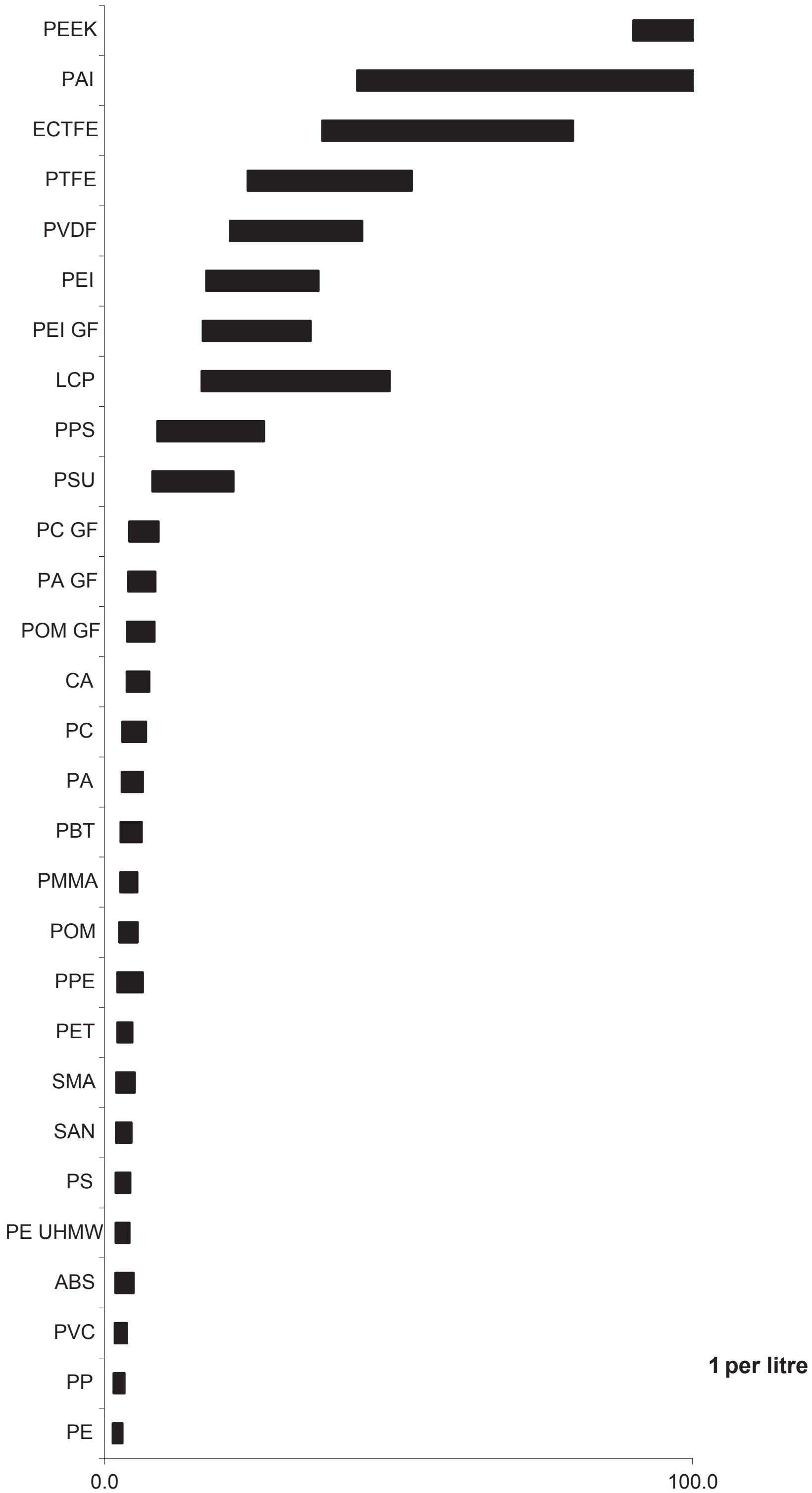

Figure 6.2 Approximate plastic raw materials costs, € per liter.

economic predictions. Only properties measured on the actual used compound must be considered.

Table 6.8 briefly displays some property examples of dense (D) and foamed (F) commodity and engineering thermoplastics. These data are only examples providing a rough idea of the significant differences between subfamilies, and other data can be found elsewhere. These theoretical data cannot

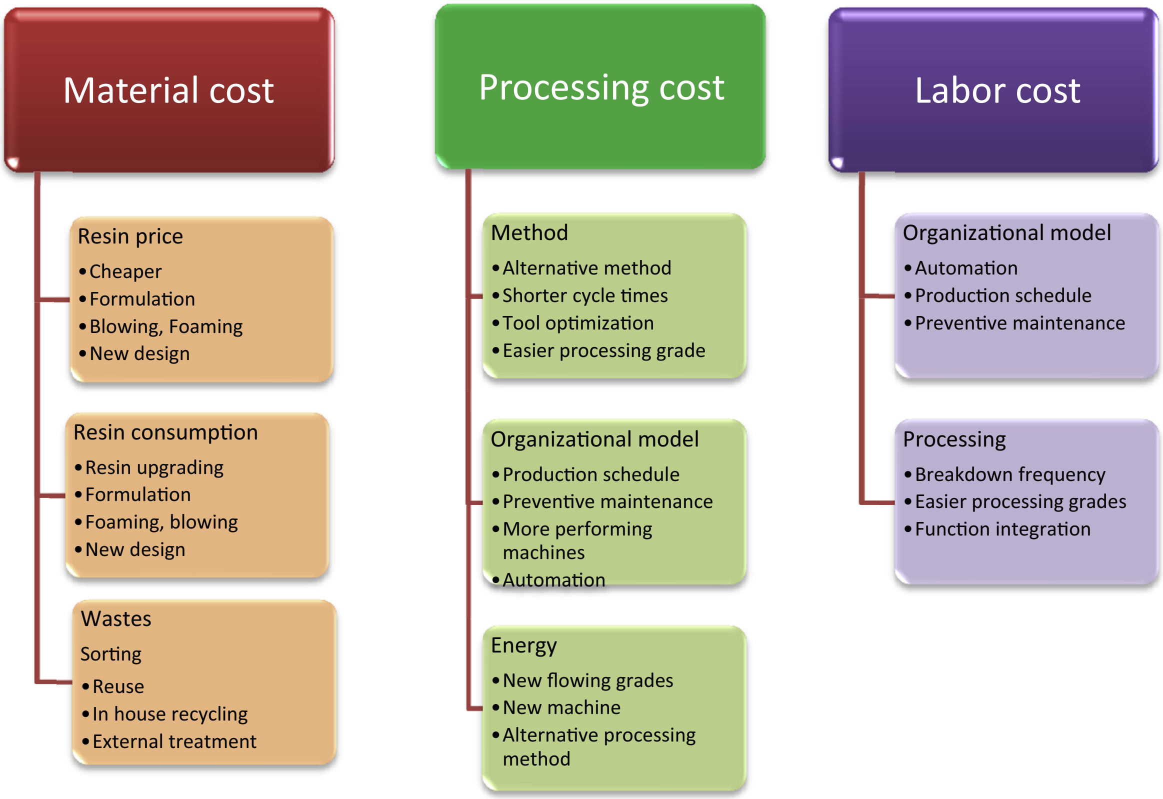

Figure 6.3 Various routes toward cost and weight savings.

Mean	**48**
Median	45
Standard deviation	21.7
Range	85
Minimum	10
Maximum	95

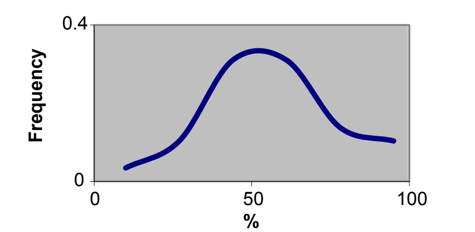

Figure 6.4 Weight-saving examples.

be used for designing, computing, or to make economic predictions. Only properties measured on the actually used compound must be considered.

6.5.1 Cost Savings Using Less Raw Material for the Same Satisfaction

Structural foams are processed by several thermoplastic processing techniques using:

- A compound containing a blowing agent that is decomposed by the heat of the melted plastic producing a large volume of gas. Standard injection molding machines are used.
- A standard compound and a specific injection machine allowing the introduction of the gas in the melted plastic. The pressure drop in the mold induces the expansion of the gas.

Advantages of injection molding of structural foams are as follows:

- Almost all thermoplastic materials can be foamed.
- Large parts of more than 40 kg and 1 m can be produced.

Table 6.7 Example of Polycarbonate Properties

	Dense PC	Foamed PC
Physical Properties		
Density	1.20 g/cc	0.900 g/cc
Water absorption	0.12%	0.15%
Water absorption at saturation	0.30%	0.30%
Linear mold shrinkage	0.0065 cm/cm	0.0050–0.0070 cm/cm
Mechanical Properties		
Tensile strength, ultimate	70.0 MPa	42.0 MPa
Elongation at break	≥50%	5.0%
Tensile modulus	2.4 GPa	2.1 GPa
Flexural yield strength	75 MPa	76 MPa
Flexural modulus	2.4 GPa	2.34 GPa
Electrical Properties		
Electrical resistivity	1.00E + 16 ohm-cm	1.00E + 16 ohm-cm
Surface resistance	1.00E + 16 ohm	1.00Ee + 15 ohm
Dielectric constant	3.0	2.9
Dielectric strength	34 kV/mm	≥16.0 kV/mm
Comparative tracking index	250 V	100–175 V
Thermal Properties		
CTE, linear	65 μm/m-°C	50 μm/m-°C
Thermal conductivity	0.20 W/m-K	0.15 W/m-K
Deflection temperature at 0.46 MPa	138 °C	138 °C
Deflection temperature at 1.8 MPa	127 °C	127 °C

- Allows the production of parts having a good balance between density and mechanical performances.
- Weight reduction is of the order of 10–35%.
- Basic properties are as those of the polymer but the foaming reduces some of them.
- Parts are less sensitive to sink marks, thickness variations, and residual stresses. Thicknesses, 5–15 mm, can be higher than with dense compounds; bosses and ribs can be oversized.
- Foams are more thermally insulating and are soundproof.
- Multimaterial parts can be processed with, for example, a foamed core of recycled material and a dense skin made of the same virgin material.
- The combination with glass fiber reinforcement allows enhanced mechanical performances for the same density.
- Total automation of the process and high output rates.
- Low labor costs.
- In certain cases, if feeding pressures are low, tools can be formed in lighter grades of metals.

Table 6.8 Property Examples of Dense and Foamed Commodity and Engineering Thermoplastics

			Tensile		Flexion		Compression	HDT
		Density (g/cm³)	Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (MPa)	1.82 MPa (°C)
ABS	D	1.05	45	2.2	77	2.5		85–100
ABS	F	0.75–0.95	29	2	63	1.8–2.2	31–37	78–86
PS HI	D	1.05	20	2	40	2.1	69	
PS HI	F	0.73	10–19	1–2	35–37	1.5–2	24	
PS HI	F	0.56	6	0.65	31	1	13	
PC	D	1.2	55–77	2.3	100	2.5		135–140
PC	F	0.85–0.95	37	1.9	70	2.3		126
PEI	D	1.27	105	3				190–200
PEI	F	0.9	40	1.8	100	2.9		175
PPO	D	1.06	45–50	2.4–2.5	85–100	2.5		110–130
PPO	F	0.8–0.85	23–32	1.6–1.7	45–58	1.8–2.1	35	83–110
PE HD	D	0.96	28		36	1	17	
PE HD	F	0.55	7		12	0.7	5	
PA	D	1.14	70		95	2.2		80
PA	F	0.8	49		85	2.1		73

- Suitable for mass production.
- Normally, the whole surface of the part has a good finish, which makes the final finishing unnecessary. However, the aspect varies with the process. A textured surface can minimize the surface irregularities.
- Apart from particular cases of resins filled with short fibers and other acicular or lamellar fillers, the parts are isotropic if there are no residual constraints.
- Shot capacities are on a large range, for example, few grams up to more than 50 kg.

Drawbacks of injection molding of structural foams include the following:

- The blowing agents must be adapted to the polymer because of the decomposition temperature, which must be compatible with the temperatures of the various processing stages.
- The optimization of the molding parameters can be difficult because of the delicate balance between the blowing agent decomposition and the part shaping. Part warpage and shrinkage are sometimes difficult to predict.
- Part sizes are limited by the mold size and the machinery performances.
- Certain processes are patented.
- The structural foams, because of the reduction of the real section of the material, are less suitable to resist the tensile stresses.
- Processing is more delicate, less widespread, and often requires particular materials and equipment.
- Very thin parts are not realizable.
- For high expansion levels, the surface quality often requires sanding and the application of a primer before painting.
- Mold and press prices are higher.

6.5.2 Microcellular Thermoplastics Thanks to Supercritical Fluids

Microcellular thermoplastic foams were invented by the Massachusetts Institute of Technology (MIT) in the early 1990s and developed from 1994 at Trexel (http://www.trexel.com/en/).

The extrusion of microcellular foams is based on the thermodynamic instability of supercritical fluids (SCF) injected into a polymer melt under specified pressure profiles. After creation, in a mixing section of the extruder, of a homogeneous solution of the SCF into the polymer melt, a controlled pressure drop in the die promotes the instability of the SCF, creating a large number of homogeneously distributed cells whose growth is controlled by the cooling kinetics.

Of course, the gas injection needs a gas source equipped with a metering system and generally:

- Extrusion or injection machines must have specific screws and barrels equipped with injectors allowing the gas injection and its good dispersion.
- The high pressure of the gas needs a sturdy machinery.
- The optimization of the process parameters can be difficult because of the delicate balance between the gas expansion and the balance pressure/temperature of the extruded or injected material.
- The part sizes are limited by the die or the mold size and the equipment performances.
- Certain processes are patented.
- The foams, because of the reduction of the real section of the material, are less suitable to resist the tensile stresses.
- The processing is less widespread and requires particular equipment and knowledge.
- The density can be very low and consequently the cost saving can be more exciting.

According to Trexel developing the MuCell process, this technique allows attractive cost cutting of cycle times, energy consumption, and of course, the material consumption is reduced of the same percentage as the actual foaming ratio in the finished part.

Trexel claims that payback periods are in the following orders, according to the material, the size, and the sophistication of the produced parts:

- 0.8 up to 1.2 years for polypropylene-based goods
- 1 year for acetal-based tribological parts
- 0.4–1.1 years for polyamide-based goods
- 0.6–0.7 year for ABS or polycarbonate-based goods.

The MuCell process has already been used successfully in Ford vehicles in Europe for valve covers, along with heating, ventilating, and air conditioning systems.

The Society of Plastics Engineers awarded Ford's use of the MuCell process (Grand Award at the association's 41st Auto Innovation Awards Competition). By creating the instrument panel structure for the Ford Escape in microcellular foam, weight is reduced to more than 1 lb, mechanical properties are improved, molding cycle time is reduced 15%, and molding clamp tonnage is reduced 45%, saving an estimated US$3/vehicle versus solid injection.

For an air intake manifold, a cycle time reduction of 20–30%, a weight reduction of 4–10%, and a better stability is claimed.

However, mechanical properties are affected in various ways depending on the density, cell structure, skin thickness, cell size:

- According to Herman Winata, Lih-Sheng Turng, Daniel F. Caulfield, Tom Kuster, Rick Spindler, Rod Jacobson (ANTEC 2003. p. 701 *Applications of Polyamide/Cellulose Fiber/Wollastonite Composites for Microcellular Injection Molding*):
  - the tensile properties of the microcellular injection-molded samples decrease compared with their conventional solid counterparts.
  - The notched impact strengths can be better, equal, or lower compared with their solid counterparts processed by the conventional injection molding process.
  - Flexural properties are less influenced than tensile properties.
- Figure 6.5(a) and (b) shows the effect of density reduction on flexural and tensile modulus on the one hand, and on the other hand, strength for the same polymer confirming that tensile properties are more sensitive than flexural properties.

6.5.3 Hollow Parts

Gas-assisted injection molding is a variant of injection molding suitable to produce parts with internal cavities or hollow parts. It is used for the manufacture of products such as household appliances and automobile parts.

Apart the injection step itself, identical to common injection, there are three steps for mold filling and gas introduction:

- The mold is partially filled with the melted thermoplastic.
- Gas is injected into the material through a specific nozzle. The plastic in contact with the mold is colder and more strengthened, thus the gas stays in the core of the plastic and presses it against the wall cavity.
- The pressure is maintained until the part is cold enough and solidified.
- At the end of the cycle, gas is vented prior to the mold opening.

In addition to the injection advantages are:

- Weight and material savings for the same external volume
- Cost cutting

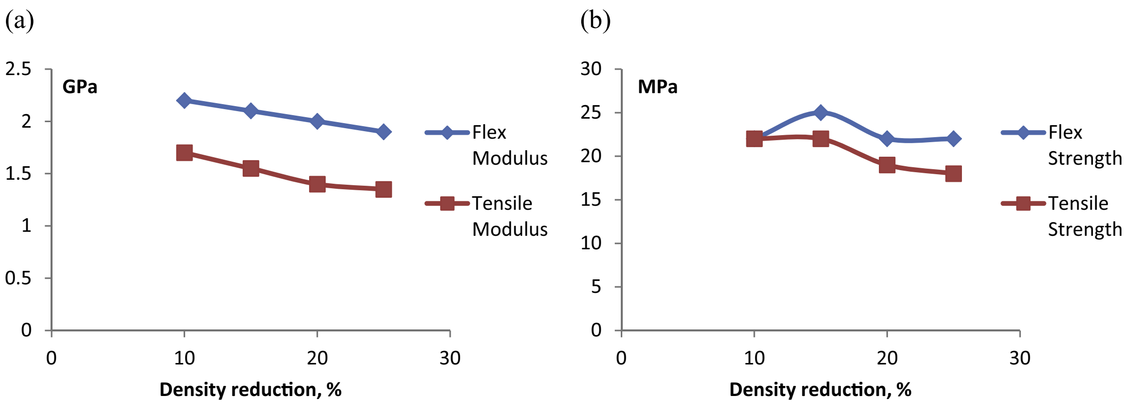

Figure 6.5 (a) Examples of modulus versus density (b) strength versus density.

Table 6.9 Property Examples of Dense (D) and Foamed (F) Commodity and Engineering Thermoplastics

		ABS	ABS	PS	PS	PC	PC	PA	PA
		D	F	D	F	D	F	D	F
GF	%	0	Yes	0	Yes	0	Yes	0	Yes
Density	g/cm^3	1.05	0.95	1.05	0.84	1.2	1	1.14	0.88
Tensile strength	MPa	45	46	20	34	55 77	45	70	70
Tensile modulus	GPa	2.2	3.6			2.3	3.1		
Flex strength	MPa	77	90	40	59	100	83		
Flex modulus	GPa	2.5	3.3	2.1	5.2	2.5	3.8	2.2	4.5
HDT 1.82 MPa	°C	85 100	92			135 140	136		

- Sink mark reduction
- Less residual stresses.

On the other hand:

- The technique is less spread.
- Machinery is specific.
- Mechanical properties are affected.

6.5.4 Combine Two Opposite Techniques: Foaming of Glass Fiber-Reinforced Thermoplastics

The foaming of glass fibers-reinforced thermoplastics allows obtaining a smart balance of density and mechanical properties.

The expansion brings thermal and sound insulation properties. The resonance frequencies of parts are modified providing new opportunities in various applications, for example, audiovisual applications.

Table 6.9 briefly displays some property examples of dense (D) and foamed (F) commodity and engineering thermoplastics. These data are only examples providing a rough idea of the significant differences between these product families and other data can be found elsewhere. These theoretical data cannot be used for designing, computing, or to make economic predictions. Only properties measured on the actual used compound must be considered.

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Trexel, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.
[6] F.A. Shutov, Integral/Structural Polymer Foams.

7 Mechanical Properties

OUTLINE

Thermoplastics have a viscoelastic behavior leading to mechanical properties depending on time and temperature. In addition, moisture can plasticize certain thermoplastics, leading to special features somewhat surprising for traditional material users. Some facets of this issue have been brought to mind in Chapters 1, 5, and 6. The goal of this chapter is:

- to point out that plastics are not ideal materials
- to complete and clarify some aspects of "immediate" or very short-term mechanical properties
- to point out differences between standard test methods and actual mechanical properties resulting from real applications.

Thermal dependency and long-time dependency of mechanical properties will be examined in a later chapter.

7.1 Plastics are not Ideal Materials Obeying to Simple Physical Laws

Ideally:

- tensile modulus of elasticity, flexural or bending modulus of elasticity, and compressive modulus of elasticity are equivalent. In reality, these values are different for plastic materials.
- Modulus is an inherent property of an ideal material. In reality, these values evolve with strain for plastic materials.

In addition, standardized test conditions are practical ones and are not scientifically ideal.

For example, for 11 compounds, the modulus of elasticity, the flexural modulus of elasticity, and the compressive modulus of elasticity claimed in the technical literature are in the following ranges (%):

- 3 for an LCP 30 GF
- 12 for a PA66 30 GF
- 19 for a PE UHMW
- 36 for a PA46
- 40 for a CPVC
- 40 for a PAI 30 GF
- 53 for a PAI
- 53 for a PBI
- 67 for a PE HD
- 111 for a PBI GF
- 145 for a PBI CF

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00007-6

Possible causes may be, for example:

- Standardized test conditions different from scientific procedures
- Anisotropy of tested samples
- Disagreeing testing directions.

For isotropic ideal materials:

E, tensile or flexural modulus of elasticity

G, Shear modulus or modulus of rigidity

ν, Poisson's ratio

These are linked by the following equation: $G = E/2*(1 + \nu)$

For 11 compounds, computed shear modulus or Poisson's ratio is not satisfying for:

- 8 compounds if tensile modulus is used
- 10 compounds if flexural modulus is used.

7.2 First of All, Fully Understand Information and Make Your Requirements Understandable

Formerly, we must remark that mechanical behavior is not an intrinsic property of a compound but depends on numerous parameters including among others, the shape of the part or the test sample, the processing conditions, and the general history of the part or the tested sample.

All the properties are influenced by the additives used with the thermoplastic matrices, notably the reinforcements but also stabilizers, plasticizers, colorants, and others.

In addition, properties are affected by the processing method and possible finishing operations.

Properties including esthetics evolve more or less quickly during storage and use, which can lead to premature failure.

Last but not least, note that a uniaxial (or biaxial) stress impacts the size of a part according to the axis of the stress, but also the sizes according to the other axes of the part.

A common and important point of lack of understanding or misinterpretation is the nature of published data:

- Standard tests are rarely representative of the defined property required for the defined part to be studied. For a very simple example, an actual impact is rarely reproduced by an impact standard test. More surprising for many people, a tensile test result may be different from actual engineering data because of the differences concerning the shape of the part, the actual rate of loading, and small differences of temperature.
- Published data are often means of high values resulting from tests on specimen produced in the best conditions. Statistical results are rare and, unfortunately, weak points are potentially failure initiators. The numerous parameters involved during the development and production of polymers and additives, plastics processing, use of parts, and products lead to a statistical distribution of the properties as far as the material is complex.
- Confusion of terms: for example, sometimes ultimate tensile strength at break and tensile stress at yield are confused making a huge difference for certain polymers. Same observations can be made for elongation at break and deformation at yield.
- Test temperatures are typically 20, 23, or 25 °C. But it must be kept in mind that little variation of temperature can cause great effects: modulus of plasticized poly(vinyl chloride) can be affected by temperature variations as low as 5 °C.
- Test hygrometry is typically "dry as molded" or more rarely 50%RH, which can cause huge differences for some thermoplastics such as polyamides. Ambient moisture can plasticize polyamides and conversely drying can lead to their embrittlement.

In no case, collected data provide ready-to-use figures. The values used for computing must result from tests on the grade of material to be really used, processed in the conditions of the part to be designed. The collected figures give only ways for a better reflection but the designer is responsible of its choices and must assume data used for designing, taking the responsibility to use low, average or high figures related to any suitable properties.

7.3 Tensile Properties

Many standards deal with tensile properties of plastics. ASTM D638-10 and ISO 527-1:2012, not strictly equivalent, are considered technically equivalent. Both standards specify the general principles for determining the tensile properties of plastics and plastic composites under defined conditions. Several different types of test specimen are defined to suit different types of material which are detailed in subsequent parts of ISO 527 or other standards.

These methods are used to investigate the tensile behavior of the test specimens and for determining the tensile strength, tensile modulus, and other aspects of the tensile stress–strain relationship including the option of determining Poisson's ratio at room temperature under the conditions defined.

According to these standards:

- Stresses are well-defined result of uniaxial loadings when in real life there is a complex combination of loadings.
- Test pieces have optimized shapes and are manufactured in the best conditions leading to the highest mechanical properties. Figure 7.1 shows an example of test piece with a well-defined shape designed to evenly distribute loads.
- Test pieces with defects are rejected.
- Test time range is in the order of one or a few minutes being not representative of high-speed loadings, on the one hand, and creep or relaxation, on the other hand. Figure 7.2(a) and (b) shows ultimate tensile strength versus test time (linear scale for Figure 7.2(a) and semilog scale for Figure 7.2(b)) with a very fast drop of tensile strength at the beginning of the curve.

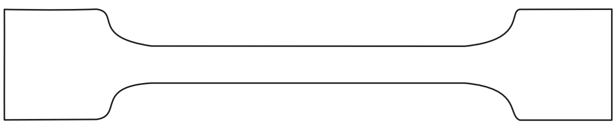

Figure 7.1 Test piece example.

- Environment is air.
- Temperature is "room temperature," often 20 °C.
- Hygrometry must be defined for thermoplastics such as polyamides.

Several typical points and values are defined, for example:

Elastic limit or proportional limit

The elastic or proportional limit is the greatest stress at which the stress is proportional to strain. Note that some materials maintain this proportionality for large stresses and strains, while others show proportionality for very low strains. For some materials, there is not proportionality.

Yield point

The yield point is the first point of the stress–strain curve for which one notes an increase in the strain without an increase in the stress. Parts must always operate well below this point during service. Note that some materials have not a yield point.

Stress and strain at yield

Stress and strain at yield are the values of the stress and strain corresponding to the yield point. Strain at yield may be slightly (one or some percent) or highly (up to more than 100%) inferior to elongation at break.

Ultimate stress and strain

Ultimate stress and strain, or stress and strain at break, are the values corresponding to the breaking of the samples.

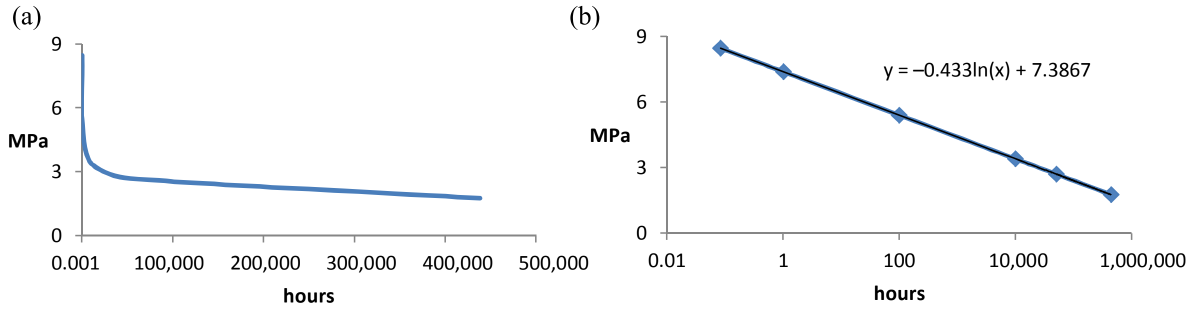

Figure 7.2 (a) Tensile strength versus time and (b) tensile strength versus ln(time).

Elastic modulus or Young's modulus

The elastic modulus is the slope of the tangent at the origin of the stress–strain curve. For some plastic materials, the elastic modulus can be misleading due to the material nonlinear elasticity leading to a flattening of the stress–strain curve.

When the beginning of the curve does not allow a determination of the modulus of elasticity according to the previous method, tensile modulus can be likened as the slope of a secant line between 0.05% and 0.25% strain on a stress–strain plot. Tensile modulus is calculated using the formula:

$$E_t = (\sigma_2 - \sigma_1) / (\varepsilon_2 - \varepsilon_1)$$

where

ε_1 is a strain of 0.0005 (0.05%),

ε_2 is a strain of 0.0025 (0.25%),

σ_1 is the stress at ε_1,

and σ_2 is the stress at ε_2.

Initial modulus

If the rectilinear region at the start of the stress–strain curve is too difficult to locate, the tangent to the initial portion of the curve must be constructed to obtain the initial modulus. For some plastic materials, the initial modulus can be misleading due to the material nonlinear elasticity leading to a flattening of the stress–strain curve.

Secant modulus

The secant modulus is the ratio of stress to corresponding strain at any point on the stress–strain curve. For example, the 1% secant modulus sometimes provided by producers or compounders is the stress at 1% strain. For a define material, the secant modulus is lower than the initial modulus.

As already pointed out, literature data are not always clearly defined or sometimes are misleading, mixing, for example, Young modulus, secant modulus, and initial modulus or mixing yield strain and elongation at break.

7.3.1 Yield and Ultimate Tensile Properties: Strength, Strain, and Elongation Work

Table 7.1 displays yield strength and tensile strength examples ranked in descending order for the minimum yield strength.

The first part of Table 7.1 displays statistical results of six different runs carried out for the determination of tensile strength of six compounds. Coefficient of variations (CV) evolves from 0.54 up to 10.4.

The second part of Table 7.1 displays average yield strength for eight subfamilies: expected neat grades, and special grades including among others carbon fiber (CF)-reinforced grades, glass fiber (GF)-reinforced grades, mineral- and glass bead (GB)-reinforced grades, conductive grades, friction grades, and wood plastic composite (WPC). Note that general purpose grades can be formulated with plasticizers, fillers, and reinforcements and are called "expected neat grades" in the following.

For the third part of Table 7.1 displaying ranges of stresses, we can remark:

- Significant lack of correlation between yield and tensile strength.
- The broad range of strengths for many families coming from formulation versatility, succinct trade appellations, test method versatility, errors, and mix-up.
- High values of yield and tensile strengths for fiber-reinforced grades, in the decreasing order: carbon, glass, aramid, natural fibers.

Table 7.2 displays yield strain and elongation at break examples ranked in descending order for minimum yield strains.

The first part of Table 7.2 displays average yield strain for eight subfamilies: expected neat grades, and special grades including among others CF-reinforced grades, GF-reinforced grades, mineral- and GB-reinforced grades, conductive grades, friction grades, WPC. The reader must be particularly careful because of mix-up between yield strain and elongation at break.

For the second part of Table 7.2, we can remark:

- the huge differences between yield and ultimate strains particularly for unreinforced grades
- the enormous ranges of elongation at break for many grades

Table 7.1 Yield and Tensile Strength Examples

Examples of Statistical Analysis of Six Tensile Strength Experiments		
Average of Each Run, MPa	**Standard Deviation of Each Run**	**Coefficient of Variation of Each Run, %**
23.8	0.4	1.7
26.9	0.8	3
59.2	0.32	0.54
77.6	2.6	3.4
288	30	10.4
266	24	9

Plastic	**Yield Strength, mean, MPa**
Neat grades	52
Special grades	109
CF-reinforced grades	165
GF-reinforced grades	127
Mineral-, GB-reinforced grades	77
Conductive grades	67
Friction grades	68
WPC	30

	Yield Strength, MPa				**Tensile Strength, MPa**			
	Neat Grades		**Special Grades**		**Neat Grades**		**Special Grades**	
Plastic	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PAA medium-level CF			270	315			270	315
PPA CF			263	270			152	270
PPA long GF			262	262			207	269
PA 6 high-level long GF			250	280			250	280

Continued

Table 7.1 Yield and Tensile Strength Examples—cont'd

Plastic	Yield Strength, MPa				Tensile Strength, MPa			
	Neat Grades		Special Grades		Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PA 66 long CF							250	260
PA 66 high-level long GF			230	323			230	323
PEEK/PBI CF			230	240			185	230
PPA GF			221	221			179	221
PI TP CF			220	230			230	250
PAA high-level GF			200	290			200	290
PAI CF			200	203			200	221
PEI conductive			190	210			200	210
PA 66 medium-level long GF			185	200			160	200
TPU long GF			180	250			182	250
PBT long CF			180	220			180	220
PPS long GF medium level			167	168			165	176
PEEK CF			160	240			160	240
PPS CF			160	210			160	210
PA 10-10 high level GF Bio			160	200			160	200
PEEK/PBI GF			160	170			160	170
PI TP GF			160	170			160	220
PA 6 medium-level long GF			157	210			157	210
PA 66 CF			150	310			150	310

PA 12 CF			150	273			140	273
PA 66 high-level GF			150	240			150	255
PPS long GF high level			150	180			165	180
PEEK GF			150	180			150	180
PAEK 30% GF			150	180			150	180
PBT long GF			150	180			150	180
PET/PBT high-level GF			150	180			150	180
PEI GF			150	160			150	160
ABS/PC medium-level long GF			150	152			150	152
LCP CF			149	240			110	240
PES CF			148	185			117	185
PAI Mineral			147	148			100	148
PPE/PA GF			140	185			120	185
PBI	140	160			110	160		
PA 6-12 GF			140	130			140	170
PEI CF			137	255			131	222
PAI	130	150			130	195		
PBT medium-level GF			130	140			130	140
PBT CF			125	175			117	175
PAA medium-level GF			125	170			125	185
PAI friction			125	170			84	170
ABS/PC_low-level long GF			125	125			125	125
PPS GF			120	195			120	195
POM long GF			120	123			123	123

Continued

Table 7.1 Yield and Tensile Strength Examples—cont'd

Plastic	Yield Strength, MPa				Tensile Strength, MPa			
	Neat Grades		Special Grades		Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PK GF			120	120			120	141
PA 6-10 CF			117	126			117	234
PES friction			115	150			115	150
LCP GF			110	220			110	220
PAI GF			110	210			110	221
LCP	110	188			110	188		
LCP Mineral			110	186			80	186
PA 4-10 GF Bio			110	170			110	170
PA Far			110	121			70	121
PPS CF+GF			109	143			109	183
PPA Mineral			107	107			103	117
PC CF			103	170			102	175
PAA Mineral			100	185			100	185
PET GF			100	170			100	170
Polyarylate GF			100	145			145	150
PLA/PBT GF			100	125			120	125
PSU GF			100	125			100	130
PSU/PBT GF			100	120			100	120
PLA GF			100	110			100	114
PEI	100	110			90	100		
PPE CF			96	99			83	103
PA 6 high-level GF			95	210			95	210
PA 6 GF recycled			95	130			90	130

PP long GF high level			92	135			92	145
PE 60% long GF			91	115			91	115
PC GF			90	160			90	160
POM GF			90	147			90	160
PTT Bio GF			90	140			120	140
PCT GF			90	130			97	130
PC/PBT GF			90	130			90	140
PPE GF			90	130			80	130
SAN GF			90	130			70	130
PMMA GF			90	105			90	105
PEI Mineral			90	100			90	100
PEEK/PBI	90	90			90	90		
PA 4-6 GF			85	250			85	250
PEI GF milled			85	85			85	85
PP/PA GF			80	170			80	160
PA 11 GF			80	135			80	135
PA 12 GF			80	115			80	115
PET/PC GF			80	110			60	110
POM Far			80	96			50	96
ABS CF			78	106			78	106
PVDF CF			78	93			78	120
PPS Far			77	100			65	100
PMI or PMMI	77	80			77	90		
Acrylique imide	77	79			77	79		
PA 66 medium-level GF			75	190			75	125
PES GF			75	169			75	150

Continued

Table 7.1 Yield and Tensile Strength Examples—cont'd

Plastic	Yield Strength, MPa				Tensile Strength, MPa			
	Neat Grades		Special Grades		Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PBT GF and mineral			75	147			70	147
PA 66 impact medium-level GF			75	120			73	120
ABS/PC GF			75	80			75	125
PSU	72	83			63	80		
POM CF			70	160			70	160
PI TP	70	140			70	140		
PA 6 medium-level GF			70	130			95	160
PPSU GF			70	120			75	140
PEEK	70	115			70	110		
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	70	115			70	110		
PPSU	70	94			70	94		
PES	70	90			70	95		
PS GF			70	85			70	85
PA CNT							69	72
ETFE GF			70	83			60	83
PA castable friction			70	80			70	88
PLA/PP 30% GF			70	75			70	75
Polyarylate	69	70			25	70		
PA 66 conductive			65	130			79	216
PPE Mineral			65	75			50	75

PSU Mineral			65	70			60	70
ASA/PBT GF			63	140			60	140
PPA	62	76			62	80		
PPS GF + Mineral			60	150			60	197
TPU GF			60	150			11	150
PPS conductive			60	140			60	169
PC/SAN GF			60	135			65	135
PA 66 GB			60	100			65	100
PVC GF			60	97			60	97
PA Transparent	60	82			50	105		
ABS GF			60	65			80	86
SAN	59	85			65	85		
PK	59	60			55	63		
PSU modified	57	66			56	66		
PSU/PC	57	65			57	65		
ABS/PC conductive			57	61			38	61
SMA GF			56	75			56	103
PA 6 mineral FR			55	120			55	120
PPE/PA	54	60			52	57		
PE GF			52	63			50	63
PVDF friction			52	56			40	60
PA 4-6 Mineral			50	106			50	106
PA 4-10 Bio	50	85			50	85		
SMMA	50	85			25	70		
PA 6 GB			50	80			50	95
PC	50	75			55	77		

Continued

Table 7.1 Yield and Tensile Strength Examples—cont'd

	Yield Strength, MPa				Tensile Strength, MPa			
	Neat Grades		Special Grades		Neat Grades		Special Grades	
Plastic	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
POM Mineral			50	75			50	75
PA 6-10	50	70			45	90		
PC CNT			50	65			30	50
POM conductive			49	68			49	151
TPU conductive			48	58			48	58
PVDF Mica			48	49			46	47
PP long GF medium level			46	125			46	125
POM GB			46	65			45	65
PA castable	45	84			70	84		
ABS/PA 20 GF			45	77			45	77
PTT Bio	45	70			45	70		
PC conductive			45	70			44	70
PET	45	70			22	70		
PPE	45	66			45	65		
ABS/PC	45	65			41	65		
PA 11	45	65			40	69		
PA 10-10 Bio	45	55			45	65		
PBT medium-level GB			45	55			45	55
ASA/PVC	45	50			45	50		
PC friction			45	50			45	50
PI TP friction			44	66			44	145
POM friction			43	57			48	70

PSU/ABS	43	50			43	50		
PP medium-level GF			42	115			42	115
COC	42	71			32	71		
MABS	41	50			41	48		
PP CF			41	42			19	48
PA 4-6	40	100			65	90		
PA 66 Mineral			40	100			40	100
ASA/PC	40	65			44	65		
PLA/PC					48	52		
ASA/PMMA	40	65			44	65		
PVCC	40	60			45	60		
PA 6 recycled	40	60			40	60		
PBT	40	60			40	55		
PET/PC	40	60			40	57		
PET Amorphous	40	40			40	40		
PA 12 GB			39	52			39	52
PA 6 FR			38	90			38	80
PLA natural reinforcement							33	102
PP cellulose fibers							33	57
PC/PBT	37	53			41	60		
ABS conductive			36	50			36	50
PA 6	35	90			40	95		
PA 66	35	85			35	95		
PP low-level GF			36	50			35	75
PMMA impact	35	65			35	65		
PP natural fibers			35	57			32	57

Continued

Table 7.1 Yield and Tensile Strength Examples—cont'd

	Yield Strength, MPa				Tensile Strength, MPa			
	Neat Grades		Special Grades		Neat Grades		Special Grades	
Plastic	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PVC unplasticized	35	55			33	60		
ASA	35	46			46	56		
PVF	35	40			40	110		
TPU Shore D					30	55		
PP Ho	35	40			20	40		
ABS GB			35	36			25	31
PMP GF			34	68			34	68
PLA wood WPC			34	36			34	35
PPS	33	90			30	90		
CP	32	41			14	50		
PA 6-12	31	65			31	65		
POM homo- or copolymer	30	80			27	80		
ECTFE	30	69			20	55		
PA 12	30	65			30	65		
PCTFE	30	50			30	41		
ABS/PVC	30	46			41	50		
PP low-level CNT			30	45			35	42
ABS/PA	30	45			30	45		
PA 12 friction			30	45			30	40
FEP GF			30	40			30	40
ETFE	27	50			21	50		
PP conductive			27	42			27	48

PLA	26	60			41	83		
PA 12 conductive			25	90			25	96
ABS FR			25	60			30	50
PVC wood WPC			25	49			10	40
PA 11 or 12 plasticized			24	30			25	35
PS 40% wood WPC			22	29			20	30
PP Talc			21	35			21	35
PP wood WPC			21	32			20	30
EVOH	20	94			26	98		
ABS	20	60			20	60		
PVDF	20	56			24	50		
PP/PA	20	50			23	56		
PLA/PE					27	28		
TPU Bio					25	39		
PFA					21	30		
Starch/copolyester					20	26		
Starch/PE					20	53		
Starch/PP					20	21		
SMA	20	50			20	55		
PLA/copolyester	20	44			20	22		
PP antistat			20	35			10	55
PVDC	20	30			20	35		
PE-X cross-linked	20	26			11	32		
PP GB			20	25			20	36
PE-HD antistat black			20	20			17	30
CA	19	51			13	67		

Continued

Table 7.1 Yield and Tensile Strength Examples—cont'd

	Yield Strength, MPa				Tensile Strength, MPa			
	Neat Grades		Special Grades		Neat Grades		Special Grades	
Plastic	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
COPE high Shore D	19	50			22	50		
PP $CaCO_3$			19	22			19	22
PE-UHMW	17	49			17	49		
CAB	17	43			18	52		
PP Co	17	35			30	35		
PP recycled	17	23			20	23		
PMP Mineral			17	21			17	22
PE-HD	16	32			18	40		
FEP					19	27		
PEBA 25 to 45 Shore D					17	40		
PEBA Bio					17	55		
Starch/PS					17	18		
PTFE friction			16	18			14	16
PS	15	60			20	60		
PTFE	15	43			15	43		
PS impact	15	40			15	45		
PP Mineral			15	35			13	35
PE wood WPC			15	34			15	23
PTFE CF			15	30			11	45
PMP	15	24			16	25		
COPE Bio	12	34			12	34		
PEBA 50 to 72 Shore D	11	34			17	62		

PP impact	11	28			23	35		
PVC plasticized			10	50			7	30
PE-LD	9	30			10	30		
TPV Shore D					12	28		
PTFE GF			7	20			7	43
CPE	6	12			6	23		
TPO Shore D	4	28			4	28		
PB	4	18			22	36		
EMA	3	37			11	39		
COPE low Shore D	3	36			3	36		
EVA	2	40			2	30		
MPR					7	13		
TPE based on PVC					6	19		
TPS Shore D					5	36		
PP/EPDM-V					1.4	28		

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)

Plastic	Strain at Yield, Mean, %
Neat	9
Special	3.3
CF	1.5
GF	2.6
Mineral, GB	4.6
Conductive	4.4
Friction	6.8
WPC	4

	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
Plastic	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
TPO Shore D	20	35			150	750
PA 11 or 12 plasticized	20	30			40	300
PEBA 25 to 45 Shore D	20	25			50	700
PEBA 50 to 72 Shore D	15	31			200	550
PEBA Bio	15	31			50	550
PE-UHMW	13	20			50	500
PA 12 friction			12	20	40	60
PVF	10	30			90	110
PK	10	25			230	350
COPE high Shore D	10	19			200	700
PA 6 recycled	10	15			50	150
PE-HD antistat black			10	10	11	100
PVC plasticized			8	10	30	500
PE-X cross-linked	8	10			10	440
PE-HD	7	100			50	700
PVDF	7	16			12	450
PP recycled	7	9			10	100
PTFE	7	8			200	400
PPSU	7	8			15	120

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

Plastic	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PEI	7	7			60	60
PI TP	7	7			8	110
PA 66	6	30			16	300
PP impact	6	13			200	700
PP Co	6	13			50	500
PA Transparent	6	10			50	300
Polyarylate	6	9			20	100
PC	6	7			50	150
PMMA antistatic			6	7	10	18
POM homo- or copolymer	5	30			10	75
EVA	5	25			50	2000
PA 12	5	20			60	400
PA 11	5	20			50	400
PA 10-10 Bio	5	20			50	100
PA 4-10 Bio	5	16			16	100
POM friction			5	14	10	70
PP Ho	5	8			11	600
PVDF friction			5	7	20	71
PPE/PA	5	7			12	100
FEP	5	6			250	340
PSU modified	5	6			90	100
PSU/PC	5	6			90	100
PSU	5	6			40	100
PTT Bio	5	6			15	20
EVOH	5	6			14	350
PVDF Mica			5	5	6	6
PVCC	5	5			4	32
ETFE	4	23			100	460
PA 6	4	18			60	300
PA 6 GB			4	10	4	12

Continued

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
Plastic	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PET/PC	4	7			50	200
PA 12 GB			4	7	18	32
PP/PA	4	6			95	400
PVC unplasticized	4	6			2	120
PP GB			4	5	8	50
PSU/ABS	4	4			4	25
Acrylique imide	4	4			4	4
PP wood WPC			1	4	1	10
CAB	3.6	40			23	90
PA 6-12	3	20			100	340
PA 6 FR			3	20	20	100
PA 12 conductive			3	20	4	60
PE-LD	3	16			200	900
PLA wood WPC			3	13	5	14
PP Talc			3	10	8	60
PA 66 GB			3	9	5	12
PA 66 Mineral			3	9	3	70
ABS/PVC	3	8			18	20
ABS/PC	3	8			3	125
PC/PBT	3	7			50	150
PPA	3	7			3	30
ETFE GF			3	7	1	10
ABS/PA	3	6			55	290
ASA/PVC	3	6			40	70
PAI friction			3	6	3	9
ASA/PC	3	5			60	100
PLA/copolyester	3	5			12	300
ASA/PMMA	3	5			10	30
PA 4-6 Mineral			3	5	4	20
PA 4-10 GF Bio			3	5	4	10
PBT	3	5			3	200

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
Plastic	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PEEK	3	5			3	150
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	3	5			3	150
PA 4-6 GF			3	5	3	10
PA 12 GF			3	5	3	8
MABS	3	4			12	20
ASA	3	4			8	40
CA	3	4			6	72
PEI Mineral			3	4	6	6
ABS/PA 20 GF			3	4	3	7
PMI or PMMI	3	4			3	6
PP $CaCO_3$			3	3.5	12	165
PPE/PA GF			3	3	3	8
PA 6 GF recycled			3	3	3	3
PPE GF			3	3	2	7
PP Mineral			2	50	3	150
TPU GF			2	25	4	65
COPE Bio	2	19			200	310
COPE low Shore D	2	10			300	900
PP antistat			2	10	2	400
PMMA	2	10			2	10
PPE	2	9			9	60
PES	2	8			6	80
PPSU GF			2	8	2.5	6
ASA/PBT GF			2	8	2	9
PP conductive			2	7	1	9
PC conductive			2	6	4	20
PET/PC GF			2	6	3	6
PA 11 GF			2	6	2.5	8
PET GF			2	6	2	6

Continued

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

Plastic	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PAI GF			2	5	2	7
SAN	2	5			2	7
PI TP friction			2	5	2	6
PSU Mineral			2	5	2	6
PVC GF			2	5	2	6
COC	2	4.5			3	140
PP/PA GF			2	4	3	5
PP low-level GF			2	4	3	4
ABS FR			2	4	2	80
PA 6 medium-level GF			2	4	2	5
PAEK 30% GF			2	4	2	4
PC GF			2	4	2	4
TPU conductive			2	3	4	5
ABS/PC conductive			2	3	3.4	11
PA 4-6	2	3			3	300
PLA natural reinforcement			2	3	3	10
PA 6-12 GF			2	3	3	5
ABS GF			2	3	3	3.5
PC/SAN GF			2	3	3	3
PK GF			2	3	2.5	3
ABS	2	3			2	100
PBT medium-level GB			2	3	2	4
PC/PBT GF			2	3	2	4
PP medium-level GF			2	3	2	4
PA 10-10 high-level GF Bio			2	3	2	3
PEEK GF			2	3	2	3
PBI	2	3			2	3
PBT medium-level GF			2	3	2	3

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

Plastic	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PBT GF and mineral			2	3	2	3
PEI GF milled			2	3	2	3
PEI GF			2	3	2	3
PSU/PBT GF			2	3	2	3
SMA GF			2	3	2	3
PI TP GF			2	3	1.5	3
PP CF			2	3	1	400
POM conductive			2	3	1	5
PA 6 medium-level long GF			2	2.6	2	4
ABS conductive			2	2.5	2.4	4
PA 66 conductive			2	2.5	2	3.5
PA 66 medium-level long GF			2	2.4	1.9	2.4
PA 6 mineral FR			2	2	2	70
PAA medium-level GF			2	2	2	5
ABS/PC GF			2	2	2	3
PAA Mineral			2	2	2	3
PPA GF			2	2	1.8	2.5
PI TP CF			2	2	1.5	2
PPA long GF			2	2	1	3
ABS GB			1.8	1.9	3	11
ABS/PC_low-level long GF			1.8	1.8	1.8	1.8
PSU GF			1.7	3	1.7	3
PA 66 high-level long GF			1.7	2	1.7	3
PET			1.5	30	2	600
PAI Mineral			1.5	4	1.6	5
PAI CF			1.5	4	1.5	6
PA 66 high-level GF			1.5	3	2	3

Continued

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
Plastic	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PE GF			1.5	2.5	1.5	2.5
Polyarylate GF			1.5	2	2	2
PE 60% long GF			1.5	1.5	1.4	1.5
PA 6 high-level GF			1.4	3.2	1.4	3.2
PA 6 high-level long GF			1.4	2	1.4	2
ABS/PC medium-level long GF			1.4	1.4	1.4	1.4
PE wood WPC			1.3	5	0.8	15
LCP Mineral			1.2	4	1.2	5.5
POM long GF			1.2	1.2	1.2	1.2
ECTFE	1	10			10	300
POM GF			1	7	1	12
POM GB			1	6	10	10
POM Mineral			1	6	2	55
PA 66 impact medium-level GF			1	6	2	10
PES GF			1	6	1.4	7
PA 66 medium-level GF			1	6	1	8
PS	1	4			1	40
PC CF			1	3	2	3
PCT GF			1	3	2	3
PP long GF medium level			1	3	2	3
TPU long GF			1	3	2	3
PA Far			1	3	1.6	8
LCP GF			1	3	1	6
PBT CF			1	3	1	4
PEEK CF			1	3	1	3
PPS GF + Mineral			1	3	1	3
PEEK/PBI GF			1	2.7	1	2.7
POM Far			1	2	2.4	10

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

Plastic	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PLA/PBT GF			1	2	2	5
PES CF			1	2	2	3
PBT long GF			1	2	1.8	2
PES friction			1	2	1.6	2.3
PA 6-10 CF			1	2	1.5	2.5
PAA medium-level CF			1	2	1.3	2
PEI CF			1	2	1.2	4
PLA GF			1	2	1	10
POM CF			1	2	1	4
PPS GF			1	2	1	4
PEEK/PBI CF			1	2	1	3.7
LCP	1	2			1	3
PA 12 CF			1	2	1	3
PA 66 CF			1	2	1	3
PMP GF			1	2	1	3
PPA CF			1	2	1	3
PTT Bio GF			1	2	1	3
SAN GF			1	2	1	3
PPE CF			1	2	1	2.7
PP long GF high level			1	2	1	2.5
PA 66 long CF			1	2	1	2
PEEK/PBI	1	2			1	2
PEI conductive			1	2	1	2
PET/PBT high-level GF			1	2	1	2
PAA high-level GF			1	1.5	1.8	2
ABS CF			1	1.5	1.3	1.5
PPS Far			1	1.4	1.3	3
PPS long GF medium level			1	1.3	1	1.3

Continued

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

Plastic	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PPA Mineral			1	1	1	2
PPS long GF high level			1	1	1	2
PS GF			1	1	1	1.5
PMMA GF			1	1	1	1
PS impact	0.9	2			2	65
PBT long CF			0.8	1.8	0.8	2
PVDF CF			0.8	1	0.8	4
PPS	0.7	4			0.7	15
FEP GF			0.5	3	0.5	3
PPS conductive			0.5	3	0.5	3
PPS CF			0.5	2	0.5	3
PPS CF + GF			0.3	0.8	0.3	2
LCP CF			0.25	1	0.25	4
Starch/PE					480	680
CPE					400	800
TPV Shore D					400	600
PP/EPDM-V					300	700
TPS Shore D					300	650
PB					300	550
PFA					280	300
TPU Shore D					250	550
PET Amorphous					250	300
MPR					210	400
EMA					200	850
PVDC					160	250
TPU Bio					100	450
PA 6-10					100	300
PTFE friction					100	180
PCTFE					80	250
PTFE CF					70	350

Table 7.2 Examples of Strain at Yield and Elongation at Break (Ultimate Strain)—cont'd

Plastic	Strain at Yield, %				Elongation at Break or Ultimate Strain, %	
	Neat Grades		Special Grades		All Grades	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PTFE GF					70	270
PP low-level CNT					50	150
CP					30	100
TPE based on PVC					20	500
PA castable					20	50
PA castable friction					20	50
PMP					15	120
PP medium CNT					15	17
PPE Mineral					10	40
PLA/PC					10	20
PLA/PE					10	20
PC friction					8	70
PAI					8	15
PMP Mineral					6	30
PLA/PMMA					6	15
PMMA impact					4	80
PP cellulose fibers					3	7
PP natural fibers					3	6
PLA					2.5	160
SMMA					2	54
SMA					2	30
PA CNT					2	4

- significant lack of correlation between yield and ultimate strains
- the broad range of strains for many families, which comes from formulation versatility, succinct trade appellations, various test methods, and some errors or mix-up.

Table 7.3 displays examples of approximate average work of elongation at yield ranked in descending order.

The work (W) produced by a uniaxial tensile force (F) for an elongation (dL) can be written as W = F*d(L). Considering the yield point, a rough approximation of the work at yield (Wy) can be represented by Fy*Sy, that is, the product of the uniaxial tensile force (Fy) and the strain at yield (Sy).

We can remark the broad range of values coming from formulation versatility, succinct trade appellation, and some errors or mix-up.

7.3.2 Tensile Modulus

Table 7.4 displays examples of tensile modulus. Beware: elastic modulus or Young's modulus, initial modulus, and secant modulus are not differentiated.

Table 7.3 Examples of Average Work at Yield (MPa*%)

Plastic	Neat Grades	Special Grades
TPU GF		14.2
PE-HD	12.8	
PA 66	10.8	
PK	10.4	
POM homo- or copolymer	9.6	
PET	9.1	
PVF	7.5	
PA 6 FR		7.4
PEI	7.4	
PI TP	7.4	
PA 4-10 Bio	7.1	
PA 11	6.9	
PA 6	6.9	
PA 11 or 12 plasticized	6.8	
PA 4-6 GF		6.7
PAI friction		6.6
PA 12 conductive		6.6
CAB	6.5	
PP Mineral		6.5
PA 10-10 Bio	6.3	
PA 6 recycled	6.3	
PPSU	6.2	
PA 12 friction		6.0
PA 12	5.9	
PA Transparent	5.7	
PA 4-10 GF Bio		5.6
PAI GF		5.6
PAI CF		5.5
PA 6-12	5.5	
PE-UHMW	5.4	
PET GF		5.4
PPA long GF		5.2

Table 7.3 Examples of Average Work at Yield (MPa*%)—cont'd

Plastic	Neat Grades	Special Grades
Polyarylate	5.2	
ETFE	5.2	
PEBA 50 to 72 Shore D	5.2	
PA 66 high-level long GF		5.1
ASA/PBT GF		5.1
COPE high Shore D	5.0	
PAEK 30% GF		5.0
PPE/PA GF		4.9
PA 66 GB		4.8
POM friction		4.8
PPSU GF		4.8
POM GF		4.7
PA 66 medium-level GF		4.6
PA 6 GB		4.6
PA 6 high-level long GF		4.5
PA 10-10 high-level GF Bio		4.5
PI TP CF		4.5
PPA GF		4.4
TPO Shore D	4.4	
PA 66 high-level GF		4.4
PAA medium-level CF		4.4
PVDF	4.4	
PA 11 GF		4.3
TPU long GF		4.3
PES GF		4.3
PSU	4.3	
PA 66 medium-level long GF		4.2
PA 6 medium-level long GF		4.2
PA 66 Mineral		4.2
PEEK GF		4.1
PI TP GF		4.1

Table 7.3 Examples of Average Work at Yield (MPa*%)—cont'd

Plastic	Neat Grades	Special Grades
PC	4.1	
PAI Mineral		4.1
PEEK CF		4.0
PES	4.0	
PPA CF		4.0
PA 12 GF		3.9
PEI GF		3.9
LCP Mineral		3.8
ETFE GF		3.8
PET/PC GF		3.8
PBI	3.8	
PC GF		3.8
PP/PA GF		3.8
PEEK	3.7	
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	3.7	
PMMA	3.5	
PEEK/PBI CF		3.5
PA 6 high-level GF		3.5
PA 66 CF		3.5
PPA	3.5	
PPE/PA	3.4	
PA 66 impact medium-level GF		3.4
PSU modified	3.4	
PA 6 GF recycled	3.4	
PA 6-12 GF		3.4
PBT medium-level GF		3.4
PSU/PC	3.4	
PEI Mineral		3.3
LCP GF		3.3
PPE GF		3.3
PVDF friction		3.2
PA 12 CF		3.2
PTT Bio	3.2	
EVA	3.2	
EVOH	3.1	
Acrylique imide	3.1	
PA 4-6 Mineral	3.1	
PAA high-level GF		3.1
PEEK/PBI GF		3.1
PPE	3.1	
ABS/PC	3.0	
PA 6 medium-level GF		3.0
PBT CF		3.0
PEI conductive		3.0
PK GF		3.0
PAA medium-level GF		3.0
PEI CF		2.9
PAA Mineral		2.9
PLA wood WPC		2.8
PBT GF and mineral		2.8
PC/PBT GF		2.8
PET/PC		2.8
PSU/PBT GF		2.8
PMI or PMMI	2.7	
PVC GF		2.7
PC CF		2.7
ECTFE	2.7	
PVC plasticized		2.7
PSU GF		2.6
PBT long CF		2.6
PMMA antistatic		2.6
SAN	2.5	
PA 12 GB		2.5
PVCC	2.5	

Continued

Table 7.3 Examples of Average Work at Yield (MPa*%)—cont'd

Plastic	Neat Grades	Special Grades
PES CF		2.5
PBT long GF		2.5
PET/PBT high-level GF		2.5
PP Co	2.5	
PC/SAN GF		2.4
PP Ho	2.4	
PVDF Mica		2.4
COPE Bio	2.4	
PSU Mineral		2.4
PPS GF		2.4
PPS CF		2.3
PA Far		2.3
PC conductive		2.3
ABS/PC low-level long GF		2.3
PC/PBT	2.3	
PVC unplasticized	2.3	
LCP	2.2	
PCT GF		2.2
PA 66 conductive		2.2
POM Mineral		2.2
PTFE	2.2	
Polyarylate GF		2.1
ASA/PVC	2.1	
ABS/PA 20 GF		2.1
PEI GF milled		2.1
ABS/PC medium-level long GF		2.1
ASA/PC	2.1	
ASA/PMMA	2.1	
PPS GF + Mineral		2.1
ABS/PVC	2.1	
PE-X cross-linked	2.1	

Table 7.3 Examples of Average Work at Yield (MPa*%)—cont'd

Plastic	Neat Grades	Special Grades
PBT	2.0	
PE-HD antistat black		2.0
PES friction		2.0
PP medium-level GF		2.0
POM GB		1.9
PPS long GF medium level		1.9
PI TP friction		1.9
PSU/ABS	1.9	
PE-LD	1.9	
PP impact	1.9	
COC	1.8	
PA 6-10 CF		1.8
PP Talc		1.8
PA 4-6	1.8	
PP/PA	1.8	
PA 6 mineral FR		1.8
PPS conductive		1.8
POM CF		1.7
PTT Bio GF		1.7
PP long GF medium level		1.7
PP long GF high level		1.7
ABS/PA	1.7	
PLA/PBT GF		1.7
PP antistat		1.7
PPS long GF high level		1.7
SAN GF		1.7
SMA GF		1.6
PP recycled	1.6	
MABS	1.6	
PLA GF		1.6
ABS GF		1.6

Table 7.3 Examples of Average Work at Yield (MPa*%)—cont'd

Plastic	Neat Grades	Special Grades
PP conductive		1.6
ABS/PC GF		1.6
PE 60% long GF		1.5
PP low-level GF		1.5
ABS/PC conductive		1.5
POM conductive		1.5
PPE CF		1.5
POM long GF		1.5
PPS	1.4	
ASA	1.4	
PEEK/PBI	1.4	
TPU conductive		1.3
POM Far		1.3
PLA/copolyester	1.3	
ABS FR		1.3
PBT medium-level GB		1.3
CA	1.2	
LCP CF		1.2
COPE low Shore D	1.2	
ABS CF		1.2
PE GF		1.2
PPA Mineral		1.1
PPS Far		1.1
PP CF		1.0
PP GB		1.0
ABS	1.0	
PMMA GF		1.0
ABS conductive		1.0
PS	0.9	
PS GF		0.8
PE wood WPC		0.8
PVDF CF		0.8
PMP GF		0.8
PPS CF+GF		0.7
PP $CaCO_3$		0.7
PP wood WPC		0.7
ABS GB		0.7
FEP GF		0.6
PS impact	0.4	

The first part of Table 7.4 displays statistical results of four different runs carried out for the determination of tensile modulus of four compounds. CVs evolve from 0.7% up to 7.1%.

The second part of Table 7.4 displays average tensile modulus for eight subfamilies: expected neat grades, and special grades including among others CF-reinforced grades, GF-reinforced grades, mineral- and GB-reinforced grades, conductive grades, friction grades, WPC. The reader must be particularly careful because of mix-up between the different modulus meanings.

For the third part of Table 7.4, we can remark:

- the huge ranges of modulus for some grades coming from formulation versatility, succinct trade appellation, various test methods, and some errors or mix-up.
- The reinforcement effect of carbon and glass fibers.

7.4 Flexural Properties

Flexural tests provide information about the flexural properties of plastics when employed under conditions approximating those under which the tests are made. The tests cannot be considered significant for engineering design in applications differing widely from the load-time scale of the standard test.

The designer must be cautious for data interpretation: there are several nonequivalent test procedures.

Table 7.4 Examples of Tensile Modulus

Statistical Analysis of Runs for the Measure of Tensile Modulus for Four Compounds				
Mean of a Run, GPa	**Standard Deviation of a Run**		**Coefficient of Variation for a Run, %**	
0.274	0.017		6.2	
0.295	0.021		7.1	
14	0.1		0.7	
13	0.7		5.4	
Plastic	**Tensile Modulus, Mean, GPa**			
Neat	1.9			
Special	9.1			
CF	17.5			
GF	9.8			
Mineral, GB	6.1			
Conductive	6.1			
Friction	4.3			
WPC	4.4			
	Tensile Modulus, Range Examples, GPa			
	Neat Grades		**Special Grades**	
Plastic	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PBT long CF			28	32
PAA medium-level CF			22	25
PEEK/PBI CF			21	28
PI TP CF			20	29
PA 66 long CF			19	25
PA 66 high-level long GF			19	24
PA 6 high-level long GF			19	22
PAA high-level GF			18	24
PAI CF			18	23
PPS long GF high level			18	21
PET/PBT high-level GF			18	19
PPA long GF			17	19
PPS CF			16	36
PPS CF + GF			16	30
LCP CF			14	37
PPS conductive			14	24

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PPS long GF medium level			13	17
PA 12 CF			12	19
POM long GF			12	14
PBT long GF			12	13.6
ABS/PC medium-level long GF			12	13
PEI conductive			12	13
PA 66 CF			11	35
PEEK CF			11	26
PAI GF			11	15
PPA GF			11	14
PEI CF			10	26
PPS GF + Mineral			10	22.6
PBT CF			10	21
PI TP GF			10	20
PA 6 high-level GF			10	18
PE 60% long GF			10	14
PEEK/PBI GF			10	14
PLA GF			10	14
LCP	9	21		
PA 10-10 high-level GF Bio			9	16
PA 66 high-level GF			9	16
PA 6 medium-level long GF			9	12
PAA medium-level GF			9	12
PEEK GF			9	12
PAEK 30% GF			9	12
PBT medium-level GF			9	11.5
PA 66 medium-level long GF			9	11
PES friction			9	11
LCP GF			8	32

Continued

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PPA CF			8	25
POM CF			8	17
PBT GF and mineral			8	14
PP long GF high level			8	13.8
ABS/PC low-level long GF			8	9
PEI GF			8	9
PA 6-12 GF			7.9	9.5
LCP Mineral			7.5	22
PK GF			7.3	10.3
PES CF			7	22
TPU long GF			7	15
PAA Mineral			7	13
PET GF			7	12
POM GF			7	11.3
PCT GF			7	11
PLA/PBT GF			7	11
PPE CF			7	10.6
PMMA GF			7	10.4
PPA Mineral			7	9
PTT Bio GF			6.5	11
PA 6-10 CF			6	27
PPS GF			6	16
PC CF			6	14
PVDF CF			6	14
ABS CF			6	13
PAI Mineral			6	12
PPE/PA GF			6	12
PSU GF			6	12
PA 4-10 GF Bio			6	10
PPS Far			6	10
PPE GF			6	9
PS GF			6	9

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PSU/PBT GF			6	9
Polyarylate GF			6	8
PEI GF milled			6	7
PEEK/PBI	5.1	5.6		
ETFE GF			5	18
PC GF			5	12
PA 6 medium-level GF			5	11
SMA GF			5	10.6
PA 66 medium-level GF			5	10
SAN GF			5	10
PA 6 GF recycled			5	9
PC/PBT GF			5	9
PC/SAN GF			5	9
PA 11 GF			5	8
ABS/PC GF			5	7
PAI friction			5	7
PEI Mineral			5	7
PLA/PP 30% GF			5	7
PBI	5	6		
PA 12 GF			4.6	6
PA 4-6 GF			4.5	10
ABS GF			4.5	6.1
ABS/PA 20 GF			4.5	5.5
ASA/PBT GF			4	10
PA 6 mineral FR			4	10
PA 66 Mineral			4	10
PP medium-level GF			4	9
PP long GF medium level			4	9
PPSU GF			4	9
PVC GF			4	9
PS 40% wood WPC			4	5.8
FEP GF			4	5

Continued

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PAI	4	5		
PLA wood WPC			4	5
PVDF Mica			4	4.2
PSU Mineral			3.8	7.7
POM Mineral			3.7	8.5
PA Far			3.6	9
PMI or PMMI	3.6	4.5		
Acrylique imide	3.6	4.3		
PA 66 conductive			3.5	23
PES GF			3.5	11
PMP GF			3.5	6
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	3.5	4.2		
PEEK	3.5	4		
PP/PA GF			3.3	10
PE GF			3.2	6.3
POM GB			3.2	4
PA CNT			3.2	3.5
PP CF			3	19
PI TP friction			3	12
PET/PC GF			3	8
PA 66 impact medium-level GF			3	7
PBT medium-level GB			3	4.1
PEI	3	4		
PLA natural reinforcement			2.8	13.2
POM Far			2.8	7
PP low-level GF			2.8	5
PPS	2.8	4.2		
SAN	2.8	4		
PA castable friction			2.8	3.6
ABS GB			2.8	3.5
PLA	2.6	3.8		

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PP wood WPC			2.5	6
PMMA	2.5	5		
PC conductive			2.5	2.8
PSU/PC	2.4	2.5		
EVOH	2.3	5.8		
PPE Mineral			2.3	3.5
PVCC	2.3	3.2		
PVC unplasticized	2.2	4		
SMMA	2.2	3.6		
PES	2.2	2.8		
ABS/PVC	2.2	2.6		
PVDF friction			2.2	2.6
PPSU	2.2	2.5		
PP natural fibers			2.1	8
PP cellulose fibers			2.1	5.6
ABS conductive			2.1	3.5
PLA/PC	2.1	3.1		
PPE/PA	2.1	2.9		
PC CNT			2.1	2.7
PSU	2.1	2.7		
PC	2.1	2.5		
PSU modified	2.1	2.5		
PSU/ABS	2.1	2.2		
TPU conductive			2.1	2.1
POM conductive			2	12
PVC wood WPC			2	8
PA 4-6 Mineral			2	6
PA 66 GB			2	5
PI TP	2	3.6		
PLA/PMMA	2	3.5		
PS	2	3.5		
PBT	2	3.2		

Continued

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
ABS FR			2	3
COC	2	3		
PPE	2	2.8		
PVF	2	2.7		
ASA	2	2.6		
Polyarylate	2	2.3		
ASA/PMMA	2	2.2		
ASA/PVC	2	2.2		
PP medium CNT			1.95	2.2
PP GB			1.9	3.3
PPA	1.9	2.7		
PA 6 GB			1.8	4.5
PET	1.8	3.5		
SMA	1.8	3.5		
POM friction			1.8	3.1
ASA/PC	1.8	2.6		
PET Amorphous	1.8	2.2		
PP low-level CNT			1.73	2.1
PE wood WPC			1.7	5
PA 12 GB			1.7	3.6
PMP Mineral			1.7	3.5
ABS/PC	1.7	3		
ABS/PC conductive			1.7	2.8
MABS	1.7	2.2		
Starch/PS	1.7	1.8		
PTT Bio	1.6	2.5		
PC/PBT	1.6	2.3		
PET/PC	1.6	2.2		
PP Talc			1.5	4
PMMA impact	1.5	3.5		
PP $CaCO_3$			1.5	2.3
PLA/PE	1.5	1.7		

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PP conductive			1.4	19
PS impact	1.4	3		
PA Transparent	1.4	2.7		
ECTFE	1.4	2		
PC friction			1.4	2
PMMA antistatic			1.4	1.7
PK	1.4	1.6		
PA castable	1.3	3		
PA 10-10 Bio	1.3	2		
ABS/PA	1.2	1.8		
PA 6 FR			1.1	3.7
PP Ho	1.1	1.8		
Starch/PP	1.1	1.1		
PP Mineral			1	4.2
POM homo- or copolymer	1	3.7		
PA 4-6	1	3.3		
ABS	1	3		
PP antistat			1	3
PA 6-10	1	2.4		
PCTFE	1	2.1		
PTFE GF			1	1.7
PA 6 recycled	1	1.5		
PA 4-10 Bio	0.9	3.1		
PP Co	0.9	1.8		
PP recycled	0.9	1.5		
PA 66	0.8	3.7		
PA 6	0.8	3		
PA 6-12	0.7	2.6		
PE-HD antistat black			0.7	0.8
CA	0.6	2.8		
PLA/copolyester	0.6	1.8		
PVDF	0.5	2.6		

Continued

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PA 12 friction			0.5	2
PA 11	0.5	1.9		
PA 12	0.5	1.9		
PMP	0.5	1.6		
ETFE	0.5	1.4		
PE-HD	0.5	1.4		
PFA	0.5	0.8		
CP	0.45	1.9		
CAB	0.4	2		
PTFE	0.4	1.4		
PTFE CF			0.4	1.4
PP impact	0.4	1.3		
PA 12 conductive			0.35	6
PE-X cross-linked	0.35	3.5		
PVDC	0.35	0.5		
TPU GF			0.3	13
PP/PA	0.3	2.3		
PE-UHMW	0.3	1.3		
FEP	0.3	0.7		
PA 11 or 12 plasticized	0.3	0.6		
COPE high Shore D	0.2	1.2		
Starch/PE	0.2	0.3		
PEBA 50 to 72 Shore D	0.16	0.8		
PE-LD	0.13	0.5		
TPO Shore D	0.1	2.3		
TPU Bio	0.1	0.7		
TPU Shore D	0.1	0.7		
TPS Shore D	0.1	0.3		
TPV Shore D	0.1	0.3		
Starch/copolyester	0.08	0.1		
COPE Bio	0.05	0.32		
PB	0.05	0.3		

Table 7.4 Examples of Tensile Modulus—cont'd

Plastic	Tensile Modulus, Range Examples, GPa			
	Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
EMA	0.02	0.5		
PEBA Bio	0.01	0.56		
PP/EPDM-V	0.01	0.35		
EVA	0.01	0.3		
PEBA 25 to 45 Shore D	0.01	0.15		
COPE low Shore D	0.006	0.17		
MPR	0.003	0.005		
CPE	0.002	0.007		
PVC plasticized			0.001	2.2
TPE based on PVC	0.001	1		

ISO 178:2010 "Plastics—Determination of flexural properties" specifies a method for determining the flexural properties of rigid and semirigid plastics under defined conditions. The method is used to investigate the flexural behavior of the test specimens and to determine the flexural strength, flexural modulus, and other aspects of the flexural stress–strain relationship under the conditions defined. It applies to a freely supported beam, loaded at midspan (three-point loading test). A standard test specimen is defined, but parameters are included for alternative specimen sizes for use where appropriate. A range of test speeds is included.

- Method A uses a strain rate of 1%/min throughout the test.
- Method B uses two different strain rates: 1%/min for the determination of the flexural modulus and 5%/min or 50%/min, depending on the ductility of the material, for the determination of the remainder of the flexural stress–strain curve.

The method is suitable for use with thermoplastic molding, extrusion and casting materials, including filled and reinforced compounds in addition to unfilled types.

ISO 178:2010 applies to fiber-reinforced compounds with fiber lengths less than or equal to 7.5 mm prior to processing. For long-fiber-reinforced materials (laminates) with fiber lengths greater than 7.5 mm, ISO 14125 is available (see below).

The method is not normally suitable for use with rigid cellular materials or sandwich structures containing cellular material. In such cases, ISO 1209-1 and/or ISO 1209-2 can be used.

ASTM D790-10 "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials" is not technically equivalent to ISO 178. These test methods (Procedures A and B) cover the determination of flexural properties of unreinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars molded directly or cut from sheets, plates, or molded shapes. These test methods are generally applicable to both rigid and semirigid materials. However, flexural strength cannot be determined for those materials that do not break or that do not fail in the outer surface of the test specimen within the 5.0% strain limit of these test methods. These test methods utilize a three-point loading system applied to a simply supported beam.

- Procedure A is designed principally for materials that break at comparatively small deflections and shall be used for measurement of flexural properties, particularly flexural modulus, unless the material specification states otherwise.
- Procedure B is designed particularly for those materials that undergo large deflections during testing. It may be used for measurement of flexural strength only.

Tangent modulus data obtained by Procedure A tend to exhibit lower standard deviations than comparable data obtained by means of Procedure B.

ISO 14125:1998 "Fiber-reinforced plastic composites—Determination of flexural properties" specifies a method for determining the flexural properties of fiber-reinforced plastic composites under three-point (Method A) and four-point (Method B) loading. Standard test specimens are defined but parameters included for alternative specimen sizes for use where appropriate. A range of test speeds is included.

The method is not suitable for the determination of design parameters, but may be used for screening materials, or as a quality control test.

The method is suitable for fiber-reinforced thermoplastic and thermosetting plastic composites.

The method is performed using specimens which may be molded to the chosen dimensions, machined from the central portion of the standard multipurpose test specimen (see ISO 3167) or machined from semifinished or finished products such as moldings or laminates.

The method specifies preferred dimensions for the specimen. Tests which are carried out on specimens of other dimensions, or on specimens which are prepared under different conditions, may produce results which are not comparable. Other factors, such as the speed of testing and the conditioning of the specimens can influence the results. For materials which are not homogeneous through the section, or above the linear–elastic response region, the result applies only to the thickness and structure tested. Consequently, when comparative data are required, these factors must be carefully controlled and recorded.

ASTM D6272-10 "Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending" covers the determination of flexural properties of unreinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars molded directly or cut from sheets, plates, or molded shapes. These test methods are generally applicable to rigid and semirigid materials. However, flexural strength cannot be determined for those materials that do not break or that do not fail in the outer fibers. This test method utilizes a four-point loading system applied to a simply supported beam.

This test method may be used with two procedures:

- Procedure A, designed principally for materials that break at comparatively small deflections.
- Procedure B, designed particularly for those materials that undergo large deflections during testing.

Procedure A shall be used for measurement of flexural properties, particularly flexural modulus, unless the material specification states otherwise. Procedure B may be used for measurement of flexural strength.

This test method is equivalent to ISO 14125 (Method B).

Table 7.5 displays averages, standard deviations of averages, CV, repeatability, Ir, and reproducibility, IR, for various thermoplastics. These data concern the average flexural properties measured by one laboratory at several time (within-laboratory standard deviation of the average flexural properties) or measured by several laboratories (between-laboratories standard deviation of the average). Dispersion of experimental data resulting from one experiment series is not concerned.

Table 7.6 displays flexural modulus and flexural strength examples ranked in descending order for modulus.

The first part of Table 7.6 displays statistical results of four different runs carried out for the determination of flexural modulus of four compounds. CV evolves from 0.6 up to 8.5.

The second part of Table 7.6 displays average flexural modulus for eight subfamilies: expected neat grades, and special grades including among others CF-reinforced grades, GF-reinforced grades, mineral- and GB-reinforced grades, conductive grades, friction grades, WPC. The reader must be particularly careful because of mix-up between different procedures used to measure flexural modulus.

For the third part of Table 7.6, we can remark:

- the enormous ranges of flexural modulus for many grades coming from formulation versatility, succinct trade appellation, the versatility of test methods, and some errors or mix-up.
- The reinforcement effect of carbon and glass fibers.

Table 7.7 displays flexural strength examples ranked in descending order.

Table 7.5 Precision Data for Flexural Properties

Precision Data for Flexural Stress at a Conventional Deflection of 3.5%—Values in MPa						
Material	**Average, MPa**	**Sr**	**CV, %**	**SR**	**Ir**	**IR**
Polycarbonate	70.5	0.752	1	1.99	2.11	5.58
ABS	72.1	0.382	0.5	2.67	1.07	7.49
PE, HD	20.4	0.129	0.6	0.505	0.36	14.42
PSU GF	156	1.65	1	3.13	4.62	8.75
Precision Data for Flexural Modulus—Values in MPa						
Polycarbonate	2310	45.6	2	146	128	410
ABS	2470	33.6	1	157	94.0	439
PE, HD	1110	15.0	1	94.4	41.9	264
PSU GF	8510	83.5	1	578	234	1618

Sr = within-laboratory standard deviation of the average; CV = coefficient of variation [Sr/average]; SR = between-laboratories standard deviation of the average; Ir = 2.83 Sr; IR = 2.83 SR.

The first part of Table 7.7 displays statistical results of six different runs carried out for the determination of flexural strength of six compounds. CVs evolve from 4.4 up to 13.

The second part of Table 7.7 displays average flexural strength for five subfamilies: expected neat grades, and special grades including among others CF-reinforced grades, GF-reinforced grades, mineral- and GB-reinforced grades. The reader must be particularly careful because of mix-up between different procedures used to measure flexural modulus.

The third part of Table 7.7 displays claimed flexural strengths for 60 compounds. Flex strength can be measured at break, at yield, or at defined deflections leading to broad ranges of data. We can remark the reinforcement effect of carbon and glass fibers.

7.5 Compressive Properties

Multiaxial loadings are rarely treated in the literature, very special tests having to be conducted for their study. Please remark that bulk modulus is much higher than uniaxial modulus.

7.5.1 Uniaxial Compression

Compression tests provide information about the compressive properties of plastics when employed under conditions approximating those under which the tests are made. The tests cannot be considered significant for engineering design in applications differing widely from the load-time scale of the standard test.

The designer must be cautious for data interpretation: there are several nonequivalent test methods.

ISO 604:2002 "Plastics—Determination of compressive properties" and ASTM D695-10 "Standard Test Method for Compressive Properties of Rigid Plastics," technically equivalent, describe several test procedures.

Compressive properties include modulus of elasticity, yield stress, deformation beyond yield point, and compressive strength (unless the material merely flattens but does not fracture). Materials possessing a low order of ductility may not exhibit a yield point. In the case of a material that fails in compression by a shattering fracture, the compressive strength has a very definite value. In the case of a material that does not fail in compression by a shattering fracture, the compressive strength is an arbitrary one depending on the degree of distortion that is regarded as indicating complete failure of the material. Many plastic materials will continue to deform in compression until a flat disk is produced, the compressive stress (nominal) rising steadily in the process, without any well-defined fracture occurring. Compressive strength can have no real meaning in such cases.

Compression tests provide a standard method of obtaining data for research and development, quality

Table 7.6 Examples of Flexural Modulus

Statistical Analysis of Runs for the Measure of Flexural Properties for 10 Compounds

	Mean of Each Run Flexural Modulus, GPa	Standard Deviation of Each Run, GPa	Coefficient of Variation for Each Run, %
	0.758	0.05	6.3
	1.2	0.104	8.5
	1.5	0.065	4
	2.5	0.015	0.6

Plastic	Flexural Modulus, Mean, GPa
Neat	2
Special	8.6
CF	16.5
GF	9.5
Mineral, GB	6
Conductive	5.6
Friction	4.15
WPC	4.1

	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
Plastic	Minimum	Maximum	Minimum	Maximum
PBT long CF			27	32
PAA medium-level CF			21	23
PEEK/PBI CF			20.6	29
PI TP CF			19	29
PA 6 high-level long GF			19	20
PA 66 long CF			19	20
PAI CF			19	20
PET/PBT high-level GF			18	19
PAA high-level GF			17	23
PA 66 high-level long GF			17	21
PPS long GF high level			17	19
PPS CF			16	31
PPS CF+GF			16	30
PPA long GF			14	19
PBT long GF			12.7	13.5
LCP CF			12	37
PA 12 CF			12	19

Table 7.6 Examples of Flexural Modulus—cont'd

	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
Plastic	Minimum	Maximum	Minimum	Maximum
PPS conductive			12	18
PA 10-10 high-level GF Bio			12	15
PEI conductive			12	13
POM long GF			12	13
PPS long GF medium level			11	16
PPA GF			11	13
ABS/PC_medium-level long GF			11	12
PA 66 CF			10	27
PEEK CF			10	26
PEI CF			10	26
PPS GF + Mineral			10	21
PA 6 high-level GF			10	18
PAI GF			10	15
PEEK/PBI GF			10	14
PLA GF			10	14
PE 60% long GF			10	12
PI TP GF			9	20
PEEK GF			9	12
PAEK 30% GF			9	12
PA 6 medium-level long GF			9	11
PA 66 medium-level long GF			9	11
PES friction			9	11
PPA CF			8	22
POM CF			8	17
PA 66 high-level GF			8	16
LCP	8	15		
PBT GF and mineral			8	14
PP long GF high level			8	12.5
PBT medium-level GF			8	11.5
PAA medium-level GF			8	11
PA 6-12 GF			8	9.5
PEI GF			8	9
LCP GF			7	33

Continued

Table 7.6 Examples of Flexural Modulus—cont'd

Plastic	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PES CF			7	22
PBT CF			7	21
LCP Mineral			7	20
PAA Mineral			7	13
TPU long GF			7	13
PET GF			7	12
POM GF			7	12
PCT GF			7	11
PLA/PBT GF			7	11
PMMA GF			7	10.4
PSU GF			7	10
PK GF			7	9
PPE CF			7	9
ABS/PC_low-level long GF			7	8
PPA Mineral			7	8
PA 6-10 CF			6	22
PPS GF			6	16
ABS CF			6	13
PAI Mineral			6	12
PVDF CF			6	12
PTT Bio GF			6	11
PA 4-10 GF Bio			6	10
PPE/PA GF			6	10
PPE GF			6	9
PS GF			6	9
PSU/PBT GF			6	9
PEI GF milled			6	8
Polyarylate GF			6	8
PPS Far			5.9	9
PC CF			5	14
PC GF			5	12
PA 6 medium-level GF			5	11
SMA GF			5	11

Table 7.6 Examples of Flexural Modulus—cont'd

Plastic	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PC/SAN GF			5	10
SAN GF			5	10
PA 6 GF recycled			5	9
PC/PBT GF			5	9
ABS/PC GF			5	8
PA 11 GF			5	8
PAI friction			5	7
PBI	5	7		
PEI Mineral			5	7
PLA/PP 30% GF			5	7
PEEK/PBI	4.8	6		
PA 4-6 GF			4.6	10
PA 12 GF			4.6	6
PVDF Mica			4.5	4.7
ETFE GF			4	15
PA 6 mineral FR			4	10
PA 66 medium-level GF			4	10
PA 66 Mineral			4	10
PP medium-level GF			4	9
PP long GF medium level			4	9
PPSU GF			4	9
PVC GF			4	9
PSU Mineral			4	7.7
FEP GF			4	6
ABS/PA 20 GF			4	5.5
PAI	4	5		
PLA wood WPC			4	5
ABS GF			3.9	4.1
PEEK	3.7	4.1		
ASA/PBT GF			3.6	9
PMI or PMMI	3.6	4.5		
Acrylique imide	3.6	4.3		

Continued

Table 7.6 Examples of Flexural Modulus—cont'd

Plastic	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PA 66 conductive			3.5	23
PES GF			3.5	11
PA Far			3.5	9
POM Mineral			3.5	8.5
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	3.5	4.2		
PE GF			3.2	5.6
PS 40% wood WPC			3.2	5
POM GB			3.2	4
PMP GF			3.1	6
PP CF			3	14
PI TP friction			3	10
PP/PA GF			3	9
PA 66 impact medium-level GF			3	7
PET/PC GF			3	7
SAN	3	4.2		
PEI	3	4		
PI TP	3	3.5		
PLA natural reinforcement			2.8	7.8
POM Far			2.8	7
PPS	2.8	4.2		
PA CNT			2.8	3.5
PA castable friction			2.8	3.2
PLA	2.6	3.9		
PSU/PC	2.6	2.7		
PP natural fibers			2.5	8
PP cellulose fibers			2.5	5.6
PMMA	2.5	5		
PP low-level GF			2.5	4.5
PC conductive			2.5	2.8
PC CNT			2.5	2.7
ABS GB			2.4	3.1
EVOH	2.3	5.8		
PPE Mineral			2.3	3.5

Table 7.6 Examples of Flexural Modulus—cont'd

Plastic	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PVCC	2.3	3.2		
PSU	2.3	2.9		
ABS/PVC	2.2	3		
PES	2.2	2.9		
PPSU	2.2	2.6		
PVDF friction			2.2	2.3
PP wood WPC			2.1	5
PBT medium-level GB			2.1	4.1
ABS conductive			2.1	3.5
PVC unplasticized	2.1	3.5		
PLA/PC	2.1	3.1		
PPE/PA	2.1	2.6		
PC	2.1	2.5		
PSU/ABS	2.1	2.2		
TPU conductive			2.1	2.1
POM conductive			2	12
PA 4-6 Mineral			2	6
PVC wood WPC			2	6
PA 66 GB			2	4.6
ABS FR			2	4
PLA/PMMA	2	3.8		
PS	2	3.5		
PBT	2	3.2		
SMMA	2	3.2		
POM friction			2	3
PPE	2	2.8		
PSU modified	2	2.7		
PVF	2	2.7		
Polyarylate	2	2.3		
ASA/PMMA	2	2.2		
ASA/PVC	2	2.2		
SMA	1.9	3.7		
PPA	1.9	2.7		

Continued

Table 7.6 Examples of Flexural Modulus—cont'd

	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
Plastic	Minimum	Maximum	Minimum	Maximum
PA 6 GB			1.8	4.5
PA castable	1.8	3.5		
PET	1.8	3.5		
COC	1.8	3		
ASA/PC	1.8	2.6		
PET Amorphous	1.8	2.2		
PP medium CNT			1.8	2.2
PA 12 GB			1.7	3.6
ABS/PC conductive			1.7	3.5
PMP Mineral			1.7	3.5
PP GB			1.7	3.1
ABS/PC	1.7	3		
MABS	1.7	2.2		
PTT Bio	1.6	2.5		
ECTFE	1.6	1.8		
PP Talc			1.5	4
PMMA impact	1.5	3.5		
PP low-level CNT			1.5	2.5
ASA	1.5	2.4		
PC/PBT	1.5	2.3		
PP $CaCO_3$			1.5	2.3
PET/PC	1.5	2.2		
PLA/PE	1.5	1.7		
Starch/PS	1.5	1.6		
PP conductive			1.4	14
PP Mineral			1.4	4
PA Transparent	1.4	3.3		
PS impact	1.4	3		
PC friction			1.4	2
PMMA antistatic			1.4	1.7
PK	1.4	1.6		
PA 10-10 Bio	1.3	2		
ABS/PA	1.2	1.8		

Table 7.6 Examples of Flexural Modulus—cont'd

Plastic	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
	Minimum	Maximum	Minimum	Maximum
PP Ho	1.2	1.8		
PCTFE	1.2	1.5		
PE wood WPC			1.1	5
PA 6 FR			1.1	3.7
POM homo- or copolymer	1	3.7		
PA 4-6	1	3.5		
PP antistat			1	3.3
ABS	1	3		
PA 6-10	1	2.4		
PTFE GF			1	1.7
PA 6 recycled	1	1.5		
Starch/PP	1	1.1		
PA 4-10 Bio	0.9	3.5		
PP Co	0.9	1.8		
PP recycled	0.9	1.5		
PA 66	0.8	3.5		
PA 6	0.8	3		
PA 6-12	0.7	2.6		
PE-HD antistat black			0.7	0.8
CA	0.6	2.8		
PVDF	0.6	2.6		
CAB	0.6	2.4		
PA 12	0.6	1.9		
PLA/copolyester	0.6	1.8		
ETFE	0.6	1.4		
PA 12 friction			0.5	2
PA 11	0.5	1.9		
PE-HD	0.5	1.6		
PMP	0.5	1.5		
PFA	0.5	0.8		
CP	0.45	1.9		
PTFE	0.4	1.4		
PTFE CF			0.4	1.4

Continued

Table 7.6 Examples of Flexural Modulus—cont'd

	Flexural Modulus, GPa			
	Expected Neat Grades		Special Grades	
Plastic	Minimum	Maximum	Minimum	Maximum
PE-UHMW	0.4	1.3		
PP impact	0.4	1.3		
PA 12 conductive			0.35	6
PE-X cross-linked	0.35	3.5		
PVDC	0.35	0.6		
TPU GF			0.3	8
FEP	0.3	0.7		
PA 11 or 12 plasticized	0.3	0.6		
PE-LD	0.25	0.75		
PP/PA	0.2	2.2		
COPE high Shore D	0.2	1.2		
PEBA 50 to 72 Shore D	0.16	0.8		
TPO Shore D	0.1	2.3		
TPU Bio	0.1	0.7		
TPU Shore D	0.1	0.7		
TPV Shore D	0.1	0.4		
TPS Shore D	0.1	0.3		
PB	0.05	0.35		
COPE Bio	0.05	0.32		
EMA	0.02	0.5		
PEBA Bio	0.01	0.56		
PEBA 25 to 45 Shore D	0.01	0.15		
EVA	0.007	0.4		
COPE low Shore D	0.006	0.17		
MPR	0.003	0.005		
CPE	0.002	0.007		
PVC plasticized			0.001	2.1
TPE based on PVC	0.001	1		

control, acceptance or rejection under specifications, and special purposes. Such applications require additional tests such as impact, creep, and fatigue.

The compressive properties determined by these methods include yield point, elastic limit, compressive yield stress and strain, ultimate and yield compressive strength, compressive strain at break, compressive stress at specified compressive strain, Young's and other moduli, and elastic limit or proportional limit.

Table 7.7 Examples of Flexural Strengths

Statistical Analysis of Runs for the Measure of Flexural Strengths for Six Compounds		
Average of Each Run, MPa	**Standard Deviation of Each Run, MPa**	**Coefficient of Variation of Each Run, %**
66.8	3.8	5.7
77.3	3.4	4.4
86.6	6.6	7.6
95.5	8.0	8.4
115.1	5.8	5
135	17.6	13

Plastic Subfamily	Flexural Strength, Mean, MPa
Neat	85
Special	173
CF	251
GF	182
Mineral	102

	Flexural Strength, MPa	
Compound	**Expected Neat Grades**	**Special Grades**
PA6/66 30 CF		330
PBI CF		320
PEI 30 CF		296
LCP 30 GF		280
PA6 33 GF Dry		280
PPS 40 GF		276
PPE+PS+PA 30 GF		248
LCP 30 CF		231
PPS Low filler		230
PBT 40 CF		228
PBI GF		225
POM 25 GF		202
PA 6 CF/PTFE		199
PEI 30 GF		186
PBT 30 GF		183
PBI	175	

Table 7.7 Examples of Flexural Strengths—cont'd

	Flexural Strength, MPa	
Compound	**Expected Neat Grades**	**Special Grades**
PPE+PS 30 GF		172
PAI	165	
PP 30 long GF		160
PEEK	159	
PEEK 30 CF		159
PPS GF		159
LCP	158	
PA6 33 GF Conditioned		155
PMMA 30 GF		152
PC 30 GF		150
PA66 30 GF		145
PPE+PS 30 GF/mineral		144
PAI 30 GF		138
PMMA	137	
PA 66 Mineral		124
PA46	117	
PS	106	
PPE+PS 30 GF/mineral foam		104
PBT CNT		103
PVC	103	
PA6 Dry	100	
PEI ESD		100
PPE+PA	92	
POM	91	
PPE+PS	91	
PEEK Bearing		89, 6
PBT	85	
PC	85	
PEEK 30 GF		82, 7
PPS Bearing		72, 4

Continued

Table 7.7 Examples of Flexural Strengths—cont'd

Compound	Flexural Strength, MPa	
	Expected Neat Grades	Special Grades
ABS	65	
ABS GP	65	
PVC GP	57, 6	
PE HD 30 GF		57
PS	52	
CPVC	46	
PP 20 Talc		43
PP 20 Mineral		36
PA6 Conditioned	35	
PP Ho	33, 1	
PP Co	33, 1	
PE HD	31, 7	
PE UHMW	24, 1	
TPO	22	

Elastic or proportional limit

The elastic or proportional limit is the greatest compression stress at which the stress is proportional to strain. Note that some materials maintain this proportionality for large stresses and strains, while others show proportionality for very low strains. For some materials, there is not proportionality.

Yield point

The yield point is the first point of the stress–strain curve for which one notes an increase in the strain without an increase in the stress. Parts must always operate well below this point during service. Note that some materials have not a yield point.

Stress and strain at yield

Stress and strain at yield are the values of the stress and strain corresponding to the yield point. Strain at yield is always inferior to strain at break.

Ultimate stress and strain

Ultimate stress and strain, or stress and strain at break, are the values corresponding to the breaking of the samples.

Elastic modulus or Young's modulus

The elastic modulus is the slope of the tangent at the origin of the stress–strain curve. For some plastic materials, the elastic modulus can be misleading due to the material nonlinear elasticity leading to a slope change in the stress–strain curve.

Theoretically, compressive modulus is equivalent to tensile modulus or Young's modulus **if loadings are in the same direction**. Results can be very different if the sample is highly anisotropic.

Table 7.8 displays comparative tensile and compressive modulus for same compounds. Averages for expected neat grades are significantly different (24%) but of the same order. For averages concerning special grades, the difference is even higher, 40%. Considering single results, compressive modulus of CF-reinforced PBI is about 6 times lower than tensile modulus. The most credible explanation is a difference of the loading direction, tensile modulus being measured in fiber direction and compressive modulus being measured in the perpendicular direction. So, tensile modulus is 24 GPa when compressive modulus (3.8 GPa) is intermediate between 24 GPa and the modulus of the neat PBI that is to say 2.9 GPa.

Secant modulus between two points

When the beginning of the curve does not allow a determination of the modulus of elasticity according to the previous method, compressive modulus can be likened as the slope of a secant line between 0.05% and 0.25% strain on a stress–strain plot. Compressive modulus is calculated using the formula:

$$E_t = (\sigma_2 - \sigma_1) / (\varepsilon_2 - \varepsilon_1)$$

where

ε_1 is a strain of 0.0005 (0.05%),

ε_2 is a strain of 0.0025 (0.25%),

σ_1 is the stress at ε_1,

and σ_2 is the stress at ε_2.

Initial modulus

If the rectilinear region at the start of the stress–strain curve is too difficult to locate, the tangent to the initial portion of

Table 7.8 Examples of Compressive and Tensile Properties

Unit	Expected Neat Grades		Special Grades	
	Tensile Modulus, GPa	Compressive Modulus, GPa	Tensile Modulus, GPa	Compressive Modulus, GPa
PBI CF			24	3.8
LCP 30 GF			15	14.5
PBI GF			12	3.6
PEEK 30 CF			9.65	4
PAI 30 CF			8.27	6.89
PAI 30 GF			6.21	4.14
PEEK 30 GF			5.86	3.45
PEI 30 GF			5.52	4.31
PBI	5	2.9		
PPS GF			5	8.96
PA66 30 GF			4.65	4.14
PEI ESD			4.41	2.55
PEEK	4.14	2.93		
PPS Bearing			3.72	2.36
PAI	3.45	2.41		
PA46	3.24	2.24		
PVC GP	3.21	2.41		
CPVC	1.8	2.4		
PE HD	1.38	0.689		
PP Ho	1.31	1.38		
PP Co	1.05	1.21		
PE UHMW	0.483	0.552		
Average	2.5	1.9	8.7	5.2

the curve must be constructed to obtain the initial modulus. For some plastic materials, the initial modulus can be misleading due to the material nonlinear elasticity leading to a slope change of the stress–strain curve.

Secant modulus

The secant modulus is the ratio of stress to corresponding strain at any point on the stress–strain curve. For a defined material, the secant modulus is lower than the initial modulus.

Table 7.9 displays compressive strength examples ranked in the descending order. The used test methods and the loading direction are unspecified and increase the uncertainty of the collected data linked to formulation versatility, succinct trade appellation, and some errors or mix-up.

7.5.2 Bulk Compression

The bulk modulus (K or B) of a substance measures the substance's resistance to isostatic compression. It is the ratio of the infinitesimal pressure increase to the resulting relative decrease in the

Table 7.9 Examples of Compressive Strengths

Unit	Expected Neat Grades, MPa	Special Grades, MPa
PAI 30 CF		255
PPS 40 GF		234
PEI 30 GF		221
PBI GF		220
PBI CF		220
PBI	206	
PEEK 30 CF		193
PAI 30 GF		186
PEI ESD		164
PEEK	138	
PEEK Bearing		138
PEEK 30 GF		131
PA66 30 GF		124
PAI	124	
PA46	110	
PPS Bearing		107
LCP 30 GF		100
PVC GP	82, 7	
POM	70	
PP Ho	34, 5	
PP Co	33, 1	
PE HD	31, 7	
PE UHMW	20, 7	
PTFE Bearing		8
Mean	85	164

volume. The bulk modulus can be formally defined by the equation:

$$K = -\mathrm{V} * \mathrm{dP/dV}$$

For ideal isotropic and elastic materials, modulus of elasticity E, bulk modulus (K or B), and Poisson's ratio (ν) are linked by the following equation:

$$K = E/\left(3 * \left(1 - 2\nu\right)\right)$$

Figure 7.3 Example of in-plan shear deformation.

Table 7.10 Shear Modulus Examples, GPa

	Expected Neat Compounds	Special Compounds
PBI CF		8.63
PPS 40 GF		5.42
PEEK 30 CF		4.51
PBI	4.48	
PPA 33 GF		4.15
PPA 33 GF		4.15
LCP 30 GF		2.47
PEEK 30 GF		2.4
LCP	1.67	
PS	1.45	
PVC	1.44	
PEI	1.38	
PE	0.117	
Average	1.9	4.8

For example, bulk moduli claimed by datasheets are:

- PEEK: 5.5–6.25 (computed value: 5.7)
- PEI: 4.6 (computed value: 3.0).

7.6 Shear Properties

Figure 7.3 shows a diagrammatic form example of in-plan shear deformation.

Shear modulus or modulus of rigidity, often denoted by G, is defined as the ratio of the shear stress to the shear strain.

Shear moduli are lower than tensile moduli. Table 7.10 displays some examples.

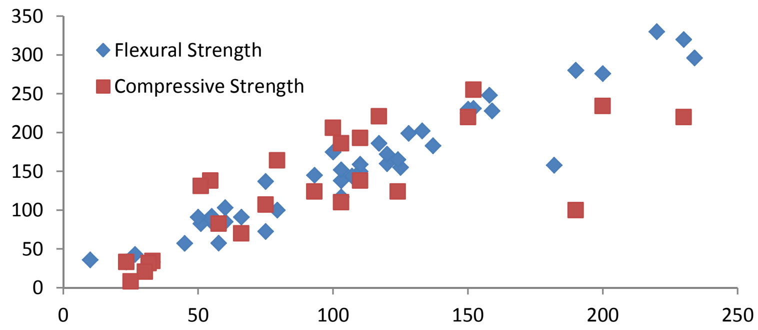

Figure 7.4 Flexural and compressive strengths versus tensile strength.

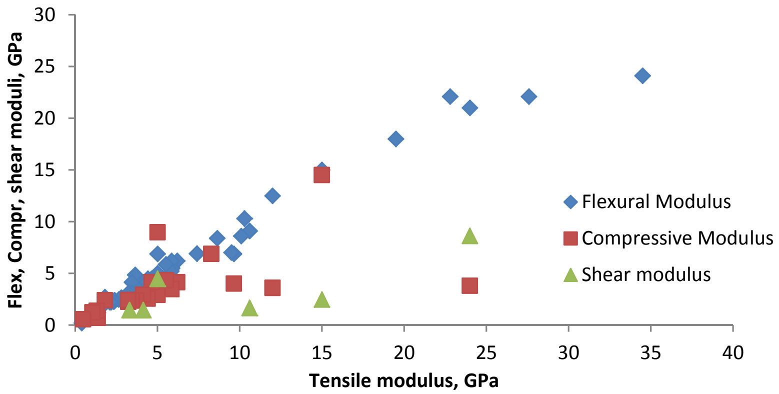

Figure 7.5 Flex, compressive, and shear moduli versus tensile modulus.

7.7 Comparison of Tensile, Flexural, Compressive, and Shear Properties

Figure 7.4 displays a fair correlation between tensile strength and flexural strength except for a liquid crystal polymer (LCP) compound. LCP is a self-reinforced polymer and this can explain that. The correlation between compressive strength and tensile strength is not so good with GF- and CF-reinforced grades deviating from the main domain of correlation.

Figure 7.5 displays:

- A fair correlation between tensile modulus and flexural modulus.
- A poor correlation between compressive modulus and tensile modulus for several GF- and CF-reinforced grades deviating from the main domain of correlation.
- An uncertain correlation between shear modulus and tensile modulus.

7.8 Impact Strength

Most common impact tests measure the energy absorbed during a specified impact of a standard weight striking, at a given speed, a defined test sample clamped with a suitable system. The hammer can be a falling weight or, more often, a pendulum. In this case, the samples can be smooth or notched. Results depend on the molecular orientation, the crystallization ratio of the material in the sample, its size, the clamping system, the possible notch and its shape, the mass, and the strike speed. Values found in the literature, even for instrumented multiaxial impact (ISO 6603-2:2000), can only be used to help material choices and do not replace tests on real parts.

As the other mechanical properties, impact strength of various polymers, mainly polyamides, is affected by the moisture content of the thermoplastic parts (see Section 5.5).

Of course, impact strengths are sensitive to temperature:

- A temperature increase leads to more or less higher values. It is rarely an issue.
- A temperature fall leads to more or less lower values. It is often an issue.

The Izod and Charpy impact tests are mostly used. A defined pendulum strikes the specimen sample, notched or unnotched, clamped with a defined device. The absorbed energy is calculated and expressed:

- in kJ/m^2: the absorbed energy divided by the specimen area at the notch
- J/m: the absorbed energy divided by the length of the notch, which is also the thickness of the sample.

There is no simple correlation between the several methods as we can see on:

- Figure 7.6 displaying the notched Charpy versus notched Izod impact strength of various neat and reinforced grades.
- Figure 7.7 displaying the notched Charpy versus unnotched Charpy impact strength of various neat and reinforced grades.

An important point when searching high-impact strength compounds is to consider the modulus. Often high impact grades of a given subfamily have lower modulus than unmodified grades. Figure 7.8 shows notched Izod impact strength versus elastic modulus for 40 neat and reinforced compounds:

- it appears generally that high impact strength and high modulus are not well matched.
- There are two populations: 37 compounds are below an envelope curve running from 4 down to 2 J/cm, on the one hand, and, on the other hand, we have three polycarbonate-based compounds in a zone 5–10 J/cm for the impact strength and 2–10 GPa for the modulus.

The notched impact tests tend to measure the notch sensitivity rather than the real impact strength of the material. It corresponds better to parts with sharp edges, ribs, and so on.

There are a multitude of standards for the determination of impact behavior, the ASTM D 256 studied in Section 5.3.3 showing a facet of the diversity (and difficulty) of these tests. Methods depend on the sample to be tested, preparation of samples, impact type, measure procedure (possibly instrumented), etc. Even apparently well defined, these tests include several variants and are difficult to run, leading to a large range of averages and standard deviations. These methods are not equivalent.

Let us quote some examples of standards without claiming to be exhaustive:

- ISO 179-1:2010 Plastics—Determination of Charpy impact properties—Part 1: Non-instrumented impact test
- ISO 179-2:1997 Plastics—Determination of Charpy impact properties—Part 2: Instrumented impact test
- ISO 180:2000 Plastics—Determination of Izod impact strength

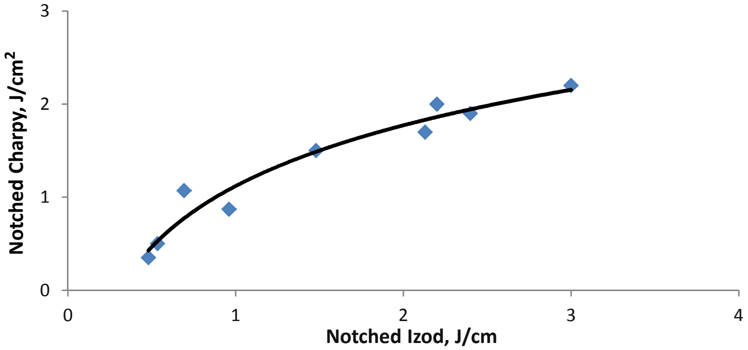

Figure 7.6 Notched impact: Charpy (J/cm^2) versus Izod (J/cm).

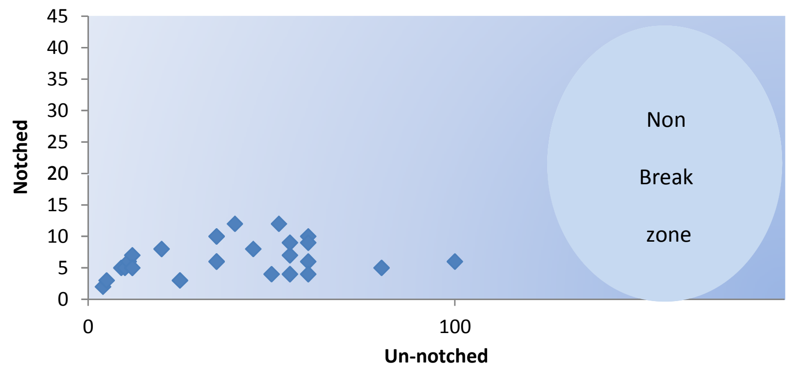

Figure 7.7 Charpy impact: notched versus unnotched.

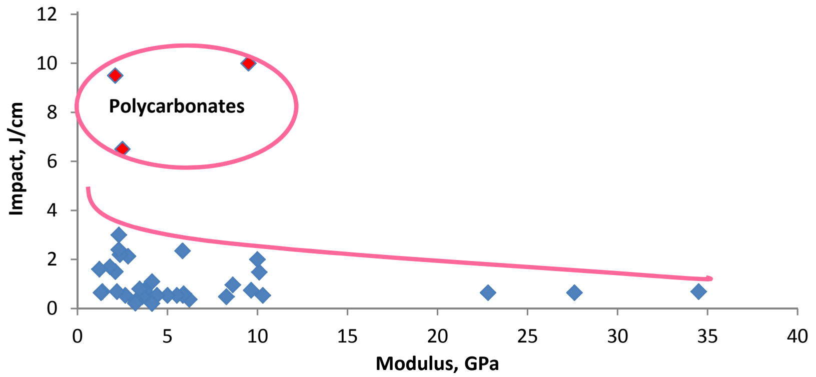

Figure 7.8 Examples of impact versus modulus.

- ISO 11673:2005 Unplasticized poly(vinyl chloride) (PVC-U) pressure pipes—Determination of the fracture toughness properties
- ISO 17281:2002 Plastics—Determination of fracture toughness (GIC and KIC) at moderately high loading rates (1 m/s)
- ISO 6603-1:2000 Plastics—Determination of puncture impact behavior of rigid plastics—Part 1: Non-instrumented impact testing
- ISO 6603-2:2000 Plastics—Determination of puncture impact behavior of rigid plastics—Part 2: Instrumented impact testing
- ISO 7765-1:1988 Plastics film and sheeting—Determination of impact resistance by the free-falling dart method—Part 1: Staircase methods
- ISO 7765-2:1994 Plastics film and sheeting—Determination of impact resistance by the free-falling dart method—Part 2: Instrumented puncture test
- ISO 8256:2004 Plastics—Determination of tensile-impact strength
- ISO 9854-1:1994 Thermoplastics pipes for the transport of fluids—Determination of pendulum impact strength by the Charpy method—Part 1: General test method
- ISO 9854-2:1994 Thermoplastics pipes for the transport of fluids—Determination of pendulum impact strength by the Charpy method—Part 2: Test conditions for pipes of various materials
- ASTM D1822-13 Standard Test Method for Tensile-Impact Energy to Break Plastics and Electrical Insulating Materials
- ASTM D2444-99(2010) Standard Test Method for Determination of the Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)
- ASTM D256-10 Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics
- ASTM D4272-09 Standard Test Method for Total Energy Impact of Plastic Films By Dart Drop
- ASTM D4495-12 Standard Test Method for Impact Resistance of Poly(Vinyl Chloride) (PVC) Rigid Profiles by Means of a Falling Weight

- ASTM D4508-10 Standard Test Method for Chip Impact Strength of Plastics
- ASTM D4812-11 Standard Test Method for Unnotched Cantilever Beam Impact Resistance of Plastics
- ASTM D5420-10 Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact)
- ASTM D5628-10 Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Falling Dart (Tup or Falling Mass)
- ASTM D6110-10 Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics
- ASTM D6395-11 Standard Test Method for Flatwise Flexural Impact Resistance of Rigid Plastics
- ASTM D7136/D7136M-12 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event
- ASTM F736-95(2011) Standard Test Method for Impact Resistance of Monolithic Polycarbonate Sheet by Means of a Falling Weight

Table 7.11 displays examples of notched Izod impact strengths ranked in a descending order. We can remark the huge ranges of impact strength, for example, 110–850 for a given subfamily, which can come from chemical structure, formulation versatility, succinct trade appellation, and some errors or mix-up.

7.9 Hardness

Hardness is an empirical test allowing comparisons of a mix of surface and bulk properties under immediate, very short creep time, and recovery conditions. Hardness is intended primarily for control purposes. No simple relationship exists between hardness and any fundamental property of the material tested.

The most usual test methods for thermoplastics are:

- Shore A for soft polymers
- Shore D for hard polymers
- Rockwell R, M, and others
- Ball indentation
- IRHD, International Rubber Hardness.

Shore D and A hardness specifies a method for the determination of the indentation hardness of plastics and ebonite by means of durometers of two types:

- type A is used for softer materials and
- type D for harder materials.

Shore D and A hardness allows measurement either of the initial indentation or of the indentation after a specified short period of time, or both.

Rockwell M, L, and R hardness scales: The Rockwell hardness number is derived from the net increase in depth of impression as the load on an indentor is increased from a fixed minor load to a major load and then returned to the same minor load. For materials having high creep and recovery, the time factors involved in application of the major and minor loads have a considerable effect on the results of the measurements.

Ball indentation consists of forcing a defined ball under a specified load into the surface of a test specimen. The depth of impression is measured under load. The surface area of the impression is computed from its depth. The ball indentation hardness is then calculated from the following relationship: Ball indentation hardness = Applied load/Surface area of impression.

ISO 48 (IRHD—international rubber hardness degrees) specifies four methods for the determination of the hardness of vulcanized or thermoplastic rubbers on flat surfaces (standard hardness methods) and four methods for the determination of the apparent hardness of curved surfaces (apparent hardness methods). These methods differ primarily in the diameter of the indenting ball and the magnitude of the indenting force.

Previous methods are only examples and there are many other methods.

There are no mathematical correlations between the various methods.

Table 7.12 displays examples of Rockwell M and Shore D hardnesses. We can remark the huge ranges of hardnesses, for example, 70–105 Rockwell M for a given subfamily, 40–90 Shore D for another subfamily. For a same subfamily seeming well defined, PA66, ranges of Rockwell M and Shore D are, respectively, <30–90 and 70–95. This can come from chemical structure, formulation versatility, succinct trade appellation, and some errors or mix-up. It must be noted that both scales have not the same range of validity.

Table 7.13 displays some examples of various hardnesses measured on same compounds, thanks to various methods. Data are comparable for a same line only.

Table 7.11 Examples of Notched Izod Impact Strengths, J/m

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
COPE low Shore D	NB	NB		
CPE	NB	NB		
EVA	NB	NB		
FEP	NB	NB		
PB	NB	NB		
PEBA 25 to 45 Shore D	NB	NB		
PEBA 50 to 72 Shore D	NB	NB		
PE-LD	NB	NB		
PE-UHMW	NB	NB		
PFA	NB	NB		
PPA	950	NB		
PEBA Bio	800	NB		
ABS/PA	400	950		
LCP	400	520		
PA 6 high-level long GF			380	530
PA 66 high-level long GF			375	670
PE 60% long GF			370	410
EMA	365	NB		
TPU long GF			363	670
POM long GF			335	335
PPS long GF medium level			310	342
ASA/PVC	300	600		
ETFE	270	NB		
PA 66 medium-level long GF			267	270
PA 12 GF			250	300
PA 6 medium-level long GF			240	270
ABS/PC_low-level long GF			220	220
PPA long GF			214	347
PA 11 or 12 plasticized	200	NB		
TPU Shore D	200	NB		
COPE Bio	200	900		
ASA/PC	200	700		
PSU/ABS	200	374		

Continued

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PA 66 long CF			200	240
PP 40% Kenaf fiber			185	185
ABS/PC medium-level long GF			180	190
PVF	180	181		
PPS long GF high level			160	370
FEP GF			160	200
PTFE	160	200		
PA 66 impact medium-level GF			150	270
PPE Mineral			150	210
PVDF	130	400		
PA 66 medium-level GF			130	160
PTFE GF			120	150
PLA/PC	117	854		
PA 6 medium-level GF			112	270
PA 6 high-level GF			112	144
PC/PBT	110	850		
PI TP GF			110	750
PPE	110	400		
PA 4-6 GF			110	190
PAA high-level GF			110	115
PET/PC GF			107	600
PA 11 GF			107	200
PA 6-12 GF			106	130
COPE high Shore D	100	NB		
ECTFE	100	NB		
PE-HD antistat black			100	NB
PP impact	100	NB		
TPU GF			100	NB
PI TP CF			100	850
ABS/PC	100	650		
ASA	100	600		
TPU Bio	100	600		

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PA 4-6	100	500		
ASA/PMMA	100	400		
ABS	100	350		
PK	100	270		
PPE/PA	100	250		
ABS/PA 20 GF			100	200
PA 6 mineral FR			100	200
PA 66 high-level GF			100	150
PAI	100	150		
PC friction			100	130
PTFE friction			100	108
Starch/PS	100	100		
PEEK GF			95	130
PPSU	91	700		
PC GF			90	200
Polyarylate GF			90	200
PBT long GF			90	180
SMA GF			90	140
PC/SAN GF			90	100
PP 40% flax fibers			89	91
PA 6 GF recycled			85	100
PEI GF			85	100
PC	80	950		
PCTFE	80	250		
PET GF			80	230
PP/PA GF			80	150
PK GF			80	140
PSU/PC	80	91		
PI TP	80	90		
PSU modified	80	90		
PPE/PA GF			78	91
ETFE GF			75	485

Continued

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
ABS/PC GF			75	105
PA 12	70	NB		
ABS/PVC	70	400		
ABS FR			70	350
Polyarylate	70	290		
PCT GF			70	150
TPU conductive			70	124
PAA Mineral			70	100
ASA/PBT GF			70	85
PEI conductive			70	75
PA 66 Mineral			69	200
Starch/PP	66	66		
PPA GF			65	530
PA 66 CF			64	265
PLA/PE	64	65		
PAEK 30% GF			63	130
PEEK	63	85		
ABS conductive			60	430
PS impact	60	350		
PA Transparent	60	150		
PLA/PP 30% GF			60	107
PE GF			60	85
ABS GF			60	70
PAA medium-level CF			60	70
PMP GF			58	64
PVDF CF			58	59
PP Co	56	500		
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	55	140		
PES GF			55	107
PPSU GF			55	100
PSU GF			55	96
PAA medium-level GF			55	75

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PVDF friction			55	60
ABS/PC conductive			54	961
PES	53	NB		
TPO Shore D	53	NB		
ABS CF			53	85
PSU	53	70		
ABS GB			53	60
PA 66	50	NB		
POM homo- or copolymer	50	900		
PET/PC	50	850		
CAB	50	530		
CA	50	400		
PP long GF high level			50	350
PS GF			50	350
LCP Mineral			50	290
PVCC	50	290		
PP natural fibers			50	185
PA 6 recycled	50	160		
PC/PBT GF			50	150
PP low-level GF			50	145
PPE GF			50	130
POM GF			50	110
MABS	50	100		
PLA/PBT GF			50	100
EVOH	50	90		
PBT medium-level GF			50	90
PAI friction			50	80
PEI	50	60		
PP cellulose fibers			50	53
PA 6	48	NB		
PA 6 FR			48	200
PC CF			48	100

Continued

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PLA GF			48	59
PMMA GF			48	53
PPA Mineral			48	53
PC CNT			48	50
PP long GF medium level			45	216
PP medium-level GF			45	160
PBT GF and mineral			45	75
PP CF			43	320
PA 6-12	43	200		
PES CF			42	53
PA 11	40	NB		
PPS GF + Mineral			40	140
PA 12 conductive			40	110
PVC GF			40	107
PA 12 GB			40	100
PAI GF			40	80
PPS conductive			40	80
PA 4-6 Mineral			40	70
PEI GF milled			40	70
POM GB			40	70
PEI Mineral			40	60
PEEK/PBI GF			40	50
PEEK/PBI CF			40	50
PAI CF			40	48
POM Far			39	302
POM CF			38	64
PA 6-10 CF			37	160
PA Far			37	146
PLA/PMMA	37	117		
PEEK CF			37	110
PA 66 conductive			37	100
PPA CF			37	70

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PEI CF			37	69
LCP CF			35	320
PPS GF			35	100
PAI Mineral			35	80
PBT	35	55		
PBT medium-level GB			35	51
PI TP friction			35	43
PEEK/PBI	35	38	35	38
POM Mineral			34	65
PPS CF + GF			32	101
PBT CF			32	69
PMMA antistatic			32	55
PA 6-10	30	NB		
PP antistat			30	290
PP Talc			30	200
PPS CF			30	168
PP $CaCO_3$			30	150
PMMA impact	30	130		
PVC wood WPC			30	107
PA castable friction			30	85
POM conductive			30	70
PP low-level CNT			30	70
SAN GF			30	65
PSU Mineral			30	55
PMP	27	150		
PPS Far			27	130
PA CNT			27	70
PBI	27	30		
PPE CF			26	80
PMP Mineral			26	43
CP	25	NB		
POM friction			25	78

Continued

Table 7.11 Examples of Notched Izod Impact Strengths, J/m—cont'd

	Expected Neat Grades		Special Grades	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PE-HD	20	220		
PP recycled	20	200		
PVC unplasticized	20	110		
PP Ho	20	107		
PSU/PBT GF			20	100
SMA	20	100		
PC conductive			20	90
PA castable	20	85		
PS 40% wood WPC			20	41
PP wood WPC			18	45
LCP GF			17	430
PP/PA	16	NB		
PVDC	16	66		
SMMA	16	50		
PE wood WPC			16	43
PET	15	100		
PTT Bio	15	40		
PP Mineral			14	240
COC	13	350		
PLA	13	267		
PP conductive			10	320
PE-X cross-linked	10	220		
PET Amorphous	10	100		
PS	10	60		
SAN	10	30		
Acrylique imide	10	25		
PMI or PMMI	10	25		
PMMA	10	25		
PPS	5	80		

NB = nonbreak.

Table 7.12 Examples of Rockwell M and Shore D Hardness

Plastic	Rockwell M		Shore D	
	Minimum	Maximum	Minimum	Maximum
MPR	<30	<30	<25	25
CPE	<30	<30	<30	30
TPE based on PVC	<30	<30	<40	40
COPE low Shore D	<30	<30	<45	45
PP/EPDM-V	<30	<30	<50	50
EVA	<30	<30	<65	65
PVC plasticized	<30	<30	<25	78
PEBA 25 to 45 Shore D	<30	<30	25	45
TPV Shore D	<30	<30	25	50
PB	<30	<30	40	53
PE-LD	<30	<30	40	55
TPU Bio	<30	<30	25	55
COPE Bio	<30	<30	40	57
TPS Shore D	<30	<30	25	60
PEBA Bio	<30	<30	25	71
PP impact	<30	<30	45	73
EMA	<30	<30	25	75
PEBA 50 to 72 Shore D	<30	<30	50	72
PTFE	<30	<30	50	66
PTFE CF	<30	<30	50	68
TPU Shore D	<30	<30	50	75
FEP	<30	<30	55	65
PFA	<30	<30	55	65
PE-HD	<30	<30	60	70
PE-UHMW	<30	<30	60	70
PMP	<30	<30	60	76
PTFE GF	<30	<30	60	72
PE-HD antistat black	<30	<30	62	65
PTFE friction	<30	<30	63	70
FEP GF	<30	<30	68	70
ABS/PVC	<30	<30	73	78
PVDF friction	<30	<30	75	79

Continued

Table 7.12 Examples of Rockwell M and Shore D Hardness—cont'd

Plastic	Rockwell M		Shore D	
	Minimum	Maximum	Minimum	Maximum
PMP GF	<30	30	75	80
PMP Mineral	<30	30	75	80
PLA natural reinforcement	<30	30	75	80
PP/PA	<30	30	50	80
ETFE	<30	30	63	80
TPO Shore D	<30	30	25	80
PP $CaCO_3$	<30	30	65	80
PE GF	<30	30	70	80
PP Co	<30	30	70	80
PA 12	<30	30	58	80
PE-X cross-linked	<30	30	30	80
ASA	<30	30	70	82
PE 60% long GF	<30	33	72	82
PA 11	<30	40	58	82
COPE high Shore D	<30	40	50	82
PP Ho	<30	43	70	84
PP GB	<30	43	70	84
PP recycled	<30	50	50	85
TPU long GF	<30	50	50	85
PP Mineral	<30	50	64	85
PS impact	<30	50	60	85
ECTFE	<30	50	70	85
PA 6-10	<30	50	70	85
PP CF	<30	50	72	85
PP conductive	<30	50	72	85
ABS	<30	50	75	85
PA castable	<30	50	75	85
PP Talc	<30	50	75	85
PP/PA GF	<30	50	75	85
SMA	<30	50	78	85
PA 4-6	<30	50	79	85
PA castable friction	<30	60	75	88
CP	<30	70	40	90

Table 7.12 Examples of Rockwell M and Shore D Hardness—cont'd

Plastic	Rockwell M		Shore D	
	Minimum	Maximum	Minimum	Maximum
PCTFE	<30	70	75	90
CAB	<30	70	60	90
PA 11 GF	<30	70	60	90
PA 12 GF	<30	70	60	90
PA 66 impact medium-level GF	<30	70	70	90
CA	<30	90	50	95
PA 66	<30	90	70	95
PVF	30	31	79	80
PVDF Mica	30	35	80	81
PK	30	50	80	85
PP low-level GF	30	50	80	85
PVC wood WPC	30	50	80	85
PVDC	30	50	80	85
PA Transparent	30	60	80	88
PSU modified	30	70	80	90
PSU/ABS	30	70	80	90
PVC unplasticized	30	70	80	90
ASA/PC	30	70	80	90
ABS FR	30	75	80	91
ABS/PA	30	75	80	90
ABS/PA 20 GF	30	75	80	90
ABS/PC	30	82	80	93
PA 6 GB	30	85	80	95
PA 6 medium-level GF	30	85	80	95
PA 6 medium-level long GF	30	85	80	95
PA 6 high-level GF	30	85	80	95
PA 66 high-level long GF	30	85	80	95
PA 6 high-level long GF	30	85	80	95
PA 66 GB	30	85	80	95
PA 66 medium-level GF	30	85	80	94
PA 66 medium-level long GF	30	85	80	95
PA 6 mineral FR	30	88	80	95

Continued

Table 7.12 Examples of Rockwell M and Shore D Hardness—cont'd

	Rockwell M		Shore D	
Plastic	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PA 6 recycled	30	90	80	95
PA 66 Mineral	30	90	80	95
PET/PC	30	90	80	95
PET/PC GF	30	90	80	95
PA 6	30	90	80	95
SAN	30	90	80	95
PVDF CF	35	40	81	83
PK GF	35	55	82	87
POM homo- or copolymer	35	94	82	>95
SMA GF	40	50	83	85
PA 6-12	40	50	82	85
PPE	40	70	82	90
PVCC	40	70	83	90
Polyarylate	40	80	83	92
PC/PBT GF	40	90	83	95
Polyarylate GF	40	95	83	>95
PC/PBT	40	97	83	>95
LCP GF	40	100	83	>95
LCP	40	100	82	>95
PCT GF	43	80	83	92
LCP Mineral	43	80	84	92
PMMA impact	43	90	83	95
PPE CF	44	70	83	90
POM Far	45	60	84	88
PA 4-6 GF	45	65	84	89
PC friction	45	97	84	>95
POM friction	45	100	84	98
PP long GF medium level	50	60	84	88
PP long GF high level	50	60	84	88
PP medium-level GF	50	60	85	88
PA 6-12 GF	50	70	85	90
PSU/PC	50	70	85	90
PVC GF	50	70	85	90

Table 7.12 Examples of Rockwell M and Shore D Hardness—cont'd

Plastic	Rockwell M		Shore D	
	Minimum	Maximum	Minimum	Maximum
PPE GF	50	71	85	90
PA 4-6 Mineral	50	70	86	90
PPE Mineral	50	70	85	90
ABS/PC low-level long GF	50	82	85	93
ABS/PC medium-level long GF	50	82	85	93
ABS/PC GF	50	82	85	93
PS	50	85	85	95
PA 66 high-level GF	50	86	85	94
COC	50	90	85	95
PMMA GF	50	90	85	95
PC	50	90	85	95
PC CF	50	90	85	95
PC/SAN GF	50	90	85	95
PPSU	50	90	85	95
SAN GF	50	93	85	>95
PET	50	97	85	>95
PEEK	51	100	85	>95
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	51	103	85	>95
SMMA	55	90	85	95
PPA	60	80	85	>90
PPA Mineral	60	80	87	92
PPS	60	90	88	95
PBT GF and mineral	60	100	88	>95
PMMA antistatic	60	100	87	>95
PEEK/PBI	60	100	88	>95
PET GF	60	100	88	>95
PPA GF	60	100	88	>95
PPA long GF	62	102	88	>95
PPS GF + Mineral	62	105	88	>95
PSU	69	75	89	91
PSU Mineral	70	74	90	91

Continued

Table 7.12 Examples of Rockwell M and Shore D Hardness—cont'd

	Rockwell M		Shore D	
Plastic	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PBT	70	90	90	95
PBT medium-level GB	70	90	90	95
PA 6 GF recycled	70	95	90	>95
PPS Far	70	95	90	>95
PC GF	70	97	90	>95
POM Mineral	70	100	90	>95
PPSU GF	70	100	90	>95
PEEK GF	70	103	90	>95
PAEK 30% GF	70	103	90	>95
EVOH	70	104	90	>95
PET/PBT high-level GF	70	105	90	>95
PMMA	70	105	90	>95
PPS conductive	70	105	90	>95
PEEK CF	70	107	90	>95
PS GF	75	85	90	95
POM GB	75	90	91	95
PSU/PBT GF	75	90	91	95
PEEK/PBI GF	76	90	92	95
PEEK/PBI CF	76	90	92	95
PEI conductive	77	90	92	95
ABS GF	80	85	90	94
ABS GB	80	85	90	94
ABS CF	80	85	90	94
POM GF	80	97	93	>95
LCP CF	80	100	92	>95
PA Far	80	100	92	>95
ABS conductive	80	108	90	>95
PI TP friction	82	100	93	>95
PSU GF	82	100	93	>95
PES	85	90	94	>95
PES CF	85	90	94	>95
PES friction	85	100	94	>95

Table 7.12 Examples of Rockwell M and Shore D Hardness—cont'd

Plastic	Rockwell M		Shore D	
	Minimum	Maximum	Minimum	Maximum
PBT medium-level GF	85	105	94	>95
PBT long GF	85	105	94	>95
PBT long CF	85	105	94	>95
PBT CF	85	105	94	>95
PAI CF	85	110	94	>95
PAI Mineral	85	110	94	>95
PAI	86	100	95	>95
PAI GF	86	110	95	>95
POM long GF	90	97	95	>95
ASA/PBT GF	90	100	85	>95
Acrylique imide	90	100	95	>95
PES GF	90	101	94	>95
PI TP	90	102	95	>95
PPS GF	90	104	95	>95
PPS long GF medium level	90	104	95	>95
PPS long GF high level	90	104	95	>95
PPS CF+GF	90	104	95	>95
PMI or PMMI	90	105	95	>95
PEI	90	109	95	>95
PEI GF milled	90	110	95	>95
PEI GF	90	110	95	>95
PEI CF	90	110	95	>95
PEI Mineral	90	110	95	>95
POM CF	92	99	95	>95
PAI friction	95	110	95	>95
PI TP GF	100	104	>95	>95
PAA Mineral	104	104	>95	>95
PPS CF	100	105	>95	>95
PI TP CF	104	105	>95	>95
PAA medium-level CF	105	110	>95	>95
PAA medium-level GF	105	112	>95	>95
PAA high-level GF	105	108	>95	>95
PBI	125	125	>95	>95

Table 7.13 Examples of Hardness Measured Thanks to Various Methods

Unit	Shore D	Rockwell R	Rockwell M	Ball Indentation, MPa
PE HD 30 GF		52		
PP 20 Talc	69	87	68	
ABS GP example 1		103		
ABS GP example 2		102		
PS		102		
LCP 30 GF			85	
TPO				30
PA6 Dry		120		
PP 20 Mineral				60
PC				115
PBT				130
POM	79		84	140
PS				150
PA 6 CF/PTFE		106		
PA 66 Mineral		117	92	
PPE+PS		119		
PPE+PS+PA 30 GF		120		
PA6 33 GF Dry		121		
PMMA 30 GF		120		
PPS GF	86	125	94	
PPS Low filler			100	
PEEK	88	127	107	
PEEK 30 GF	86	124	103	
PEI 30 GF	86	127	114	
PEEK 30 CF	91	125	108	
PBT 30 GF				164
PBT 25 Mineral				170
PAI	90		119	
PAI 30 GF	90		125	

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, Fiber-Cote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Omnexus, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, Specialchem, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Trexel, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

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8 Thermal Properties

OUTLINE

First, we must remind some general features:

- Thermoplastics are viscoelastic materials
- Thermoplastics are often semicrystalline polymers
- Thermoplastics properties are temperature-dependent: glass transition temperature is an important parameter for property evolution
- Thermal behavior isn't an intrinsic property but depends on numerous parameters including, among others, the shape and thickness of the part, the processing conditions, and the general history of the part.

Of course, following data are only examples providing a rough idea of the significant differences between subfamilies but other data can be found elsewhere. These theoretical data cannot be used for designing, computing, or to make economic predictions. Only properties measured on the actual used compound must be considered.

8.1 Overview

A temperature rise causes two different phenomena:

- Immediate physical effects:
  - Decay of the modulus and other mechanical and physical properties, physicochemical softening.
  - Dimensional stability: reversible thermal expansion and, eventually, irreversible shrinkage and warpage.
- Long-term effects:
  - Physical: more or less irreversible creep and relaxation.
  - Chemical: irreversible degradation of the material, decrease in the mechanical properties, even after a return to ambient temperature.

The maximum service temperatures depend on the duration of service time and the possible simultaneous application of mechanical or other stresses.

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00008-8

A fall in temperature has only physical effects:

- Increase in the modulus and rigidity.
- Reduction in the impact resistance; the material can become brittle.
- Eventually, crystallization for semicrystalline polymers.

Immediate effects of high and low temperatures on engineering mechanical properties are examined in Chapter 10.

8.2 Glass Transition Temperature (See Also Section 2.3.3)

For amorphous polymers or amorphous domains of semicrystalline polymers, the glass transition temperature (Tg) is a reversible transition from a hard and brittle state into a molten or rubber-like state. Designers must be aware of abrupt evolutions of some properties when temperature overcomes the glass transition temperature. The transition temperature value depends on the testing conditions, notably the cooling or heating rate and the frequency of the measured parameter.

The glass transition temperature may be negative or positive in °C and is lower than the melting temperature of the crystalline domains.

Table 8.1 displays 209 examples of glass transition temperatures for various grades including carbon fiber (CF)-reinforced grades, glass fiber (GF)-reinforced grades, mineral and glass bead (GB)-reinforced grades, conductive grades, friction grades, wood plastic composite (WPC):

- 57 materials have a negative Tg,
- nine are approximately in the ambient temperature range,
- 143 range from 40 °C up to 425 °C.

These results must be carefully read because measuring methods aren't known.

We can remark the broad range of Tg for many families arising from formulation versatility, succinct trade appellations, test method versatility, errors, and mix-up. For example, Tg of listed polyvinylchloride (PVC) grades evolve from −50 °C up to 60 °C according to the plasticization system.

Glass transition temperature is rarely used as a criterion of first rank for the selection of a plastic but is very interesting for the low-temperature behavior (brittleness hazard) and the possible abrupt changes in many properties.

8.3 Thermal Behavior above Room Temperature (See Also Section 1.1.3)

Thermal behavior above room temperature can be featured by some conventional heat properties such as:

- Heat deflection temperature (HDT).
- Continuous use temperature (CUT).
- UL temperature index.
- Vicat softening temperature (VST).
- Accelerated aging.

8.3.1 HDT or Deflection Temperature under Load

The HDT (ISO 75) is the temperature at which a standard deflection occurs for defined test samples subjected to a given three-point bending load and a linear increase in temperature. The outer fiber stresses usually selected are 0.45 MPa (HDT B) or 1.8 MPa (HDT A) and must be indicated with the results. Sometimes the outer fiber stress is 8 MPa (HDT C). Of course, for the same compound, HDT A (1.8 MPa) is lower than HDT B (0.45 MPa).

Usually, a polymer cannot be used under this load at that temperature.

The first part of Table 8.2 displays average HDT A and B for eight subfamilies: expected neat grades, and special grades including among others CF-reinforced grades, GF-reinforced grades, mineral and GB-reinforced grades, conductive grades, friction grades, WPC. Note:

- General purpose grades can be formulated with plasticizers, fillers, and reinforcements and are called "expected neat grades" in the following.
- Eight subfamilies are not based on the same polymers.

Table 8.1 Glass Transition Temperature Examples

	Subzero Temperatures		Overzero Temperatures	
	Minimum	Maximum	Minimum	Maximum
PE GF	–110	–110		
PE wood WPC	–110	–110		
PE 60% long GF	–110	–110		
PE-HD	–110	–110		
PE-HD antistat black	–110	–110		
PE-LD	–110	–110		
PE-UHMW	–110	–110		
TPS Shore D	–80	–40		
COPE low Shore D	–78	–10		
PEBA 25 to 45 Shore D	–65	–50		
POM homo or copolymer	–60	–50		
POM GF	–60	–50		
POM long GF	–60	–50		
POM GB	–60	–50		
POM CF	–60	–50		
POM conductive	–60	–50		
POM Far	–60	–50		
POM low friction	–60	–50		
POM Mineral	–60	–50		
COPE high Shore D	–60	50		
PEBA Bio	–50	–40		
PVC plasticized	–50	–5		
TPE based on PVC	–50	–5		
TPU GF	–48	–20		
TPU long GF	–48	–20		
TPU Bio	–48	–20		
TPU conductive	–48	–20		
TPU Shore D	–48	6		
PVDF	–46	–22		
PEBA 50 to 72 Shore D	–40	–40		
PVDF CF	–40	–35		
PVDF low friction	–40	–35		

Continued

Table 8.1 Glass Transition Temperature Examples—cont'd

	Subzero Temperatures		Overzero Temperatures	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PVDF Mica	–40	–22		
PVF	–35	–15		
COPE Bio	–35	–2		
PB	–34	–18		
PP impact	–30	–20		
PP recycle	–30	–10		
PP Co	–20	–20		
PP low-level GF	–20	–10		
PP medium-level GF	–20	–10		
PP GB	–20	–10		
PP Mineral	–20	–10		
PP Talc	–20	–10		
PP low-level CNT	–20	–10		
PP medium CNT	–20	–10		
PP cellulose fibers	–20	–10		
PP long GF medium level	–20	–10		
PP $CaCO_3$	–20	–10		
PP long GF high level	–20	–10		
PP antistat	–20	–10		
PP CF	–20	–10		
PP conductive	–20	–10		
PP natural fibers	–20	–10		
PP wood WPC	–20	10		
PVDC	–15	–15		
PP Ho	–10	–10		
SMMA			7	80
EVOH			15	72
PTFE			19	30
PTFE CF			19	30
PTFE low friction			19	30
PTFE GF			19	30
PMP			20	30

Table 8.1 Glass Transition Temperature Examples—cont'd

	Subzero Temperatures		Overzero Temperatures	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PMP GF			20	30
PMP Mineral			20	30
PBT	40	60		
PBT medium-level GB			40	60
PBT medium-level GF			40	60
PBT GF and Mineral			40	60
PBT long GF			40	60
PBT long CF			40	60
PBT CF			40	60
PA 6			40	65
PA 6 GB			40	65
PA 6 medium-level GF			40	65
PA 6 medium-level long GF			40	65
6 GF recycled			40	65
PA 6 high-level GF			40	65
PA 6 high-level long GF			40	65
PA 6 FR			40	65
PA 6 Mineral FR			40	65
PA 6 recycled			40	65
PVCC			45	45
PA 6-10			45	50
PA 6-10 CF			45	50
PLA			45	65
PLA GF			45	65
PLA natural reinforcement			45	65
PLA wood WPC			45	65
PA 6-12			45	70
PA 6-12 GF			45	70
PA 66			50	60
PA 66 CF			50	60
PA 66 GB			50	60
PA 66 medium-level GF			50	60

Continued

Table 8.1 Glass Transition Temperature Examples—cont'd

	Subzero Temperatures		Overzero Temperatures	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PA 66 long CF			50	60
PA 66 medium-level long GF			50	60
PA 66 Mineral			50	60
PA 66 high-level GF			50	60
PA 66 high-level long GF			50	60
PA 66 conductive			50	60
PA 66 impact medium-level GF			50	60
PTT Bio			55	55
PTT Bio GF			55	55
PVC GF			60	100
PVC unplasticized			60	100
PET			70	78
PET GF			70	78
PET Amorphous			70	78
COC			70	180
PA 4-6			75	75
PA 4-6 GF			75	75
PA 4-6 Mineral			75	75
CAB			80	120
CP			80	120
PS impact			83	95
PS 40% wood WPC			83	100
PS			83	102
ECTFE			85	85
PAA medium-level CF			85	100
PAA medium-level GF			85	100
PAA high-level GF			85	100
PAA Mineral			85	100
PPS			88	93
PPS GF			88	93
PPS long GF medium level			88	93
PPS long GF high level			88	93

Table 8.1 Glass Transition Temperature Examples—cont'd

	Subzero Temperatures		Overzero Temperatures	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PPS CF			88	93
PPS CF + GF			88	93
PPS conductive			88	93
PPS Far			88	93
PPS GF + Mineral			88	93
PS GF			90	90
PMMA GF			90	110
PMMA impact			90	110
PMMA			90	135
PA Transparent			93	155
ABS			95	115
ABS GF			95	115
ABS GB			95	115
ABS CF			95	115
ABS conductive			95	115
ABS FR			95	115
CA			95	130
PCT GF			100	105
SAN			100	115
SAN GF			100	115
PPE GF			100	150
PPE CF			100	150
PPE Mineral			100	150
PPE			100	210
ASA			103	104
MABS			107	115
SMA			110	115
SMA GF			110	115
LCP			120	150
LCP CF			120	150
LCP GF			120	150
LCP Mineral			120	150

Continued

Table 8.1 Glass Transition Temperature Examples—cont'd

	Subzero Temperatures		Overzero Temperatures	
	Minimum	Maximum	Minimum	Maximum
PPA			135	135
PPA GF			135	135
PPA Mineral			135	135
PPA long GF			135	135
PPA CF			135	135
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)			137	182
PAEK 30% GF			137	182
PET/PC			140	150
PEEK			143	157
PEEK GF			143	157
PEEK CF			143	157
Acrylique imide			143	168
PMI or PMMI			143	168
PC CF			145	150
PC CNT			145	150
PC conductive			145	150
PC low friction			145	150
PC			145	200
PC GF			145	200
PEEK/PBI			150	155
PEEK/PBI GF			150	155
PEEK/PBI CF			150	155
Polyarylate			185	190
Polyarylate GF			185	190
PSU			187	190
PSU GF			187	190
PSU Mineral			187	190
PES			210	230
PES GF			210	230
PES CF			210	230
PES low friction			210	230
PEI			215	217

Table 8.1 Glass Transition Temperature Examples—cont'd

	Subzero Temperatures		Overzero Temperatures	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PEI GF milled			215	217
PEI GF			215	217
PEI CF			215	217
PEI conductive			215	217
PEI Mineral			215	217
PPSU GF			220	250
PPSU			220	265
PAI			275	275
PAI GF			275	275
PAI CF			275	275
PAI low friction			275	275
PAI Mineral			275	275
PI TP			315	315
PI TP CF			315	315
PI TP GF			315	315
PI TP low friction			315	315
PBI			400	425

For the second part of Table 8.2 displaying ranges of HDT A and B we can remark:

- Some soft material cannot be tested by those methods
- The data range stretches from ambient temperature up to 435 °C
- For the same material, HDT A and B are not correlated
- For a given polymer, HDTs increase with the filler level and decrease with plasticizers
- Chemical structure can dramatically change data. For example, HDT B of COPE is in the range 20–150 °C when other grades are not rigid enough to be tested.
- The wide range of HDT for many families coming from polymer structure diversity, formulation versatility, succinct trade appellations, errors and mix-up. For example, HDT B of listed PVC grades evolve from 20 °C up to 120 °C according to the plasticization and reinforcement. In addition, softer grades cannot be tested.

The number of studied samples is limited and other data may be found elsewhere.

8.3.1.1 Comparison of HDT A and B (See Also Section 5.8.4)

Section 5.8.4 shows an example limited to 34 neat polymers. Figure 8.1 shows HDT A versus HDT B for 224 compounds for which both characteristics are known. HDT A increases with HDT B but there isn't a true correlation. One of the possible hypotheses is the glass transition temperature as suggested by Table 8.3 showing a high relative difference between both HDTs (A and B) when Tg is weak. In that case, HDTs are in the rubbery domain leading to a higher sensitivity to the higher load of HDT A.

Table 8.2 HDT A and B Examples for 261 Grades

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Average, °C		Average, °C	
All thermoplastics	162		134	
Neat TP	122		89	
CF-reinforced TP	217		199	
GF-reinforced TP	202		184	
Mineral-reinforced TP	177		143	
Conductive TP	135		114	
Low friction TP	165		130	
WPC	90		78	
	Minimum	**Maximum**	**Minimum**	**Maximum**
PBI			427	435
PEEK/PBI CF			320	358
PEEK/PBI GF			310	310
PEEK GF	330	340	290	323
PAI CF			282	282
PAI low friction			279	280
PAI GF			278	282
PAI			278	280
PEEK CF	323	323	270	320
PA 4-6 GF			270	290
PPA GF	285	300	266	294
PPA long GF	285	290	266	282
PPS long GF high level	280	290	266	282
PPS CF	280	297	260	277
PPS CF + GF	278	290	260	272
PPS long GF medium level	270	290	250	280
PPS GF	270	280	250	270
PAI Mineral			250	270
PA 66 long CF	270	275	250	255
PPA CF			249	277
PI TP CF			245	319
PA 4-6 Mineral			245	245
PA 66 high-level long GF	260	285	243	263

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
PI TP GF			240	319
PA 66 medium-level long GF	260	275	240	252
PI TP	260	343	235	319
PI TP low friction			235	300
PAA high-level GF	250	295	230	285
PA 66 CF	250	265	230	260
PPS conductive	230	275	225	268
PAA medium-level CF	245	285	224	270
PCT GF	268	280	221	263
PAA medium-level GF	240	280	220	270
PET GF	225	250	220	240
LCP CF			216	320
PBT long CF	230	250	216	220
PA 66 high-level GF	220	255	215	255
PK GF	220	222	215	216
PAEK 30% GF	270	360	213	350
PA 6 high-level long GF	230	265	212	240
PPSU GF	220	270	210	260
PA 4-10 GF Bio	240	243	210	215
PEI CF	215	230	206	223
PA 6 medium-level long GF	220	263	205	238
PES low friction	210	230	205	223
PLA/PBT GF	215	225		
PPS Far	225	278	204	260
PES GF	210	224	204	220
PPSU	210	270	200	255
PA 66 medium-level GF	215	255	200	240
PA 66 impact medium-level GF	215	250	200	240
PPE/PA GF	220	254	200	235
PBT long GF	220	250	200	225
PES CF	210	230	200	225
ETFE GF	260	265	200	210

Continued

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
PET/PBT high-level GF	220	250	200	210
PA 6 high-level GF	215	220	200	210
PEI conductive	210	215	200	210
PEI GF	205	212	196	210
PBT medium-level GF	215	250	195	225
PES	205	220	195	204
PA 6 medium-level GF	210	255	190	230
PA 6-12 GF	205	215	190	210
PEI Mineral	200	215	190	210
PA 6 GF recycled	205	220	190	205
PTT Bio GF	200	226	190	205
PEI GF milled	205	210	190	200
PEI	195	210	190	200
PA 10-10 high-level GF Bio			185	190
LCP Mineral	220	320	180	315
PP/PA GF	200	245	180	225
PPE/PA	191	195		
PEEK/PBI			174	180
PSU Mineral	177	185	172	180
PBT CF	180	225	171	220
PPS GF + Mineral	200	280	170	270
Polyarylate GF	180	185	170	171
PA 11 GF	175	192	165	177
LCP GF	210	370	160	355
PBT GF and Mineral	205	220	160	205
PSU	170	210	160	205
PSU GF	170	190	160	185
PA 12 CF			160	170
PSU/PBT GF	170	180	160	166
POM long GF	170	174	160	166
PA 12 GF	170	185	160	165
POM CF	162	168	158	163

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
PPA Mineral	240	260	157	200
PA 4-6	250	280	150	190
PP long GF high level			150	162
FEP GF	250	260	150	160
PA Far	170	255	149	240
PSU/ABS	150	170	149	150
PSU/PC	150	160	149	150
PSU modified	150	180	145	175
PLA GF	152	165	145	150
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	250	300	140	170
PEEK	250	295	140	165
PC CF	141	152	136	146
PC GF	140	220	135	205
PVDF CF	146	170	134	159
Acrylique imide	140	170	132	160
PMP GF	140	177	130	166
PMI or PMMI	140	170	130	160
PPE GF	132	154	127	144
PC conductive	130	138	126	132
PC	130	195	125	180
POM GF	145	174	125	166
PP long GF medium level	140	165	125	160
PP medium-level GF	140	165	125	152
PC CNT	135	160	125	145
PC low friction	130	150	125	140
PPE CF	127	190	121	173
POM Far	140	168	121	160
PE 60% long GF	127	130	121	121
PC/SAN GF	130	135	120	126
ABS/PC GF	130	135	115	137
PVDF low friction	148	150	115	117
ABS/PC medium-level long GF	125	130	113	113

Continued

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
Polyarylate	120	180	110	174
POM Mineral	158	175	110	150
PE GF	125	130	110	121
ABS/PC low-level long GF	120	128	107	108
LCP	180	310	105	275
PAA Mineral	190	240	105	220
ASA/PBT GF	135	220	105	205
PC/PBT GF	125	220	105	185
PET/PC GF	130	205	105	170
POM GB	158	163	105	150
SMA GF	113	130	105	120
ABS GF	105	117	102	111
PA 6-10 CF	216	232	100	227
POM conductive	125	170	100	160
PP CF	132	166	100	150
PP natural fibers	110	156	100	134
PTFE GF	120	125	100	110
PK	200	210	100	105
ABS CF	102	110	98	99
SAN GF	100	115	95	110
PS GF	100	105	95	100
PA castable low friction	200	220	93	204
PA castable	180	220	93	204
ABS GB	102	103	93	99
PPE	100	190	90	170
ABS/PA 20 GF	120	160	90	150
PP low-level GF	110	155	90	140
POM low friction	130	172	90	136
ABS/PC conductive	110	130	90	110
SMA	105	125	90	110
PPE Mineral	100	120	90	110
TPU long GF	135	175	85	130

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
PPA			85	125
ABS conductive	95	107	85	104
SAN	90	105	84	100
PPS	150	200	83	135
PA 66 Mineral	150	245	80	205
PA 6 Mineral FR	185	230	80	185
ABS/PC	90	140	80	132
PA 66 GB	190	220	80	121
ABS	90	125	80	120
PMMA GF	99	120	80	100
PVF	120	120	80	80
PVCC	94	120	79	106
PP cellulose fibers	110	142	78	134
PA 66 conductive	175	240	76	220
PA Transparent	85	165	75	135
SMMA	76	101	75	100
ASA	80	101	75	96
PS 40% wood WPC	80	100	75	81
PA 4-10 Bio	160	165	75	80
ASA/PVC	80	85	75	77
ABS FR	90	120	74	110
MABS	92	94	73	90
ASA/PC	100	130	72	115
PMMA impact	75	100	70	95
PA 6 GB	180	185	70	90
TPU conductive	60	130	70	85
PA 6 FR	170	220	70	80
PVC GF	75	80	70	76
COC	68	150	66	148
ABS/PVC	72	94	66	75
TPU GF	120	175	65	130
PC/PBT	107	140	65	120

Continued

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
ABS/PA	90	100	65	75
PMMA antistatic	70	80	65	75
PVC wood WPC			64	80
PBT medium-level GB	170	210	63	100
ECTFE	90	116	63	77
PS	70	110	62	100
PS impact	70	100	62	85
PP wood WPC			61	98
PP low-level CNT			60	120
PMMA	75	115	60	106
PA 66	160	240	60	105
PET	66	115	60	80
PET Amorphous	66	72	60	70
PP GB	98	110	56	100
POM homo or copolymer	110	172	55	136
PA 6	150	240	55	105
PA 6-10	150	175	55	85
PLA/PP 30% GF	150	157		
PA 6 recycled	130	170	55	70
PCTFE	120	125		
PA 12 GB	100	155	55	65
PP $CaCO_3$	90	110	55	65
EVOH	95	100		
PVC unplasticized	57	80	54	71
PLA/PC	65	124	54	68
PVDC	80	90	54	65
PTT Bio	75	150	53	80
PA 6-12	135	180	51	90
PP conductive	82	166	50	150
PET/PC	110	135	50	120
PP antistat	80	149	50	120
PMP Mineral	90	121	50	110

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	Maximum	Minimum	Maximum
ETFE	88	105	50	100
PP Ho	75	120	50	100
PP Mineral	65	135	50	100
PBT	115	185	50	85
PP Talc	89	135	48	85
PP impact	75	104	46	70
PFA	70	75		
CAB	54	108	45	95
PP/PA	60	200	45	80
PTFE	70	126	45	70
PA 12	100	140	45	65
PA 12 low friction	100	140	45	65
PA 12 conductive	95	135	45	65
PEBA 50 to 72 Shore D	50	106	45	55
PA 10-10 Bio	120	125	45	50
CP	60	120	44	110
CA	50	100	44	90
COPE high Shore D	50	156	44	55
PE wood WPC			43	62
PP Co	75	108	43	60
PP recycled	75	100	43	55
TPU Shore D	61	81	42	50
PVDF	68	135	40	113
PA 11	70	150	40	65
PE-X cross-linked	54	107	40	63
PE-HD	57	99	40	60
PMP	80	100	40	55
TPU Bio	60	80	40	50
PA 11 or 12 plasticized	50	100	40	45
PE-HD antistat black	50	57	40	42
PE-UHMW	65	82	35	50
TPO Shore D	50	130	30	72

Continued

Table 8.2 HDT A and B Examples for 261 Grades—cont'd

Plastic	HDT B 0.45 MPa, °C		HDT A 1.8 MPa, °C	
	Minimum	**Maximum**	**Minimum**	**Maximum**
FEP	70	77	30	48
PLA/PMMA	57	66		
PLA/PE	54	55		
PLA	51	65		
PLA natural reinforcement	51	65		
PE-LD	40	50	30	40
CPE	35	35	25	25
PEBA Bio	40	100	20	55
COPE Bio	20	150	20	55
PVC plasticized	20	69	20	53
COPE low Shore D	20	85	20	48
PEBA 25 to 45 Shore D	42	65	20	45
EMA	40	48		
EVA	20	72		

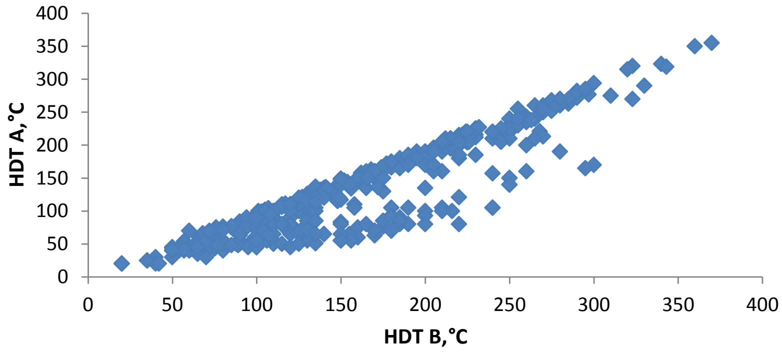

Figure 8.1 Examples of HDT A versus HDT B.

8.3.2 General Assessments Concerning CUT

The CUT is an arbitrary temperature resulting from general experience and observation. It is the maximum temperature that an *unstressed* part can generally withstand for a very long time without failure or unacceptable loss of function even if there is a significant reduction in the initial properties.

This subjective value is not measurable and is deduced from aging test interpretations and information collected in the technical literature.

Stabilized grades are proposed for each polymer families aiming higher use temperatures and/or longer service life.

To fix ideas, CUTs of thermoplastics are in the range of 45 °C up to 425 °C for exceptional families.

Table 8.4 displays CUTs for unstressed applications.

Table 8.3 Examples of HDTs versus Tg

HDT B, °C	HDT A, °C	Relative Difference, %	Tg, °C
170	160	6	187
210	205	2	190
130	125	4	145
195	180	8	200
150	83	45	88
200	135	32.5	93
170	70	59	40
240	105	56	65
150	55	63	45
175	85	51	50

Table 8.4 Continuous Use Temperatures (CUT) for 259 Unstressed Grades

Plastic	Average CUT	
All TP	124	
Expected neat grades	117	
CF-reinforced TP	152	
GF-reinforced TP	128	
Mineral-reinforced TP	125	
Conductive TP	110	
Low-friction TP	148	
WPC	69	
	Minimum	**Maximum**
PBI	260	425
PEEK/PBI	240	300
PFA	240	260
PEEK	180	260
PAI	200	220
FEP	200	205
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	180	260
PI TP	180	250
PI TP low friction	180	250
PAI low friction	180	220
PAI Mineral	180	220

Continued

Table 8.4 Continuous Use Temperatures (CUT) for 259 Unstressed Grades—cont'd

Plastic	Minimum	Maximum
PPS	180	220
PPS conductive	180	220
PPS Far	180	220
PPSU	170	200
PEI	105	180
PEI conductive	170	180
PEI Mineral	170	180
PES	160	180
PES low friction	160	180
PTFE	150	260
PTFE low friction	150	260
ECTFE	150	170
PVDF	150	150
PVDF low friction	150	150
PVDF Mica	150	150
PPA	140	180
PPA Mineral	140	160
PSU Mineral	140	160
PSU	140	160
ETFE	135	150
LCP	130	240
LCP Mineral	130	240
Acrylique imide	120	150
PCTFE	120	150
PMI or PMMI	120	150
PSU/PC	120	140
PA 4-6	110	150
PA 4-6 Mineral	110	150
PSU modified	110	130
PSU/ABS	110	130
PVF	105	110
PAA Mineral	100	150
PA Far	100	140
Polyarylate	100	140

Table 8.4 Continuous Use Temperatures (CUT) for 259 Unstressed Grades—cont'd

Plastic	Minimum	Maximum
TPV Shore D	100	135
PP Ho	100	130
PP low-level CNT	100	130
PP medium CNT	100	130
PP conductive	100	130
PP/PA	100	130
PP/EPDM-V	100	120
PB	95	105
PC	90	140
PC CNT	90	140
PET/PC	90	130
PE-X cross-linked	90	130
PC conductive	90	125
PC low friction	90	125
PE-UHMW	90	120
PK	90	120
COC	90	110
PMP	90	110
PMP Mineral	90	110
MPR	90	107
COPE high Shore D	85	135
COPE low Shore D	85	135
COPE Bio	85	135
ASA/PC	85	105
TPE based on PVC	85	105
SAN	85	95
PA 11	80	150
PA 12	80	150
PA 6	75	140
PA 6 GB	75	140
PA 6 FR	75	140
PA 6 Mineral FR	75	140
PA 6-10	75	140
PA 6-12	75	140

Continued

Table 8.4 Continuous Use Temperatures (CUT) for 259 Unstressed Grades—cont'd

Plastic	Minimum	Maximum
PA 66	75	140
PA 66 GB	75	140
PA 66 Mineral	75	140
PBT	80	155
PBT medium-level GB	80	140
PA 66 conductive	80	130
PEBA 25 to 45 Shore D	80	130
PEBA 50 to 72 Shore D	80	130
PP impact	80	130
PP Co	80	130
PP GB	80	130
PP Mineral	80	130
PP Talc	80	130
PP $CaCO_3$	80	130
PP antistat	80	130
PA 12 GB	80	120
PA CNT	80	120
PA 4-10 Bio	80	120
TPU conductive	80	120
TPU Shore D	80	120
PA 12 conductive	80	110
PA 12 low friction	80	110
PA 6 recycled	80	110
PA castable	80	110
PA castable low friction	80	110
POM homo or copolymer	80	110
POM GB	80	110
POM Far	80	110
PP recycled	80	110
POM conductive	80	105
POM low friction	80	105
POM Mineral	80	105
PVCC	80	105
PA 10-10 Bio	80	100

Table 8.4 Continuous Use Temperatures (CUT) for 259 Unstressed Grades—cont'd

Plastic	Minimum	Maximum
PA Transparent	80	100
PEBA Bio	80	100
PE-HD	80	100
PE-LD	80	100
PP cellulose fibers	80	100
PP natural fibers	80	100
SMA	80	100
ASA	80	90
PA 11 or 12 plasticized	80	90
PE-HD antistat black	80	90
PC/PBT	75	140
PET	75	155
PET Amorphous	75	140
ASA/PMMA	75	90
ABS/PA	70	110
ABS/PC	70	110
ABS/PC conductive	70	110
TPU Bio	70	110
PVDC	70	100
ASA/PVC	70	85
ABS	60	110
ABS conductive	65	110
PPE	65	110
PPE Mineral	65	110
ABS GB	65	100
ABS FR	65	100
TPO Shore D	60	120
CAB	60	105
CP	60	105
CPE	60	80
ABS/PVC	60	70
PLA	50	100
PLA natural reinforcement	50	100

Continued

Table 8.4 Continuous Use Temperatures (CUT) for 259 Unstressed Grades—cont'd

Plastic	Minimum	Maximum
TPS Shore D	50	100
PMMA	50	90
PMMA antistatic	50	90
PMMA impact	50	90
PLA/CoPolyester	50	80
PS	50	80
PS impact	50	80
PVC plasticized	50	80
PVC unplasticized	50	80
PVC wood WPC	50	75
CA	45	95
EVA	45	70

The first part of Table 8.4 displays average CUT for eight subfamilies: expected neat grades and special grades including among others CF-reinforced grades, GF-reinforced grades, mineral and GB-reinforced grades, conductive grades, friction grades (bearings), WPC. Note:

- General purpose grades can be formulated with plasticizers, fillers, and reinforcements and are called "expected neat grades" in the following.
- The eight subfamilies are not based on the same polymers. CF-reinforced compounds and friction grades have higher CUTs because of the choice of high-performing polymers and/or because of special formulations.

For the second part of Table 8.4 displaying ranges of CUTs, we can remark:

- The data range stretches from 45 °C up to 425 °C.
- The wide range of CUTs for many families coming from:
  - Formulation versatility, succinct trade appellations, errors and mix-up.
  - Requirement levels depending on the targeted application. Packaging, automotive, building, aerospace, electricity, etc., do not have the same requirements.

The number of studied samples is limited and other data may be found elsewhere.

8.3.3 Other Thermal Property Examples: UL Relative Temperature Index, VST

8.3.3.1 UL Relative Temperature Index

The relative temperature index (RTI), derived from long-term oven-aging test programs, is the maximum temperature that causes a 50% decay of the studied characteristics in the very long term. The UL RTI depends on (see Tables 8.5 and 8.6):

- the grade
- the thickness of the tested samples
- the studied characteristics gathered into three classes: electrical, mechanical with impact, and mechanical without impact.

Data must be carefully examined, the RTI fluctuation, for example, from 130 °C up to 240 °C for different grades of a defined polymer family. In the end,

Table 8.5 Effect of Thickness

Effect of thickness for a defined grade		
	Temperature, °C	Thickness, mm
UL RTI, Electrical	80	0.5
	120	1.6
UL RTI, Mechanical with impact	80	0.5
	105	1.6
	110	3
UL RTI, Mechanical without impact	80	0.8
	120	1.6
Effect of thickness and grade for a defined polymer family		
Grade, thickness	A, thickness 0.8 mm	B, thickness 1.5 mm
UL RTI, Electrical	130	240
UL RTI, Mechanical with impact	130	220
UL RTI, Mechanical without impact	130	240

Table 8.6 Examples of Relative Temperature Index

	UL RTI, °C		
Plastic	**Electrical**	**Mechanical with Impact**	**Mechanical without Impact**
PEEK general purpose	260	180	240
PEI example A	170	170	170
PSU	160	140	160
FR 30 GF PET	155	155	155
PBT 3 GF	140	130	140
PA66 30 GF	140	125	140
LCP GF FR	130	130	130
PP Mineral	120	115	120
PC	120	105	120
PEI example B	115	115	115
PEI GF PTFE	105	105	105
POM	105	85	85
ABS FR	85	75	75
Acrylic/PVC FR	50	50	50
PVC 20 GF	50	50	50
PS FR	50	50	50

only properties measured on the actual used compound must be considered.

8.3.3.2 Impact Strength above Room Temperature

Generally speaking, a temperature increase above room temperature has a plasticizing effect, sometimes negligible. For example, between 20 and 85 °C, Izod impact strength (kJ/m^2) of PPE/PS alloys more or less increases or is virtually unchanged:

Temperature, °C	20	45	65	85
PPE + PS	13	17	23	26
PPE + PS 30 GF	24	24	24	24

8.3.3.3 Vicat Softening Temperature

The VST is the temperature at which a standard indentation occurs for defined test samples subjected to a given linear temperature increase and a compression loading from a defined indenter of a specified weight. The load used is often 10 N (Vicat A) or 50 N (Vicat B) and must be indicated with the results. In either case, the polymer cannot be used under this compression load at this temperature.

For a given thermoplastic family, VST is affected by reinforcements, fillers, and plasticizers.

Table 8.7 displays some examples.

HDT and VST are not strictly linked but there is a certain relationship and when HDT is low, VST is also low.

8.4 Low-Temperature Behavior (See Also Section 1.1.4)

A fall in temperature (see also Section 1.1.4) has only physical effects:

- Increase in the modulus and rigidity. The modulus can be up to 100 and more times higher than that measured at room temperature.
- Reduction in the impact resistance; the material can become brittle. For example, commodity thermoplastics can have low service temperature as varied as −110, −10, 0, or even 20 °C.
- Eventually, crystallization for semicrystalline polymers.

Apart from mechanical effects, low temperatures reduce degradations by aging and are sometimes used to store parts, which lead to longer lifetimes.

8.4.1 Expected Minimum Service Temperatures

To provide a general rough idea of low-temperature behaviors, Table 8.8 displays examples of minimum service temperatures for 207 grades. The minimum service temperature is an arbitrary temperature resulting from general experience and observation. It depends on general service conditions and mechanical loading notably dynamic constraints and impact.

The first part of Table 8.8 displays a statistical analysis.

For the second part of Table 8.8 displaying ranges of "minimum service temperature," we can remark:

- The data range stretching from −269 up to 20 °C.
- The wide range of minimum service temperature for many families comes from:
  - Formulation versatility, succinct trade appellations, errors and mix-up.
  - Requirement levels depending on the targeted application. Packaging, automotive, building, aerospace, electricity do not have the same requirements.
- Often, minimum service temperatures of reinforced and unfilled grades are similar, which implies that impact resistance isn't considered or formulation is adapted, addition of plasticizers counterbalancing the harmful effect of fillers.

8.4.2 Low-Temperature Tests

There are many methods to test low-temperature behavior but no result can be used directly needing careful interpretations. The possibility of using a thermoplastic at low temperature depends on the service conditions including loading and impacts. Some grades can be used at −200 °C or less if there are no impacts. Some other thermoplastics can be brittle at ambient temperature like the polystyrene used for yoghurt packaging.

Table 8.7 Examples of Vicat Softening Temperature (VST)

	VST B (50 N)	VST A (10 N)
PEEK CF	320	
TPI	260	
PA66 FR	250	
PEEK	250	
PEI 40 GF	221	230
PA6	204	
LCP 40 Mineral	195	
PBT 12 Mineral	186	
PBT FR	180	
PBT	175	
POM	158	
PPE	135	140
PP 20 GF	132	165
PC/ABS	108	
PC/ASA	103	111
SAN	102	106
CPVC	100	
PP 20 Talc	95	152
PS	91	95
PS	88	97
Acrylic	86	98
PP	85	150
PE HD	80	129
PVC	75	

Table 8.8 Minimum Service Temperatures for 207 Grades

Statistical Analysis		
Average	–60	
Median	–40	
Minimum	–269	
Maximum	20	
Minimum Service Temperature Ranges	**Minimum**	**Maximum**
PPS	–269	–20
PPS GF	–269	–20
PPS long GF medium level	–269	–20

Continued

Table 8.8 Minimum Service Temperatures for 207 Grades—cont'd

Minimum Service Temperature Ranges	Minimum	Maximum
PPS long GF high level	–269	–20
PPS CF	–269	–20
PPS CF + GF	–269	–20
PPS conductive	–269	–20
PPS Far	–269	–20
PPS GF + Mineral	–269	–20
PCTFE	–250	–150
PI TP	–250	–60
PI TP CF	–250	–60
PI TP GF	–250	–60
PI TP low friction	–250	–60
PE-UHMW	–200	–100
PTFE	–200	–80
PTFE CF	–200	–80
PTFE low friction	–200	–80
PTFE GF	–200	–80
LCP	–200	–50
LCP CF	–200	–50
LCP GF	–200	–50
LCP Mineral	–200	–50
PAI	–196	–60
PBI	–160	–100
PFA	–150	–150
FEP	–150	–100
FEP GF	–150	–100
PA 11	–120	–70
PA 11 or 12 plasticized	–120	–70
PA 12	–120	–70
PA 11 GF	–120	–50
PA 12 CF	–120	–50
PA 12 GF	–120	–50
PA 12 GB	–120	–50
PA 12 low friction	–120	–50
ETFE	–100	–100
PES	–100	–80

Table 8.8 Minimum Service Temperatures for 207 Grades—cont'd

Minimum Service Temperature Ranges	Minimum	Maximum
PES GF	–100	–80
PES CF	–100	–80
PES low friction	–100	–60
EMA	–100	–50
ETFE GF	–100	–50
PA 6-10	–100	–50
PA 6-10 CF	–100	–50
PA 6-12	–100	–50
PAI GF	–100	–50
PAI CF	–100	–50
PAI low friction	–100	–50
PAI Mineral	–100	–50
PEEK/PBI	–100	–50
PEEK/PBI GF	–100	–50
PEEK/PBI CF	–100	–50
Polyarylate	–100	–50
PSU	–100	–50
COPE high Shore D	–100	–40
COPE low Shore D	–100	–40
PA 6-12 GF	–100	–40
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	–100	–40
PPSU	–100	–40
PPSU GF	–100	–40
PC	–100	–25
PC GF	–100	–25
PC CF	–100	–25
PC CNT	–100	–25
PC conductive	–100	–25
PC low friction	–100	–25
Polyarylate GF	–100	–25
PA 12 conductive	–80	–50
PA CNT	–80	–50
PA 6	–80	–50
PA 6 GB	–80	–50

Continued

Table 8.8 Minimum Service Temperatures for 207 Grades—cont'd

Minimum Service Temperature Ranges	Minimum	Maximum
PA 6 medium-level GF	–80	–50
PA 6 medium-level long GF	–80	–50
PA 6 high-level GF	–80	–50
PA 6 high-level long GF	–80	–50
PA 66 impact medium-level GF	–80	–50
PA 6 GF recycled	–80	–40
PA 6 FR	–80	–40
PA 6 Mineral FR	–80	–40
PA 6 recycled	–80	–40
PA 66	–80	–40
PA 66 CF	–80	–40
PA 66 GB	–80	–40
PA 66 medium-level GF	–80	–40
PA 66 long CF	–80	–40
PA 66 medium-level long GF	–80	–40
PA 66 Mineral	–80	–40
PA 66 high-level GF	–80	–40
PA 66 high-level long GF	–80	–40
PA 66 conductive	–80	–40
ECTFE	–76	–76
PE-LD	–70	–60
PE GF	–70	–50
PE 60% long GF	–70	–50
PE-HD	–70	–50
PE-HD antistat black	–70	–50
PSU modified	–70	–50
PEEK	–70	–40
PEEK GF	–70	–40
PEEK CF	–70	–40
PAEK 30% GF	–70	–40
PSU GF	–70	–40
PSU Mineral	–70	–40
CPE	–70	–35
PVF	–70	–35
TPU GF	–70	–30

Table 8.8 Minimum Service Temperatures for 207 Grades—cont'd

Minimum Service Temperature Ranges	Minimum	Maximum
TPU long GF	–70	–30
TPU conductive	–70	–30
TPU Shore D	–70	–30
PP/EPDM-V	–63	–30
PEBA 25 to 45 Shore D	–60	–60
PEBA Bio	–60	–40
TPS Shore D	–60	–40
TPE based on PVC	–60	–30
TPO Shore D	–60	–30
TPV Shore D	–60	–30
ABS/PA	–60	–20
ABS/PA 20 GF	–60	–20
ABS/PC	–60	–20
ABS/PC low-level long GF	–60	–20
ABS/PC medium-level long GF	–60	–20
ABS/PC conductive	–60	–20
ABS/PC GF	–60	–20
POM homo or copolymer	–50	–40
POM GF	–50	–40
POM long GF	–50	–40
POM GB	–50	–40
POM CF	–50	–40
POM conductive	–50	–40
POM Far	–50	–40
POM low friction	–50	–40
POM Mineral	–50	–40
COPE Bio	–50	–30
MPR	–50	–30
PE-X cross-linked	–50	–30
PPE	–50	–30
PPE GF	–50	–30
PPE CF	–50	–30
PPE Mineral	–50	–30
PC/PBT	–50	–25
PC/PBT GF	–50	–25

Continued

Table 8.8 Minimum Service Temperatures for 207 Grades—cont'd

Minimum Service Temperature Ranges	Minimum	Maximum
TPU Bio	–50	–25
PA castable	–40	–40
PEBA 50 to 72 Shore D	–40	–40
PTT Bio	–40	–40
PTT Bio GF	–40	–40
PA castable low friction	–40	–30
PBT	–40	–30
PBT medium-level GB	–40	–30
PBT medium-level GF	–40	–30
PBT GF and Mineral	–40	–30
PBT long GF	–40	–30
PBT long CF	–40	–30
PBT CF	–40	–30
PET/PC	–40	–30
PK	–40	–30
PK GF	–40	–30
PET/PC GF	–40	–25
ABS	–40	–20
ABS GF	–40	–20
ABS GB	–40	–20
ABS CF	–40	–20
ABS conductive	–40	–20
ABS FR	–40	–20
PET	–40	–20
PET GF	–40	–20
PET Amorphous	–40	–20
PET/PBT high-level GF	–40	–20
PMP	–40	–20
PMP GF	–40	–20
PMP Mineral	–40	–20
PP impact	–40	–20
PS impact	–40	–20
PVDF	–40	–20
PVDF CF	–40	–20
PVDF low friction	–40	–20

Table 8.8 Minimum Service Temperatures for 207 Grades—cont'd

Minimum Service Temperature Ranges	Minimum	Maximum
PVDF Mica	–40	–20
PP Co	–40	–10
PVC plasticized	–40	–5
CA	–30	–25
PP low-level GF	–30	–5
PP medium-level GF	–30	–5
PP Mineral	–30	–5
PP Talc	–30	–5
PP low-level CNT	–30	–5
PP medium CNT	–30	–5
PP long GF medium level	–30	–5
PP long GF high level	–30	–5
PP antistat	–20	–10
PP CF	–20	–10
PP Ho	–20	–5
PP recycled	–20	–5
PP GB	–20	–5
PP cellulose fibers	–20	–5
PP $CaCO_3$	–20	–5
PP conductive	–20	–5
PP natural fibers	–20	–5
PS GF	–20	20
PVDC	–15	–15
PVC GF	–10	0
PVC unplasticized	–10	0
PVCC	0	0
ASA/PVC	0	8

It is necessary to distinguish between:

- short-term tests: brittle point, low-temperature impact test, low-temperature rigidity, and elastic recovery for elastomers and thermoplastic elastomers
- long-term tests: crystallization tests, which make it possible to detect a slow crystallization by the evolution of hardness with time.

8.4.2.1 Standardized Impact Tests Processed at Low Temperatures

Low-temperature impact tests: cooled samples are subjected to a conventional impact test. Generally, the most often used temperatures are –20, –30, or –40 °C.

Table 8.9 displays examples of impact strength tested at low temperatures.

Table 8.9 Examples of Low-Temperature Impact Tests According to Various Methods

Izod Impact, Notched				
Temperature, °C	–40	–30	–18	23
Unit	J/cm	J/cm	J/cm	J/cm
PPE + PS	1.33			2.13
PA6 33 GF conditioned	1.07			2.35
PA6 33 GF Dry	1.07			1.48
PPE + PS 30 GF	0.96			1.17
PA6 Dry	0.32			0.48
PA6 Conditioned	0.21			1.6
PPE + PA		1		2.2
ABS GP		0.8	0.85	2.4
PPE + PS + PA 30 GF		0.8		1.06
ABS GP		0.6	1	3
PS		0.6		1.5
Izod Impact, Notched (ISO)				
Temperature, °C	–40	–30	–20	23
Unit	kJ/m²	kJ/m²	kJ/m²	kJ/m²
PA6 33 GF Dry	8.5			10
PC		12		65
PPE + PA		10		20
PPS Low filler		7	7	7
PPE + PS		5		17
TPO			4	45
PP 20 Mineral			2.1	6
Charpy Impact, Unnotched				
Temperature, °C		–30	–20	23
Unit		J/cm²	J/cm²	J/cm²
ABS GP		10		18
PC		NB	NB	NB
TPO			NB	NB
PA11 30 GF		8.39	8.31	8.24
PA6/66 30 CF			5	4.5
PP 20 Mineral			3	7
PPS Low filler		2.8	2.8	2.8

Table 8.9 Examples of Low-Temperature Impact Tests According to Various Methods—cont'd

ABS GP	9		12.5
PP 30 long GF	5.5		5
LCP	5.3		26.7
Charpy Impact, Notched			
Temperature, °C	–30	–20	23
Unit	J/cm²	J/cm²	J/cm²
ABS GP	0.8		2.2
PC	1.2		5.5
TPO	0.5	0.6	5.8
PA11 30 GF	1.2		2.06
PA6/66 30 CF		0.4	0.7
PP 20 Mineral		0.24	0.6
PPS Low filler	0.7	0.7	0.7
ABS GP	0.7		1.9
PA11 Conditioned	1	1	1
PA11 Dry	1.1		0.8
PA6 33 GF Dry	1		1.5
PPE+PA	1		2

8.4.2.2 Brittle Point

The—very fuzzy—definition of the brittle point is based on a more or less sudden reduction in the impact resistance or the flexibility. The indicated values must be carefully considered.

- Low-temperature brittleness or toughness: the samples are cooled to a temperature far lower than the supposed temperature of brittleness, and then gradually warmed up. At each selected step temperature, the test specimens are subjected to a specified impact. The temperature at which specimens deteriorate or fail is the "brittle point." In some other tests, the lowest temperature to which specimens can be cooled without deterioration is regarded as the limiting temperature of "toughness" or "no brittleness."
- Low-temperature flexibility of thin products: the product is rolled up on a specified mandrel at one or several temperatures.

8.4.2.3 Other Test Examples: Dynamic Torsion Modulus, Crystallization Test

Dynamic Torsion Modulus

The oldest test is the "Clash & Berg" based on the evolution of the dynamic torsion modulus when the temperature decreases. Results can be:

- plotted versus the temperature
- expressed as the value of the modulus for specified temperatures
- recorded as the temperatures for which the modulus is 2, 5, 10, 100… times higher than that measured at room temperature.

Table 8.10 displays, on the one hand, general ranges and some examples of low-temperature assessments and characteristics linked to minimum service temperatures, and on the other hand, brittleness temperatures. We can remark:

Table 8.10 Examples of Low-Temperature Assessments and Characteristics

Plastic	Minimum Service Temperature, °C			Brittleness, °C
	General Range		Examples	
	Minimum	Maximum		
PPS	–269	–20	–50	
PPS GF	–269	–20	–50	
PE-UHMW	–200	–100	–150; –250	
PTFE	–200	–80	–250; –268	–200
ETFE	–200	–50	–200; –100	
PFA	–150	–150	–200	
FEP	–150	–100	–100	
PA 11	–120	–70	–50	
PA 12	–120	–50	–50	
PA 6-12	–100	–50	–100	
PES	–100	–50	–50	
COPE low Shore D	–100	–40		–75
COPE high Shore D	–100	–40		–50
PC	–100	–25	–60; –50	–130
PA 6	–80	–50	–30	
PA 66	–80	–40	–30	–80; –65
PA 66 medium-level GF	–80	–40	–20	
PE-LD	–70	–60		–80; –76; <–70
PE-HD	–70	–50	–50	–75
PEEK GF	–70	–40	–40	–65
PEEK	–70	–40	–50; –40	–65
PEEK CF	–70	–20	–20	–65
PP/EPDM-V	–63	–30		–60
TPE based on PVC	–60	–30		–44
POM homo or copolymer	–50	–40	–50	
PPE	–50	–30	–50	
PPE GF	–50	–30	–50	
MPR	–50	–30	–49	–69; –68
POM conductive	–50	–20	–20	
PA castable	–40	–40	–40	
ABS	–40	–20	–40	
PET	–40	–20	–40; –20	
PVDF	–40	–20		–53; –37

Table 8.10 Examples of Low-Temperature Assessments and Characteristics—cont'd

	Minimum Service Temperature, °C			Brittleness, °C
Plastic	General Range		Examples	
	Minimum	Maximum		
PVDF CF	–40	–20		0
PP Co	–40	–10	–30; 4; 5	–20
PVC plasticized	–40	–5		–47; –44; –25
PP medium-level GF	–30	–5	5	
PP Ho	–20	–5	0; 5	
PVC unplasticized	–10	0		–15; –6; –3; 15
PVCC	0	0		–24
PA 46			–40	
Acrylic			–40; –34	
EVA				<–70; –100

- some examples of minimum service temperatures are out of the general range probably because of special applications and/or special formulations
- brittleness temperatures can be in or out the general range of minimum service temperatures according to the user's requirements.

Crystallization Test

The crystallization test consists of measuring the evolution of hardness at a specified temperature over several weeks. This method is of special interest for those polymers that can slowly crystallize at service temperatures.

The combination of low-temperature periods and immersion in chemicals at temperatures superior to their melting point leading to chemical uptake can induce worsening of existing defects by volume increase in solidified chemicals during cooling.

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cuming, EMS, Enichem, Epotecny, Eval, Evonik, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Omnexus, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, Specialchem, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Trexel, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

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[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
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9 Dimensional Stability

OUTLINE

Anybody has already seen too little (or too big) a polymer part disturbing a device made by assembling several parts of various materials. Sometimes, the dimension is fair but a more or less strong warpage prevents a correct assembly.

These phenomena are consequences of:

- The coefficient of thermal expansion (CTE) contributing to the mold shrinkage
- Formulation fluctuations into a part or between parts
- Part and mold designs
- Temperature, pressure, and time variations at the various processing steps
- Anisotropy of fiber- or acicular filler-reinforced compounds
- Some crystallization after demolding
- Residual internal stresses
- The water uptake particularly known for polyamides. Other chemicals can also swell polymers but they are rather relevant from chemical behavior
- Differential properties into the part
- The desorption of humidity or additives such as plasticizers or other low-molecular weight organic additives
- Deformation under stress at more or less high temperatures.

The variations in the above parameters are also responsible for warpage and other dimensional issues.

Moreover, plastics and rubbers are often simultaneously used with conventional materials, notably metals whose coefficients of thermal expansion can be 10 to 100 times lower. Sometimes, it is forgotten that part sizes increase with temperature, which can block a device and can induce high stresses if the part has not a sufficient space to expand. In the same way, cold temperatures decrease part sizes.

Dimension variations can be immediate (thermal expansion) or progressive (water uptake, crystallization) or delayed after a given time of aging.

Seldom high coefficients of thermal expansion or high water uptakes are targeted for specific applications such as:

- Temperature sensors leading to a significant displacement for a given increase in temperature.
- Swelling seals creating water tightness in case of water presence.

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00009-X

Remember that:

- Shrinkage is induced by the retraction of the molded part when cooling after injection: consequently, the part size is always different in the mold size.
- Warpage is induced by random changes in the shape of the part (and its size) when cooling or aging.
- The used compound is only one of the parameters of shrinkage and warpage, part and mold designs, processing conditions are other important factors.

Of course, following data are only examples providing a rough idea of the significant differences between subfamilies but other data can be found elsewhere. These theoretical data cannot be used for designing, computing, or to make economic predictions. Only properties measured on the actually used compound must be considered.

9.1 Coefficients of Thermal Expansion—CTE or CTLE

The CTE can be volumetric or more frequently linear (CTLE: coefficient of thermal linear expansion). It is defined as the fractional variation of volume (volumetric coefficient) or length (linear coefficient) per unit change in temperature.

Being thermal dependant, the validity range of test temperatures must be indicated.

For isotropic plastics, the volumetric coefficient is roughly three times the linear one.

Anisotropic materials have different linear expansion coefficients in different directions.

The CTE is significantly changed by:

- The temperature, particularly if the glass transition temperature is crossed
- The structure and morphology of the polymer
- The additives eventually used
- The degree of cross-linking for cross-linked thermoplastics such as XPE.

Of course, a temperature decay leads to a retraction.

Table 9.1 displays CTLE (10^{-5}/°C) for 193 grades including expected neat grades and special ones.

The first part of Table 9.1 displays average CTLE for eight subfamilies: expected neat grades, and special grades including carbon fiber (CF)-reinforced grades, glass fiber (GF)-reinforced grades, mineral- and glass bead (GB)-reinforced grades, conductive grades, low-friction grades, and wood plastic composite (WPC). Note:

- General purpose grades can be formulated with plasticizers, fillers, and reinforcements and are called "expected neat grades" in the following.
- Eight subfamilies are not based on the same polymers.

For the second part of Table 9.2 displaying ranges of CTLE, we can remark:

- Some grades, for example, based on liquid crystal polymer (LCP), have a negative CTLE induced by anisotropic orientation
- The data range stretches from $-1 * 10^{-5}$/°C to $20 * 10^{-5}$/°C
- Generally, reinforced and filled grades have lower CTLE
- For a given subfamily, the CTLE range can be as high as $1 * 10^{-5}$/°C to $20 * 10^{-5}$/°C. The broad range of CTLE for many families can come from polymer structure diversity, formulation versatility, orientation, succinct trade appellations, errors, and mix-up.

The number of studied samples is limited and other data may be found elsewhere.

CTLEs for most neat thermoplastic grades range from $2 * 10^{-5}$/°C to $20 * 10^{-5}$/°C (average $8 * 10^{-5}$/°C) which must be compared to other traditional materials (see examples, Table 9.2):

- Metals: 0.4 to $4 * 10^{-5}$/°C
- Ceramics, glass, oxides, carbides, nitrides, carbon, graphite: 0.2 to $1.6 * 10^{-5}$/°C
- Wood: 0.3 to $5 * 10^{-5}$/°C, highly dependent on the direction.

9.1.1 Effect of Structure of Tested Polymer

Copolymers can differ by the ratio of monomers having a more or less severe effect on the CTE.

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)

Neat	7.8
Special	4.4
CF-reinforced grades	3.7
GF-reinforced grades	3.7
Mineral, GB-reinforced grades	4.8
Conductive grades	6.8
Friction grades	5.9
WPC	7.2

Expected Neat Grades			Special Grades		
			LCP Mineral	–1	8
LCP	–0.5	7.5			
			LCP CF	–0.3	7
			LCP GF	–0.1	9
ASA/PVC	0.1	9			
			PBI	0.2	3
			PI TP GF	0.5	5.3
			PI TP CF	0.6	4.7
			PPS CF	0.7	2
			PC CF	0.8	2.3
			PAI CF	1	2
			PAA medium-level CF	1	2.5
			PAEK 30% GF	1	3
			PAI GF	1	3
			PAI friction	1	3
			PAI Mineral	1	3
			PBT long GF	1	3
			PPS long GF high level	1	3
			TPU GF	1	3
			TPU long GF	1	3
			PPS GF+Mineral	1	3.2
			PEI CF	1	4
			PEEK CF	1	5
			PES friction	1	5
			PPS GF	1	5

Continued

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)—cont'd

Expected Neat Grades			Special Grades		
			PPS long GF medium level	1	5
			PPS CF + GF	1	5
			PET/PC GF	1	6
			PA 10-10 high level GF Bio	1	8
			PAA Mineral	1	9
			PPS conductive	1	9
			POM GF	1	10
			PAA high-level GF	1.1	4
			PA 66 high-level long GF	1.3	2
			PA 6-10 CF	1.4	10
			PTT Bio GF	1.4	10
PTT Bio	1.4	14			
			PEEK GF	1.5	3
			PPE GF	1.5	3
			PPSU GF	1.5	3
			PA 66 high-level GF	1.5	5
			PES GF	1.5	5
			PET/PBT high-level GF	1.5	6
			PET GF	1.5	7.5
			PAA medium-level GF	1.5	9
			PA 6-12 GF	1.5	10
			PA Far	1.6	2
PPSU	1.7	6			
			ABS/PC GF	1.8	2
			PEI GF	1.8	5
			PPE CF	1.8	5
			PEI conductive	2	2.5
			ETFE GF	2	3
			PA 6 medium-level GF	2	3
			PA 6 medium-level long GF	2	3
			PA 6 high-level GF	2	3
			PA 6 high-level long GF	2	3
			PBT GF & Mineral	2	3

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)—cont'd

Expected Neat Grades			Special Grades		
			PEEK/PBI GF	2	3
			PEEK/PBI CF	2	3
			PEI GF milled	2	3
			POM long GF	2	3
			PSU GF	2	3
			PSU/PBT GF	2	3
PAI	2	4			
			PE 60% long GF	2	4
			PMP GF	2	4
			PP medium-level GF	2	4
			PP long GF medium level	2	4
			PP long GF high level	2	4
			PVC GF	2	4
			SAN GF	2	4
			SMA GF	2	4
			PA 66 medium-level GF	2	5
			PA 66 medium-level long GF	2	5
			PA 66 Mineral	2	5
			PBT medium-level GF	2	5
			PC GF	2	5
			PEI Mineral	2	5
			PPE Mineral	2	5
			PA 66 CF	2	7
			PA 66 long CF	2	7
			PEEK/PBI	2	7
			PA 4-6 GF	2	8
			PC/PBT GF	2	8
			PC/SAN GF	2	8
SMA	2	8			
			PA 66 impact medium-level GF	2	9
ECTFE	2	10			
			PA 12 CF	2	10
			PA 66 conductive	2	10

Continued

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)—cont'd

Expected Neat Grades			Special Grades		
			PA 12 GF	2	12
			PP/PA GF	2	12
			PA 11 GF	2	13
ETFE	2	14			
			PI TP friction	2.3	4
			PPE/PA GF	2.3	5
			PPA long GF	2.4	4
			PPA GF	2.4	6
			PS GF	2.5	3.5
PES	2.7	6			
			ABS GF	3	3.5
			PA 6 GF recycled	3	4
			PES CF	3	4
			PPA Mineral	3	4
			PSU Mineral	3	4
			ABS GB	3	5
			PA 6 mineral FR	3	5
			ASA/PBT GF	3	6
PPS	3	6			
PSU	3	6			
			Polyarylate GF	3	6.3
			PBT long CF	3	7
			PP GB	3	7
			PP wood WPC	3	7
			PBT CF	3	8
PPE	3	8			
PA Transparent	3	9			
			PCT GF	3	9
			PVDF CF	3	9
			PE wood WPC	3	9.9
			POM CF	3	10
			PP Mineral	3	10
			PLA natural reinforcement	3	12

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)—cont'd

Expected Neat Grades			Special Grades		
			ABS/PA 20 GF	4	6
PI TP	4	6			
Acrylique imide	4	7			
PMI or PMMI	4	7			
			PP low-level GF	4	7
			PA 4-6 Mineral	4	8
ABS/PC	4	9			
PEEK	4	9			
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	4	9			
PMMA	4	9			
			POM Mineral	4	9
			PA 6 GB	4	10
			PA 66 GB	4	10
			PP Talc	4	10
EVOH	4	12			
PCTFE	4	15			
			FEP GF	5	6
PEI	5	6			
			PC friction	5	7
			PE GF	5	7
ABS/PVC	5	9			
ASA/PMMA	5	9			
PMMA impact	5	9			
PS	5	9			
			PVDF Mica	5	9
			PA castable friction	5	10
ASA	5	11			
Polyarylate	5	11			
			PA 6 FR	5	12
PA 6 recycled	5	12			
			PP cellulose fibers	5	12
			PP natural fibers	5	12

Continued

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)—cont'd

Expected Neat Grades			Special Grades		
PA 6	5	14			
PA 66	5	14			
PA castable	5	15			
			PA 12 conductive	5	18
PVC unplasticized	5	18			
PS impact	5	20			
TPE based on PVC	5	20			
PSU modified	5.5	11			
PSU/ABS	6	7			
PVCC	6	8			
SAN	6	8			
ASA/PC	6	9			
COC	6	9			
PC	6	9			
PET	6	9			
			ABS FR	6	11
ABS/PA	6	11			
PBT	6	11			
ABS	6	13			
PC/PBT	6	13			
PA 6-10	6	14			
PP Ho	6	17			
PP recycled	6	17			
TPO Shore D	6	17			
PP/PA	6	20			
PE-HD	6	22			
			POM GB	7	9
			PTFE friction	7	10
			PVC wood WPC	7	10
PVF	7	10			
PA 4-6	7	11			
			PA 12 GB	7	12
			POM conductive	7	12
PET/PC	7	13			

Table 9.1 Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C)—cont'd

Expected Neat Grades			Special Grades		
			PTFE GF	7	14
POM homo- or copolymer	7	15			
			PA 12 friction	7	16

Table 9.2 Coefficient of Thermal Linear Expansion Examples for Traditional Materials (10^{-5}/°C)

	Metals	Ceramics	Wood
Mica		0.3	
Glass		0.4–0.9	
Molybdenum	0.5		
Alumina		0.5	
Brick masonry		0.6	
Clay tile		0.6	
Chromium	0.6		
Porcelain		0.7	
Granite		0.8	
Titanium	0.9		
Concrete		1–1.5	
Steels	1–1.7		
Iron	1.2		
Nickel	1.3		
Plaster		1.6	
Copper	1.7		
Bronze	1.8		
Brass	1.9		
Aluminum	2.2		
Duralumin	2.3		
Magnesium	2.5		
Lead	2.8		
Zinc	3		
Wood, perpendicular to grain			3–5
Wood, parallel to grain			0.3–0.5

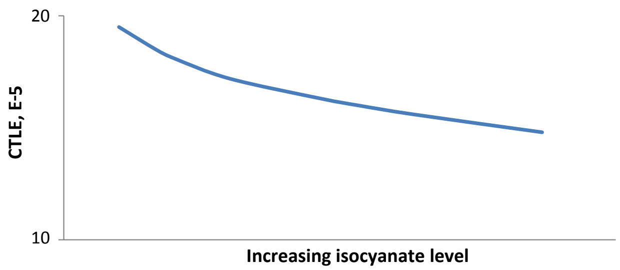

Figure 9.1 Coefficient of thermal linear expansion of thermoplastic polyurethane versus increasing Isocyanate levels.

For example, all other things being equal, the linear CTE of a family of thermoplastic polyurethanes can evolve between 14 and 20 * 10^{-5}/°C according to the ratio of comonomers (see Figure 9.1).

9.1.2 Effect of Morphology

Generally speaking, amorphous polymers have a lower CTLE than semicrystalline ones. For example, for neat grades:

- 48 amorphous grades have an average CTLE of 8.2
- 68 semicrystalline grades have an average CTLE of 11.0.

9.1.3 Effects of Additives

Intuitively, it makes sense that the addition of low-CTLE GFs or CFs, minerals, metal powders, or GBs decreases the coefficients of thermal expansion of polymers.

Effectively:

- For a PA6, a semicrystalline thermoplastic, filled with 18 up to 50% of GFs, the CTE decreases from 7 * 10^{-5}/°C down to 1.8 * 10^{-5}/°C

Table 9.3 Liquid Crystal Polymer: Examples of Coefficient of Thermal Linear Expansion (10^{-5}/°C) in Flow and Transverse Directions

Reinforcement	Flow Direction	Transverse Direction
None	−0.3	3.9–6.6
15% glass fibers	0.5–1.1	5.9–6
30% glass fibers	−1–2	4.5–4.7
50% glass fibers	0.5–1	4.8
15% mineral filler	0.4	6.2
30% mineral filler	1.7	5.7
50% mineral filler	1.2	4.6

- For a polycarbonate, an amorphous thermoplastic, filled with 10 up to 40% of GFs, the CTE decreases from $7 * 10^{-5}$/°C down to $2 * 10^{-5}$/°C
- For a PTFE, a highly crystalline thermoplastic, the addition of 60% of bronze powder reduces the CTE from 14 to $8.6 * 10^{-5}$/°C, that is to say a 40% drop in round figure.

9.1.4 Effect of Molecular Orientation on CTE

LCPs are exemplary from this point of view with some CTLEs being negative in the flow direction and CTLE being higher than $6 * 10^{-5}$/°C in the transverse direction as displayed in Table 9.3.

9.2 Shrinkage after Molding

Shrinkage after molding is a universal problem depending on (see Figure 9.2):

- The CTE: for given conditions, the mold shrinkage increases as the CTE increases.
- The molding temperatures: for given conditions, the shrinkage increases as the molding temperatures increase.
- The additives.
- The orientation of the macromolecules.

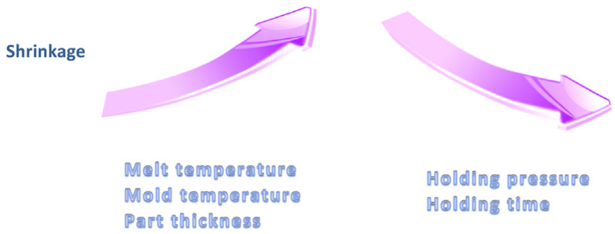

Figure 9.2 Effects of some processing parameters on shrinkage.

- The orientation of fibers or acicular fillers.
- The crystallinity: A possible crystallization after molding leads to a volume increase that minimizes the total shrinkage.

Table 9.4 displays shrinkage after molding for 223 grades including CF-reinforced grades, GF-reinforced grades, mineral- and GB-reinforced grades, conductive grades, friction grades, and WPC. Note that general purpose grades can be formulated with plasticizers, fillers, and reinforcements and are called "expected neat grades" in the following.

The first part of Table 9.4 displays average values for eight subfamilies. Shrinkage of neat grades is approximately two times that of special grades.

For the second part of Table 9.4, compounds are ranked in an ascending order of minimum of shrinkage. We can remark:

- The broad range of shrinkage for many families arising from formulation versatility, succinct trade appellations, test method versatility, errors, and mix-up.
- Lower values of shrinkage for fiber reinforced grades, in the ascending order: CFs, GFs, wood fibers. On the other hand, fiber orientation can lead to irregular shrinkage.

9.2.1 Effect of Morphology

Generally speaking, shrinkage of amorphous polymers is lower than that of semicrystalline ones. For example, for neat grades:

- 48 amorphous grades have an average shrinkage after molding of 0.75%
- 68 semicrystalline grades have an average shrinkage after molding of 1.9%.

Table 9.4 Examples of Shrinkage, %

Averages	
Neat grades	1.3
Special grades	0.6
CF-reinforced grades	0.4
GF-reinforced grades	0.5
Mineral, GB-reinforced grades	0.8
Conductive grades	0.8
Friction grades	0.8
WPC	0.7

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	Minimum	Maximum	Plastic	Minimum	Maximum
			PVC GF	0.01	0.2
			LCP CF	0.01	0.3
			PAI CF	0.01	0.3
LCP	0.01	0.6			
			LCP GF	0.01	1.3
			PEEK/PBI CF	0.05	0.2
			PEEK CF	0.05	1.4
			PC CF	0.1	0.2
			PPS long GF high level	0.1	0.2
			ABS/PC GF	0.1	0.3
			PAI GF	0.1	0.3
			PI TP CF	0.1	0.3
			SMA GF	0.1	0.3
			PA 10-10 high level GF Bio	0.1	0.4
			PP long GF high level	0.1	0.4
			PPS CF	0.1	0.4
			SAN GF	0.1	0.4
			ABS/PA 20 GF	0.1	0.5
			PA 11 GF	0.1	0.5
			PA 66 high-level long GF	0.1	0.5
			PC GF	0.1	0.5

Continued

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	Minimum	Maximum	Plastic	Minimum	Maximum
			PEI CF	0.1	0.5
			PI TP GF	0.1	0.5
			PPA long GF	0.1	0.5
			PS GF	0.1	0.5
			PA 6 high-level GF	0.1	0.6
			PAI friction	0.1	0.6
			PES GF	0.1	0.6
			PPE GF	0.1	0.6
			PPE CF	0.1	0.6
			PSU GF	0.1	0.6
PVC unplasticized	0.1	0.6			
			PA 66 medium-level GF	0.1	0.7
			PA 66 medium-level long GF	0.1	0.7
			PAA high-level GF	0.1	0.7
			PAA medium-level CF	0.1	0.7
			PPS GF + Mineral	0.1	0.7
			PA 66 high-level GF	0.1	0.8
			PBT long CF	0.1	0.8
			POM long GF	0.1	0.8
PS	0.1	0.8			
CP	0.1	0.9			
			PA 12 CF	0.1	1
			PA 66 CF	0.1	1
			PA 66 conductive	0.1	1
			PA Far	0.1	1
			PBT GF & Mineral	0.1	1
			PBT long GF	0.1	1
			PCT GF	0.1	1
			PP long GF medium level	0.1	1
			PP/PA GF	0.1	1
			LCP Mineral	0.1	1.1
			PA 6-12 GF	0.1	1.1

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	**Minimum**	**Maximum**	**Plastic**	**Minimum**	**Maximum**
			PBT CF	0.1	1.1
			PP medium-level GF	0.1	1.2
			PAEK 30% GF	0.1	1.5
			POM conductive	0.1	1.5
			PA 6-10 CF	0.1	1.6
			POM GF	0.1	1.8
			ETFE GF	0.1	2
			PP Mineral	0.1	2
			POM CF	0.14	1
			PPS CF+GF	0.15	0.5
ECTFE	0.2	0.3			
			ABS GF	0.2	0.4
			PES CF	0.2	0.4
			PI TP friction	0.2	0.4
			PES friction	0.2	0.5
			PPS long GF medium level	0.2	0.5
			PTFE CF	0.2	0.5
			PEEK/PBI GF	0.2	0.6
			PEI GF	0.2	0.6
			PEI GF milled	0.2	0.6
			PSU Mineral	0.2	0.7
SAN	0.2	0.7			
Acrylique imide	0.2	0.8			
PMI or PMMI	0.2	0.8			
PMMA	0.2	0.8			
PMMA impact	0.2	0.8			
			PPA GF	0.2	0.8
			PPS GF	0.2	0.8
			PPSU GF	0.2	0.8
PS impact	0.2	0.8			
CAB	0.2	0.9			

Continued

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	Minimum	Maximum	Plastic	Minimum	Maximum
			PA 6 medium-level GF	0.2	0.9
			PAA medium-level GF	0.2	0.9
			PAA Mineral	0.2	0.9
			PE GF	0.2	0.9
CA	0.2	1			
			PA 6 mineral FR	0.2	1
PA 66 impact medium-level GF	0.2	1			
			PC/PBT GF	0.2	1
PET Amorphous	0.2	1			
			PET GF	0.2	1
			PET/PBT high-level GF	0.2	1
			PP wood WPC	0.2	1
			PPS conductive	0.2	1
			PEEK GF	0.2	1.1
			ASA/PBT GF	0.2	1.3
			PBT medium-level GB	0.2	1.5
			PBT medium-level GF	0.2	1.5
			PET/PC GF	0.2	1.7
			PA 4-6 GF	0.2	1.8
			PTT Bio GF	0.2	2
PPA	0.2	2.2			
			FEP GF	0.2	3
PET	0.2	3			
PVC plasticized	0.2	5			
			PSU/PBT GF	0.25	0.6
			PC/SAN GF	0.3	0.5
			ABS GB	0.3	0.6
			PP cellulose fibers	0.3	0.6
ABS/PVC	0.3	0.7			
ASA/PVC	0.3	0.7			
COC	0.3	0.7			

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	Minimum	Maximum	Plastic	Minimum	Maximum
			PA 12 GF	0.3	0.7
			PMP GF	0.3	0.7
			PPE Mineral	0.3	0.7
PVCC	0.3	0.7			
			ABS FR	0.3	0.8
ABS/PC	0.3	0.8			
			PPE/PA GF	0.3	0.8
ASA/PC	0.3	0.9			
			PA 6 GF recycled	0.3	0.9
			Polyarylate GF	0.3	0.9
			PP natural fibers	0.3	1
			PP low-level GF	0.3	1.2
			PVDF CF	0.3	1.3
			PA 6 high-level long GF	0.4	0.5
			PA 6 medium-level long GF	0.4	0.5
			PAI Mineral	0.4	0.5
MABS	0.4	0.6			
			PC friction	0.4	0.7
SMA	0.4	0.8			
ABS	0.4	0.9			
ASA	0.4	0.9			
PA Transparent	0.4	1			
PC	0.4	1			
PC/PBT	0.4	1			
PA 11	0.4	1.8			
COPE Bio	0.4	2			
COPE low Shore D	0.4	2			
TPO Shore D	0.4	2			
EVA	0.4	3.5			
			PEEK/PBI	0.5	0.7
			PEI Mineral	0.5	0.7

Continued

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	**Minimum**	**Maximum**	**Plastic**	**Minimum**	**Maximum**
PEI	0.5	0.8			
PA 10-10 Bio	0.5	1			
			PA 12 GB	0.5	1
			PA 6 GB	0.5	1
PES	0.5	1			
PPE	0.5	1.2			
			PE wood WPC	0.5	1.4
			PA 6 FR	0.5	1.5
			PA 66 Mineral	0.5	1.5
PEBA 25 to 45 Shore D	0.5	1.5			
PEBA Bio	0.5	1.5			
			PPA Mineral	0.5	1.5
PA 6 recycled	0.5	2			
			PA castable friction	0.5	2
PET/PC	0.5	2			
PBT	0.5	2.2			
PVDC	0.5	2.5			
PA 6	0.5	3			
PCTFE	0.5	4			
PSU	0.6	0.7			
PSU/ABS	0.6	0.7			
PSU/PC	0.6	0.9			
			PA 66 GB	0.6	1
PAI	0.6	1			
PPSU	0.6	1			
PSU modified	0.6	1.2			
PA 6-10	0.6	1.3			
PPS	0.6	1.4			
PEBA 50 to 72 Shore D	0.6	1.5			
			PP GB	0.6	1.7
			PA 12 friction	0.7	1
PEEK	0.7	1.2			

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	Minimum	Maximum	Plastic	Minimum	Maximum
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	0.7	1.3			
			PA 12 conductive	0.7	1.4
PA 11 or 12 plasticized	0.7	1.5			
PA 12	0.7	1.5			
ABS/PA	0.7	2			
PP/PA	0.7	2			
PA 66	0.7	3			
PE-X cross-linked	0.7	5			
PI TP	0.8	0.9			
			PP Talc	0.8	1.4
PA 6-12	0.8	2.4			
			POM friction	0.8	3
Polyarylate	0.9	1.2			
			PVDF Mica	1	1
PPE/PA	1	1.6			
			POM GB	1	1.7
			POM Mineral	1	2
PTT Bio	1	2			
COPE high Shore D	1	2.2			
POM homo- or copolymer	1	2.2			
			PE-HD antistat black	1	3
PP Co	1	3			
PP Ho	1	3			
PP recycled	1	3			
			PVDF friction	1	3
ETFE	1	4			
			PA 4-6 Mineral	1.3	2
PA castable	1.5	2			
PA 4-6	1.5	2.4			
PE-HD	1.5	4			

Continued

Table 9.4 Examples of Shrinkage, %—cont'd

Expected Neat Grades			Special Grades		
	Shrinkage, %			Shrinkage, %	
Plastic	Minimum	Maximum	Plastic	Minimum	Maximum
PMP	1.6	3			
			PTFE GF	1.8	2
PP impact	2	3			
PE-LD	2	4			
PE-UHMW	2	4			
PVDF	2	4			
PVF	2.5	6			
PFA	3	5			
FEP	3	6			
PTFE	3	6			

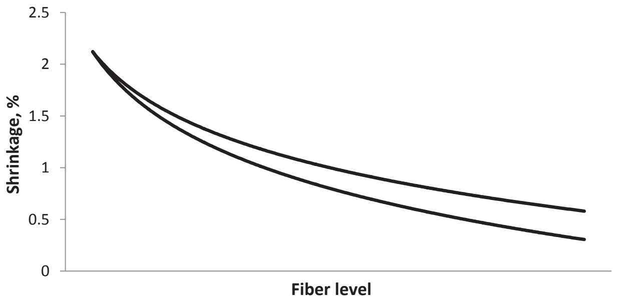

Figure 9.3 Mold shrinkage versus GF level.

Table 9.5 Liquid Crystal Polymer: Examples of Shrinkages (%) in Flow and Transverse Directions

Reinforcement	Flow Direction	Transverse Direction
None	0	0.6–1.2
30 CF	0–0.1	0.4
30 GF	0	0.4
Mineral	0	0.5

9.2.2 Effect of Fibers

Figure 9.3 shows examples of the shrinkage according to two perpendicular directions versus the GF content. In round figures, all other things being equal, shrinkage is divided by 2 for a 20% GF level.

9.2.3 Effect of Filler on Shrinkage of LCPs

LCPs are not inherently isotropic compounds. Ratio of shrinkages in flow and transverse directions can be higher than 10 as we can see in Table 9.5. We can notice that, exceptionally, the shrinkage can reach zero in the flow direction.

9.3 Warpage

Warpage or distortion can be due to:

- Anisotropy
- Internal stresses
- Shrinkage variations induced by local changes of formulation or processing parameters.

Fibers and acicular fillers can accumulate in certain spots of the mold leading to local decreases of CTE, shrinkage, and increases in moduli… leading to warpage.

Calcium carbonate ($CaCO_3$) fine powder and other spheroid fillers such as microballoons or GBs decrease shrinkage and easily flow in the mold, reducing warpage.

IPN technology based on silicone network acts as flow modifier controlling shrinkage and warpage of some crystalline resins such as neat or reinforced polyamide, thermoplastic polyester, acetal, polypropylene…

9.4 Water Uptake

All the polymers absorb more or less humidity or water in amounts depending on:

- The form of the water: humid air, liquid water, pure or polluted water
- The temperature
- The recipe of the compound
- The crystallinity of the polymer…

The volume of absorbed water causes a dimensional increase. For a given polyamide, Table 9.6 displays examples of the length increase versus the water content at equilibrium. Really, the absorption of water is very slow and, in the case of atmospheric changes, the equilibrium is not always reached damping the effects of humidity variations.

Table 9.7 displays water uptakes for 248 grades including CF-reinforced grades, GF-reinforced grades, mineral- and GB-reinforced grades, conductive grades, low-friction grades, and WPC. Note that general purpose grades can be formulated with plasticizers, fillers, and reinforcements and are called “expected neat grades” in the following.

These results must be carefully read because measuring methods aren’t known. Nature of water and time (often 24 h) are not defined which can lead to broad variations in results.

The first part of Table 9.7 displays average values for eight subfamilies. Water uptake data of neat grades are generally higher than that of special grades. However, hydrophilic additives can increase the water uptake of polymers: this technique is used for hydroswelling parts and seals.

Table 9.6 For a Given Polyamide: Examples of the Length Increase versus the Water Content

Water Content, %	Length Increase, %
0	0
2	0.2
4	0.7
6	1.6
8	2.6

For the second part of Table 9.7, compounds are ranked by the ascending order of minimum of water uptake. We can remark:

- The broad range of water uptake for many families arising from formulation versatility, succinct trade appellations, test method versatility, errors, and mix-up.
- The lower average values of water uptake for special grades.

All other parameters being equal, insensitive-to-water additives decrease the water uptake as displayed in Table 9.8 gathering some water uptake examples for a given polyamide filled with GFs.

Anisotropic absorption of water can cause more warpage, so that the material modulus is low. For example, a thermoplastic elastomer membrane covering a water container can curve because of the swelling of the inner face.

9.5 Releasing of Organic Additives: Choose High-Molecular Weight or Reactive Additives

Residual monomers, oligomers, organic additives, particularly plasticizers can degas more, so that the temperature and the airflow increase. Consequently, dimensions decrease. Components can also migrate toward other materials or bleed.

Released volatile organic compounds (VOCs) pollute other materials and surroundings. VOCs form a broad category of chemical compounds, some of which pose health hazards and can also lead to greenhouse effect, ozone layer depletion, and acidification of the global atmosphere.

For example, among other things, remember that:

- Some VOCs are well known or intuitively suspected such as chlorofluorocarbons (CFCs), halogenated fluorocarbons, perfluorinated carbons, hydrofluorocarbons, Freons, and other halogenated species… Their use is now regulated or banned in many countries.
- Not so well-known VOCs may be initiated by photochemical oxidants.

Table 9.7 Examples of Water Uptake, %

Averages	
Neat grades	0.8
Special grades	0.5
CF-reinforced grades	0.4
GF-reinforced grades	0.5
Mineral, GB-reinforced grades	0.5
Conductive grades	0.4
Friction grades	0.5
Natural fiber	1

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	Minimum	Maximum	Thermoplastic	Minimum	Maximum
PB	0.005	0.01			
PE-X cross-linked	0.005	0.01			
PTFE	0.005	0.01			
			PTFE CF	0.005	0.01
PE-UHMW	0.005	0.015			
PE-HD	0.005	0.1			
PE-LD	0.005	0.1			
COC	0.01	0.01			
CPE	0.01	0.01			
FEP	0.01	0.01			
PMP	0.01	0.01			
LCP	0.01	0.03			
PFA	0.01	0.03			
			PP Talc	0.01	0.03
PCTFE	0.01	0.05			
			PVDF CF	0.01	0.05
			PP low-level CNT	0.01	0.06
			PP medium CNT	0.01	0.06
			PP long GF medium level	0.01	0.06
			PP long GF high level	0.01	0.06
PPS	0.01	0.07			
ECTFE	0.01	0.1			

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	Minimum	Maximum	Thermoplastic	Minimum	Maximum
			FEP GF	0.01	0.1
			PE-HD antistat black	0.01	0.1
			PMP GF	0.01	0.1
PP impact	0.01	0.1			
PP Co	0.01	0.1			
			PP low-level GF	0.01	0.1
			PP medium-level GF	0.01	0.1
			PP GB	0.01	0.1
			PTFE GF	0.01	0.15
PP Ho	0.01	0.2			
			PVC GF	0.01	0.2
			PP antistat	0.01	0.3
			PP CF	0.01	0.3
			PP conductive	0.01	0.3
PS	0.01	0.3			
			PP Mineral	0.01	0.7
			PPS GF	0.02	0.05
			PE GF	0.02	0.06
			PE 60% long GF	0.02	0.06
			PPS GF + Mineral	0.02	0.08
			LCP GF	0.02	0.1
			LCP Mineral	0.02	0.1
			PPS Far	0.02	0.2
TPV Shore D	0.02	0.2			
PVCC	0.02	0.3			
PVDF	0.03	0.06			
			PPS conductive	0.03	0.07
ETFE	0.03	0.1			
			ETFE GF	0.03	0.1
			LCP CF	0.03	0.1
			PVDF friction	0.04	0.04

Continued

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	Minimum	Maximum	Thermoplastic	Minimum	Maximum
			PVDF Mica	0.04	0.04
			PPS long GF medium level	0.04	0.05
			PPS long GF high level	0.04	0.05
			PPS CF	0.04	0.05
			PPS CF+GF	0.04	0.05
PVC unplasticized	0.04	0.4			
PVF	0.05	0.05			
PPE	0.05	0.12			
EVA	0.05	0.2			
			PBT long CF	0.05	0.2
			PBT CF	0.05	0.2
			PC CF	0.05	0.2
PP recycled	0.05	0.3			
PS impact	0.05	0.3			
			PC GF	0.05	0.4
			PPE CF	0.06	0.1
			PPE Mineral	0.06	0.12
			PBT medium level GB	0.06	0.3
			PPE GF	0.06	0.3
			PEEK GF	0.06	0.4
			PEEK CF	0.06	0.4
			PAEK 30% GF	0.06	0.4
PET/PC	0.06	0.5			
			PS GF	0.07	0.3
			PTT Bio GF	0.08	0.4
PVDC	0.1	0.1			
			PMP Mineral	0.1	0.15
			ABS CF	0.1	0.2
ASA/PVC	0.1	0.2			
PET Amorphous	0.1	0.2			
			PSU/PBT GF	0.1	0.2
			PA 6-10 CF	0.1	0.3

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	Minimum	Maximum	Thermoplastic	Minimum	Maximum
			PAI GF	0.1	0.3
			PBT medium-level GF	0.1	0.3
PC	0.1	0.3			
			PC CNT	0.1	0.3
			PEI CF	0.1	0.3
			PI TP friction	0.1	0.3
			SAN GF	0.1	0.3
SMA	0.1	0.3			
			SMA GF	0.1	0.3
PAI	0.1	0.33			
			ASA/PBT GF	0.1	0.4
			PAI friction	0.1	0.4
			PAI Mineral	0.1	0.4
			PBT long GF	0.1	0.4
			PC friction	0.1	0.4
PC/PBT	0.1	0.4			
			PC/PBT GF	0.1	0.4
			PC/SAN GF	0.1	0.4
			PET/PC GF	0.1	0.4
			PPA Mineral	0.1	0.4
			ABS GF	0.1	0.5
			ABS GB	0.1	0.5
PEEK	0.1	0.5			
			PAI CF	0.1	0.5
PBT	0.1	0.5			
			PBT GF & Mineral	0.1	0.5
			PEI GF milled	0.1	0.5
			PEI GF	0.1	0.5
			PET/PBT high-level GF	0.1	0.5
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	0.1	0.6			

Continued

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	Minimum	Maximum	Thermoplastic	Minimum	Maximum
			PET GF	0.1	0.6
			PLA/PBT GF	0.1	0.6
			PLA/PP 30% GF	0.1	0.6
PMMA	0.1	0.6			
			POM GB	0.1	0.6
			ABS/PA 20 GF	0.1	0.7
			PSU GF	0.1	0.7
ABS	0.1	0.8			
			ABS conductive	0.1	0.8
			ABS FR	0.1	0.8
PET	0.1	0.8			
PLA	0.1	0.8			
			PCT GF	0.1	0.9
POM homo- or copolymer	0.1	1			
			POM conductive	0.1	1
SMMA	0.1	1			
ABS/PA	0.1	1.1			
PES	0.1	2.2			
			PAA high-level GF	0.1	3.5
SAN	0.15	0.3			
ABS/PC	0.15	0.7			
PVC plasticized	0.15	1			
PSU/PC	0.2	0.2			
			ABS/PC medium-level long GF	0.2	0.3
			ABS/PC conductive	0.2	0.3
			ABS/PC GF	0.2	0.3
ABS/PVC	0.2	0.3			
PEI	0.2	0.3			
			PEI Mineral	0.2	0.3
			PMMA GF	0.2	0.3

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	Minimum	Maximum	Thermoplastic	Minimum	Maximum
			Polyarylate GF	0.2	0.3
			PPA GF	0.2	0.3
			PPA long GF	0.2	0.3
			PPA CF	0.2	0.3
PSU/ABS	0.2	0.3			
			ABS/PC low-level long GF	0.2	0.4
Acrylique imide	0.2	0.4			
ASA/PC	0.2	0.4			
			PI TP CF	0.2	0.4
			PI TP GF	0.2	0.4
ASA/PMMA	0.2	0.5			
			PEI conductive	0.2	0.5
			POM Far	0.2	0.5
PSU modified	0.2	0.5			
			POM GF	0.2	0.6
			POM long GF	0.2	0.6
			POM CF	0.2	0.6
			PSU Mineral	0.2	0.7
PMMA impact	0.2	0.8			
			POM friction	0.2	0.9
			POM Mineral	0.2	0.9
PI TP	0.2	1			
PSU	0.2	1.1			
ASA	0.2	1.2			
			PES friction	0.2	1.5
PA 6-12	0.2	1.6			
			PES GF	0.2	1.6
			PES CF	0.2	1.7
			PA castable friction	0.2	2
COPE high Shore D	0.2	2.5			
			PAA medium-level GF	0.2	4.5

Continued

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
	Water Uptake, %			Water Uptake, %	
Thermoplastic	**Minimum**	**Maximum**	**Thermoplastic**	**Minimum**	**Maximum**
PMI or PMMI	0.2	6			
COPE low Shore D	0.2	7			
COPE Bio	0.2	7			
			PEEK/PBI GF	0.24	2
Polyarylate	0.25	0.3			
PA 12	0.25	1.5			
PA 11	0.25	2			
			PK GF	0.3	0.5
PPE/PA	0.3	0.5			
MABS	0.3	0.7			
			PPE/PA GF	0.3	1
			PPSU GF	0.3	1
			PA 66 high-level long GF	0.3	1.2
			PAA Mineral	0.3	1.4
			PA 12 GF	0.3	1.5
			PA 12 conductive	0.3	1.5
			PA 12 friction	0.3	1.5
PA castable	0.3	2			
PEEK/PBI	0.3	2			
			PEEK/PBI CF	0.3	2
PPSU	0.37	1			
PBI	0.4	0.4			
			PA 12 GB	0.4	0.8
			PA 11 GF	0.4	1.4
			PA 66 CF	0.4	1.6
PA 6-10	0.4	1.7			
			PA 66 conductive	0.4	1.8
PA Transparent	0.4	4.8			
PK	0.45	0.5			
			PP/PA GF	0.5	0.8
PPA	0.5	1			
PA 11 or 12 plasticized	0.5	1.5			

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
Thermoplastic	Water Uptake, % Minimum	Water Uptake, % Maximum	Thermoplastic	Water Uptake, % Minimum	Water Uptake, % Maximum
			PA 6-12 GF	0.5	1.8
			PLA natural reinforcement	0.5	2
PP/PA	0.5	3			
			PAA medium-level CF	0.5	5
			PP natural fibers	0.6	0.9
			PA Far	0.6	1
			PA 12 CF	0.6	1.2
			PA 66 high-level GF	0.6	1.4
			PA 66 medium-level GF	0.6	1.8
			PA 10-10 high-level GF Bio	0.6	2
			PA 66 impact medium-level GF	0.6	2
			PA 6 medium-level long GF	0.65	1.1
			PA 6 high-level long GF	0.65	1.1
PA 6	0.7	2.9			
PEBA Bio	0.7	3			
			PA 66 medium-level long GF	0.8	1.1
			PA 66 Mineral	0.8	1.2
			PA 66 GB	0.8	1.5
			PA 6 mineral FR	0.8	1.6
			PA 66 long CF	0.8	1.6
			PA 6 medium-level GF	0.8	1.9
PA 66	0.8	3			
CAB	0.9	2.2			
PEBA 50 to 72 Shore D	0.9	6			
			PA 6 high-level GF	1	1.5
PA 10-10 Bio	1	2			
			PA 6 GB	1	2.2
			PA 4-6 GF	1	2.6
			PA 4-6 Mineral	1	3

Continued

Table 9.7 Examples of Water Uptake, %—cont'd

Expected Neat Grades			Special Grades		
Thermoplastic	Water Uptake, %		Thermoplastic	Water Uptake, %	
	Minimum	Maximum		Minimum	Maximum
PEBA 25 to 45 Shore D	1	6			
			PA 6 GF recycled	1.1	1.9
			PA CNT	1.2	1.9
CP	1.2	3			
			PA 4-10 GF Bio	1.5	2.6
			PA 6 FR	1.6	2.5
PA 6 recycled	1.6	2.9			
CA	1.9	7			
			PA 4-6	2.3	3.7

Table 9.8 Water Uptake Examples for a Given Polyamide Filled with Increasing Glass Fiber Contents

Glass Fiber Content, %	Absorption (%) by Immersion in Hot Water
0	2
10	1.7
20	1.5
30	1.1
40	0.9
50	0.8

- VOCs include various tiny solid or liquid particulates such as soot, dust, fumes, or mist. Dust can penetrate a person's lungs and pose health hazard. Asbestos is a well-known example.

Generally, if possible, choose low-volatile additives with high boiling temperatures and reactive additives linked to the polymer macromolecules after processing.

9.6 Some Other Causes of Dimensional Variations

Don't forget that a uniaxial (or biaxial) stress impacts not only the size of a part according to the axis of the stress but also the sizes according to the other axes of the part.

9.6.1 Interactions between Loaded and Unloaded Axes

Usually, when an isotropic thermoplastic is stretched in one direction, it usually tends to shrink in the other directions perpendicular or parallel to the direction of flow.

Usually, when an isotropic thermoplastic is compressed in one direction, it usually tends to expand in the other directions perpendicular or parallel to the direction of flow.

The ratio of lateral strain and axial strain is defined as Poisson's ratio ν.

The bulk modulus (K or B) of a substance measures the substance resistance to isostatic compression. It is the ratio of the infinitesimal pressure increase to the resulting relative decrease of the volume. The bulk modulus can be formally defined by the equation:

$$K = -V * dP/dV$$

For ideal isotropic and elastic materials, modulus of elasticity E, bulk modulus (K or B), and Poisson's ratio (ν) are linked by the following equation:

$$K = E/(3*(1-2\nu))$$

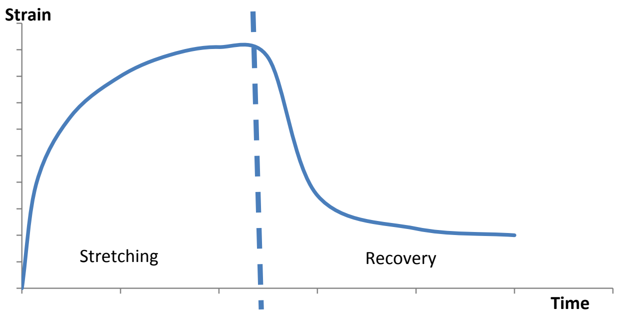

Figure 9.4 Extension and recovery.

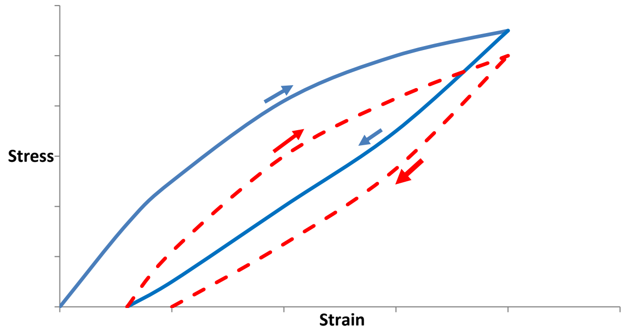

Figure 9.5 Hysteresis loops.

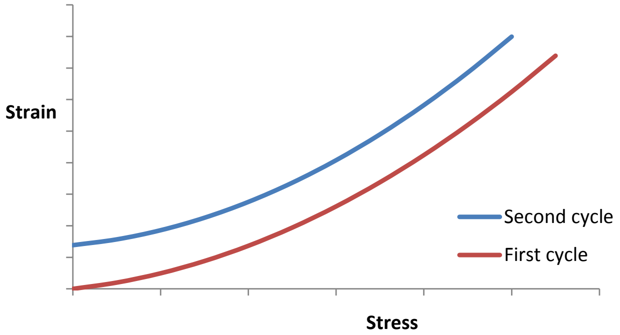

Figure 9.6 Strain versus stress for first and second loading cycles.

9.6.2 Strain Recovery, Permanent Set

Figure 9.4 shows a strain versus time graph divided into two steps:

- First: a force applied to the tested material leads to a size increase during the loading phase (other curve shapes can be observed depending on the rate of deformation).
- Secondly: the stress is removed leading to a strain decrease during the recovery phase.

Over time, the material returns to its original configuration if the strain reached during the first step is inferior to the elastic limit. If not, there is a permanent set.

9.6.3 Relaxation of Residual Stresses: Annealing

Since most plastics have low thermal conductivity, any uneven or rapid heating and cooling during molding, extrusion, forming, cutting, drilling, and machining can result in internal stresses.

Residual stresses can lead to poorer mechanical performance, dimensional changes (warping, twisting, or other), cracking and crazing, poorer chemical resistance. Of course, sensitivity depends on the nature of the used plastic and its recipe.

To avoid this phenomenon, the fundamental solution is to adopt proper design and processing. In other cases, an annealing treatment can lower or suppress residual stresses thanks to a slow heating followed by a slow cooling. Temperatures and time depend on the type of plastic and the shape of the part, notably its thickness. Generally, the annealing process includes a slow heating just below the softening point, a stage at this temperature for a given period of time, and then a very slow cooling down to room temperature.

Mechanical and chemical properties, impact behavior, crystallinity for semicrystalline plastics can be modified.

9.6.4 Mechanical Hysteresis: Decrease in Stress for a Defined Strain

During loops of dynamic loading/unloading, more or less mechanical energy is converted into heat by internal friction leading to two consequences (see Figure 9.5):

- During a given cycle of loading/unloading, the stress versus the strain is lower during the unloading step.
- During two successive cycles of loading/unloading, stresses for the second loop are inferior to those of the first cycle (see Figure 9.5).

Of course, as we can see in Figure 9.6, for two successive loading cycles, strain for a defined stress increases for the second cycle versus the first cycle, which leads to a higher dimensional variation.

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil,org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Omnexus, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, Specialchem, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Trexel, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

10 Advanced Mechanical Properties

OUTLINE

Most properties of thermoplastics are temperature-dependent including mechanical, physical, electrical, chemical, and aging characteristics among others. Many properties are also time dependent such as creep, relaxation, fatigue etc.

Glass transition temperature, heat deflection temperature, continuous use temperatures (CUTs), and minimum service temperatures are reported in Chapter 8.

The current chapter focuses on temperature and time effects on a limited number of short- and long-term mechanical properties. This fragmented information does not cover all other properties and cases.

Of course, following data are only examples providing a rough idea of the significant differences between subfamilies but other data can be found elsewhere. For a same trade name and for identical conditions, published data related to a given property can be very different. Of course, these theoretical data cannot be used for designing, computing, or to make economic predictions. Only properties measured on the actual used compound must be considered.

10.1 Thermal Dependency of Mechanical Properties

Formerly, from an engineering point of view, we must remark that thermal behavior isn't an intrinsic property of a compound but depends on numerous parameters including among others, the shape of the part, the processing conditions, and the general history of the part.

A temperature rise causes two different phenomena:

- Immediate physical effects, generally: decay of the modulus and other mechanical and physical properties (apart from strain that increases), physicochemical softening, reversible thermal expansion and, eventually, irreversible shrinkage and warpage. After a return to the room temperature, modulus and other mechanical properties recover their initial values.
- Long-term effects: irreversible creep and relaxation for stressed parts, irreversible chemical aging and related degradation of the material with decrease in mechanical properties, even after a return to the room temperature.

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00010-6

Generally, a temperature drop causes opposite effects. Very low temperatures, notably cryogenic ones can have some surprising effects.

10.1.1 Short-term Heat Effect

In the following, property retentions are ratios:

(property at temperature t divided by property at 20 °C) expressed in %. Property retentions are lower than 100% if the property decreases but may be higher than 100% if the property increases.

Decrease of performance when temperature rises depends on:

- The considered property: stress at yield or at break, modulus, elongation at break…Generally, for a same compound there isn't correlation between stress, modulus, and elongation variations as we can see in Figure 10.1. Tensile strength decreases when elongation at break increases.
- The loading mode: tensile, flexion, compression, shear etc.
- The used plastic and more precisely the recipe: see Figure 10.2 showing examples of tensile stress (TS) retentions for 3 grades of the same polymer
- The test conditions: short term is a fuzzy expression.

For a same property, evolution of retention versus temperature can obey to very diversified scenarios as shown in Figure 10.3 relating to modulus.

10.1.1.1 Behavior above Room Temperature

Table 10.1 for high-performance thermoplastics and Table 10.2 for engineering and commodity thermoplastics display strength retentions approximately ranked in a descending order.

In all likelihood, PBI offers the highest retentions of TS or stress at yield with a 50% level and more at 300 °C.

At the opposite, plasticized PVC presents 50% retention at temperature as low as 60 °C.

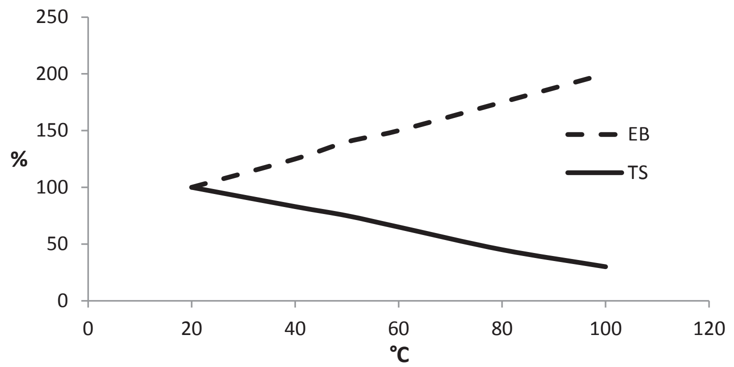

Figure 10.1 Examples of elongation at break and tensile strength retentions for a same compound.

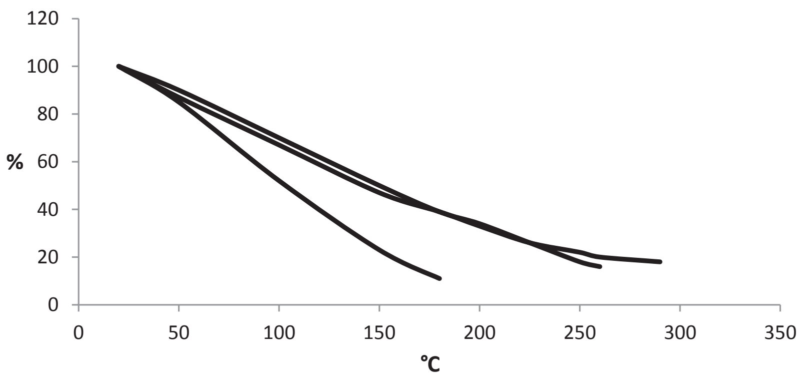

Figure 10.2 Examples of tensile stress retentions for 3 grades of the same polymer.

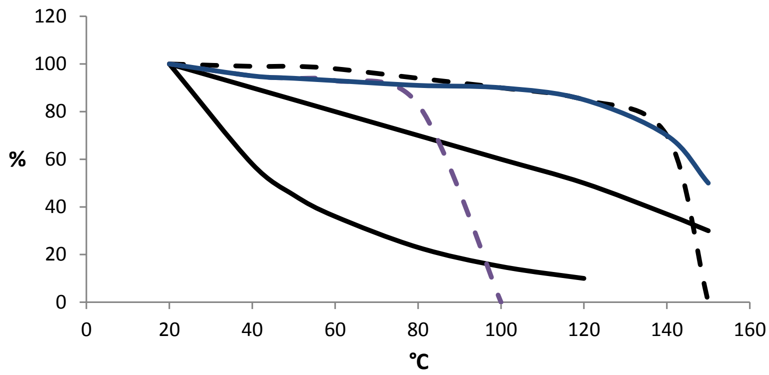

Figure 10.3 Examples of curves for modulus retention.

Please note the broad range of values for same compound.

Table 10.3 displays examples of modulus retentions approximately ranked in descending order.

Please note the broad range of values for same compound.

Table 10.4 displays examples of elongation at break retentions approximately ranked in ascending order. On the contrary of previous properties, elongation at break increases when the temperature rises.

10.1.1.2 Behavior below Room Temperature

(See also Chapter 8.4.1 "Expected Minimum Service Temperatures") and Chapter 8.4.2 for Low-temperature impact tests.

Table 10.5 displays examples of mechanical property retentions versus subzero temperatures.

10.1.2 Long-term Heat Effect on Oxidizing Aging

Please see also:

- Chapters 5.6 and 5.7 for sudden variations of kinetics and modeling
- Chapter 8.3.2 General assessments concerning Continuous use temperature (CUT—Table 8.4) and Relative Temperature Index (Table 8.6)

Long-term resistance assessments related to heat aging result from conventional accelerated aging tests in air and predictions by modeling.

Conventional accelerated aging tests consist in exposing defined samples to controlled-temperature air in ovens protected from light, ozone, and chemicals, during one or more given times. The degradation is measured by the variation at room temperature (RT) of one or several physical or mechanical characteristics during the aging. The variations of impact resistance, hardness, tensile, or flexural strength and color are the most frequently studied. Electrical properties, fire behavior, weight, and other characteristics may be also tested according to the targeted application. Sometimes, properties are measured at the aging temperature, which is a more severe method.

Accelerated aging is an arbitrary measurement that must be interpreted and must constitute only one of the elements used in making a judgment:

- All the properties do not degrade at the same rate.
- It is impossible to establish a direct relationship between the accelerated aging of a part and its real life span.
- For an unknown polymer, the results of accelerated aging must be compared with those obtained on a known polymer of a very similar formula.

Be careful on the accelerated aging conditions: More severe conditions can activate chemical reactions different of those observed at service conditions, which can lead to false predictions. For example, degradation at 150 °C of commodity plastics is not of the same nature as the degradation at RT.

For long life-time prediction, testing in actual conditions is not useable and it is necessary to run accelerated testing in more severe conditions and use mathematical models to predict the lifetime in actual conditions. It must be pointed out that kinetics may

Table 10.1 Examples of Strength and Stress Retentions for High-Performance Thermoplastics

		Temperature, °C										
		20	**50**	**100**	**150**	**180**	**200**	**225**	**250**	**300**	**350**	**400**
		Retentions, %										
PBI	TS	100	102	103	99	95	91		80	65	45	25
PAI GF	Flex strength	100	97	87	72	63	58	51				
PAI CF	Flex strength	100	97	85	70	60	56	48				
PAI CF	Flex strength	100			77			62	57			
PAI neat	Flex strength	100	97	86	72	59	55	47				
PAI neat	Strength	100			48	40	35					
PPS	TS	100	89	75	60	49	40					
PPS	TS	100			36–68		24–35					
PES	TS	100	94	82	65	47	35					
PEI CF	TS	100	90	72	55	47						
PEI neat	TS	100	82	59	41	35						
LCP mineral	TS	100	90	70	50	41	34	26	10–18			
LCP mineral	TS	100	87	67	47	39	34	26	22			
LCP mineral	TS	100	85	52	23	11						
LCP GF	TS	100	90	85	78	53	38	27	15			
PTFE	TS	100	76	47	34	32	31	29	28			
PEEK CF	TS	100	90	66	42	28	23	21	20			
PEEK CF	TS	100							30			
PEEK neat	TS	100	82	52	26	13	12		12			
PEEK neat	TS	100			39				15			
ECTFE	TS	100	82	57	11							

Table 10.2 Examples of Strength and Stress Retentions for Engineering and Commodity Thermoplastics

		Temperature, °C								
		20	**40**	**50**	**60**	**80**	**100**	**120**	**150**	**175**
		Retention, %								
PES	TS						82		65	
PSU	Strength						74		53	
PC	TS						85			
POM GF	TS					81		49		
POM	Stress yield	100	87	80	74	63	52	38		
POM antifriction	Stress yield	100	86	78	72	61	48	36		
PA12 neat	TS	100	86	82	78	63	48			
PA12 GF	TS	100	81	77	74	70	67			
PA12 GB	TS	100	80	72	66	55	44			
PA6 GF dry	TS	100				57	55	44		
PA6 dry	TS	100				44		27		
PBT GF	Stress yield	100	76	68	61	52	46	41	36	33
PBT neat	Stress yield	100	71	62	55	44	37	33		
ETFE	TS	100	69	60	50	45	40	10–35	25	18
PVDF	Stress at yield	100	88	81	74	56	37	24	12	
PVF	TS	100	83	75	65	45	30			
ABS	Stress yield	100				42				
HDPE	Stress yield	100	79	70	59	39	20	12		
PMP	Stress yield	100	80	66	54	36	33	18	12	
PMMA	TS	100	80		55	32				
PVC	TS	100	81	69	56	31				
PVC plasticized	TS	100			50					

Table 10.3 Examples of Modulus Retentions versus Temperature

		Temperature, °C									
		20	40	50	60	80	100	120	140	150	200
		Retention, %									
PBI	Modulus	100									75
PAI CF	Modulus	100								88	83
PAI	Modulus	100								77	67
PPS	Modulus	100									30–60
PPS	Modulus	100					60			35	
PES	Modulus	100					95			90	55
PSU	Modulus	100					95			90	
PEEK high temperature	Modulus	100								75	
PEEK	Modulus	100								68	15
PEI	Modulus	100		91			71–90			35–82	
PC GF	Modulus	100	99	99	98	94	90	85	80	0	
PC neat	Modulus	100	98	96	95	92	90	86	82	0	
PPE GF	Modulus	100	97	95	92	88	84				
PPE GF	Modulus	100					75				
PPE neat	Modulus	100	94	91	87	80	73				
PPE neat	Modulus	100					65				
COC	Modulus	100	95	94	93	83	0				
COC	Modulus	100	95	94	93	87	80	50	0		
COC	Modulus	100	95	94	93	91	90	85	70	50	
PA6 GF	Modulus	100	93	89	85	78	70	62	54	50	

PA6 GF	Modulus	100	90	85	80	70	60	50	37	30	
PA6	Modulus	100	83	73	64	48					
PA6 GF	Modulus	100								65	
PA6 GF	Modulus	100								50	
PA6	Modulus	100								25	
PA6 GF dry	Modulus	100				43		38			
PA6 dry	Modulus	100				19		13			
PA46 GF	Modulus	100						49			
PA46 mineral	Modulus	100						31			
PA46	Modulus	100						24			
POM GF	Modulus	100					36				
POM	Modulus	100					23				
HIPS	Modulus	100	85	80	75	68					
HIPS	Modulus	100	93	91.5	90	88	86				
ABS	Modulus	100	92	86	79	62.5					
SAN	Modulus	100	95	89.5	84	71					
LCP	Shear modulus	100	84	73	64	48	31	23	19	18	
PTFE	Modulus	100	70	61	52	42	36	30	27	25	
PMP	Modulus	100	75	67	58	46	36	28			
PMMA	Modulus	100	86		66	32					
ECTFE	Modulus	100	80	70	60	40	18				
ETFE	Modulus	100					11			10–20	
LDPE	Modulus	100				40					
PP	Modulus	100	58	49	36	23	15	10			

change during long-term tests in steady conditions. For example, aging kinetics can suddenly evolve with abrupt changes, thresholds, knees or sudden failure, crossing of glass transition, and so on. Generally speaking, it must be noticed that a mathematical model is an equation giving a result in all cases. In real life, results can be completely different and the part may fail when the model predict a longer life. Conversely real life may be longer. The user must be aware of those risks. So, certain predictions can be disastrous leading to completely false estimations. In the optimistic cases, modeling can save time and money by reducing trials and property testing. The mathematical laws binding the effect of one property and a parameter such as time suppose that the property continuously evolves without abrupt changes. These laws cannot predict thresholds or knees or sudden failures and so on. These phenomena must be specifically modeled from specific studies analyzed with specific models.

Table 10.4 Examples of Elongation at Break Retentions versus Temperature

		Temperature, °C						
		20	**50**	**80**	**100**	**150**	**180**	**200**
		Retention, %						
LCP	EB	100						
ETFE	EB	100	135	157	170	193	198	200
PVF	EB	100	140	175	200			
PVC	**EB**	**100**	**158**	**194**				

Table 10.5 Examples of Mechanical Property Retentions versus Subzero Temperatures

		Temperature, °C			
		–50	**–40**	**0**	**20**
		Retention, %			
ABS	Stress yield		140		100
PA6 GF dry	TS		149		100
PA6 dry	Modulus		104		100
PA6 dry	TS		152		100
PMP neat	Stress yield			170	100
POM GF	TS		132		100
POM GP	Stress yield	146		110	100
POM antifriction	Stress yield	154		115	100
PTFE	TS			118	100
PTFE	Modulus	182		132	100
PPE GF	Modulus			106	100
PPE neat	Modulus			108	100
LCP GF	EB		62	88	100

For broad ranges of temperatures, contrary to widespread expectations, an approach according to Arrhenius can lead to distorted life-time predictions. The Arrhenius relation can yield a good fit for amorphous polymers but for semicrystalline materials, such as polybutylene terephthalate (PBT), this approach needs to be deeply examined when the material is tested above and below its glass transition temperature (Tg). The temperature interpolation required, at minimum, two tests above and two tests below Tg allowing to compute two different Arrhenius equation with different slopes.

For a PBT grade with a Tg of 50 °C, Figure 10.4 shows LN(TS) versus 1000/T: we can remark two different kinetics (bold lines) and the related trend lines (thin lines) intersecting approximately for 50 °C.

Another widespread statement relates to the doubling of degradation for each increase of 10 °C of the temperature that is to say a constant acceleration factor of 2. The following values of factor F, see Table 10.6, for a given polypropylene (PP) grade, vary from around 1.5 up to around 2.9. In the real world, the acceleration factor depends on the temperature and must be defined for each temperature.

For a series of compounds based on a same polymer, the following parameters influence the aging behavior significantly:

- Used additives, notably stabilizers and other antioxidants
- Alloying with other copolymer(s): ABS, for example

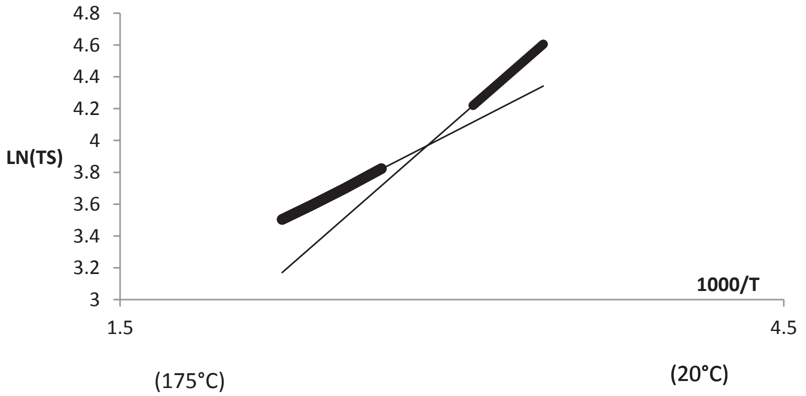

Figure 10.4 Arrhenius plot for a polybutylene terephthalate with a Tg of 50 °C (1000/T = ~3).

Table 10.6 Example of a Polypropylene-Grade Degradation: Acceleration Factors for Gaps of Temperature of 10 °C

Service Temperature, °C \ Aging Temperature, °C	70	80	90	100	110	120	130	140	150
60	2.9								
70		2.8							
80			2.7						
90				2.7					
100					2.5				
110						2.3			
120							2.3		
130								2	
140									1.5

- Sample thickness
- Checked property: elongation at break, impact, yellowing are often very sensitive
- In the real life, shape of the actual part…

Table 10.7 displays some examples of property retentions ranked by temperature and time in descending order. Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary
- Reinforcement, plasticization, impact modification etc., aren't always pointed out
- The lack of data for a defined temperature and/or time isn't an indication of unsuitability but is due to the unsuccessful research of data.
- A defined compound or family can be found in several lines because property, temperatures, and/or times are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be interpreted as an indication of the expected service life for any targeted application.

10.2 Time-Dependent Mechanical Properties

Due to their structure, thermoplastics have a viscoelastic behavior leading to time-dependent mechanical properties, particularly creep and stress relaxation. Some facets of this issue have been brought to mind in previous Chapters 1, 2, and 5.

10.2.1 Creep

Creep is the time-dependent strain induced by a constant mechanical loading. The strain is a function of the stress level, the loading time, and the temperature. The results can be presented graphically in various ways by combining these three parameters or in quantified forms: creep modulus and creep strength, for example.

The creep modulus for a specified stress, time, and temperature is the value of the stress divided by the strain measured after the selected time.

The creep strength for a specified time and temperature is the value of the stress leading to failure after the time under consideration.

Figure 10.5(a–d) show some aspects of creep for PP and polyethylene:

- (a) and (b) are the same strain results plotted against arithmetic(a) or logarithmic (b) scales for time
- (c) shows examples of creep strain according to the load level
- (d) shows examples of creep strength at 100, 10,000, and more than 20,000 h according to the temperature. It is not comparable with (a), (b), and (c).

Creep modulus values are broadly inferior to their counterparts measured by dynamometry as we can see on Table 10.8 displaying some examples of engineering modulus (EM in MPa), creep modulus at 1 and 1000 h (CM1 and CM1000 in MPa), ratios (CM1/EM) and (CM1000/EM), %) Data are ranked by descending order of (CM1000/EM) ratio. It should be noted that the creep modulus after 1000 h can be half of the engineering modulus for less than 42 days (1000 h), which is a short duration for usual applications.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary.
- Reinforcement, plasticization, impact modification etc., aren't always pointed out.
- PA may be conditioned, dry as molded, or in unknown state.
- The lack of data for a defined time or a defined load isn't an indication of unsuitability but is due to the unsuccessful research of data.
- A defined family can be found in several lines because grades and/or loads are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of the expected service life for any targeted application.

Table 10.7 Examples of Property Retentions versus Temperature and Time

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
370	500	PBI	Compressive strength	~40	
370	500	PBI	Weight	~45	
315	500	PBI	Compressive strength	~90	
315	500	PBI	Weight	~90	
310	430	PEEK	TS	50	
310	240	PEEK	EB	50	
270	3000	LCP	TS	60	
270	3000	LCP	Impact	30	
260	20,000	PFA	EB	50	
260	20,000	PTFE	EB	50	
260	10,000	PAI	TS	67	
260	4400	PAI	TS	83	
260	1500	PAI	TS	104	
260	500	PBI	Compressive strength	~100	
260	500	PBI	Weight	~100	
250	19,000	PEEK	TS	50	
230	168	ETFE	TS	90	
230	168	ETFE	EB	90	
230	168	ETFE	Dielectric strength	90	
220	20,000	LCP GF	Mechanical and electrical	50	
220	20,000	PAI	Mechanical and electrical	50	
220	20,000	PEEK	Mechanical and electrical	50	
220	17,000	PES	TS	50	
220	8760	PES	TS	50	
210	3600	ETFE	TS	60	
210	3600	ETFE	EB	50	
210	3600	ETFE	Dielectric strength	25	
205	20,000	FEP	EB	50	
204	3000	LCP	TS	80	
204	3000	LCP	Impact	60	
200	43,800	PES	TS	50	
200	20,000	LCP GF	Mechanical and electrical	50	
200	20,000	PAI	Mechanical and electrical	50	

Continued

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
200	8760	PEEK	EB	50	
200	8760	PPS	TS	57	
200	8760	PPS	EB	50	
200	5760	ETFE	TS	50	
200	2000	PA6 OR 66 GF super heat stab	TS	95	
200	2000	PA6 OR 66 GF super heat stab	EB	50	
200	1800	ETFE	EB	50	
200	1700	PA6 OR 66 GF heat stabilized	TS	50	
181	8760	ECTFE	EB	50	
180	157,000	PES	TS	50	
180	96,000	PES	TS	50	
180	21,900	ETFE	TS	50	
180	20,000	PEEK	Mechanical and electrical	50	
180	5760	ETFE	EB	50	
180	1000	PBT GF	TS	50	
180	960	PBT	TS	~80	
180	960	PBT	TS	~30	
180	100	PA6 OR 66	TS	50	
180	100	PBT	TS	~100	
177	2000	PA6 OR 66 GF	TS	82	
175	17,500	ECTFE	EB	50	
175	1200	COPE polyesterester	TS, EB	50	
170	20,000	PEI	Mechanical and electrical	50	
170	5000	PA6 and 66 GF	TS at 170 °C		50–70 MPa
170	5000	PA6 and 66 GF	Modulus at 170 °C		3.5 GPa
170	2000	PBT GF	TS	50	
170	700	PA11 OR 12	TS	50	
170	400	PA11 OR 12	TS	50	
170	200	PA11 OR 12	TS	50	
169	43,800	ECTFE	EB	50	
165	87,600	ECTFE	EB	50	

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
165	24,000	PVDF	Yield stress	85	
165	24,000	PVDF	TS	100	
160	43,800	ETFE	TS	50	
160	20,000	PSU	Mechanical and electrical	50	
160	17,500	ETFE	EB	50	
160	10,500	PA11 OR 12	TS	50	
160	4500	PA11 OR 12	TS	50	
160	3000	PA6 OR 66	TS	50	
160	3000	PBT GF	TS	50	
160	700	PA11 OR 12	TS	50	
160	250	PA6 OR 66	TS	50	
160	150	PA6 OR 66	TS	50	
160	4	PA6 OR 66	TS	50	
155	20,000	PET 30 GF FR	Mechanical and electrical	50	
155	240	PA11 OR 12	EB	50	
150	10,000	PBT GF	TS	50	
150	5000	PA6 and 66 GF	TS at 150 °C		70–80 MPa
150	5000	PA6 and 66 GF	Modulus at 150 °C		4 GPa
150	5000	PA6 OR 66	Modulus at 150 °C		0.4 GPa
150	3000	LCP	TS	90	
150	3000	LCP	Impact	70	
150	1200	COPE polyesterester	TS, EB	50	
150	960	PVF	TS	50	
150	960	PVF	EB	25	
150	960	PVF	Impact	10	
149	2000	PA6 OR 66 GF	TS	95	
140	157,000	ETFE	TS	50	
140	43,800	ETFE	EB	50	
140	30,000	PA11 OR 12	TS	50	
140	20,000	PSU	Mechanical and electrical	50	
140	20,000	PBT GF	Mechanical and electrical	50	
140	20,000	PA66 GF	Mechanical and electrical	50	
140	20,000	PBT GF	TS	50	

Continued

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
140	13,000	PA11 OR 12	TS	50	
140	4500	PA11 OR 12	TS	50	
140	2500	PA11 OR 12	TS	50	
140	2000	PA11 OR 12	EB	50	
140	1500	PA11 OR 12	EB	50	
140	1000	PA6 OR 66	TS	50	
140	1000	PP, GF stabilized	TS	95–99	
140	1000	PP, GF stabilized	Modulus	98–113	
140	1000	PP, GF stabilized	EB	89–97	
140	900	PA6 OR 66	TS	50	
140	840	COPE	TS, EB	50	
140	800	PA11 OR 12	EB	50	
140	480	COPE	TS, EB	50	
140	30	PA6 OR 66	TS	50	
130	20,000	PBT GF	Mechanical and electrical	50	
130	20,000	PC	Mechanical and electrical	50	
130	20,000	LCP GF FR	Mechanical and electrical	50	
130	2400	PP, stabilized	Brittleness		Embrittlement
130	50	PP, unstabilized	Brittleness		Embrittlement
130	48	TPU	TS	50	
130	24	TPU	TS	50	
125	20,000	PA66 GF	Mechanical and electrical	50	
125	20,000	PC	Mechanical and electrical	50	
125	8760	PMP	TS	50	
125	1000	TPO-V	EB	88	
125	1000	TPO-V	TS	93	
121	2000	PA6 OR 66 GF	TS	105	
120	50,000	PA11 OR 12	TS	50	
120	48,000	PA6 OR 66 GF	TS	50	
120	48,000	PA6 OR 66 GF	TS	50	
120	36,000	PA6 OR 66 GF	TS	50	
120	24,000	PA6 OR 66 unreinforced	TS	50	

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
120	21,000	PA11 OR 12	TS	50	
120	20,000	PP mineral	Mechanical and electrical	50	
120	20,000	PC	Mechanical and electrical	50	
120	16,800	PA6 OR 66 unreinforced	TS	50	
120	10,000	PA11 OR 12	TS	50	
120	4800	PA6 OR 66 unreinforced	TS	50	
120	4300	COPE polyesterether	TS, EB	50	
120	3000	PA11 OR 12	EB	50	
120	500	TPO	TS	73	
120	500	TPO	EB	65	
120	400	PE, stabilized	EB	60–90	
120	400	PE, unstabilized	EB	40	
120	240	PE, stabilized	EB	80–100	
120	240	PE, unstabilized	EB	60	
120	216	TPU	TS	50	
120	24	TPU	TS	50	
115	20,000	PEI	Mechanical and electrical	50	
115	20,000	PP mineral	Mechanical and electrical	50	
110	20,000	PPE + PS, GF FR	Mechanical and electrical	50	
110	20,000	PVC	Mechanical and electrical	50	
110	20,000	PEBA	Mechanical and electrical	50	
110	2160	PEBA	EB	50	
110	480	TPU	TS	50	
110	48	TPU	TS	50	
105	20,000	POM	Mechanical and electrical	50	
105	20,000	PC	Mechanical and electrical.	50	
105	20,000	PPE + PS, GF FR	Mechanical and electrical	50	
105	20,000	PEI GF PTFE	Mechanical and electrical	50	
105	20,000	PPE + SEBS	Mechanical and electrical	50	
105	20,000	PVCC	Mechanical and electrical	50	
100	87,600	PMP	TS	50	
100	70,000	PA11 OR 12	TS	50	

Continued

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
100	50,000	PA11 OR 12	EB	50	
100	48,000	PA11 OR 12	EB	50	
100	43,800	PMP	TS	50	
100	43,800	SEBS	TS, EB	50	
100	30,000	PA11 OR 12	TS	50	
100	20,000	PA11 OR 12	EB	50	
100	20,000	PA6 OR 66	TS	50	
100	20,000	SEBS	TS, EB	50	
100	7200	PP, stabilized	Brittleness		Embrittlement
100	3500	PA6 OR 66	TS	50	
100	2500	PA6 OR 66	TS	50	
100	1000	PP/NBR-V	EB	84	
100	1000	PP/NBR-V	TS	147	
100	960	PP, unstabilized	Brittleness		Embrittlement
100	250	PA6 OR 66	TS	50	
100	200	PA11 OR 12 unstabilized	EB	50	
95	20,000	PPE+PS, GF FR	Mechanical and electrical	50	
95	20,000	PEBA	Mechanical and electrical	50	
90	16,800	ABS+PC	Yellowing degree		47
90	16,800	ASA	Impact	42	
90	16,800	ASA	Yellowing degree		8
90	16,800	ASA+PC	Impact	83	
90	16,800	ASA+PC	Yellowing degree		5
90	9240	ABS+PC	Impact	0	
90	8760	PB	Stress	40	
90	6720	ABS	Impact	5	
90	6720	ABS	Yellowing degree		70
90	6720	ABS+PC	Yellowing degree		20
90	6720	ASA	Yellowing degree		4
90	6720	ASA+PC	Yellowing degree		3
90	3500	ABS+PC	Impact	50	
90	2500	ABS	Impact	10	
85	48,000	TPU	EB	50	

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
85	43,800	SEBS	TS, EB	50	
85	43,000	TPE/PVC	TS	50	
85	35,000	SEBS	TS, EB	50	
85	26,000	TPU	TS	50	
85	26,000	COPE polyesterether	TS, EB	50	
85	21,600	TPE/PVC	EB	50	
85	20,000	POM	Mechanical and electrical	50	
85	20,000	ABS FR	Mechanical and electrical	50	
85	20,000	PVC	Mechanical and electrical	50	
85	20,000	COPE	Mechanical and electrical	50	
85	12,000	TPU	EB	50	
85	8000	SBS	TS, EB	50	
85	7200	TPU	TS	50	
85	1300	TPE/PVC	EB	50	
80	100,000	PA6 OR 66	TS	50	
80	30,000	PA6 OR 66	TS	50	
80	26,000	PEBA	EB	50	
80	20,000	PPE+PS, GF FR	Mechanical and electrical	50	
80	20,000	PC generic RTI	Mechanical and electrical	50	
80	10,000	PA6 OR 66	TS	50	
80	4000	PA6 OR 66	TS	50	
80	1000	PS	TS	83	
80	1000	PS	EB	70	
75	20,000	ABS FR	Mechanical and electrical	50	
70	438,000	PB	Stress	52	
70	43,800	SBS	TS, EB	50	
70	43,800	SEBS	TS, EB	50	
70	19,000	PP, stabilized	Brittleness		Embrittlement
70	8760	PB	Stress	63	
70	8000	SBS	TS, EB	50	
70	3600	PP, unstabilized	Brittleness		Embrittlement
60	438,000	PB	Stress	62	
60	8760	PB	Stress	73	

Continued

Table 10.7 Examples of Property Retentions versus Temperature and Time—cont'd

Temperature, °C	Time, h	Plastic	Property	Retention	Engineering Data
55	43,800	SBS	TS, EB	50	
55	26,300	SBS	TS, EB	50	
50	20,000	Acrylic/PVC FR	Mechanical and electrical	50	
50	20,000	PPE+PS, GF FR	Mechanical and electrical	50	
50	20,000	PS FR	Mechanical and electrical	50	
50	20,000	SMA	Mechanical and electrical	50	
50	20,000	PVC	Mechanical and electrical	50	
50	20,000	PVC GF	Mechanical and electrical	50	
50	20,000	COPE	Mechanical and electrical	50	
50	9600	PP, unstabilized	Brittleness		Embrittlement
50	8760	PB	Stress	80	
40	43,800	SBS	TS, EB	50	
20	450,000	PE100	Pipe standard		
20	450,000	PVC	Pipe standard		

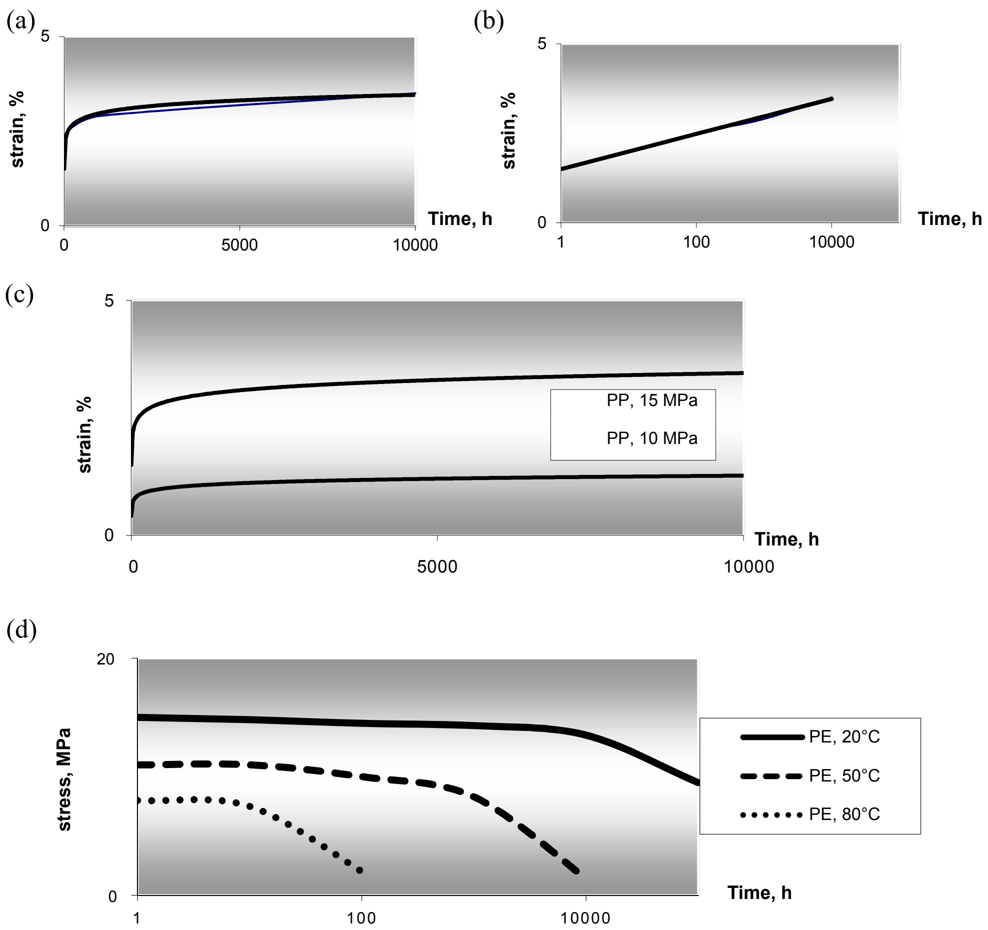

Figure 10.5 (a) Creep strain versus time: Example of polypropylene at 23 °C under 10 MPa in tensile loading. (b) Creep strain versus time: Example of polypropylene at 23 °C under 10 MPa in tensile loading. (c) Creep strain versus time: Example of polypropylene at 23 °C under 10 and 15 MPa in tensile loading. (d) Creep strength versus time: Example of polyethylene at 20 °C, 50 °C, and 80 °C.

Table 10.8 Examples of Engineering Modulus, Creep Modulus, (CM/EM) Ratios versus Time (1 and 1000 h)

Expected Neat Grades						Modified Grades					
	EM, MPa	**CM1, MPa**	**CM1000 MPa**	**(CM1/ EM), %**	**(CM1000/ EM), %**		**EM, MPa**	**CM1, MPa**	**CM1000 MPa**	**(CM1/ EM), %**	**(CM1000/ EM), %**
						PBT 30% GF	10,000	9800	8900	98	89
PSU	2480		2210		89						
PS	3300	3300	2600	100	79						
						PPE 20 GF	6500	6100	5150	94	79
						PEEK, reinforced	3500		3040		87
PC	2400	2200	1900	92	79						
SAN	3700	3500	2800	94	76						
PPE	2500	2300	1900	92	76						
						LCP 30 GF	15,000	12,600	10,900	84	73
						PEEK PTFE	3500		2500		71
						PBT 30% GF	9700		6700		69
						PPE 30 GF	9000	7100	6100	79	68
						PBT 30% GF	10,000	9000	6600	90	66
LCP	10,600	9000	6600	85	62						
ABS	2500	2200	1500	88	60						
ASA	2300	1850	1400	80	61						

Continued

Table 10.8 Examples of Engineering Modulus, Creep Modulus, (CM/EM) Ratios versus Time (1 and 1000 h)—cont'd

Expected Neat Grades						Modified Grades					
	EM, MPa	**CM1, MPa**	**CM1000 MPa**	**(CM1/ EM), %**	**(CM1000/ EM), %**		**EM, MPa**	**CM1, MPa**	**CM1000 MPa**	**(CM1/ EM), %**	**(CM1000/ EM), %**
PMMA impact	1700	1400	1000	82	59						
POM	2400	2000	1400	83	58						
PPE	2100	1700	1200	81	57						
						PA6 30 GF	5300		3000		57
						PA66 40 mineral conditioned	3800	3500	2100	92	55
PA12/PEBA	370		200		54						
PMMA	3100	2600	1600	84	52						
POM	2760	2450	1350	89	49						
PBT	2480	1800	1200	72	48						
PBT	2480		1200		48						
POM	2850	2500	1300	88	45						
PA66 conditioned	1600	1100	680	69	43						
						PA6 GF/mineral	5000	2800	1850	56	37
Mean				85.1	60.9					84.7	68.3

Compounds are diverse and creep moduli are broadly spread for given times and loads (see Table 10.9). For a given time, generally creep modulus decreases when the load increases.

Table 10.9 displays example of 15 compounds named "ABS" without any additional indication. Total creep modulus range evolves from 910 MPa up to 2520 MPa with an average value of 1624 MPa that is to say a deviation of −44% up to +55%. For a defined load of 14 MPa, total creep modulus range evolves from 1127 MPa up to 1988 MPa with an average value of 1600 MPa that is to say a deviation of −30% up to +24%. For a defined load and a defined time (100 h), total creep modulus range evolves from 1127 MPa up to 1715 MPa with an average value of 1468 MPa that is to say a deviation of −23% up to +17%.

Table 10.10 displays some examples of creep modulus (MPa) versus time at RT for various loads.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary.
- Reinforcement, plasticization, impact modification etc., aren't always pointed out.
- PA may be conditioned, dry as molded, or in unknown state.
- The lack of data for a defined time or a defined load isn't an indication of unsuitability but is due to the unsuccessful research of data.
- A defined family can be found in several lines because grades and/or loads are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of the expected service life for any targeted application.

Table 10.11 displays examples of creep modulus (MPa) versus time at various temperatures for

Table 10.9 Examples of Creep Modulus for 15 Compounds Named "ABS" Without Any Additional Indication

		Time, h			
	Load, MPa	1	10	100	1000
		Creep Modulus, MPa			
ABS	7	2520	2380	2100	1540
ABS	10.5	1610	1568	1477	1316
ABS	10.5	1988	1946	1841	1680
ABS	10.5	2450	2310	2030	1470
ABS	14	1512	1372	1127	
ABS	14	1610	1540	1400	
ABS	14	1974	1841	1631	1344
ABS	14	1988	1876	1715	1477
ABS	17.5	1561	1456	1260	
ABS	17.5	1946	1771	1512	1092
ABS	21	1267	952		
ABS	21	1477	1295	910	
ABS	21	1778	1568	1190	
ABS	21	1855	1638	1232	
ABS	24.5	1631	1155		

Table 10.10 Examples of Creep Modulus (MPa) versus Time at Room Temperature for Various Loads

		Time, h	**1**	**10**	**100**	**1000**
	Grade	**Load, MPa**	**Creep Modulus, MPa**			
PAI	Unknown	105	3400	2900	2500	
LCP	Unknown	80	10,200	9900	9600	9200
PA66	High GF	70		10,710	9450	9240
PAI	Unknown	70	4400	3700	3200	
PAEK		50	3400	3330	3225	3105
PES		50		2200	2010	1790
PEI	30% GF	49	8680	8680	8120	8120
PEI	20% GF	49	6650	6580	6160	5950
PEI	10% GF	49	4900	4900	4340	4200
PEI		49	3080	3010	2730	2660
PES		39		2360	2260	2160
PA66	CF	35		13,440	13,300	13,300
PA66	High GF	35		14,700	10,290	9695
PA66	CF	35		10,290	9310	9100
ETFE	30% GF	35		9660	9240	8820
PEI	30% GF	35	9240	9240	8540	8470
POM homo	40% GF	35		9240	8200	8050
PEI	20% GF	35	6860	6860	6510	6300
PPE	GF	35	6601	6601	6482	5495
ETFE	30% GF	35		5670	5320	5145
PEI	10% GF	35	5180	5180	4760	4480
PP	40% GF	35		5600	4550	3360
PA66	GF	35		5075	4200	3990
PP	20% GF	35	3710	3360	3220	2800
PEI		35	3360	3360	3010	2870
POM Co		35	2660	2380	1890	1540
PA66	Mineral	35	2450	1960	1400	1050
ABS	HR	35	1953	1659		
PPS	Unknown	30	15,200	15,000	13,500	
PPS	Unknown	30	9000	8900	8800	
PAEK		30	3658	3658	3658	3409
PES		30		2550	2410	2280
PVC		30	2600	2400	1950	

Table 10.10 Examples of Creep Modulus (MPa) versus Time at Room Temperature for Various Loads—cont'd

		Time, h	**1**	**10**	**100**	**1000**
	Grade	**Load, MPa**	**Creep Modulus, MPa**			
PES		29		2420	2370	2320
PA6 RH	Medium GF	28	4270	3780	3360	3010
PA6 dry	Low GF	28	3220	2835	2135	
ABS	HR	28	2156	1946	1610	
PA6 RH	Rather low GF	28	1960	1645	1400	1190
PA6 RH	Low GF	28	644	539	406	
PVC		25	2900	2700	2400	2200
ABS		24.5	1631	1155		
PET	GF	21	9800	9205	7770	5460
PSU		21		2450	2350	2200
PA6 dry		21	3150	2856	2324	
PA6 dry	Low GF	21	3220	2835	2240	
PPE		21	2415	2275	2177	1827
ABS	HR	21	2296	2135	1855	1519
ABS		21	1855	1638	1232	
ABS		21	1778	1568	1190	
ABS		21	1477	1295	910	
PA6 RH	Low GF	21	1078	931	749	
ECTFE		21	567	469	371	273
ABS		21	1267	952		
FEP		21	119	107		
SAN		20		3800	3000	2200
PES		20		2500	2400	2350
ASA		20		2200	1800	1400
PA66	CF	17.5		14,560	13,720	13,300
PA66	CF	17.5		12,460	10,010	9205
ETFE	30% GF	17.5		10,745	9660	8820
ABS		17.5	1946	1771	1512	1092
ABS		17.5	1561	1456	1260	
FEP		17.5	161	147	130	
PPE	GF	14	7910	7882	7875	7280
PET	GF	14	9590	9170	7700	6510
POM homo	30% GF	14		8050	5950	5530

Continued

Table 10.10 Examples of Creep Modulus (MPa) versus Time at Room Temperature for Various Loads—cont'd

		Time, h	**1**	**10**	**100**	**1000**
	Grade	**Load, MPa**	**Creep Modulus, MPa**			
POM homo	20% GF	14	6090	5460	4410	3430
PA66	GF, PTFE	14		6510	4200	3920
PA6 dry		14	3360	3094	2569	
PA6 dry	Low GF	14	3255	2905	2415	
PPE		14	2499	2450	2373	2058
ABS	HM	14	2380	2380	2240	2100
PE	20% GF	14		2415	2170	1820
PE	20% GF	14	2590	2380	2170	
ABS	HR	14	2310	2240	2100	1680
PA6 RH	Rather low GF	14	2660	2310	2030	1750
ABS	HR	14	2310	2261	2030	1708
ABS	FR	14	2100	2100	1890	1750
ABS	HI FR	14	2100	2100	1890	1680
PA6 dry		14	2352	2177	1841	
PA66	Mineral	14	3360	2380	1820	1260
ABS		14	1988	1876	1715	1477
PVC	Impact	14	2050	2000	1700	1260
ABS	HI	14	1890	1820	1680	1330
ABS	FR	14	2030	2030	1680	1190
ABS		14	1974	1841	1631	1344
ABS	HI	14	2100	1960	1610	1260
ABS		14	1610	1540	1400	
ABS	HI	14	1540	1470	1330	1050
ABS		14	1512	1372	1127	
PA6 RH	Low GF	14	1176	980	826	
ECTFE		14	931	819	707	581
PA6 RH		14	427	385	336	308
PTFE	GF	14	385	329	294	
PTFE	CF	14	350	292	266	
FEP		14	252	217	189	
POM homo	20% GF	10.5	6160	5250	4340	3500
PE	30% GF	10.5		3850	3290	2940
ABS		10.5	2450	2310	2030	1470

Table 10.10 Examples of Creep Modulus (MPa) versus Time at Room Temperature for Various Loads—cont'd

		Time, h	1	10	100	1000
	Grade	Load, MPa	Creep Modulus, MPa			
POM homo		10.5	2730	2660	1960	1680
ABS	HI	10.5	2100	2100	1890	1400
ABS		10.5	1988	1946	1841	1680
PVC	Impact	10.5	2100	2050	1750	1280
ABS		10.5	1610	1568	1477	1316
PA6 RH		10.5	868	714	595	483
FEP		10.5	210	130	65	
PBT	50% GF	10	14,000	13,700	13,000	12,200
PBT	30% GF	10	9400	9100	8700	7900
PC	20% GF	10	5516	5390	5285	5110
PAEK		10	4000	3921	3846	3703
PES		10		2820	2810	2770
PVC		10	3100	3000	2800	
PC		10	2415	2345	2240	2170
PBT	Neat	10	2500	2450	2200	1700
PS		10	2100	2100	1850	1350
PA12RH		10	840	679	546	434
HDPE		8.75	420	294	224	
HDPE		8.75	385	252	182	154
PP		8	571	444	320	140
POM homo	20% GF	7	6580	5810	4690	3780
PPE		7	2751	2744	2632	2338
PMMA		7		2870	2625	2394
PMMA		7		2800	2590	2380
PA66	Mineral	7	4025	3150	2520	1960
PS		7	2800	2800	2450	1800
ABS	HM	7	2380	2380	2310	2100
ABS		7	2520	2380	2100	1540
POM homo		7	2800	2520	2030	1750
PVC	Impact	7	2300	2200	1900	1250
ABS	HI	7	2170	2100	1890	1400
ABS	HM HR	7	2450	2310	1820	1400
ABS	FR	7	2030	2030	1750	1260

Continued

Table 10.10 Examples of Creep Modulus (MPa) versus Time at Room Temperature for Various Loads—cont'd

		Time, h	1	10	100	1000
	Grade	Load, MPa	Creep Modulus, MPa			
ABS	FR	7	1820	1820	1540	1050
ABS	HI	7	1540	1470	1400	1260
PA6 RH		7	868	777	672	532
PP		7	882	658	581	448
FEP		7	392	329	273	
HDPE		7	861	434	252	
PTFE		7	196	140	105	77
PP		6	666	500	387	187
PA12Dry		5	1225	1120	1036	959
PMP		5	1130	850	575	370
PTFE		4.55	329	273	224	175
PP		4	666	571	470	228
POM homo	20% GF	3.5	8540	7700	5600	4480
PE	30% GF	3.5		4865	4270	4165
POM Co		3.5	2660	2380	2170	1890
POM homo		3.5	2800	2590	2030	1750
ABS	HI	3.5	1680	1540	1540	1330
ETFE		3.5	1400	1169	945	875
PP homo		3.5	1043	805	707	532
PP Co		3.5	735	560	518	374
FEP		3.5	469	420	371	
FEP		3.5	336	315	287	
PTFE		3.5	434	350	280	220

various loads. Test temperatures are in a descending order. They range from 180 °C down to −50 °C.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary
- Type of loading isn't known: often data result from tensile creep tests but some others result from bending tests or others
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown
- Reinforcement, plasticization, impact modification etc., aren't always pointed out
- The lack of data for a defined time or a defined load isn't an indication of unsuitability but is due to the unsuccessful research of data.
- A defined family can be found in several lines because grades and/or loads are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Table 10.11 Examples of Creep Modulus (MPa) versus Time at Various Temperatures for Various Loads

			Time, h	1	10	100	1000
	Grade	Temperature, °C	Load, MPa	Creep Modulus, MPa			
LCP	Unknown	180	8	4000	3500	3000	2500
FEP		175	1.4	26	21	16	
FEP		175	0.7	32	28	24	
PAI	Unknown	150	70	3200	2500	1925	
PES	30 GF	150	62	6000	5400	4900	4500
PPS	40 GF	150	49	2800	2600	2520	2450
PES	30 GF	150	37	6150	5500	5000	4600
PSU		150	21		995	700	500
PES		150	20		2100	2000	1900
PAEK		150	20	1111	909	727	
PES		150	10		2200	2100	2000
PTFE		150	7	39	36	32	
PPS	Unknown	120	30	6800	5450	5260	
PA6	Medium GF	120	28	1890	1750	1470	1260
LCP	Unknown	120	20	6000	4500	3200	2200
PA6		120	7	490	420	385	315
PA6		120	4.9	560	490	455	
ECTFE		120	3.5	84	56	35	
PTFE		120	3.5	42	35	35	
ECTFE		120	1.4	119	91	63	
POM Co		110	7	504	434	385	315
POM Co		110	3.5	504	441	399	329
POM Co	25% GF	110	3.5	2275		1652	1302
PSU		100	21		1650	1450	1300
PAEK		100	20	2780	2564	2439	2272
LCP	Unknown	100	17	8400	7500	6400	5300
LCP	Unknown	100	17	8200	7400	6800	6200
ETFE	25% GF	100	14	2590	2030	1680	1540
POM homo		100	10.5	770	630	525	
POM homo		100	7	840	700	560	420
FEP		100	5.25	78.4	61.6	53.9	
POM homo		100	3.5	910	770	630	490

Continued

Table 10.11 Examples of Creep Modulus (MPa) versus Time at Various Temperatures for Various Loads—cont'd

			Time, h	1	10	100	1000
	Grade	Temperature, °C	Load, MPa	Creep Modulus, MPa			
FEP		100	3.5	93.1	73.5	62.3	
FEP		100	3.5	31.5	20.3	17.5	
FEP		100	1.4	119	94.5	78.4	
FEP		100	1.4	51.1	42	37.1	
COC		90	20	500	180	40	
COC		90	15	750	400	214	
POM homo	20% GF	90	14	2310	1750	1330	1120
COC		90	8.6	1800	720	430	
ABS	HR	90	7	980	497	385	280
ABS	HR	90	7	770	357	224	161
ABS	HR	90	7	700	308	203	133
PTFE		90	7	84	77	70	
PA6	Low GF	90	5.6	623	574	532	
ABS	HI	90	3.5	770	371	238	168
PTFE		90	3.5	105	84	70	
PEI	30% GF	80	35	8050	8050	6230	6020
PEI	20% GF	80	35	6090	5810	4690	4480
PEI	10% GF	80	35	4200	3920	2940	2800
PEI		80	35	2660	2520	2240	2030
POM homo	20% GF	80	22	3745		2870	2590
PEI	30% GF	80	21	8610	8540	7000	6510
PEI	20% GF	80	21	6650	6510	5110	4900
PEI	10% GF	80	21	4480	4130	3430	3150
PEI		80	21	2800	2730	2520	2450
POM homo		80	17.5	2100	1610	1260	
PA	Transparent	80	14	1974	1750	1463	1078
POM homo		80	14	1120	910	700	
POM homo		80	10.5	2310	2100	1680	1400
POM homo	20% GF	80	10.5	1120	980	770	525
PA12		80	9.8	252	245	210	189
POM homo		80	7	2660	2100	1540	1260
PA	Transparent	80	7	1995	1792	1526	1162
POM homo	20% GF	80	7	1190	980	770	560

Table 10.11 Examples of Creep Modulus (MPa) versus Time at Various Temperatures for Various Loads—cont'd

			Time, h	1	10	100	1000
	Grade	Temperature, °C	Load, MPa	Creep Modulus, MPa			
POM Co	25% GF	80	3.5	2870	2380	1820	1330
POM homo	20% GF	80	3.5	1260	1050	840	630
POM Co		80	3.5	700	616	539	476
POM Co	25% GF	80	3.5	3745		2870	2660
ABS	HR	70	10.5	1841	1421	945	525
PA6		70	10.5	714	581	490	
ABS	HR	70	7	1841	1631	1029	588
ABS	HR	70	7	1190	910	567	427
ABS	HI	70	7	910	658	399	273
ABS	HI	70	7	770	420	245	175
ABS	HR	70	3.5	1841	1750	1400	728
ABS	HI	70	3.5	770	441	252	182
ABS	HM FR	70	3.5	840	434	273	168
ABS	HI	70	3.5	700	413	252	168
ABS	HM	70	3.5	770	413	238	154
ABS	FR	70	3.5	644	364	210	140
ABS	HI FR	70	3.5	504	266	154	105
PSU		60	21		2250	2200	2050
PA6	Low GF	60	21	651	518	420	
PA6		60	21	231	196	168	
ASA		60	15		1000	600	400
POM homo	20% GF	60	14	2940	2240	1750	1330
ABS	HR	60	14	1680	1120	840	644
POM homo		60	14	1330	980	840	700
ABS	HI	60	14	1330	700	511	385
PA6	Low GF	60	14	714	616	560	
PA6		60	14	329	280	224	
ABS		60	10.5	1176	889		
ABS	HI	60	10.5	980	770	546	378
ABS	HI	60	10.5	1260	490	315	231
POM homo	20% GF	60	7	3710	3220	2450	1960
POM homo		60	7	1610	1330	1050	840
ABS		60	7	1197	952	532	

Continued

Table 10.11 Examples of Creep Modulus (MPa) versus Time at Various Temperatures for Various Loads—cont'd

			Time, h	1	10	100	1000
	Grade	Temperature, °C	Load, MPa	Creep Modulus, MPa			
ABS	HM HR	60	7	1330	910	630	490
PA6	Low GF	60	7	917	798	665	
ABS	HI	60	7	1050	770	581	406
ABS	HM FR	60	7	1190	686	441	301
ABS	FR	60	7	910	567	357	245
ABS	HI	60	7	840	546	364	259
ABS	FR	60	7	1050	469	266	189
ABS	HI FR	60	7	700	413	259	175
ECTFE		60	7	469	322	252	
PTFE		60	7	129	114		
POM homo	20% GF	60	3.5	4760	4130	2870	2100
POM homo		60	3.5	1680	1400	1050	840
ABS		60	3.5	1127	924	539	
ABS		60	3.5	1190	770	525	378
ABS	HM	60	3.5	1120	630	392	287
ABS	HI	60	3.5	1260	525	350	252
ABS	FR	60	3.5	770	504	336	245
ABS	FR	60	3.5	1050	483	294	196
PP homo		60	3.5	360	294	276	234
PTFE		60	3.5	217	182	105	
ABS	HR	50	14	1890	1750	1260	980
ABS	HI	50	14	1470	1330	840	616
POM homo		50	14	1680	1330	1120	840
ABS	FR	50	14	1610	1120	658	413
ABS	HM	50	10.5	2030	1540	980	581
POM homo		50	10.5	1750	1400	1120	910
ABS	FR	50	10.5	1540	1120	770	483
ABS	HI	50	10.5	1330	910	595	420
ABS	HI FR	50	10.5	1330	840	511	322
POM homo		50	7	1750	1400	1190	980
ABS	HM HR	50	7	1680	1330	980	770
ABS		50	7	1680	1190	840	602
ABS	HI	50	7	1330	1190	910	665

Table 10.11 Examples of Creep Modulus (MPa) versus Time at Various Temperatures for Various Loads—cont'd

			Time, h	1	10	100	1000
	Grade	Temperature, °C	Load, MPa	Creep Modulus, MPa			
ABS	FR	50	7	1610	1120	700	462
PMMA		50	3.5		1869	1617	1400
PMMA		50	3.5		1820	1540	1365
ABS	HM	50	3.5	2030	1610	1050	630
POM homo		50	3.5	1820	1470	1190	1050
ABS		50	3.5	1610	1190	840	581
ABS	HI	50	3.5	1330	1050	672	434
ABS	HI	50	3.5	1470	1050	700	525
ABS	FR	50	3.5	1260	840	560	392
PA6	Low GF	40	28	1435	1029	728	
PE	20% GF	40	14	1960	1750	1610	
PA6	Low GF	40	14	1505	1197	903	
PTFE		40	7	168	140	112	
PMMA		40	3.5		2212	1925	1680
PMMA		40	3.5		2170	1890	1645
PTFE		40	3.5	413	329	280	
FEP		–50	21	392	336	259	
FEP		–50	14	609	560	504	

For temperatures increasing from 10 to 50 °C, creep under comparable loads during 100 h lead to very different modulus decreases:

- PA6 GF: creep modulus decreases by –49% for temperature increasing from 40 to 60 °C
- POM Co: creep modulus decreases by –28% for temperature increasing from 80 to 110 °C
- POM Homo: creep modulus decreases by –5% for temperature increasing from 50 to 60 °C
- POM Homo: creep modulus decreases by –50% for temperature increasing from 50 to 100 °C
- PTFE: creep modulus decreases by –45% for temperature increasing from 60 to 40 °C.
- PTFE: creep modulus decrease by –69% for a temperature in the range 90–40 °C

Results should not be directly interpreted as an indication of the expected service life for any targeted application.

Creep can lead to more or less premature break or failure as far as load and/or temperature are higher.

Table 10.12 displays time to rupture for various loads leading to creep strengths definitely lower than engineering strength at break. We can note that time to rupture can be as low as 100 h (or less) at RT for a PP GF compound or a SAN.

10.2.2 Relaxation

Relaxation is the time-dependent stress resulting from a constant strain. The stress is a function of the strain level, the application time, and the temperature.

The results of tests at a defined temperature can be presented as the curve of the stress versus the time or the curve of the stress retention versus the time.

The stress retention for a defined time and temperature is the quotient of the actual measured stress by the original stress at time zero.

Figure 10.6 shows a diagrammatic example of the retention percentage of stress with a fast drop at the beginning of the test followed by a gentle slope.

Table 10.13 displays stress retention for various strains leading to actual stresses definitely lower than the original stress. We can note that stress retention can be as low as 26% (or less) at RT for a specific engineering compound.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain notably concerning loading scenario and test temperature for the original stress.
- Reinforcement, plasticization, impact modification etc., aren't always pointed out
- The lack of data for a defined time or a defined strain isn't an indication of unsuitability but is due to the unsuccessful research of data.
- A defined family can be found in several lines because grades and/or loads are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of the expected service life for any targeted application.

Table 10.12 Creep Strength Examples

Polymer	Temperature, °C	Load MPa	Time to Rupture, h
PE	RT	8.75	800
PP GF	RT	35	8000
PP GF	RT	49	1000
PP GF	RT	49	1000
PP GF	RT	60	1000
SAN	RT	42	152
PP GF	80	17	11,000
PP GF	80	23	1000
PP GF	80	28	1000
PP GF	80	32	1000
PP GF	80	38	100
PPE	100	14	5900
PPE	100	21	3700

10.2.3 Fatigue

The cyclic mechanical loading of a polymer leads to a speedier failure than an instant loading. The Wohler curves or SN curves plot the level of stress or strain (S) leading to failure after N cycles of cyclic loading.

According to the actual thermoplastic and formulation, stress can:

- Continuously decrease during fatigue test or
- Decrease abruptly at the beginning of fatigue test and then gently decrease
- Decrease abruptly at the beginning and then stabilize.

Figure 10.7 shows three diagrammatic examples of the SN curves for three engineering plastics tested between 100,000 and 10,000,000 cycles.

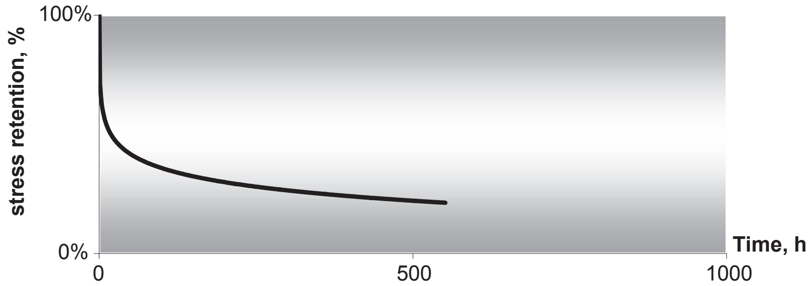

Figure 10.6 Relaxation: Diagrammatic example of stress retention versus time.

Table 10.13 Stress Relaxation of Some Specific Grades

	Temperature, °C	Strain	Time				
			1 h	10 h	30 h	100 h	1000 h
			Stress Retention, %				
PVC	RT	0.03	86	80	76		
PVC	RT	0.005	83	75	67	58	50
PE HD	RT	0.02	87	77	70	65	46
PP	RT	0.02	88	78	73	70	67
PS	RT	0.01	85	73	66	61	38
PS	RT	0.01	87	77	71	65	47
POM	RT	0.003	80	70	63	57	50
POM	RT	0.009	79	70	60	54	45
POM	RT	0.05	70	57	53	45	37
POM	RT	0.125	65	50	45	35	26
PBI	RT	0.01	80	75	71	67	58
PEEK	RT	0.01	88	84	82	79	74
PEI	RT	0.01	75	70	68	65	57
PPS	RT	0.01	80	77	77	76	75
PMMA	RT	0.05	80				
PVC	40	0.03	74	68	64		
PVC	50	0.03	68	62	58		
PVC	60	0.03	53	37	31		
PBI	150	0.01	46	45	43	41	38
PEEK	150	0.01	32	28	25	21	18
PEI	150	0.01	51	45	41	37	27
PPS	150	0.01	19	15	14	13	12

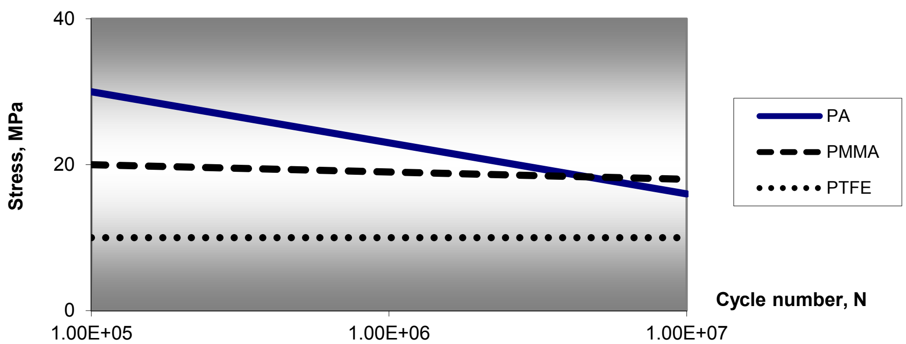

Figure 10.7 SN curves: Diagrammatic examples based on polyamide, polymethyl methacrylate, and polytetrafluoroethylene.

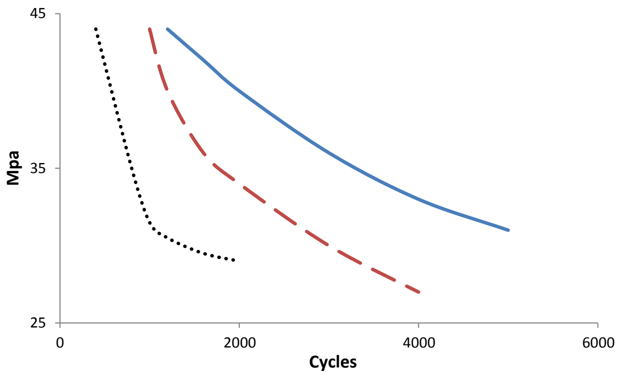

Figure 10.8 SN curves for a same polymer at three frequencies from 0.03 up to 0.5 Hz.

The fast drop of strength at the beginning is not visible because it generally appears before 100,000 cycles.

Two basic types of tests coexist "at defined stress" or "at defined strain." Thermoplastics being sensitive to creep, the fatigue tests at defined strain are less severe than those at defined stress for comparable original stresses.

Experiment has shown that the frequency of loading may affect the number of cycles leading to failure at a given level of stress (see Figure 10.8). Often tests are run below frequencies of 30 Hz. Generally speaking, higher frequencies lead to higher internal generation of heat and more rapid failure. The waveform (Sine, square, triangle, sawtooth etc.) is also of importance.

In addition to the mode of loading, the loading level must be examined in detail taking into account minimum, maximum, and average stresses (or strains).

The surrounding temperature and the geometry of the tested sample have an effect on heat dissipation. Thick samples and "high" surrounding temperatures lead to a temperature rise and have a harmful effect when low temperatures, notably subzero ones, lead to a modulus increase and brittleness. According to the type of solicitation, a higher thickness can lead to a higher deformation of the outer surface.

We must note that the increase of the temperature of the material under dynamic loading leads to the usual consequences, such as modulus reduction and aging.

Table 10.14 displays the stress leading to failure for the mentioned number of cycles. Stresses are definitely lower than the engineering strength at break. Most tests are run at RT and some are run at higher temperatures.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain notably concerning the loading scenario (minimum, maximum, and average stresses or strains) and loading conditions (frequencies, waveform).
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown
- Reinforcement, plasticization, impact modification etc., aren't always pointed out
- The lack of data for a defined number of cycles isn't an indication of unsuitability but is due to the unsuccessful research of data.
- A defined family can be found in several lines because grades and/or loads are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of the expected service life for any targeted application.

10.3 Poisson's Ratios

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force. Tensile deformation is considered positive and compressive deformation is considered negative.

The Poisson's ratio (ν) is linked to E (tensile or flexural modulus of elasticity) and G (Shear modulus or modulus of rigidity):

$$\nu = (E - 2G)/2G = (E/2G) - 1$$

$$\nu = -(E - 3K)/6K = -(E/6K) + 1/2$$

Table 10.15 displays some Poisson's ratios of thermoplastics and a few inorganic materials for comparison. Most tests are run at RT and some are run at higher temperatures.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain
- Test results depend on the sample processing method

Table 10.14 Dynamic Fatigue Examples

		Number of Cycles					
		1.E+03	1.E+04	1.E+05	1.E+06	1.E+07	1.E+08
	Temperature	Stress to Failure, MPa					
PEI CF	RT	150	110	77			
PAI CF	RT		110	98	81	68	
PASA GF	RT		105	85	65	55	
PEI GF	RT	120	90	65			
PAI GF	RT		96	70	53	41	
PASA GF	RT		90	70	50	35	
PEEK CF	RT	93	85	79	73		
PPS 40 GF	RT	95	85	75	70	65	
LCP GF	RT		85	72	62	50	
LCP mineral	RT		80	63	47	30	
PAI	RT		80	55	41	35	
PC 20 GF	RT		75	55	40	35	
PBT 30 GF	RT		70	51	36	29	
PEEK	RT	72	70	69	68		
PEEK GF	RT	75	70	65			
PA GF	RT			63	52	41	
PPS GF and Mineral	RT	75	67	60	50	41	
POM 30 GF	RT			50	45	40	35
PEI	RT	75	58	23			
PVDF	RT	55	52				
PPE 30 GF	RT		50	45	40	35	
PVDF	RT	48	45	42	40	38	
PP talc	RT			42	32	28.5	
PP talc	RT			38	22	17	
POM	RT			35	27	21	15
PMMA	RT	44					
PA46	RT	42	38	32	29		
PA	RT			31	25	20	
PE, HD	RT			31	24	17	
PPE	RT		35	28	21	15	
ETFE GF	RT		29	26	24.5		

Continued

Table 10.14 Dynamic Fatigue Examples—cont'd

	Temperature	Number of Cycles					
		1.E+03	1.E+04	1.E+05	1.E+06	1.E+07	1.E+08
		Stress to Failure, MPa					
PC	RT		40	25	15	10	
ABS	RT		33	25	17		
PVC	RT		33	23	17	12	
PES	RT		42	15	12		
PS	RT			14	10.5		
ETFE	RT		14	13	12		
PMMA	RT		25				
POM	RT				32		
PMMA	RT	31					
PVDF	60	40	35				
PVDF	100	24	22				
PPS 40 GF	120	75	65	55	49	38	
PPS GF and Mineral	120	55	49	41	37	33	
PPS 40 GF	150	51	45	35	27	25	
PPS GF and Mineral	150	41	35	30	25	20	

Table 10.15 Examples of Poisson's Ratios at Room Temperature

Poisson's ratio	Thermoplastics	Poisson's ratio	Inorganic Materials
0.46–0.48	PTFE		
0.46	PE UHMW		
0.46	FEP		
0.45	PE-HD		
0.45	COPE		
0.45	PE HD		
0.45	PEEK 30 GF		
0.44	PEEK 30 CF		
		0.43–0.44	Lead
0.43–0.45	ETFE		
0.4	PP		
0.4	PA66, extruded		

Table 10.15 Examples of Poisson's Ratios at Room Temperature—cont'd

Poisson's ratio	Thermoplastics	Poisson's ratio	Inorganic Materials
0.4	PESU		
0.4	PEEK, PEK		
0.38–0.40	PBT 30 GF		
0.39	PC		
0.36–0.39	PVC		
0.38	PET/PC		
0.38	PC GF		
0.38	PA/ABS		
0.37–0.38	COC		
0.34–0.41	PMMA		
0.35–0.39	PA6 33 GF		
0.35–0.39	ABS		
0.37	PSU		
0.36	PC/ABS		
0.36	PEI		
0.35–0.40	PPS 40 GF		
0.35	PP 40 GF		
0.35	POM		
0.35	PS cross-linked		
		0.35	Aluminum
		0.34–0.37	Copper
0.34–0.35	PET 30 GF		
0.34	PS impact		
0.34	PVDF		
0.33–0.35	PS		
0.33	PCTFE		
0.32–0.34	PA66 mineral		
0.31–0.38	PPE		
		0.29–0.30	Steel
0.27–0.28	PPE GF		
0.25	TPU		
		0.17	Fused quartz
0.1–0.12	Twintex PP/GF fabric		

- Reinforcement, plasticization, impact modification etc., aren't always pointed out
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown
- A defined family can be found in several lines because grades and compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

The Poisson's ratio of a given compound can vary with the temperature. For example, between −100 °C and 80 °C:

- Poisson's ratio evolves between 0.386 and 0.401 for a specific PC
- Poisson's ratio evolves between 0.352 and 0.359 for a specific PS
- Poisson's ratio evolves between 0.339 and 0.376 for a specific PMMA
- Poisson's ratio evolves between 0.364 and 0.385 for a specific PVC
- Poisson's ratio evolves between 0.35 and 0.39 for a specific PPS 40 GF

10.4 Friction and Wear; Tribological Thermoplastics

When a thermoplastic is sliding on a counterpart:

- There is always:
  - A resistance to the movement.
  - An interface heating and consequently:
    - A decrease of the modulus, tensile strength, and abrasion resistance.
    - A change of the coefficient of friction
    - A thermal expansion of the polymer.
  - A wear of one or the two materials.
- There is possibly:
  - Fouling after a more or less long time that modifies the roughness, the coefficient of friction, and leads to the formation of abrasive particles.
  - Stick-slip phenomenon or stick-slip is the jerky motion that can occur while two materials are sliding over each other. High differences between static and dynamic coefficients of friction favor stick-slip.

Friction and wear can be characterized by the coefficient of friction (CoF), the wear factor and the PV limit.

The CoF is the ratio of the friction force and the vertical force. It is always less than 1, if the polymer is not bonded. In practice, unlike the metals the polymers have a low modulus and the vertical force alters the shape of their sliding face. The CoF depends on:

- The substrate material
- The surface aspect and roughness of the plastics and the substrate
- The loading pressure
- The moving velocity: Notably, it must be distinguished between the static and dynamic coefficients of friction
- The environmental conditions: hygrometry, temperature
- The initial and final shapes of the sliding surface
- The possible use of lubricants
- The duration.

The **PV** is the product of the pressure by the velocity. The used units affect the value. Each polymer has a PV limit and must be used only below it.

For a defined test, the **wear** can be expressed by:

- The weight or volume loss.
- The height loss.
- The wear factor $k = h/(P*V*t)$ where h is the wear expressed in height or weight or volume, P is the pressure, V is the velocity, t is the test duration.
- The specific wear rate $= V/P*d$ where V is the volume loss, P is the pressure, and d is the sliding distance.

10.4.1 Tribological Additives

Tribological properties of a selected thermoplastic family may be unsuitable for the aimed application needing the use of tribological additives. Of course those products can modify the other properties.

The most current are:

- Specific fillers: MoS_2, graphite, and more rarely boron nitride or silicon carbide
- Polymers: PTFE, silicone masterbatches
- Oils: silicones, perfluoropolyether (PFPE)
- Carbon or aramid fibers to decrease coefficient of friction and wear, and enhance mechanical properties; glass fibers enhance mechanical properties and decrease the wear but they are abrasive and attack the antagonist surface. According to the circumstances they can increase the coefficient of friction.

Molybdenum disulfide (*MoS_2*) decreases the CoF, creates a more wear-resistant surface and fills metal surface unevenness creating a smoother metal surface. It is ideal for applications where thermoplastics wear against metal.

Graphite reduces friction, especially in underwater applications.

PTFE (*Polytetrafluoroethylene*) exhibits a very low CoF and forms a lubricating film on the counterpart surface after initial break-in period. It eases higher dynamic load bearing capability.

Silicone migrates to the surface over time forming an interface lubricant. As alloying material in the compound, it remains efficient over its service lifetime, reducing start-up wear.

V.B. John & H. Rubroeder test the CoF of PP modified with silicone masterbatch of DOW:

- 1% of silicone reduces the coefficient of friction by 15%
- 5% of silicone reduces the coefficient of friction by 20%
- 10% of silicone reduces the coefficient of friction by 35%

At 3% level in PP, Jane chappelle and Milas masalovic observe a 30–40% reduction of the CoF.

Perfluoropolyether (PFPE), Fluoroguard® polymer additives by DuPont are based on a fluorinated synthetic oil, colorless, odorless, and chemically inert. Those additives migrate to the surface, reducing wear and abrasion, as well as improving processing.

For example, 1% Fluoroguard® loading in acetal (Delrin® 500P) reduces the static CoF by 30%, and dynamic CoF by 20%, for a metal counter surface. Wear of acetal is reduced by 97% and nylon 6 by 58%.

Carbon or aramid fibers decrease CoF and wear, and enhance mechanical properties. In addition, carbon fibers can increase the thermal and electrical conductivities of the host resin. For example, a 30% carbon fiber-reinforced PEEK can provide 3.5 times higher thermal conductivity than unreinforced PEEK dissipating heat from the bearing surface faster.

Proprietary additives are proposed to enhance tribological behaviors. For example, All-polymeric wear Additive (APWA by RTP Company), an olefin-based additive, is halogen-free and all-polymeric in nature improving wear resistance of host resins and preserving other properties.

Heat dissipaters: The sliding surface of the polymer heats and, the polymers being thermal insulating, the temperature rises and can reach the melting temperature resulting in bearing failing. To ease dissipating the thermal flow, it is interesting to use additives such as metal powders, ceramic additives (boron nitride or silicon carbide, for example) or carbon fibers having a high thermal conductivity. The silicon carbide at less than 10% levels could significantly improve the surface properties:

- Decreasing the wear weight loss
- Reducing the coefficient of friction
- Reducing the stick-slip.

The influence on the mechanical properties could be tolerable.

Table 10.16 displays examples of properties obtained with several tribological fillers used in polyamides 6 or 66.

10.4.2 Coefficient of Friction

Table 10.17 displays examples of static and dynamic coefficients of friction. Tests are run at RT. When some details are given concerning the composition, percent of fibers, and percent of tribological additives are possibly specified, for example, "PA6 13PTFE 2Silicone 30GF" is a PA6 modified with 13% of PTFE, 2% of silicone oil, and reinforced with 30% of glass fiber. Ranking is in ascending order, polymers modified with tribological additives being at the top of the list.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain notably concerning the equipment and the test method. The substrate or counterpart may be not enough identified (steel for example) or unknown for several data

Table 10.16 Effects of Several Tribological Fillers on the Tribological Properties of PA6 and PA66

Tribological Additive	Level	Polymer Compound	Static CoF	Dynamic CoF	Wear
Unmodified PA6 and PA66					
None	0	PA6 or PA66	0.22	0.28	
None	0	PA6 or PA66 30 GF		0.45–0.5	
None	0	PA6 or PA66 CF	0.13–0.25	0.15–0.25	
Effect of MoS2					
MoS2	5	PA6 30 GF	0.3	0.3	2.2
MoS2	5	PA66 30 GF	0.3	0.3	2.8
Effect of PTFE					
PTFE	15	PA6 30 GF	0.26	0.1	2
PTFE	15	PA66 30 GF	0.22	0.08	1.9
PTFE	15	PA6	0.18	0.11	120
PTFE	15	PA66	0.17	0.11	100
Effect of CF					
Carbon fibers	10	PA66 10 CF	0.13–0.25	0.18–0.25	
Carbon fibers	20	PA6 20 CF	0.22		
Carbon fibers	20	PA66 20 CF	0.2		
Carbon fibers	30	PA6 30 CF	0.2		
Carbon fibers	30	PA66 30 CF	0.19		
Effect of PTFE and silicone oil					
PTFE/silicone oil	13/2	PA6 30 GF	0.19	0.13	2
PTFE/silicone oil	13/2	PA66	0.1	0.11	120
PTFE/silicone oil	13/2	PA66 30 GF	0.17	0.1	2.3
Effect of CF and PTFE					
CF/PTFE	15/20	PA66 15 CF	0.11	0.08	1.5
CF/PTFE	30/15	PA66 30 CF	0.16	0.1	1
Effect of CF, PTFE and silicone oil					
CF/PTFE/silicone oil	30/13/2	PA66 30 CF	0.13	0.09	2
CF/PTFE/silicone oil	15/13/2	PA66 15 CF	0.12	0.08	0.8

- Reinforcement, plasticization, impact modification etc., aren't always pointed out. Some compounds are mentioned as general-purpose grades but are tribological grades.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- A defined family can be found in several lines because grades and/or test conditions are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Table 10.17 Examples of Static and Dynamic Coefficients of Friction

		CoF	
		Static	**Dynamic**
PS 2Silicone	Unknown	0.06	0.08
PPS 18 PTFE 2Silicone	Unknown	0.07	0.08
POM PTFE/silicone	Unknown	0.1	0.08
PA66 15 CF PTFE	Unknown	0.11	0.08
PA66 15 CF PTFE/silicone	Unknown	0.12	0.08
POM PTFE	Unknown	0.13	0.08
PA66 30 GF PTFE	Unknown	0.22	0.08
PBI tribological	Metal	0.3	0.08
PP 15 PTFE GF	Unknown	0.09	0.09
PA66 30 CF PTFE/silicone	Unknown	0.13	0.09
PC 15 CF PTFE	Unknown	0.16	0.09
PTFE	Metal	0.05–0.1	0.1–0.13
PA66 30 CF PTFE	Unknown	0.16	0.1
PA66 30 GF PTFE/silicone	Unknown	0.17	0.1
PA6 30 GF PTFE	Unknown	0.26	0.1
POMCo 18 PTFE 2Silicone	Unknown	0.06	0.11
PA66 PTFE/silicone	Unknown	0.1	0.11
POM silicone	Unknown	0.16	0.11
PA66 PTFE	Unknown	0.17	0.11
PA66 PTFE	Unknown	0.17	0.11
PA6 PTFE	Unknown	0.18	0.11
PA6 PTFE	Unknown	0.18	0.11
PVDF	Metal	0.1–0.55	0.1–0.54
PVDF	Metal	0.1–0.15	0.12–0.15
PEEK tribological	Metal	0.1–0.15	0.12–0.15
PEHD	Unknown		0.027–0.3
PEEK	Metal		0.11–0.5
PEEK PTFE	Metal		0.12–0.43
PBT 18 PTFE 2Silicone	Unknown	0.08	0.13
PEHD 20 PTFE	Unknown	0.09	0.13
PA6 30 GF silicone	Unknown	0.19	0.13
PSU 15 PTFE	Unknown	0.09	0.14
ABS 2Silicone	Unknown	0.11	0.14

Continued

Table 10.17 Examples of static and dynamic coefficients of friction—cont'd

		CoF	
		Static	**Dynamic**
PC 22 PTFE	Steel		0.15
POM 22PTFE	Steel		0.15
PTFE Milled glass	Unknown	0.08	0.16
PA12 15 PTFE	Unknown	0.09	0.16
PPE 15 PTFE	Unknown	0.1	0.16
PA66 20 PTFE	Unknown	0.1	0.18
PA66 44 PTFE	Steel		0.18
PA66 20 PTFE	Steel XC 40		0.18
PEEK CF	Metal		0.18–0.22
PPE 25 GF graphite	Unknown	0.29	0.19
PA6 13 PTFE 2Silicone 30 GF	Unknown	0.17	0.2
PC	Unknown	0.18	0.2
PC 15 PTFE 30 GF	Steel		0.2
POM Co	Steel XC 40	0.14	0.21
POM Co	Steel XC35	0.14	0.21
POM Co	Unknown	0.14	0.21
COPE 13 PTFE 2Silicone	Unknown	0.2	0.21
POM	Steel XC 40		0.21
PA aromatic 20 PTFE	Unknown	0.13	0.22
PA11 25 GF 10 graphite	Unknown	0.18	0.22
POM	Unknown	0.18–0.34	0.19–0.28
PC 30 CF	Unknown	0.18	
PBT 30 CF	Unknown	0.18	
PA66 30 CF	Unknown	0.19	
PC 20 CF	Unknown	0.19	
PBT 20 CF	Unknown	0.19	
PA66 20 CF	Unknown	0.2	
PA6 30 CF	Unknown	0.2	
PA66 10 CF	Unknown	0.22	
PA6 20 CF	Unknown	0.22	
PPS 30 CF	Unknown	0.22	
PPS 20 CF	Unknown	0.24	
FEP 20 GF	Unknown	0.32	0.22

Table 10.17 Examples of static and dynamic coefficients of friction—cont'd

		CoF	
		Static	**Dynamic**
ETFE	Metal	0.31–0.51	0.23
PEEK GF	Unknown		0.24–0.45
PPS	Steel XC 40	0.3	0.24
PPS	Steel XC35	0.3	0.24
PPS 15 PTFE 30 GF	Unknown	0.3	0.24
PBT	Steel XC 40	0.19	0.25
PBT	Steel XC35	0.19	0.25
PBT	Unknown	0.19	0.25
PEI GF PTFE graphite	Metal	0.24	0.25
PA6	Steel XC 40	0.22	0.26
PA6	Steel XC35	0.22	0.26
PA6	Unknown	0.22	0.26
PA66 15 PTFE 30 GF	Steel		0.26
PA66	Steel XC 40	0.2	0.28
PA66	Steel XC35	0.2	0.28
PA66	Unknown	0.2	0.28
POM 15 PTFE 30 GF	Steel		0.28
PA66	Steel XC 40		0.28
PA6 30 GF MoS2	Unknown	0.3	0.3
PA66 30 GF MoS2	Unknown	0.3	0.3
FEP	Unknown	0.4	0.3
PA612	Steel XC 40	0.24	0.31
PA612	Steel XC35	0.24	0.31
PA transparent	Steel XC 40	0.23	0.32
PA transparent	Steel XC35	0.23	0.32
PA aromatic	Unknown	0.23	0.32
PS	Steel XC 40	0.28	0.32
PS	Steel XC35	0.28	0.32
PS	Unknown	0.28	0.32
SAN	Steel XC35	0.28	0.33
ABS	Steel XC 40	0.3	0.35
ABS	Steel XC35	0.3	0.35
ABS	Unknown	0.3	0.35

Continued

Table 10.17 Examples of static and dynamic coefficients of friction—cont'd

		CoF	
		Static	Dynamic
PSU	Steel XC 40	0.29	0.37
PSU	Steel XC35	0.29	0.37
PSU	Unknown	0.29	0.37
PC	Steel XC 40	0.31	0.38
PC	Steel XC35	0.31	0.38
PC	Unknown	0.31	0.38
PPE	Steel XC 40	0.32	0.39
PPE	Steel XC35	0.32	0.39
PPE	Unknown	0.32	0.39
PA6 30 GF	Metal		0.45–0.5
PC GF PTFE	Metal	0.41	0.46
COPE	Steel XC 40	0.27	0.59
COPE	Steel XC35	0.27	0.59
COPE	Unknown	0.27	0.59

Table 10.18 Examples of Static and Dynamic Coefficients of Friction for Plastics Sliding on Plastics

		Static CoF	Dynamic CoF
PA6	POM Co	0.04	0.01–0.05
PA66 20 PTFE	POM 20 PTFE		0.04
POM	POM	0.19	0.04–0.15
PA66	POM		0.05
PA66	POM Co	0.04	0.05
PA66	PA66		0.07
POM	PA66		0.07
PBT	PBT	0.17	0.07–0.24
PA66	PA66	0.12	0.09–0.21
POM Co	POM Co	0.19	0.15
PA66	PA66	0.12	0.21
PBT	PBT	0.17	0.24

Results should not be directly interpreted as an indication of suitability for any targeted application.

Table 10.18 displays examples of static and dynamic coefficients of friction for plastics sliding on plastics. Tests are run at RT. When some details are given concerning the composition, percent of fibers, and percent of tribological additives are possibly specified, for example, "POM 20PTFE" is an undefined POM (homo or copolymer) modified with 20% of PTFE.

Hygrometry of polyamides and other moisture-sensitive polymers is unknown.

Results must be carefully examined for the reasons already mentioned for Table 10.16.

10.4.3 PV: Limiting Pressure Velocity

A plastic subjected to sliding heats up and can eventually reach a point of failure known as the PV limit (maximum of the pressure by the velocity product). The used units affect the value. Each polymer has a PV limit and must be used only below it. In addition, the PV limit is valid only within P limit on the one hand and V limit on the other hand. The failure point is usually manifested by an abrupt increase in the wear rate. As long as the mechanical strength of the material is not exceeded, the temperature of the sliding surface is generally the most important factor.

PV limit depends on many parameters such as:

- Hardness, surface finish, conductivity of the plastic part
- Hardness, surface finish, conductivity of the counterpart
- Coefficient of friction
- Ambient temperature
- Cooling
- Device design
- Lubrication if relevant

It is usually prudent to allow a generous safety margin in using PV limits, because real operating conditions often are harsher than test conditions.

Table 10.19 displays some examples of PVs for general purpose and tribological grades. Tests are run at RT. When some details are given concerning the composition, percent of fibers, and percent of tribological additives are possibly specified, for example, "PC 15PTFE 30 GF" is a PC modified with 15% of PTFE, and reinforced with 30% of glass fiber. Ranking is in descending order.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain notably concerning the equipment and the test method. The substrate or counterpart is unknown
- Reinforcement, plasticization, impact modification etc., aren't always pointed out. Some compounds are mentioned as general-purpose grades but are tribological grades
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown
- A defined family can be found in several lines because grades and/or test conditions are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of suitability for any targeted application.

10.4.4 Wear and Abrasion

There are an abundance of testing methods. Most often, the material to be tested is applied with a known load on an abrasive of reference. Other tests can use, for example, the projection of sand, shot of other abrasive particles on the sample of material. It should be noted that the results obtained by different methods are not comparable among themselves and even rankings of materials can be affected if the methods are based on two dissimilar principles.

The range of abrasives is very extensive, from very soft felts up to metal blades or tungsten carbide. So, it is necessary to choose a method representative of the targeted application.

Damage criteria are very often the loss of material, thickness, volume, or weight, but also evaluation of aspect changes: more or less numerous and deep scratches, loss of gloss or transparency, haze for organic glazing, for example.

We have retained two tests among many others relating to abrasion and wear: The wear factor (K) and the Taber's abrasion test.

The Wear factor (K) is an indication of resistance to wear being useful for material comparison purposes.

$K = h/(P*V*t)$ in $(mm^3/Nm)10^{-8}$

where:

h is the wear expressed in volume (mm^3)

P is the pressure

V is the velocity (m/s)

t is the test duration (s).

Table 10.19 Examples of PV for Thermoplastics

	Limiting Pressure Velocity, MPa m/sec
PA66 CF tribological	3.3
PA66 CF PTFE	3.3
PEI GF PTFE graphite	2
PBI	1.3
POM	1.1
PBI	1.1–1.8
PPS tribological	0.9
PC lubricated	0.8
PA66 CF PTFE	0.77–3.3
PC PTFE	0.7
PEEK CF	0.6–13
PC 15 PTFE 30 GF	0.46–1.05
PA66 15 PTFE 30 GF	0.46–0.7
PA66 PTFE	0.33–0.70
PPS	0.3
POM 15 PTFE 30 GF	0.28–0.44
PA66 44 PTFE	0.28–>1.4
PEEK PTFE	0.25–0.6
POM 22 PTFE	0.17–>1.4
PEEK	0.17–0.5
PET tribological	0.16
PA66	0.1
PEI	0.07–2.80
PC 22 PTFE	0.06
POM	0.05
PE-UHMW GB	0.05–0.08
PE-UHMW	0.05–0.08
PTFE	0.04–0.35
PTFE bronze	0.005–0.009
PTFE GF	0.003–0.005

A material with a low wear factor (K) has a high resistance to wear.

Table 10.20 displays some examples of wear factors for general purpose and tribological grades. Tests are run at RT. When some details are given concerning the composition, percent of fibers, and percent of tribological additives are possibly specified, for example, "PA66 15PTFE 30 GF" is a PA66 modified with 15% of PTFE, and reinforced with 30% of glass fiber. Ranking is in ascending order.

Table 10.20 Examples of Wear Factors

	Wear Factor (K), 10^{-8} mm³/Nm
PA66 CF PTFE	10–30
PES	8–342
PA66 CF tribological	15
PA66 PTFE	12–359
PA66 44 PTFE	23
PAI	26–35
PC/ABS	14–2520
PEI	24–5840
PA66 CF PTFE	30–101
PPS CF PTFE	30–95
PA66 15 PTFE 30 GF	31
POM 22 PTFE	32
PC 15 PTFE 30 GF	58
PPS GF PTFE	66–141
PC PTFE	62–3000
POM	111
PC lubricated	117
PBI	121
PPS	125
PEI GF PTFE graphite	125–3800
ABS PTFE	870
PPS tribological	1610
PTFE	5040

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain notably concerning the equipment and the test method. The substrate or counterpart is unknown
- Reinforcement, plasticization, impact modification etc., aren't always pointed out. Some compounds are mentioned as general-purpose grades but are tribological grades
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown
- A defined family can be found in several lines because grades and/or test conditions are different and because compounds are different
- Data ranges for a same family may be as high as 24–5840, for example
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of suitability for any targeted application.

Taber abrasion test involves mounting a flat specimen approximately 100 mm square to a turntable platform that rotates on a vertical axis at a fixed speed. Two Taber abrasive wheels are applied at a specific pressure on the specimen surface. Most often, loss of weight or volume is checked after 1000 cycles.

Results must be carefully examined concerning the type of the wheel, load, cycle number, measured criteria (loss of material, optical properties…).

Table 10.21 displays examples of Taber Abrasion with three types of wheels applied with a 1 kg load.

Table 10.21 Examples of Taber Abrasion with Three Types of Wheels Applied with a 1 kg load. Loss of Weight After 1000 Cycles Is Expressed in mg.

Taber Abrasion, mg/1000 Cycles	CS-17 Wheel; 1 kg	H-18 Wheel, 1 kg	H-22 Wheel, 1 kg
TPU		9	
COPE low modulus	3	100	
POM	2–5	280	
PMMA	2–5		
PA66	1–12		
COPE medium modulus	7	77	
TPE	7		
PVDF	7–10		
CA	9–10		
PVDC	9–12		
PEI	10		
CAB	9–15		
ABS	9–20		
PEI GF	15–17		
PS	9–26		
POM 20 Mineral	19		
TPU GF	20		
PES	18–22		

Continued

Table 10.21 Examples of Taber Abrasion with Three Types of Wheels Applied with a 1 kg load. Loss of Weight After 1000 Cycles Is Expressed in mg—cont'd

Taber Abrasion, mg/1000 Cycles	CS-17 Wheel; 1 kg	H-18 Wheel, 1 kg	H-22 Wheel, 1 kg
PSU	20		
PP	18–28		
PC/PET	20–30		
ECTFE	25		
PET 30 GF	30–38		
PC/PBT	74		
PBT/PET	74		
PPE/PP	75		
PPE/PP GF	85		
TPU	100	30–50	
TPE		1610	2130

Loss of weight after 1000 cycles is expressed in milligram. Tests are run at RT. When some details are given concerning the composition, percent of fibers are possibly specified, for example, "POM 20Mineral" is an undefined POM (homo or copolymer) modified with 20% of undefined mineral filler.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary. Test conditions are uncertain notably concerning the equipment and the test method.
- Results of the three methods are not correlated.
- Reinforcement, plasticization, impact modification etc., aren't always pointed out. Some compounds are mentioned as general purpose grades but are tribological grades.
- Hygrometry of polyamides and other moisture sensitive polymers is unknown.
- A defined family can be found in several lines because grades and/or test conditions are different and because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be directly interpreted as an indication of suitability for any targeted application.

Further Reading

Technical guides, newsletters, websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, BP Chemicals, Bryte, Ceca, Celanese, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Matweb, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Taber, Technochemie GmbH, Telenor, The European Alliance for SMC, Thieme, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

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[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

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[2] J. Chappelle, Milas Masalovic, in: SPE Automotive TPO, 2000, p. 287.

11 Fire Behavior

OUTLINE

Worldwide, fires kill or injure several tens of thousands of people, and result in huge property losses.

In Europe, at the beginning of the twenty-first century, the CTIF (International Association of Fire and Rescue Services) estimates that there are approximately:

- 2,000,000–2,500,000 fires: dwelling and other building account for 90%, and transport for 5%
- 20,000–25,000 fire deaths
- 250,000–500,000 fire injuries.

In 2011, for the United States alone and for residential building fires only, the U.S. Department of Homeland Security—U.S. Fire Administration estimates that there are approximately:

- Fires: 364,500, 20% involving electrical distribution and appliances; another 10% concerning upholstered furniture and mattresses.
- Deaths: 2450.
- Injuries: 13,900.
- Dollar Loss: $6.6 billion.

This brief overview shows the need for fire retardant (FR) plastics in such sectors as building and construction, E&E, automobile, aeronautics etc. Moreover, it is pointed out that the use of FR materials had cut fire deaths by 20% in recent years although there is a marked increase in the number of electric and electronic devices in every home.

Fire behavior depends, initially, on the nature of the polymer. However, the use of fire-proofing agents, special plasticizers and specific fillers can modify this behavior very significantly. The market of fire retardant additives evolves at an annual growth rate exceeding the plastics market.

Environmental, health, and technical concerns over several FR chemicals change the market face. Among others, REACH, RoHS, WEEE, regulations concerning specific applications such as food contact, automobile and transports, building and so on, and voluntary bans decided by trade associations or by companies reduce the suitable fire retardancy formulations. However, brominated compounds will continue to lead the market in total value.

Fire behavior of plastics may be surprising for designers familiar with metals:

- Mainly used thermoplastics are made out of carbon and hydrogen such as polyethylene, polypropylene, polystyrene with possibly another atom in lower proportion, for example, oxygen or azote for polyacetal, polyester, polyamide, etc. All those polymers easily burn. Some other

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00011-8

halogen-containing polymers are more fire resistant but contain halogens, which isn't in line with the green wave.

- Thermoplastics melt at relatively low temperature losing their mechanical performances.
- Burning of thermoplastics emits smokes and gases that can lead to opacity, toxicity, and corrosivity issues.
- Improvement of fire behavior of a polymer by using additives may modify other performances.

The problem being complex, regulations and standards are overabundant and continuously evolve according to countries and application sectors.

11.1 Preliminary Remarks: Define the Problem Correctly

To make short, fire requirements evolve from ignition and spreading issues up to health hazards and toxicity.

Generally speaking, plastics are not enough fire resistant; needing addition of fire retardant additives including:

- Flame retardants (FR) to prevent a fire or limit its development
- Halogen-free FR (HFFR) suppressing production of hydrogen halides, which favors a reduction of toxicity and corrosivity
- No or low smoke additives reducing smoke opacity. In case of fire, people are able to see their way to escape and firefighters can work more easily
- Low toxicity FR additives: In a fire, people are not asphyxiated by toxic fumes during their escape
- Low corrosivity FR compounds: In a fire, operating, financial and capital losses are more limited.

It must be pointed out that plastics parts have generally long lifetimes, so fire resistance must withstand the application conditions during long periods. For instance, certain standards such as UL94 fire rating include tests after accelerated aging.

For more in-depth information, the reader must have a look on the chemical aspect of fire, the chemical entities produced during a fire vary greatly, depending on the material and the fire scenario. For example:

- Polymers containing carbon can emit large quantities of carbon monoxide, an asphyxiating gas, which is a concern within the immediate vicinity of the fire.
- Compounds containing nitrogen (nylons, polyurethanes, polyacrylonitrile…) can emit significant amounts of hydrogen cyanide, another asphyxiating gas and nitrogen oxides (NOx), irritant gases.
- Polymers containing halogens, mainly chlorine, bromine, fluorine, can produce, respectively, hydrogen chloride, hydrogen bromide, and hydrogen fluoride. In addition, in particular contexts, chlorinated plastics can release phosgene, another asphyxiating gas, and polychlorodibenzo-p-dioxines (PCDD) and polychlorodibenzofurane (PCDF). In addition to hydrogen fluoride, PTFE can liberate perfluoroisobutene (PFIB), about 10 times as toxic as phosgene.
- Polymers containing sulfur can emit sulfur dioxide, an irritant gas.
- Phosphorous flame retardants developed as alternative to halogenated FR additives can release phosphorous oxides and phosphoric acids.

Note that many other species can be produced in case of fire.

Another face of fire requirement is the nature of the produced part or device and the countries of commercialization, use, and disposal.

Each application sector concerned by fire risks applies its own requirements, regulations, standards etc. For example, building, electricity and electronics, aerospace, mass transportation, automotive sectors do not have the same methods and apply different assessment levels with sometimes the same name. For example, RoHS (Restriction of Hazardous Substances) may be EU RoHS, China RoHS, Korean RoHS, or Japan RoHS directives.

WEEE, FST, and many other regulations concern specific applications as diverse as electricity and electronics, railway, building, automobile and transports, food contact, and so on. For specific cases, voluntary bans decided by trade associations or by companies restrict more harshly the suitable possibilities of fire retardancy formulations.

There is overabundance of worldwide, national, local regulations; standards; industrial corporation and company specifications; application sector rules. Certain polymers and compounds may be banned, regulated, suspected, or authorized according to the country and the application. The situation evolves continuously.

Among other involved players, let us quote, for example, without claiming to be exhaustive:

- Independent certifiers such as UL
- Federal Aviation Association (FAA)
- Military
- Federal/state/city laws/local and country ordinances
- European directives
- Building codes in various countries
- Railway codes in various countries
- Automobile makers
- Insurance underwriters (factory mutual), etc.

> Of course, regulations, safety requirements, specific, and general standards applied in the various countries to the manufacture, application, and disposal of plastics products must be fulfilled.
>
> Please note that certain tests required for fire agreement must be run by accredited certifiers.
>
> It is the responsibility of the reader to search the specific rules applicable to his own problem.

Even for a limited area such as the FST (Flame, Smoke and Toxicity), regulations involve different methods and require more or less severe property levels for aerospace, transportation, and building. Among others, without claiming to be exhaustive, let us quote some examples of applied standards for some countries and for some applications:

- US: ASTM E 162, SMP 800C, ASTM E 662, FAR 25.853
- European regulation: EN 45545
- Airbus ABD0031 and Boeing D6-51377
- Germany: DIN 53438, 5659-2, 54 837
- France NF T 51-071, NF C 20-455, NF16 101
- UK: EN ISO 4589, BS 6853, 7238, 7239

Other rules, methods, standards, and requirements concern other countries and other applications.

For the traditional fire behavior, the reader can see the subchapter "1.1.8 Fire behavior: some ins and outs" briefly quoting:

- UL94 fire ratings
- Oxygen index
- Smoke opacity, toxicity, and corrosivity
- Cone calorimeter
- Ignition temperature
- Rate of burning

The main FR thermoplastics may be sliced into two families based on compounds having:

- Chemical actions on the gas or solid phase: generally containing phosphorus, bromine, chlorine, nitrogen, etc. They are the most effective.
- Physical actions: aluminum and magnesium hydrates, Intumescent Systems. They are less efficient and must be used at higher levels.

Brominated FRs, often combined with antimony trioxide, contain halogen but are still widely used.

For halogen-free FR (HFFR) systems:

- Organic and inorganic phosphorous compounds have a good fire safety performance and are fast developing to meet halogen-free requirements. Phosphorus-based flame retardants will grow at the fastest rate, driven by increasing trends toward nonhalogenated products.
- Nitrogen-containing flame retardants are of lower efficiency and are combined with phosphorous compounds to boost their efficiency.
- Inorganic compounds, particularly aluminum and magnesium hydroxides, must be used at high levels to compensate for their lower efficiency and to meet high fire safety performances. Rapid gains are expected in aluminum hydroxide and magnesium hydroxide which are finding more use in polyethylene, polypropylene, and other polyolefins.

11.2 Predisposition to Burn: More or Less Easily, All Thermoplastics Burn

It is just a problem of oxygen, temperature, and ignition source; at the end, all thermoplastics (and thermosets or many other materials) burn including PTFE and FR versions of thermoplastics. FRs allow one to improve resistance to ignition, fire spreading, heat release, smoke emission etc., but don't prevent burning. Carefully selected FR solutions are used very effectively to reduce risks of fire, reduce their severity and also to allow people to have more time to evacuate. US research has shown that in the event of a fire, versus general purpose grades, FR compounds may multiply up to 15-fold; the time available for people to escape.

For the most fire-resistant thermoplastic, PTFE, Figure 11.1 displays diagrammatic examples of TGA in air. The gray space includes the various curves obtained with various grades of PTFE tested with diverse testing scenarios. 100% weight loss ranges from 550 °C up to 650 °C according to the heating rate. The oxygen index of PTFE can be as high as 95% but the other side of the coin is the emission of highly toxic and corrosive fumes.

The oxygen index is the minimum percentage of oxygen in an atmosphere of oxygen and nitrogen that sustains the flame of an ignited polymer sample. Table 11.1 displays examples of oxygen indexes (OI):

- Inherent oxygen indexes are values for (expected) unmodified polymers.
- Due to formulation, the oxygen index of a defined thermoplastic can be increased or decreased. FR additives improve OI and flammable additives reduce OI.

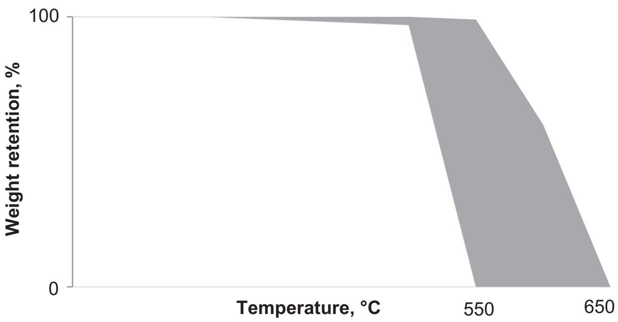

Figure 11.1 "Examples of TGA in air for a PTFE grade".

- Note that quoted maxima are the highest values found in the literature taken in to consideration. Higher values may be possibly found elsewhere according to the considered literature and specific formulations for special applications. Maximum oxygen indexes correspond to FR versions.

11.3 Inherently FR polymers

The following inherently FR polymers are categorized in:

- Halogen-free that don't include halogens (fluorine, chlorine, bromine or iodine) in their molecule but halogen can be present as an impurity.
- Halogen-containing with halogen included in the polymer molecule.

For example, the molecule of PPS contains only carbon, hydrogen, and sulfur but, in fact, chlorine content can be higher than those required by some specifications. Therefore, Polyplastics Co Ltd has developed Fortron 1140A66, a grade of PPS resin that enables significant reduction of chlorine level, less than 900 ppm, while high mechanical strength and toughness are also featured. This new PPS resin satisfies the UL94V-0 flammability rating without the addition of FRs.

The following list and Figure 11.2 display some families of polymers having a higher oxygen index that common polymers, being inherently more or less fire resistant. Some contain zero or very little halogen for suitable grades. Others contain halogen into their molecule.

- Halogen-containing
  - FEP
  - PFA
  - PTFE
  - PCTFE
  - PVDC
  - ECTFE
  - PVCC
  - PVC
  - PVF

Table 11.1 Examples of Oxygen Index

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
FEP			95	96
PFA			95	96
PTFE			95	96
PTFE CF			95	96
PTFE GF			95	96
FEP GF			95	95
PCTFE			90	98
PVDC			60	60
PBI	58	58		
ECTFE			52	60
PES CF	51	52		
PAI GF	51	51		
PVCC			50	65
PEI GF	50	50		
PES friction	48	52		
PEI GF milled	47	50		
PEI mineral	47	48		
PEI	47	50		
PPS GF + mineral	45	53		
PAI CF	45	52		
PPS conductive	45	48		
PAI	45	45		
PI TP	44	53		
PI TP GF	44	53		
PAI friction	44	44		
PAI mineral	44	44		
PVDF Mica			44	44
PPS CF + GF	43	50		
PPS GF	43	49		
PPS long GF medium level	43	49		
PPS long GF high level	43	49		
PPS far	43	49		

Continued

Table 11.1 Examples of Oxygen Index—cont'd

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PPS	43	47		
PPSU	43	44		
PVDF			42	67
PVDF friction			40	67
PVDF CF			40	65
PVC unplasticized			40	52
PPS CF	40	49		
PES GF	40	48		
PVC GF			40	45
PEEK CF	38	47		
PPSU GF	38	42		
LCP GF	37	49		
LCP MINERAL	36	37		
LCP	35	50		
PEEK/PBI	35	45		
PEEK/PBI GF	35	45		
PSU/PBT GF	35	35		
PVF			35	35
PES	34	39		
PSU	32	40		
PA 6 FR	31	32		
ETFE			30	40
PSU	30	40		
PSU GF	30	40		
PSU mineral	30	40		
PSU modified	30	38		
ETFE GF			30	32
ABS/PVC			28	37
ABS FR	28	28		
Polyarylate	26	36		
PPA	26	35		
PA 66 MINERAL	26	33		
Polyarylate GF	26	28		

Table 11.1 Examples of Oxygen Index—cont'd

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PPA mineral	26	26		
PA 4–6	25	27		
PEEK GF	24	45		
PAEK 30% GF	24	45		
PEEK	24	35		
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	24	35		
PPA GF	23	35		
PET	23	30		
PPA long GF	23	24		
PC	22	41		
PC GF	22	40		
ABS/PC	22	34		
ABS/PC-medium level long GF	22	34		
ABS/PC conductive	22	34		
PA 11	22	33		
PA 12	22	33		
CPE			22	25
PAA high level GF	22	25		
ABS/PC-low level long GF	22	24		
ABS/PC GF	22	23		
PA 11 GF	22	22		
PA 11 or 12 plasticized	22	22		
PA 12 GF	22	22		
TPE based on PVC			21	39
PA 66	21	36		
PBT	21	35		
PC/PBT	21	35		
PC/PBT GF	21	35		
PA 66 medium level GF	21	33		
PA 66 medium level long GF	21	33		
PCT GF	21	30		
PA 66 high level long GF	21	27		

Continued

Table 11.1 Examples of Oxygen Index—cont'd

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PA Transparent	21	26		
PAA medium level GF	21	25		
PAA MINERAL	21	25		
PET Amorphous	21	25		
PK GF	21	24		
PA 6	21	23		
PA 66 high level GF	21	23		
PA 66 impact medium level GF	21	23		
PET GF	21	23		
PAA medium level CF	21	22		
PBT medium level GB	21	22		
PBT medium level GF	21	21		
PBT GF and mineral	21	21		
PBT long GF	21	21		
PK	21	21		
PVC plasticized			20	40
PA 6 GB	20	30		
PA 6 medium level GF	20	30		
PA 6 medium level long GF	20	30		
PA 6 GF recycled	20	30		
PA 6 high level GF	20	30		
PA 6 high level long GF	20	30		
PA 6 mineral FR	20	30		
PA 66 GB	20	30		
COPE high Shore D	20	28		
PA 6–10	20	27		
PA 6–12	20	23		
PA 6–12 GF	20	23		
PA 6 recycled	20	22		
ABS/PA	20	21		
ABS/PA 20 GF	20	21		
COPE low Shore D	20	21		

Table 11.1 Examples of Oxygen Index—cont'd

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
COPE bio	20	21		
EVA	19	39		
ASA/PC	19	30		
PET/PC	19	25		
Acrylique Imide	19	21		
ASA/PBT GF	19	21		
PBT long CF	19	21		
PBT CF	19	21		
PET/PC GF	19	21		
PMI or PMMI	19	20		
PTT bio	19	20		
PTT bio GF	19	20		
PPE	18	36		
PPE GF	18	36		
PPE/PA	18	36		
ABS conductive	18	28		
SAN GF	18	28		
TPS Shore D	18	27		
PPE MINERAL	18	22		
ASA/PMMA	18	20		
PMMA	18	20		
PMMA GF	18	20		
PMMA antistatic	18	20		
PMMA impact	18	20		
ABS	18	19		
ABS GF	18	19		
ABS GB	18	19		
ABS CF	18	19		
ASA	18	19		
MABS	18	19		
POM GF	18	19		
POM long GF	18	19		

Continued

Table 11.1 Examples of Oxygen Index—cont'd

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
POM GB	18	19		
POM CF	18	19		
POM far	18	19		
POM friction	18	19		
POM mineral	18	19		
PPE CF	18	19		
SAN	18	19		
SMA	18	19		
SMA GF	18	19		
POM conductive	18	18		
PP antistat	18	18		
PP conductive	18	18		
TPO Shore D	18	18		
TPV Shore D	18	18		
PS GF	17	38		
PE-HD	17	30		
PP mineral	17	30		
PP talc	17	30		
PS	17	30		
PS impact	17	30		
PP Co	17	27		
PP Ho	17	27		
PP/PA	17	20		
PP/PA GF	17	20		
Starch/copolyester	17	20		
Starch/PS	17	20		
PE GF	17	19		
PE 60% long GF	17	19		
CA	17	18		
CAB	17	18		
COC	17	18		
CP	17	18		

Table 11.1 Examples of Oxygen Index—cont'd

	Nonhalogenated Molecule		Halogenated Molecule	
Extremum from the Examined Literature	**Minimum**	**Maximum**	**Minimum**	**Maximum**
PB	17	18		
PE-HD antistat black	17	18		
PE-LD	17	18		
PE-UHMW	17	18		
PE-X cross-linked	17	18		
PMP	17	18		
PMP GF	17	18		
PMP mineral	17	18		
PP impact	17	18		
PP recyclé	17	18		
PP low level GF	17	18		
PP medium level GF	17	18		
PP GB	17	18		
PP low level CNT	17	18		
PP medium CNT	17	18		
PP cellulose fibers	17	18		
PP long GF medium level	17	18		
PP CaCO3	17	18		
PP long GF high level	17	18		
PP CF	17	18		
PP natural fibers	17	18		
PP/EPDM-V	17	18		
Starch/PE	17	18		
Starch/PP	17	18		
TPU GF	17	18		
TPU long GF	17	18		
TPU bio	17	18		
TPU conductive	17	18		
TPU Shore D	17	18		
POM homo or copolymer	16	19		

- Halogen-free (see Figure 11.2)
  - Polysulfones (PSU, PES, PPSU)
  - Polyamide-imide (PAI)
  - Polyetherimide (PEI)
  - Polyphenylenesulfide (PPS)
  - Thermoplastic polyimides
  - Polyetherether ketone (PEEK)
  - Liquid crystal polymers (LCP)
  - Polybenzimidazole (PBI)

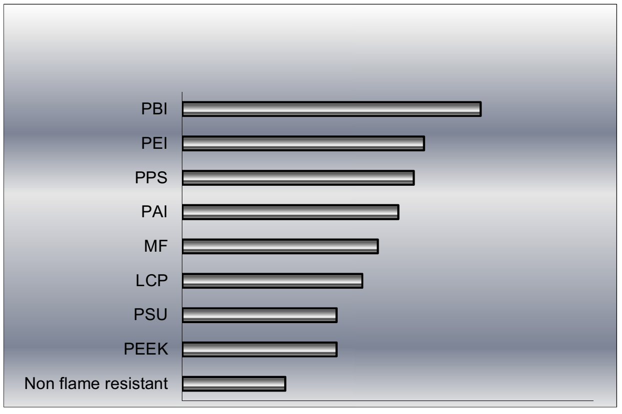

Figure 11.2 "Oxygen-Index-Examples".

For example, inherently FR Ultem resin grades offer full FST compliance, and allow one to produce light weight aircraft interior parts.

11.4 FR Solutions

FR solutions are categorized in to:

- Halogen-containing (HCFR) solutions: the oldest route and always often used but less environment friendly
- Halogen-free (HFFR) solutions: recent and ecological ways.

Figure 11.3 shows some examples of halogen-free and conventional FR routes.

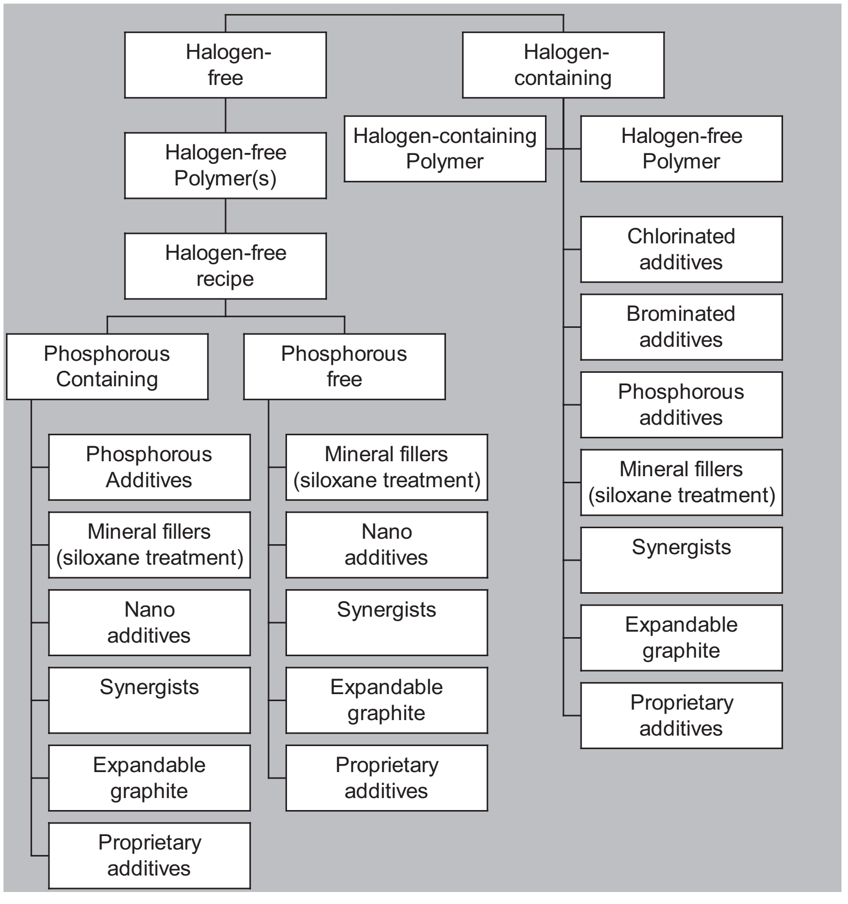

Figure 11.3 "Examples of halogen-free and conventional FR routes".

Generally speaking:

- Halogenated FR (Br or Cl containing) may include some of the following advantages:
  - Lower cost
  - Wider processing window
  - Good FR efficiency
  - Good physical properties retention
  - Well-known technology
- Nonhalogenated FR may include some of the following advantages:
  - Lower corrosivity
  - Lower smoke generation
  - Lower Toxicity
  - Environment-friendly

Figure 11.4 shows market shares of the main FR routes.

Among others, HFFR solutions can be based on:

- Phosphorous additives: When subjected to heat, they react to form polymeric phosphates that build a hard glassy layer on the surface of the plastic. This inhibits access of oxygen to the combustible material and prevents flammable gases from being released. As a result, the plastic chars rather than burning. Among others, we can quote:
  - Phosphates ester plasticizers, ammonium polyphosphate…
  - Metal phosphinates
  - Organic phosphonates
  - Organic phosphinates
  - Polymeric flame retardant (FRX polymers), a phosphorus-based system bound onto the polymer. It is nonvolatile and nonmigrating. The plastics have high limiting oxygen index according to FRX Polymers
  - Red phosphorous

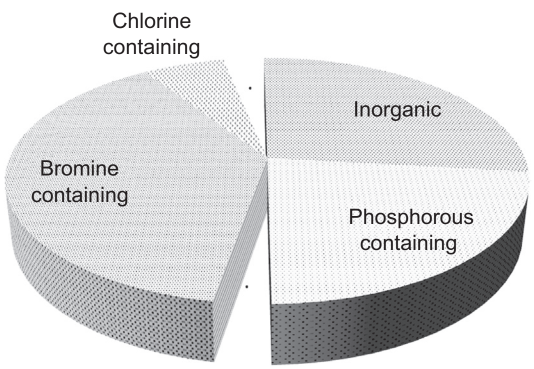

Figure 11.4 "Market shares of Halogen-free Flame Retardant and Halogen-containing flame retardant solutions".

Some phosphorus are banned by some regulations, standards, or private specifications requiring halogen-free and phosphorus-free additives.

- Nitrogen-based flame retardants such as melamine compounds. The mechanism of fire retarding is not fully understood and probably is a combination of effects. Inert nitrogen is released and stable barrier layers of "char" are built on material surfaces. Melamines and their derivatives such as melamine phosphates, melamine pyrophosphates, and other products combining nitrogen and phosphorous derivatives lead to synergistic effects.
- Metal hydroxides such as aluminum and magnesium hydroxides have several effects. When heated, they release large volumes of water vapor, which inhibits oxygen access to the surface and dilutes any released flammable gases. Also, they decompose endothermically which means that they adsorb heat, thereby cooling the material. Metal hydroxides include aluminum trihydroxide (ATH), magnesium hydroxide (MDH) for the most used but aluminum oxide hydroxide is also quoted.
- Intumescent materials, for example ammoniumpolyphosphate (APP), are chemicals that produce a bulky porous ceramic coating that covers the material surface preventing it from burning. These materials release large amounts of inert gases and a thick viscous liquid which together form a foam. This foam loses its organic constituents when hot to leave a hard ceramic foam coating.
- Nano fillers:
  - Nanosilicates and nano-oxides, for example, MARTINAL® and MAGNIFIN® CHAR™, are flame retardant grades launched by Albemarle and based on nanotechnology
  - MWCNT (Multiwalled carbon nanotubes) are claimed efficient in PE cables and PUR foam

  - FlexB™ by Applied NanoWorks (ANW): a boron-based, nonhalogenated flame retardant (FR) additive
  - Nanocomplexes such as Fe-montmorillonite
- Expanded graphite: The limiting oxygen index (LOI) and thermal gravimetric analysis (TGA) show that the incorporation of expanded graphite in polypropylene (PP) including intumescent flame retardant (IFR) would impart extra flame retardancy and thermal stability to the virgin formulation PP-IFR.
- Siloxanes for mineral filler treatments or as an FR additive. Siloxanes can improve the compatibility of the mineral fire retardant with the polymer matrix and improve the performance for a given loading level or allow a higher filler loading for the same performance level. Fire retardant effect is claimed in particular cases.
- Metal functionalized silsesquioxane Me-POSS. The combustion behavior of thermoplastics containing dimeric and oligomeric Al- and Zn-isobutyl silsesquioxane are claimed to have improved. Al-POSS or Zn-POSS modified polypropylene (PP) show that the presence of Al-POSS leads to a decrease in the combustion rate with respect to neat PP, resulting in a decrease in heat release rate (−43% at 10 wt% Al-POSS loading) as well as reduction in CO and CO_2 production rates. Al-POSS favors the formation of a moderate amount of char residue.
- Others
  - Boron compounds function in a similar way as phosphorous flame retardants.
  - Zinc borate works by a variety of mechanisms including synergistic effects with ATH.
  - Tin derivatives, ammonium salts, molybdenum derivatives, magnesium sulfate heptahydrate, etc. are more or less used.
  - Zinc and tin compounds are added to PVC to reduce smoke emission and increase the effectiveness of other types of flame retardant.
  - Inorganic complexes or compounds such as Kemgard® products, flame retardant/smoke suppressant additives including zinc molybdate, calcium zinc molybdate, zinc oxide/phosphate, zinc molybdate–magnesium silicate, zinc molybdate/magnesium hydroxide.

It must be noted that the efficiency of each way is linked to the nature of the thermoplastic resin.

Of course, those techniques have generated a multitude of proprietary additives.

11.5 The Top Solutions: HFFR and FST grades

The ready-to-use HFFR compounds are one of the easiest solutions but grades are limited to the most used resins for E&E, building and construction, automobile, etc. The most common are polyamides, thermoplastic polyesters, polyolefins, ABS and polycarbonate alloys, polyphenylene oxide but the plastics range is fast developing.

Let us quote some examples without claiming to be exhaustive.

11.5.1 Polyamides

- Chem polymer, a unit of Teknor Apex Company proposes a grade of 25% glass fiber-reinforced polyamide with a UL 94 flammability listing of V0 at thicknesses down to 0.8 mm.
- Rhodia polyamide proposes halogen and red phosphorous-free versions of flame retardant polyamide resins. Rhodia polyamide claims that these products meet RoHS and WEEE directives. Halogen and red phosphorus-free flame retardant, Thirty percent glass-filled grade combines high mechanical performance (impact, strength, and stiffness) and UL94 V0 rating.
- SABIC Innovative Plastics proposes Starflam compounds, glass fiber-reinforced polyamides providing good impact performance, and electrical properties together with a V-0 flame rating at 0.8 mm thickness.
- RTP proposes PA 66 halogen-free flame retardant, V-0 at 0.8 mm.
- VAMPTECH has launched grades of flame retardant glass reinforced polyamides (PA) that are free from halogens, phosphorus, and heavy metals.
- Grupo Repol markets 20 up to 45% glass fiber or mineral-reinforced PA6 or PA66, halogen and red phosphorous-free grades with UL94 V0 rating, and good mechanical properties in a wide range of colors.

- DSM markets ultraflow polyamides, halogen-free FR.
- HFFR PA compound is marketed by S&D corp.

11.5.2 Thermoplastic polyesters

- Ticona engineering polymers market a halogen-free flame retardant grade with improved processability and fair properties
- DSM proposes a halogen-free material specifically designed for connectors that meet the requirements in IEC 60335-1. The material offers excellent thermal performance in addition to a high CTI, good moldability, and lower moisture uptake in comparison with general purpose PA 6 and PA 66.

11.5.3 Polyolefins

- Teknor Apex Company proposes various HFFR polyolefin cable compounds with oxygen indexes superior to 30, for example, 34 and 35.
- RTP proposes a polypropylene grade, flame retardant—halogen-free—UL94 V-0 at 1.5 mm with an oxygen index of 34.
- Solvay Padanaplast markets a series of HFFR cable compounds with an oxygen index of 37.

11.5.4 Polycarbonate

- SABIC Innovative Plastics proposes FST grades tested for smoke, heat release, and fire safety hazard level according to relevant FAR 25.853, ASTM E 662, ISO 5660-1, ISO 5659-2, EN 45545-2:2013.
- GINAR Engineering Plastics proposes KAPEX ®Flame Retardant PC rated V0 at 0.8 mm.

11.5.5 Polycarbonate/polyester blend resin

- Bayer MaterialScience LLC (BMS) has developed a new class of eco-compliant, flame retardant Makroblend® polycarbonate/polyester blend resin without the use of brominated or chlorinated FR additives or heavy metals. Specifically, Makroblend DP EC100 offers V0/5VA at 3.0 mm and is being evaluated at 2.0 mm, while Makroblend DP EC150 is rated V0 at 0.75 mm and 5VA at 2.3 mm.

11.5.6 ABS/PC alloys

- RTP proposes grades of flame retardant PC/ABS, halogen-free, UL94 V0.
- DSM markets a good flowing grade of ABS/PC.

11.5.7 Polyphenylene oxide

- RTP markets HFFR PPO.

11.5.8 Copolyester thermoplastic elastomer

- DSM proposes a hydrolysis-resistant HFFR TPEE for automotive class D cables. Continuous use temperature is claimed to be 3000 h at 175 °C.

11.5.9 Thermoplastic polyurethane

- A Korean compounder proposes an HFFR thermoplastic polyurethane (TPU) compound for optical fiber cable and electric cables.

11.6 Examples of Effect of FR Modifications on Properties

FR grade properties are often affected versus those of similar non-FR formula. Tables 11.2–11.14 display some examples without claiming to be exhaustive. Other data can be found elsewhere.

There are exceptions but generally, on average for the quoted grades:

- Density of FR grades is 12% higher than the density of GP grades
- Modulus of FR grades is 18% higher than the modulus of GP grades
- Strength of FR grades is 9% lower than the strength of GP grades.

Results must be carefully examined:

- Those data aren't comparable and are quite arbitrary
- Formulation is unknown

Table 11.2 Example of Polyethylene Cable

Physical Properties	Low Smoke Zero Halogen FR	GP	Comments
Density	1.15	0.931	
Mechanical Properties			
Hardness, Shore D	40	50	
Tensile strength at break, MPa	13	≥15	
Elongation at break, %	550	≥600	
Flexural modulus, GPa	0.215	0.250 GPa	
Electrical Properties			
Volume resistivity, ohm/cm	1.00e + 6	1.00e + 6	
Dielectric strength, kV/mm	≤20.0	≥20.0	
Thermal Properties			
Maximum service temperature, Air	200 °C		
Brittleness temperature, °C	≤–60	≤–76	
Aging: 240 h, 100°C; or UV Aging			
Tensile strength at break, MPa	≤2.60		
Elongation at break	≤110%		
FST Tests			
Oxygen index, %	27		
NBS smoke density	49		6 min; flaming mode
NBS smoke density	104		20 min; nonflaming mode
Average heat release, kW/m^2	244		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)
CO, kg/dm^3	0.023		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)
CO_2, kg/dm^3	1.7		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)
Corrosivity of combustion fumes	1.5		IEC 60754-2
Dielectric duration	Pass		IEC 60227-2/2.3
Heat combustion, MJ/dm^3	29		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)
Ignition time, s	125		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)
Max heat release, kW/m^2	400		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)
Smoke obscuration, m^2/dmm^3	520		ISO 5660; Cone calorimeter (heat flux 35 kW/m^2, 3 mm)

Table 11.3 Example of Polypropylene, 20% Glass Filled

Physical Properties	**FR V0**	**GP**
Density	1.34	1.12
Linear mold shrinkage, cm/cm	0.005–0.0080	0.005–0.0080
Mechanical Properties		
Tensile strength at break, MPa	55	
Flexural strength, MPa		≤95
Elongation at break, %	3	
Elongation at yield, %		5
Flexural modulus, GPa	5	2.3
Thermal Properties		
HDT A 1.8 MPa, °C	135	108
Vicat softening Point at load 5.00 kg, °C	120	120
Flammability, UL94 at thickness 1.60 mm	V-0	HB

Table 11.4 Example of PA6, 15 GF

	FR–Halogen and Red Phosphorus Free, Low Smoke and Toxic Gas	**GP**
Density	1.67	1.23
Moisture absorption at 23 °C, %	1.10	2.5
Linear mold shrinkage, flow, cm/cm	0.0030	0.0030
Linear mold shrinkage, transverse, cm/cm	0.007	0.011
Mechanical Properties		
Tensile strength at break, MPa	70	125
Elongation at break, %	2	3.5
Tensile modulus, GPa	9	6
Izod impact, notched (ISO) kJ/m² at –30.0 °C	6	6
Izod impact, notched (ISO) kJ/m² at 23 °C	7	7
Izod impact, unnotched (ISO) kJ/m² at 23 °C	10	45
Electrical Properties		
Volume resistivity, ohm/cm	1.00e + 15	1.00e + 15
Surface resistance, 13 Ω	1.00e + 13	1.00e + 13
Thermal Properties		
Melting point, °C	223	223
HFT B 0.46 MPa, °C	205	215

Continued

Table 11.4 Example of PA6, 15 GF—cont'd

	FR–Halogen and Red Phosphorus Free, Low Smoke and Toxic Gas	GP
HDT a 1.8 MPa, °C	185	200
Vicat softening point, °C at load 5.10 kg	205	210
Flammability, UL94 at thickness 1.60 mm	V-0	HB
Flammability, UL94 at thickness 0.75 mm	V-0	HB

Table 11.5 Example of PA6, 25 GF

Physical Properties	FR	GP
Density	1.69	1.32
Moisture absorption at equilibrium, %	0.9	2.3
Mechanical Properties		
Tensile strength at break, MPa	157	
Elongation at break, %	3	
Elongation at yield, %		3.5
Flexural strength, MPa	232	220
Flexural modulus, GPa	9	7.4
Thermal Properties		
HDT A 1.8 MPa, °C	195	210
UL RTI, electrical at thickness 1.50 mm	130 °C	
UL RTI, mechanical with impact at thickness 1.50 mm	115 °C	
UL RTI, mechanical without impact at thickness 1.50 mm	115 °C	
Flammability, UL94 at thickness ≥ 1.50 mm	V-0	HB

Table 11.6 Example of PA6, 30 GF

Physical Properties	FR	HFFR	GP
Density	1.65	1.32	1.33
Tensile strength at break, MPa	138	121	165
Flexural strength, MPa	207	192	248
Flexural modulus, GPa	9.6	9.1	9
Flammability, UL94 at thickness ≥ 1.50 mm	V-0	V0	HB

Table 11.7 Example of PA 66 25 GF

	V-0(Phosphorous)	GP
Physical Properties		
Density	1.35	1.31
Moisture absorption at equilibrium, %	≤0.25	
Mechanical Properties		
Elongation at break, %		3
Elongation at yield, %	3	
Flexural strength, MPa	180	175
Flexural modulus, GPa	6.5	4.7–8
Charpy impact unnotched, J/cm² at 23.0 °C	4	
Charpy impact, notched, J/cm² at 23.0 °C	1	
HDT A 1.8 MPa, °C	250	250
Vicat softening point, °C	≥230	
Flammability, UL94 at Thickness 1.60 mm	V-0	HB

Table 11.8 Example of PC, 20 GF

	FR	GP
Density	1.34	1.34
Water absorption, %	0.15	0.08
Linear mold shrinkage, cm/cm	0.0015	0.0030–0.0050
Mechanical Properties		
Tensile strength, yield, MPa	105	105
Elongation at break, %	3.0%	5
Flexural modulus, GPa	6	5.6
Izod impact, unnotched, J/m	90	90
Electrical Properties		
Comparative tracking index	150	150
Thermal Properties		
HDT a 1.8 MPa, °C	147	139
Vicat softening point, °C	150	147
Flammability, UL94 at thickness 1.60 mm	V-0	V-1

Table 11.9 Example of PBT, 15 GF

	FR	GP
Density	1.54	1.41
Mechanical Properties		
Tensile strength at break	95	89
Flexural strength, MPa	148	136
Flexural modulus, GPa	5.2	4.3
Izod impact, notched, J/m	54	53
Thermal Properties		
HDT a 1.8 MPa, °C	182	168
Flammability, UL94 at thickness 1.5 mm	V-0	

Table 11.10 Example of PBT, 30 GF

Physical Properties	FR	HFFR	GP
Density	1.65	1.56	1.5
Tensile strength at break, MPa	138	106	150
Flexural strength, MPa	228	170	248
Flexural modulus, GPa	9.6	10.3	8
Izod notched J/m	87	88	80
Flammability, UL94 at thickness ≥ 1.50 mm	V0	V0	HB

Table 11.11 Example of PC/ABS Blend

	Flame Retardant	GP
Density	1.19	1.12
Linear mold shrinkage, cm/cm	0.0050–0.0070	0.0050–0.0070
Melt index g/10 min, 5.00 kg, 260 °C	25	15
Mechanical Properties		
Elongation at yield, %	4.5	5
Flexural strength, MPa	≤90	≤95
Flexural modulus, GPa	2.4	2.3
Charpy impact, notched J/cm² at –20.0 °C	2.2	2.5
Charpy impact, notched J/cm² at 23.0 °C	3.5	4
Thermal Properties		
HDT B 0.46 MPa, °C	115	125
HDT a 1.8 MPa, °C	95	108
Vicat softening point at load 5 kg, °C	110	120
Flammability, UL94 at thickness 1.60 mm	V-2	HB
Flammability, UL94 at thickness 2.50 mm	V-0	

Table 11.12 Example of PC/PBT Blend

Physical Properties	Flame Retardant	GP
Density	1.29	1.17
Mechanical Properties		
Tensile strength at break, MPa	≤40	≤50
Elongation at yield, %	5	6
Flexural strength, MPa	≤67	≤70
Flexural modulus, GPa	2.3	2
Charpy impact, notched, J/cm² at 23.0 °C	1.3	4.5
Thermal Properties		
HDT B 0.46 MPa, °C	90	90
HDT A 1.8 MPa, °C	81	81
Vicat softening point, °C at load 5 kg	110	108
Vicat softening point, °C at load 1 kg	134	132
Flammability, UL94 at Thickness 1.60 mm	V0	HB

Table 11.13 Example of COPE (Copolyesters), 55 Shore D

Physical Properties	HFFR Phosphorous Free	GP
Density	1.28	1.26
Water absorption, %	0.6	0.6
Moisture absorption at equilibrium, %	0.25	0.25
Mechanical Properties		
Hardness, Shore D	55	55
Tensile strength, yield, MPa	16.5	15
Elongation at break, %	≥50	≥50
Elongation at yield, %	20	23
Tensile modulus, GPa	0.25	0.25
Charpy impact, notched at 23.0 °C	No break	No break
Electrical Properties		
Comparative tracking index	600	600
Thermal Properties		
Melting point, °C	200	195
HDT B 0.46 MPa, °C	85	80
Vicat softening point, °C	90	85
Flammability, UL94 at thickness 1.60 mm		HB

Table 11.14 Example of TPU 55 Shore D

Physical Properties	HFFR	GP
Density	1.27	
Mechanical Properties		
Tensile strength, MPa	20	40
Elongation at break, %	400	460
Tear strength, kN/m	110	180
Thermal Properties		
Flammability, UL94	V-0	

- Compounds may be conditioned, dry as molded or in unknown state
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

These theoretical data should not be directly used for compliance to specifications, designing, computing, or to make economic predictions. For fire requirements, only properties measured by an authorized organization on the specific samples required by the relevant standards must be considered.

Further Reading

Technical guides, newsletters, websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, Borealis, BP Chemicals, Bryte, Ceca, Celanese, Chem Polymer, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eurotec, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, GINAR Engineering Plastics,Grupo Repol, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Matweb, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, RTP, Sabic, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Taber, Technochemie GmbH, Teknor Apex, Telenor, The European Alliance for SMC, Thieme, Ticona, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vamptech, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.Com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

12 Electrical Properties

OUTLINE

Most thermoplastics are generally insulating materials. Electrostatic build-up and discharges are widespread, leading to many issues from minor to very high and even tragic seriousness:

- Dust and other pollutant attraction with marketing, use, and processing problems, notably for continuous processing of plastics such as films.
- Electrostatic build-up or discharges when touching the plastic parts: synthetic carpets, knobs, car handles; electronic manufacturing, handling, and repairing.
- Painting defects.
- Fire or explosion of inflammable or explosive environment such as fine organic powders, solvents…: packaging of dusty organic materials, electrostatic discharge of car fuel lines leading to fires, lightning and interferences for planes, healthcare, operating theater, painting shops…

Antistatic behavior, electrostatic build-up, and discharge (see Figure 12.1) depend on the surface resistivity of the part. Generally, antistatic or electrostatic dissipative (ESD) polymers have:

- A surface resistivity in a range from 10^5 or 10^6 up to $10^{12}\,\Omega$.
- A static discharge half-life generally inferior to 60 s.

The most usual tested characteristics are:

- Volume resistivity
- Permittivity or dielectric constant
- Dielectric strength
- Loss factor
- Surface resistivity

But there are many other characteristics, for instance:

- Arc resistance
- Static decay

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00012-X

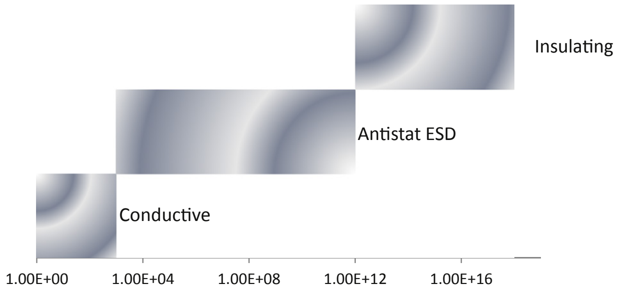

Figure 12.1 Surface resistivity range of plastics.

- Comparative tracking index
- High-voltage arc tracking rate (HVTR)
- Needle flame test
- High current arc ignition (HAI)
- Hot-wire ignition (HWI), etc.

Apart from these electrical properties, EE are also subjected to fire and service temperature laws; standards and regulations such as UL 94 fire ratings, UL temperature index; and many other international, national, regional, or application sector specifications.

All electrical properties may be dependent on the current frequency, the actual temperature, and moisture content of the thermoplastic, heat history, and mechanical aging.

For example, certain conductive thermoplastics may be insulating after cyclic loading.

A few thermoplastics can have piezoelectric properties.

12.1 Volume Resistivity

The volume resistivity is the electrical resistance of a polymer sample of unit area and unit thickness when electrodes placed on two opposite faces apply an electrical potential across it. The volume resistivity is expressed in Ω·cm.

Classification of polymers varies depending on the country and application. Each case must be examined in its context, and the following data are only arbitrary and fuzzy examples with overlapping of different subfamilies:

- insulating polymers: resistivity higher than 10^{10} Ω·cm
- antistatic and ESD polymers: resistivity lower than 10^{12} Ω·cm
- conductive polymers: resistivity lower than 10^{5} Ω·cm
- polymers for electrical heating: resistivity lower than 10^{2} Ω·cm.

These data are not a rule and other figures can be found elsewhere. They cannot be used for designing any parts or goods, the requirements for the targeted application have to be defined and tested in actual conditions according to relevant standards and procedures.

Table 12.1 displays examples of volume resistivity (ranked by a descending order of maximum resistivity) for about 250 grades including about 200 insulating ones. Used standards aren't indicated but are expected to be more or less similar to ASTM D257.

Results must be carefully examined:

- Those data aren't strictly comparable.
- Grades taken into account are in limited number.
- Other data can be found elsewhere; in fact all polymers can be made conductive, thanks to additives such as carbon blacks, metal powders, carbon or steel fibers, etc.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- Reinforcement, plasticization, impact modification, conductive recipe, etc. aren't always pointed out.
- A defined family can appear in insulating column but some grades can be conductive. For instance, the range for "PI TP friction" is 3–13, which means that some grades are conductive when others are insulating.
- A defined family can be found in several lines because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound with the standards required for the targeted application.

Results should not be interpreted as an indication of the suitability for any targeted application.

Table 12.1 Examples of Volume Resistivity at Room Temperature

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
COC	15	18		
EMA	15	18		
FEP	15	18		
PB	15	18		
PAI GF	14	18		
PFA	14	18		
PMP	14	18		
PP impact	14	18		
PTFE	14	18		
PCTFE	13	18		
PE-LD	13	18		
PE-UHMW	13	18		
PE-HD	12	18		
ECTFE	15	17		
ETFE	15	17		
ETFE GF	15	17		
PAI	15	17		
PMMA GF	15	17		
PP Ho	15	17		
PAEK (PEK, PEKK, PEEK, PEEKK, PEKEKK)	14	17		
PEI	14	17		
PMP GF	14	17		
Polyarylate	14	17		
LCP GF	13	17		
PEEK	13	17		
PEEK GF	13	17		
PAEK 30% GF	13	17		
PE GF	13	17		
PE 60% long GF	13	17		

Continued

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
PP low-level GF	13	17		
PP medium-level GF	13	17		
PP long GF, medium level	13	17		
PP long GF, high level	13	17		
PSU	13	17		
PTFE GF	13	17		
PP mineral	12	17		
PP talc	12	17		
PSU modified	12	17		
Acrylique imide	15	16		
ASA/PBT GF	15	16		
EVA	15	16		
PMI or PMMI	15	16		
ABS	14	16		
ABS/PC low-level long GF	14	16		
ABS/PC medium-level long GF	14	16		
PEI GF	14	16		
PEI mineral	14	16		
PET	14	16		
PET GF	14	16		
PET Amorphous	14	16		
PET/PBT high-level GF	14	16		
PI TP	14	16		
PI TP GF	14	16		
PMP mineral	14	16		
Polyarylate GF	14	16		
POM Far	14	16		
PSU/ABS	14	16		
PSU/PBT GF	14	16		
PSU/PC	14	16		
SMA	14	16		

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
SMMA	14	16		
TPO Shore D	14	16		
TPS Shore D	14	16		
TPV Shore D	14	16		
ABS/PC GF	13	16		
PAI mineral	13	16		
PBT medium-level GF	13	16		
PC	13	16		
PC GF	13	16		
PC/SAN GF	13	16		
PCT GF	13	16		
PET/PC	13	16		
PET/PC GF	13	16		
PE-X cross-linked	13	16		
PK	13	16		
PMMA impact	13	16		
PP/EPDM-V	13	16		
PP/PA GF	13	16		
PPA GF	13	16		
PPA mineral	13	16		
PPA long GF	13	16		
PPE	13	16		
PPE GF	13	16		
PPE/PA GF	13	16		
PPS	13	16		
PPS GF	13	16		
PPS long GF medium level	13	16		
PPS long GF high level	13	16		
PPS Far	13	16		
PPS GF + mineral	13	16		
PS	13	16		

Continued

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	**Maximum**	**Minimum**	**Maximum**
	Log (Volume Resistivity, ohm·cm)			
PS GF	13	16		
PS impact	13	16		
PSU mineral	13	16		
PVC unplasticized	13	16		
PVCC	13	16		
SAN	13	16		
SMA GF	13	16		
LCP mineral	12	16		
PAA mineral	12	16		
PC friction	12	16		
PES GF	12	16		
POM friction	12	16		
PP/PA	12	16		
PPA	12	16		
PPE/PA	12	16		
PSU GF	12	16		
PAA medium-level GF	11	16		
PMMA	11	16		
PPE mineral	11	16		
PVC plasticized	10	16		
TPE based on PVC	10	16		
ABS FR	14	15		
ABS/PVC	14	15		
CP	14	15		
FEP GF	14	15		
PBI	14	15		
PEEK/PBI	14	15		
PEEK/PBI GF	14	15		
PEI GF milled	14	15		
PVDF Mica	14	15		
ABS GF	13	15		

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
ABS GB	13	15		
ABS/PA 20 GF	13	15		
ABS/PC	13	15		
ASA/PMMA	13	15		
ASA/PVC	13	15		
CA	13	15		
LCP	13	15		
MABS	13	15		
PBT	13	15		
PBT medium-level GB	13	15		
PBT GF and mineral	13	15		
PBT long GF	13	15		
PC/PBT	13	15		
PC/PBT GF	13	15		
PES	13	15		
PK GF	13	15		
POM homo or copolymer	13	15		
POM GF	13	15		
POM long GF	13	15		
PP $CaCO_3$	13	15		
PPSU	13	15		
PPSU GF	13	15		
PTT Bio	13	15		
PTT Bio GF	13	15		
PVC GF	13	15		
SAN GF	13	15		
ASA	12	15		
PA 610	12	15		
POM mineral	12	15		
PP GB	12	15		
PVDC	12	15		

Continued

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
ABS/PA	11	15		
ASA/PC	11	15		
CAB	11	15		
PA 11	11	15		
PA 6 GB	11	15		
PA 6 medium-level GF	11	15		
PA 6 medium-level long GF	11	15		
PA 6 high-level GF	11	15		
PA 6 high-level long GF	11	15		
PA 66 GB	11	15		
PA 66 medium-level GF	11	15		
PA 66 medium-level long GF	11	15		
PA 66 high-level GF	11	15		
PA 66 high-level long GF	11	15		
PA transparent	11	15		
PAA high-level GF	11	15		
PP Co	11	15		
PP recycled	11	15		
PA 6 FR	10	15		
PA 6 mineral FR	10	15		
PA 4-6 GF	9	15		
PA 4-6 mineral	9	15		
PA 4-6	7	15		
PAI friction	7	15		
CPE	13	14		
POM GB	13	14		
PVF	13	14		
PA 12 GF	12	14		
PA Far	12	14		
PP cellulose fibers	12	14		
PP natural fibers	12	14		

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	**Maximum**	**Minimum**	**Maximum**
	Log (Volume Resistivity, ohm·cm)			
PVDF friction	12	14		
PA 11 GF	11	14		
PA 12	11	14		
PA 4-10 GF Bio	11	14		
PA 6	11	14		
PA 612	11	14		
PA 66	11	14		
PA 66 mineral	11	14		
PA 66 impact, medium-level GF	11	14		
PA castable	11	14		
PA castable, friction	11	14		
COPE high Shore D	10	14		
COPE low Shore D	10	14		
COPE Bio	10	14		
PA 6 GF recycled	10	14		
PVDF	10	14		
TPU long GF	10	14		
TPU Bio	10	14		
TPU GF	8	14		
TPU Shore D	8	14		
PA 10-10 high-level GF Bio	11	13		
PA 11 or 12 plasticized	11	13		
PA 12 GB	11	13		
PA 12 friction	11	13		
PA 410 Bio	11	13		
PA 612 GF	11	13		
PA 6 recycled	10	13		
PEBA 25 to 45 Shore D	10	13		
PEBA 50 to 72 Shore D	10	13		
PEBA Bio	9	13		
PI TP friction	3	13		

Continued

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
PA 10-10 Bio			9	12
PMMA antistat			9	11
PP antistat			3	11
PES CF			2	10
PE-HD antistat black			5	9
PA CNT			2	9
ABS/PC conductive			0.1	9
MPR			8	8
LCP CF			1	8
PA 610 CF			1	8
PP low-level CNT			4	7
PEI conductive			4	6
PEEK CF			3	6
PC CF			3	6
PEEK/PBI CF			3	6
PES friction			3	6
PA 12 conductive			2	6
PAI CF			2	6
PBT CF			2	6
PEI CF			2	6
PPA CF			2	6
PPS CF + GF			2	6
ABS CF			1	6
PAA medium-level CF			1	6
PVDF CF			1	6
PA 66 CF			1	5
PA 66 long CF			1	5
PI TP CF			3	4
PPS CF			3	4
PPE CF			2	4
POM CF			1	4

Table 12.1 Examples of Volume Resistivity at Room Temperature—cont'd

Extremum from the Examined Literature	Insulating		Conductive	
	Minimum	Maximum	Minimum	Maximum
	Log (Volume Resistivity, ohm·cm)			
PTFE CF			3	3
PBT long CF			2	3
PA 12 CF			1	3
PP CF			0.1	3
PC conductive			–0.05	3
PP conductive			–0.05	3
PA 66 conductive			–0.3	3
PPS conductive			–1	3
PC CNT			1	2
ABS conductive			0.1	2
POM conductive			–0.05	2
PP medium CNT			1	1
TPU conductive			–0.3	–0.01

12.2 Relative Permittivity or Dielectric Constant

Dielectric constant is a dimensionless number (without unit) relating the ability of a material to carry alternating current to the ability of vacuum (index 1) to carry alternating current.

Relative permittivity or dielectric constant can be tested according, for example, to ASTM D150—11 Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation.

Permittivity is typically associated with dielectric materials.

A low value of permittivity is desirable for insulating materials used to support and insulate components of an electrical network from each other and from ground. For a capacitor, it is generally desirable to have a high value of permittivity, so that the capacitor is able to be physically as small as possible.

Table 12.2 displays examples of permittivity or dielectric constant of plastics and some other media at room temperature. Used standards aren't indicated but are expected to be more or less similar to ASTM D150. These data are not a rule and other figures can be found elsewhere. They cannot be used for designing any parts or goods, the requirements for the targeted application having to be matched.

Results, ranked by an ascending order of minimum values, must be carefully examined:

- Those data aren't strictly comparable.
- Grades taken into account are in limited number.
- Frequency isn't indicated.
- Other data can be found elsewhere because all polymers can be modified, thanks to additives. For example, liquid crystal polymer (LCP) has a permittivity in the order of 3–4 for a general-purpose grade and 13–15 for a carbon fiber-reinforced grade, etc.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- Reinforcement, plasticization, impact modification, conductive recipe, etc. aren't always pointed out.

Table 12.2 Examples of Permittivity or Dielectric Constant at Room Temperature

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
Vacuum	1		
Air	1		
Glass	4–7		
Mica	5–9		
Alumina	8–10		
Water	80		
PCTFE		2	3
ABS/PC FR recycled		2	3
ABS/PC recycled		2	3
PMMA cast		2	5
PMMA molded		2	5
PMMA HT		2	5
FEP		2.1	2.1
PFA		2.1	2.1
PTFE		2.1	2.1
PMP		2.1	2.1
PE-UHMW		2.1	3
PE-X		2.2	2.2
PP antistat		2.2	2.3
EMA		2.2	2.5
PTFE GF		2.2	2.8
PE-HD		2.3	2.3
PE-L		2.3	2.3
PP 10-40 talc		2.3	2.3
PP 10-40 mineral		2.3	2.3
PE-LD		2.3	2.3
PP homopolymer		2.3	2.3
PP FPP tape		2.3	2.3
PP FPP sheet		2.3	2.3
PP impact		2.3	2.3
PP copolymer		2.3	2.3
COC optical		2.3	2.3

Table 12.2 Examples of Permittivity or Dielectric Constant at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
PE-HD colored		2.3	2.4
PE-HD avec recycled		2.3	2.4
TPV Shore D		2.3	2.4
TPO Shore D		2.3	2.4
COC GP		2.3	2.4
ETFE		2.3	2.6
TPO Shore D		2.3	2.6
PMP 30 GF		2.4	2.4
TPS Shore D		2.4	2.4
PS HT		2.4	2.7
PS		2.4	2.7
PS impact		2.4	4.8
ABS HT		2.4	5
ABS impact		2.4	5
FEP GF		2.5	2.5
ECTFE		2.5	2.6
PS 30 GF		2.5	3.2
SAN		2.5	3.4
EVA		2.5	4
PP 10-20 GF		2.6	2.6
PP 30-40 GF		2.6	2.6
PPE FR		2.7	2.7
PPE		2.7	2.7
SMA		2.8	2.8
PS impact V0		2.8	3
MABS		2.8	3
PPE 30 GF		2.9	2.9
PPE 30 GMT		2.9	2.9
PPE 20 GF FR		2.9	3
PET/PC		2.9	3.3
PP 40 Talc recycled		3	3
PC 20-30 GF FR		3	3

Continued

Table 12.2 Examples of Permittivity or Dielectric Constant at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
PBT		3	3
PC		3	3
ABS/PVC		3	3
ABS FR		3	3
Acrylic imide		3	3
PSU/PC		3	3
PC HT		3	3
PC 20 GF HT V0		3	3
PCT 30 GF FR		3	3.1
PMI		3	3.2
PC/SAN 10 GF		3	3.3
PCT 30 GF		3	3.3
ETFE GF		3	3.4
ASA/PC		3	3.4
ABS 15 GF		3	3.4
PVC 30 GF V0		3	3.5
PC 20-40 GF		3	3.5
PC 30 GMT		3	3.5
PI TP		3	4
PEI 30 GF		3	4
POM friction		3	4
PET 30 GF		3	4
PEI 30 GF milled		3	4
PET		3	4
PA 66 impact		3	4
PBT 35 GMT		3	4
PBT 30 GF		3	4
PET Amorphous		3	4
PA transparent		3	4
PSU/PBT GF		3	4
PET/PC GF		3	4

Table 12.2 Examples of Permittivity or Dielectric Constant at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
PVC rigid		3	4
PAA 30 GF		3	4
CP		3	4
PBT/ASA GF		3	4
ABS/PA GF		3	4
LCP high modulus		3	4
LCP mineral		3	4
COPE 50-82 Shore D		3	4
LCP low modulus		3	4
PEI mineral		3	4
PA cast friction		3	4
PAA 60 GF		3	4
PA cast		3	4
LCP GF		3	5
PVC plasticized		3	5
PVC plasticized filled		3	5
TPE PVC-based		3	5
ABS/PA		3	6
PA 610		3	6
PVDC V0		3	6
PVCC V0		3	6
PA 612		3	6
PVCC		3	6
CAB		3	7
CA		3	8
PA 11 or 12		3	9
PEBA 50-72 Shore D		3	10
PEBA 25-45 Shore D		3	10
Polyarylate FR		3.1	3.1
PSU		3.1	3.2
PEI		3.1	3.2

Continued

Table 12.2 Examples of Permittivity or Dielectric Constant at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
PEEK		3.2	3.2
PEEK 30 GF		3.2	3.2
ASA/PC FR		3.2	3.3
PBI		3.2	3.5
PEEK HT		3.2	4
Polyarylate		3.3	3.3
ASA		3.3	3.8
PI TP		3.3	4
PPSU		3.4	3.5
PA66 30 mineral		3.4	4
Polyarylate 30 GF		3.5	3.5
PES		3.5	3.5
PA 66 FR		3.6	4
PA 4-6		3.6	21.6
PPS 20-30 GF		3.7	3.8
POM homopolymer		3.7	4
POM copolymer		3.7	4
POM impact		3.7	4
PA 66 GF V0		3.8	4.5
PA 66 50 GF		3.8	9
PAI		3.9	4.2
PAI		3.9	4.2
PA 66 impact 15-30 GF		3.9	4.4
PA 66 30 GF		3.9	4.4
POM 25-30 GF		3.9	5
PPS 40 GF		4	4
PA 12 50 GB		4	4
PA 12 30 GF		4	4
PA 11 OR12 plasticized		4	4
PPS 60 GF mineral V0		4	4.1
PAA mineral		4	4.4

Table 12.2 Examples of Permittivity or Dielectric Constant at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
PA 66		4	5
PA 6		4	5
PBT 20-30 GB		4	5
PPA 40 mineral		4	5
PPA 33 GF		4	5
PBT 40 GF mineral		4	5.5
COPE 25-45 Shore D		4	5.6
PA 4-6 30 GF		4	16
PA 4-6 40 mineral		4	16
PAI 30 GF		4.2	6.3
PAI 30 GF		4.2	6.3
PPA 50 GF long		4.4	4.4
PPS GF mineral		5	5
PAI mineral		5	6
CPE		5	6
PAI friction		5	8
TPU Shore D		5	8
TPU GF		5	8
TPU 60 GF long		5	8
TPU 50 GF long		5	8
TPU 40 GF long		5	8
TPU 30 GF long		5	8
TPU		5	8
PVDF homopolymer		5	10
PAI graphite		5.4	6
PVDF copolymer		6	9
PI antifriction		6.6	14
PVF transparent		7	11
MPR		9	11
PI TP 15 graphite		13	14
LCP CF		16	32

- A defined family can be found in several lines because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound with the standards required for the targeted application.

Results should not be interpreted as an indication of the expected service life for any targeted application.

12.3 Alternating Current Loss Tangent or Loss Factor

Alternating current loss characteristics can be tested according, for example, to ASTM D150—11 Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation.

The AC loss generally needs to be small, in order to reduce both the heating of the material and its effect on the rest of the network. In high frequency applications, a low value of loss index is particularly desirable, since for a given value of loss index, the dielectric loss increases directly with frequency.

Table 12.3 displays examples of loss factor (1.0E−4) for unknown frequencies. Minima are expected true values but maxima are highly dependent on frequency. These data are not a rule and other figures can be found elsewhere. They cannot be used for designing any parts or goods, the requirements for the targeted application having to be matched.

Results, ranked by an ascending order of minima, must be carefully examined:

- Those data aren't strictly comparable.
- Grades taken into account are in limited number.
- Frequency isn't indicated.
- Other data can be found elsewhere because all polymers can be modified, thanks to additives.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- Reinforcement, plasticization, impact modification, conductive recipe, etc. aren't always pointed out.
- A defined family can be found in several lines because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound with the standards required for the targeted application.

Results should not be interpreted as an indication of the expected service life for any targeted application.

12.4 Dielectric Strength

The dielectric strength is the maximum voltage before breakdown divided by the thickness of the sample. It is expressed in kV/mm. Data depend on the test conditions.

Dielectric strength can be tested according to standards such as ASTM D149 or IEC 60243.

ASTM D149 describes three methods for voltage application:

- Method A, short-time test;
- Method B, step-by-step test;
- Method C, slow rate-of-increase test.

Method A is the most commonly used test for quality control tests. Unless otherwise specified, the tests shall be made at 60 Hz. However, this test method is suitable for use at any frequency from 25 to 800 Hz. At frequencies above 800 Hz, dielectric heating is a potential problem.

Table 12.4 displays examples of dielectric strength for unknown frequencies. Data are time and frequency dependent. These data are not a rule and other figures can be found elsewhere. They cannot be used for designing any parts or goods, the requirements for the targeted application having to be matched.

Results, ranked in a descending order for minima, must be carefully examined:

- Those data aren't strictly comparable.
- Grades taken into account are in limited number.
- Frequency isn't indicated.
- Other data can be found elsewhere because all polymers can be modified, thanks to additives.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- Reinforcement, plasticization, impact modification, conductive recipe, etc. aren't always pointed out.
- A defined family can be found in several lines because compounds are different.

Table 12.3 Examples of Loss Factor (1.0E−4) at Room Temperature

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
Glass	10–500		
Quartz	0.6–2		
Alumina	1–3		
Wood	300–400		
PS HT		1	28
PS		1	28
PE-HD W recycled		2	2
PTFE		2	2
PMP		2	2
COC GP		2	2
PE-R		2	4
COC optical		2	4
PFA		2	5
PE-UHMW		2	10
PE-HD		2	20
PE-HD colored		2	20
PE-LD		3	4
PP homopolymer		3	5
PP FPP tape		3	5
PP FPP sheet		3	5
PP impact		3	5
PP copolymer		3	5
PPE		4	9
PS impact		4	20
COPE 50—82 Shore D		4	400
FEP GF		5	5
PS 30% GF		5	50
PS impact V0		6	10
ETFE		6	100
ECTFE		6	150
PAA mineral		6	170
PPA 40% mineral		6	170

Continued

Table 12.3 Examples of Loss Factor (1.0E−4) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	**Maximum**
FEP		7	7
PEEK/PBI		7	9
PP 10–40% Talc		7	11
PP 10–40% mineral		7	11
PPE FR		7	31
PC		7	100
PC HT		8	100
PC 20–30% GF FR		9	75
PC 20–40% GF		9	75
PPE 30% GF		10	15
PEI mineral		10	15
PP 10–20% GF		10	20
PP 30–40% GF		10	20
PEEK		10	30
PES		10	35
POM copolymer		10	95
EMA		10	110
PBI		10	140
ASA/PC FR		10	170
PBT		10	200
PCTFE		10	250
LCP mineral		10	290
PAI		10	310
PAI		10	310
COPE 25—45 Shore D		10	600
PSU		11	50
PEI		13	25
PPS 40% GF		13	50
PC 20% GF HT V0		14	85
PEI 30% GF milled		15	50
PEI 30% GF		15	53
PET/PC		15	1000
ASA/PC		16	190

Table 12.3 Examples of Loss Factor (1.0E−4) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
PBT 40% GF mineral		17	240
PI TP		18	36
PPE 20% GF FR		20	20
PSU/PC		20	30
PP 40% Talc recycled		20	40
POM 25–30% GF		20	80
POM friction		20	90
PSU/PBT GF		20	90
ABS/PC GF		20	90
PPS 20–30% GF		20	100
ETFE GF		20	120
PBT 35% GMT		20	120
PBT 30% GF		20	120
PCT 30% GF FR		20	140
PET 30% GF		20	160
PET		20	200
Polyarylate		20	200
Polyarylate FR		20	200
PET/PC GF		20	200
PET Amorphous		20	300
ABS HT		20	350
ABS impact		20	350
PVC rigid		25	250
PVC plasticized		25	1600
PVC plasticized filled		25	1600
TPE PVC-based		25	1600
PTFE GF		30	30
ABS/PC FR recycled		30	80
PC/SAN 10% GF		30	100
Polyarylate 30% GF		30	180
PBT/ASA GF		30	180
PEEK HT		35	35

Continued

Table 12.3 Examples of Loss Factor (1.0E−4) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
ABS/PC		35	80
SMA		40	40
ABS/PC FR		40	70
ABS/PC recycled		40	70
PPS 60% GF mineral V0		40	80
LCP high modulus		40	100
LCP low modulus		40	200
LCP GF		40	350
POM homopolymer		50	70
PPA 33% GF		50	250
PA transparent		50	325
PI TP 15% graphite		53	106
PI antifriction		53	106
CP		60	300
SAN		70	100
POM impact		70	160
PCT 30% GF		70	180
PPS GF mineral		70	580
PA 610		70	900
PA 46 30% GF		70	6000
PA 46		70	8700
PA 46 40% mineral		80	6000
PBT 20–30% GB		85	180
PAA 60% GF		90	100
ASA		90	340
PMI		100	100
Acrylic imide		100	100
PVCC V0		100	250
PVCC		100	250
PA 66		100	400
CAB		100	400
EVA		100	500
PK 30% GF		100	500

Table 12.3 Examples of Loss Factor (1.0E−4) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	**Maximum**
PA 6		100	600
PVDF copolymer		100	1000
CA		100	1000
CPE		100	1000
PA 66 30% GF		100	1500
PA 66 50% GF		100	1500
ABS FR		120	120
MABS		130	160
ABS/PA GF		130	500
PVF transparent		140	400
PEBA 50—72 Shore D		150	6000
PEBA 25—45 Shore D		150	6000
ABS 15% GF		170	170
PP/PA GF		170	660
PP/PA		170	1100
PMMA cast		200	600
PA 66 impact 15–30% GF		200	1000
PA 66 impact		200	1200
PA 66 30% mineral		200	1500
PA 612		200	1500
PA 11 or 12		200	2000
PMMA molded		200	2000
PVDF homopolymer		200	2900
PA 66 GF V0		210	900
PAI 30% GF		220	500
PAI 30% GF		220	500
LCP CF		250	260
PK		250	600
PA 12 50% GB		300	450
ABS/PA		300	900
TPU Shore D		300	2200
TPU GF		300	2200

Continued

Table 12.3 Examples of Loss Factor (1.0E−4) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Materials	Plastics	
		Minimum	Maximum
TPU 30% GF long		300	2200
TPU 40% GF long		300	2200
TPU 50% GF long		300	2200
TPU 60% GF long		300	2200
TPU		300	2200
PAI graphite		370	420
PAI mineral		370	420
PAI friction		370	630
ABS/PVC		400	400
PA 12 30% GF		450	450
PVDC V0		500	800
PA Ar 30% GF		700	700
PAA 30% GF		700	1000
PA 11 or 12 plasticized		1300	1300

- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be interpreted as an indication of the expected service life for any targeted application.

12.5 Surface Resistivity

The surface resistivity is the electrical resistance between two electrodes placed on the same face of a polymer sample. The surface resistivity is expressed in ohms (or in ohms per square).

Classification of polymers depends on the country and application. Each case must be examined in its context, and the following data are only arbitrary and fuzzy examples with overlapping of different subfamilies:

- insulating polymers: resistivity higher than $10^{12}\,\Omega$ per square
- dissipative polymers: resistivity in a range from 10^5 up to $10^{12}\,\Omega$ per square
- antielectrostatic parts for coalmines: resistivity lower than $10^9\,\Omega$ per square
- conductive polymers: resistivity lower than $10\,\Omega$ per square.

Surface resistance or conductivity evolves rapidly with humidity, while volume resistivity changes slowly.

Among the various standards, let us quote, for example:

- ASTM D257-14—Standard Test Methods for DC Resistance or Conductance of Insulating Materials
- ASTM D4496-13—Standard Test Method for DC Resistance or Conductance of Moderately Conductive Materials—volume resistivity in the range of 10^0–$10^7\,\Omega$-cm or surface resistivity in the range of 10^3–$10^7\,\Omega$ per square.
- ANSI/ESD STM11.11-2006—Surface Resistance Measurement of Static Dissipative Planar Materials. This standard test method defines a direct current test method for measuring

Table 12.4 Examples of Dielectric Strength (kV/mm) at Room Temperature

Extremum from the Examined Literature	Miscellaneous Media	Plastics	
		Minimum	Maximum
Alumina	16–17		
Fused silica	25–40		
Glass	10–45		
Ceramic	9–10		
PMP		64	65
PET		60	60
PET 30% GF		55	55
PBT 30% GF		50	50
PBT		45	60
PET Amorphous		45	45
COC GP		40	71
LCP low modulus		40	47
COC optical		40	40
LCP mineral		35	41
PC/SAN 10% GF		35	40
PC HT		35	38
PC 20% GF HT V0		35	38
PA 12 30% GF		35	35
LCP GF		34	50
MABS		34	37
PA 12 50% GB		34	34
LCP high modulus		32	37
PP antistat		32	34
PAI 30% GF		32	33
PA 11 or 12 plasticized		32	32
EMA		31	43
PP 10–40% talc		30	70
PP 10–40% mineral		30	70
PP 10–20% GF		30	45
PP 30–40% GF		30	45
ABS/PA GF		30	40
PP/PA GF		30	36

Continued

Table 12.4 Examples of Dielectric Strength (kV/mm) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Media	Plastics	
		Minimum	Maximum
PA 66 impact		30	35
PPS 20–30% GF		30	31
ABS/PC FR recycled		30	30
PA 66 FR		28	37
PP/PA		28	36
PEI		28	33
PAA 30% GF		28	30
PA Ar 30% GF		28	28
PBT 20–30% GB		26	28
PE-HD with recycled		25	45
PEBA 50—72 Shore D		25	40
PEBA 25—45 Shore D		25	40
PBT 40% GF mineral		25	36
PA 66 30% mineral		25	30
PA 11 or 12		25	30
PEI 30% GF		25	30
PA transparent		25	30
TPV Shore D		25	26
TPS Shore D		25	26
PA 66 30% GF		25	25
PA 46 30% GF		24	37
PA 46 40% mineral		24	37
ABS/PC		24	24
ABS/PC recycled		24	24
PK 30% GF		24	24
PAI		23	24
PAA 60% GF		23	24
ABS/PVC		23	23
PA 66 50% GF		22	35
PAA mineral		22	22
PPE 30% GF		22	22
PPA 40% mineral		22	22

Table 12.4 Examples of Dielectric Strength (kV/mm) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Media	Plastics	
		Minimum	**Maximum**
PA 66 impact 15–30% GF		21	23
PBI		21	22
PPA 33% GF		21	22
PPA 50% GF long		21	21
PA 12 friction		21	21
POM copolymer		20	70
PVCC V0		20	60
PVCC		20	60
POM homopolymer		20	32
PSU		20	30
PA 66		20	30
PSU/PBT GF		20	30
PP Ho		20	28
PP impact		20	28
PP Co		20	28
EVA		20	27
PEI mineral		20	25
PI TP		20	22
PPE		20	22
PA castable		20	22
PA 66 GF V0		20	21
PCT 30% GF FR		20	21
PC 20–30% GF FR		20	20
PEEK		20	20
PC 20–40% GF		20	20
PSU/PC		20	20
POM 25–30% GF		19	23
PET/PC GF		19	21
ECTFE		19	20
PK		18	18
PE-HD colored		17	45

Continued

Table 12.4 Examples of Dielectric Strength (kV/mm) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Media	Plastics	
		Minimum	Maximum
PE-UHMW		17	45
PE-HD		17	24
PTFE		17	24
PE-R		17	21
PPS 40% GF		17	17
Polyarylate		17	17
PMI		17	17
Acrylique imide		17	17
PEEK/PBI		17	17
TPO Shore D		16	45
PA 46		16	29
PE-LD		16	28
PS		16	28
PA 610		16	26
PPE FR		16	25
PCTFE		16	24
Polyarylate 30% GF		16	23
PA castable friction		16	22
COPE 25—45 Shore D		16	20
POM friction		16	19
POM impact		16	19
PCT 30% GF		16	17
PES		16	16
SMA		16	16
TPU Shore D		15	50
TPU GF		15	50
TPU 60% GF long		15	50
TPU 50% GF long		15	50
TPU 40% GF long		15	50
TPU 30% GF long		15	50
TPU		15	50

Table 12.4 Examples of Dielectric Strength (kV/mm) at Room Temperature—cont'd

Extremum from the Examined Literature	Miscellaneous Media	Plastics	
		Minimum	**Maximum**
PC		15	30
PVDC V0		15	23
Polyarylate FR		15	23
PMMA cast		15	22
PMMA molded		15	22
PS impact V0		15	18
PS 30% GF		15	15
PET/PC		14	24
PPSU		14	18
PC foamed		14	15
PTFE GF		13	40
ABS/PA		13	40
PPS GF mineral		13	13
FEP GF		13	13
SAN		12	24
PS impact		12	24
ABS HT		12	20
ABS impact		12	20
CP		12	18
PVDF homopolymer		10	60
PVC rigid		10	50
PVC plasticized		10	30
PVC plasticized filled		10	30
TPE PVC-based		10	30
PA 6		10	20
CAB		10	17
CPE		10	12
CA		8	15
MPR		5	12
COPE 50—82 Shore D		1	20

electrical resistance, replacing ASTM D257. This test method is designed specifically for static dissipative planar materials used in packaging of ESD sensitive devices and components.

Table 12.5 displays examples of volume resistivity (Ohm-cm), surface resistivity (Ohm per Square), and surface resistance (Ohm). Data are moisture-dependent. These data are not a rule and other figures can be found elsewhere. They cannot be used for designing any parts or goods, the requirements for the targeted application having to be matched.

Results must be carefully examined:

- Those data aren't strictly comparable.
- Grades taken into account are in limited number.
- Moisture isn't indicated.
- Other data can be found elsewhere because all polymers can be modified, thanks to additives.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- Reinforcement, plasticization, impact modification, conductive recipe, etc. aren't always pointed out.
- A defined family can be found in several lines because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be interpreted as an indication of the expected service life for any targeted application.

12.6 Arc Resistance

There are several standards that differ by the used current, the operating mode, the possible use of a complementary product, the presentation of results. Some methods are briefly outlined but other methods can be used:

- Arc resistance (D495)
- Comparative tracking index (CTI)
- High-voltage arc tracking rate (HVTR)

12.6.1 Arc Resistance (D495)

Arc resistance, in accordance with ASTM D495, is expressed as the number of seconds that a material resists the formation of a surface-conducting path when subjected to an intermittently occurring arc of high-voltage, low-current characteristics. The results of testing the nominal 3 mm thickness are considered to be representative of the material performance in any thickness. The high-voltage, low-current type of arc resistance test is intended to simulate only approximately such service conditions that exist in alternating current circuits operating at high voltage, but at currents limited to units and tens of milliamperes. The test method is intended for preliminary screening of material, for detecting the effects of changes in formulation, and for quality control testing. Because this test method is usually conducted under clean and dry laboratory conditions, rarely encountered in practice, it is possible that the prediction of a material relative performance in typical applications and in varying "clean to dirty" environments will be substantially altered.

Table 12.6 displays examples of arc resistance (used standards are expected more or less similar to ASTM D495). Data are time- and frequency-dependent.

Results, ranked in a descending order for minima, must be carefully examined:

- Those data aren't strictly comparable.
- Grades taken into account are in limited number.
- Frequency isn't indicated.
- Other data can be found elsewhere because all polymers can be modified, thanks to additives.
- Hygrometry of polyamides and other moisture-sensitive polymers is unknown.
- Reinforcement, plasticization, impact modification, conductive recipe, etc. aren't always pointed out.
- A defined family can be found in several lines because compounds are different.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be interpreted as an indication of the expected service life for any targeted application.

Table 12.5 Examples of Volume Resistivity (Ohm-cm), Surface Resistivity (Ohm per Square), and Surface Resistance (Ohm)

	Volume Resistivity (Ohm-cm)		Surface Resistivity (Ohm per Square)		Surface Resistance (Ohm)	
Grades	General Purpose	ESD	General Purpose	ESD	General Purpose	ESD
ABS/PC ESD		1.00E+9–9.90E+9		1.00E+10–9.90E+11		1.00E+9–9.90E+10
CPVC			≥1.00E+12			
LCP	1.00E+13				1.00E+14	
LCP GF	1.00E+13				≥1.00E+15	
PA11 cond	1.00E+14				1.00E+14	
PA11 GF cond	7.00E+13				1.00E+14	
PA46			≥1.00E+13			
PA66 ESD				1.00E+11		
PA66 ESD		≤1.00E+3		≤1.00E+6		≤1.00E+5
PAI			≥1.00E+13			
PAI ESD				1.00E+10–1.00E+12		
PAI GF			≥1.00E+13			
PBT	1.00E+16				1.00E+13	
PBT CNT ESD		1.00E+1–1.00E+3		1.00E+5–1.00E+8		
PBT ESD		≤1.00E+5		≤1.00E+9		
PBT mineral	≥1.00E+16				1.00E+13	
PC	1.00E+16				1.00E+16	
PC GF	≥1.00E+15				≥1.00E+15	
PC/PLA ESD		1.00E+8–1.00E+11		1.00E+10–1.00E+12		
PE-HD	≥1.00E+15		≥1.00E+15			
PE-UHMW			≥1.00E+13			
PEEK			≥1E+13			
PEEK bearing				≤1E+5		
PEEK CF				≤1E+5		
PEEK ESD				1.00E+6–1.00E+9		

Continued

Table 12.5 Examples of Volume Resistivity (Ohm-cm), Surface Resistivity (Ohm per Square), and Surface Resistance (Ohm)—cont'd

Grades	Volume Resistivity (Ohm-cm)		Surface Resistivity (Ohm per Square)		Surface Resistance (Ohm)	
	General Purpose	ESD	General Purpose	ESD	General Purpose	ESD
PEEK GF			≥1.00E+13			
PEI ESD				1.00E+6–1.00E+9		
PEI GF			≥1.00E+13			
PES CF ESD		≤1.00E+3		≤1.00E+6		≤1.00E+5
PMMA ESD		1.00E+9–9.90E+10		1.00E+10–9.90E+11		1.00E+9–9.90E+10
POM	≥1.0E+14		≥1.0E+13			
POM ESD				1.00E+9–1.00E+10		
PP copolymer	≥1.00E+15		≥1.00E+15			
PP homo			≥1.00E+15			
PPE+PS 30 GF/mineral dense	1.00E+17				1.00E+17	
PPE+PS 30 GF/mineral foam	1.00E+17				1.00E+17	
PPS bearing			≥1.00E+13			
PPS GF			≥1.00E+13			
PPS low filler	≥1.00E+15				≥1.00E+15	
PTFE ESD				1.00E+10–1.00E+12		
PVC			≥1.00E+12			
PVC ESD				1.00E+10		1.00E+09
TPU ESD						1.00E+08
Overall range	7E+13–E+17	E+1–E+11	E+12–E+15	1E+5–1E+12	E+13–E+17	E+5–E+10

Table 12.6 Examples of Arc Resistance (seconds) According to ASTM D495 or More or Less Similar Method.

Extremum from the Examined Literature	Minimum	Maximum
PCTFE	350	400
PFA	300	350
PTFE	200	300
POM homopolymer	200	220
PBI	180	185
CP	175	190
PCT 30% GF FR	175	182
POM 25–30% GF	170	170
PTFE GF	165	180
FEP	165	180
PEI mineral	140	140
PP homopolymer	135	180
PP impact	135	180
PP copolymer	135	180
PE-LD	130	160
PA 66	130	140
LCP low modulus	130	137
PEI	128	128
POM friction	126	183
Polyarylate	125	125
PSU/PBT GF	120	130
PSU/PC	120	130
POM impact	120	120
PPS GF mineral	116	182
ETFE GF	110	110
SAN	100	150
PP 10–40% talc	100	130
PP 10–40% mineral	100	130
LCP mineral	100	100
PEI 30% GF	85	85
PAA 30% GF	85	85
PET	75	125
PET Amorphous	75	125
ETFE	75	122
PP 10–20% GF	75	100
LCP high modulus	70	74
LCP GF	66	209
PS	60	80
PVC rigid	60	80
PP 30–40% GF	60	75
PSU	60	60
PPE	53	80
CA	50	300
PPS 20–30% GF	50	86
PVDF homopolymer	50	70
PVDF copolymer	50	70
PVF transparent	50	51
ABS HT	45	85
ABS impact	45	85
PPS 40% GF	34	50
PES	20	120
PS impact	20	100
PC	10	120

UL (Underwriters Laboratories) expresses the results of testing as performance level categories (PLCs) (see Table 12.7).

12.6.2 Comparative Tracking Index

Comparative tracking index is expressed as that voltage which causes tracking after 50 drops of 0.1% ammonium chloride solution have fallen on the material. The results of testing the nominal 3 mm thickness are considered to be representative of the material performance in any thickness. UL expresses the results of testing as PLC (see Table 12.8).

Table 12.7 Correlation between D495 results and Performance Level Categories (PLC)

D495 Range—Mean Time of Arc Resistance (in seconds)	PLC Assigned
420 and longer	0
360–419	1
300–359	2
240–299	3
180–239	4
120–179	5
60–119	6
Less than 60	7

Table 12.8 Correlation between CTI Results and Performance Level Categories (PLC)

CTI Range Tracking Index (in volts)	PLC Assigned
600 and greater	0
400–599	1
250–399	2
175–249	3
100–174	4
Less than 100	5

12.6.3 High-Voltage Arc Tracking Rate

Thermoplastics can be sensitive to tracking appearing when a high-voltage source current creates an unwanted path across the surface of a plastic part. High-voltage arc tracking rate (HVTR) is denoted as the rate, in millimeters per minute, that a tracking path can be produced on the surface of the material under standardized test conditions. The results of testing the nominal 3 mm thickness are considered to be representative of the material's performance in any thickness.

HVTR range can be less than 10 up to more than 150 mm/min.

UL expresses the results of testing as PLC (see Table 12.9).

Apart from these electrical properties, EE are also subjected to fire and service temperature laws; standards and regulations such as UL 94 fire ratings, UL temperature index; and many other international, national, regional, or application sector specifications.

Table 12.9 Correlation between HVTR Results and PLC

HVTR Range (in mm/min)	PLC Assigned
0–10	0
10.1–25.4	1
25.5–80	2
80.1–150	3
Greater than 150	4

12.7 Frequency, Temperature, Moisture, Physical, and Dynamic Aging Effects

All electrical properties can be more or less modified by the current frequency, the actual temperature, and moisture content of the thermoplastic, historical heat, and mechanical aging. For example, certain conductive thermoplastics may be insulating after cyclic loading.

Among others, let us quote some examples showing the erratic variations in dielectric properties versus those parameters. Used data for design must be measured on the actual used compound according to the conditions of use.

12.7.1 Examples of Temperature Effect

For a defined grade based on polyoxymethylene (POM), all other parameters being equal, dissipation factor is found to be

- 0.025 at −50 °C
- 0.001 at 0 °C
- 0.001 at 50 °C
- 0.005 at 100 °C.

For a defined grade based on polyamide (PA), all other parameters being equal, dielectric strength is found to be

- 25 kV/mm at room temperature
- 23 kV/mm at 60 °C
- 19 kV/mm at 80 °C
- 12 kV/mm at 100 °C.

12.7.2 Examples of Moisture Effect

For a defined grade based on POM, all other parameters being equal, volume resistivity is found to be

- $10^{16}\,\Omega$-cm for a dry sample
- $10^{15}\,\Omega$-cm for a 50% RH conditioned sample
- $10^{14}\,\Omega$-cm for a polymer with 1% moisture.

For a defined grade based on PA, all other parameters being equal, dielectric strength is found to be

- 25 kV/mm for a dry sample
- 22 kV/mm for a polymer with 3% moisture.

For a defined grade based on PA46, all other parameters being equal, loss factor at 1 GHz is found to be

- 0.008 for a dry sample
- 0.01 for a conditioned sample
- 0.055 for a wet sample.

For a defined grade based on PA46, all other parameters being equal, dielectric constant at 1 GHz is found to be

- 3.6 for a dry sample
- 3.65 for a conditioned sample
- 4.6 for a wet sample.

12.7.3 Examples of Frequency Effect

The effect of frequency depends on the considered characteristic and the formulation of the considered grade. Following examples relate to commodity and engineering polymers:

Polyethylene (PE): all other parameters being equal, loss tangent of a given grade is found to be

- 0.0002 at 100 MHz
- 0.0003 at 3 GHz.

PE: all other parameters being equal, dielectric constant of a given grade is found to be

- 2.26 at 1 MHz
- 2.26 at 3 GHz.

LCP: all other parameters being equal, dielectric constant of a given grade is found to be

- 3.4 at 1 GHz
- 3.55 at 5 GHz
- 3.7 at 20 GHz.

LCP: all other parameters being equal, loss tangent of a given grade is found to be

- 0.004 at 1 GHz
- 0.002 at 5 GHz
- 0.0023 at 20 GHz.

LCP: all other parameters being equal, loss tangent of a given grade is found to be

- 0.025 at 1 MHz
- 0.02 at 10 MHz
- 0.01 at 100 MHz
- 0.008 at 1 GHz.

Conditioned PA46: all other parameters being equal, loss factor of a given grade is found to be

- 0.01 at 1 GHz
- 0.01 at 5 GHz
- 0.01 at 20 GHz.

Conditioned PA46: all other parameters being equal, dielectric constant of a given grade is found to be

- 3.65 at 1 GHz
- 3.6 at 5 GHz
- 3.55 at 20 GHz.

Polyethersulfone (PES): all other parameters being equal, dielectric constant of a given grade is found to be

- 3.84 at 60 Hz
- 3.84 at 1 kHz
- 3.88 at 1 MHz.

PES: all other parameters being equal, dissipation factor of a given grade is found to be

- 0.0015 at 60 Hz
- 0.0018 at 1 kHz

- 0.0081 at 1 MHz

Polyphenylenesulfone: all other parameters being equal, dissipation factor of a given grade is found to be

- 0.0006 at 60 Hz
- 0.0076 at 1 MHz.

12.8 Electrically Conductive Thermoplastics

A lot of conductive additives are well known but continuous development efforts pave the way to more performing versions. Intensive research studies lead to more innovative solutions such as inherently dissipative polymer (IDP) or inherently conductive polymer (ICP), carbon nanotubes (CNTs), conductive micro- or nanofibers, metal nanopowders, non-black interpenetrated networks, indium tin oxide coatings… A few polymers, of natural or synthetic origin, are inherently antistatic such as cotton, wood fibers, polyamides 11 or 12, and others. Figure 12.2 shows some solutions.

12.8.1 Efficiency of Conductive Additives: The Percolation Threshold

To make an insulating polymer conductive, it is necessary to create a continuous path for the electricity by adding a sufficient level of conducting additive in such a way that a conductive path is achieved. Consequently, the resistivity decreases abruptly when a threshold of the amount of the well-dispersed conductive additive is obtained as we can see in Figure 12.3, showing two different examples. The amount of conductive additive corresponding to the threshold depends on the conductive additive, its dispersion and distribution in the matrix, and can range, for example, between a few percents and a few tens of percent.

12.8.2 Examples of Conventional Conductive Additives

Some conductive additives have been used for a long time, for example:

- Conductive carbon blacks
- Metal powders or flakes

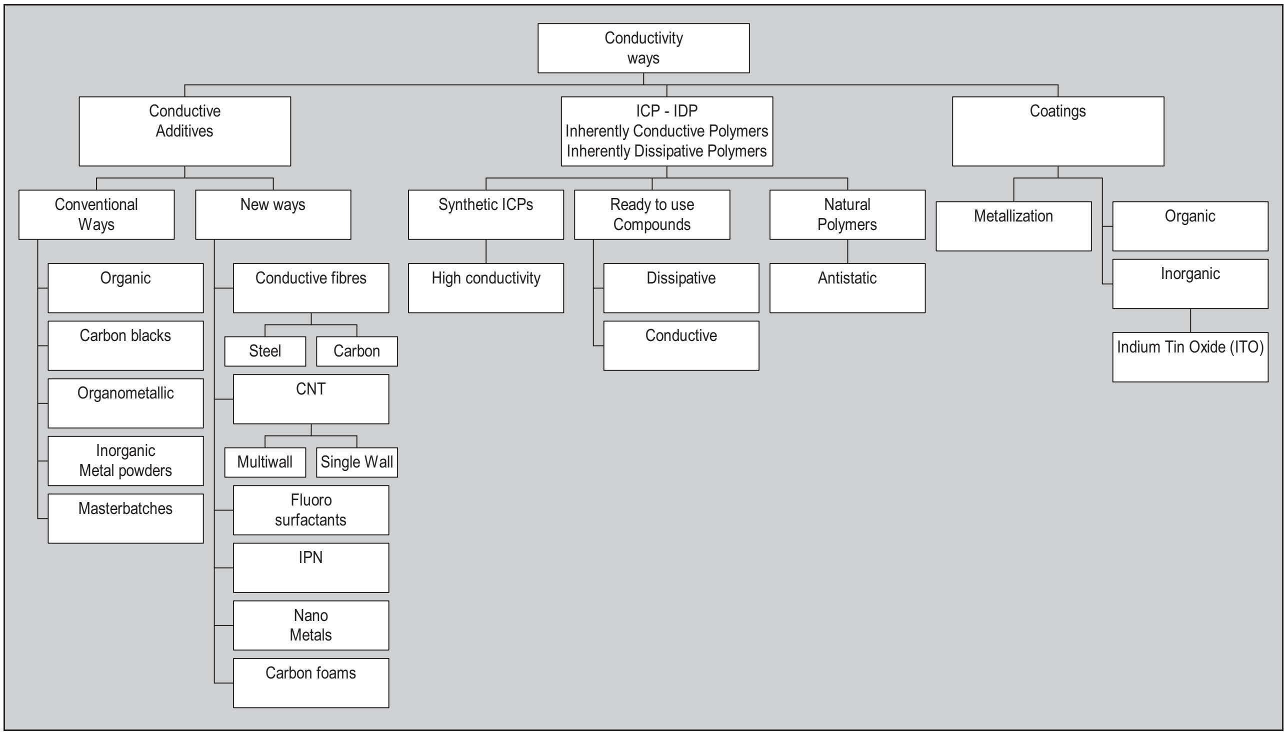

Figure 12.2 Extrinsic and intrinsic conductive thermoplastics.

- Conductive carbon and steel fibers
- Antistatic specialties.

12.8.2.1 Conductive Carbon Blacks

The resistivity of the final material depends on:

- The used carbon black grade. There are specific grades and masterbatches of carbon blacks especially marketed as additives for conductive plastics and rubbers. Efficiency depends on the surface area of the carbon black and the ion level on its surface. The resistivity decreases when the surface area increases for a given carbon black.
- The level of carbon black. The percolation thresholds are roughly less than 10% and near 20%.
- The grade of the polymer. For two grades of low-density polyethylene with significantly different melt flow index (0.3 and 30), the resistivities for 15 parts of the same carbon black are 10^5 for one grade and 10^1 for the other one.
- The mixing method. For the same polystyrene and the same highly conductive carbon black, the mixing methods, a conventional and a 3D chaotic mixing processes, lead to very different resistivities.

It will be noted that carbon blacks modify other properties of the polymer, especially its color.

12.8.2.2 Metal Powders or Flakes

Aluminum, copper, nickel, silver powders, or flakes are used to increase the electrical conductivity.

The resistivity of the final material depends on:

- The particle size and form of the metal.
- The level of metal.
- The mixing method.

There are specific grades especially marketed as additives for conductive plastics and rubbers. The polymer influences the metal choice. The sulfur vulcanization can particularly cause some troubles with metals attacked by sulfur as copper and silver.

The other properties such as color, modulus, impact strength are modified.

Compared to general-purpose versions, the electromagnetic interference (EMI) grades have high or increased modulus, better heat deflection temperature, and high density. The elongation, the coefficient of thermal expansion, and the strength are reduced.

The metal powders are also used in paints and adhesives.

12.8.2.3 Conductive Carbon and Steel Fibers

The carbon and steel fibers are industrially used to make the thermoplastics and composites conductive. There are specific grades especially marketed as additives for conductive plastics and rubbers.

The resistivity of the final material depends on:

- The size, aspect ratio, chemical nature of the fibers.
- The level of the used fiber and its dispersion, distribution, and orientation.
- The mixing method.

The other properties of the final material such as color, modulus, impact strength… are modified.

12.8.2.4 Antistatic Specialties

The nonblack antistatic grades have been used for a long time but their action depends on the hygrometry. Some are proposed in masterbatches based on polyolefins, polystyrenes, polyesters, acrylics,

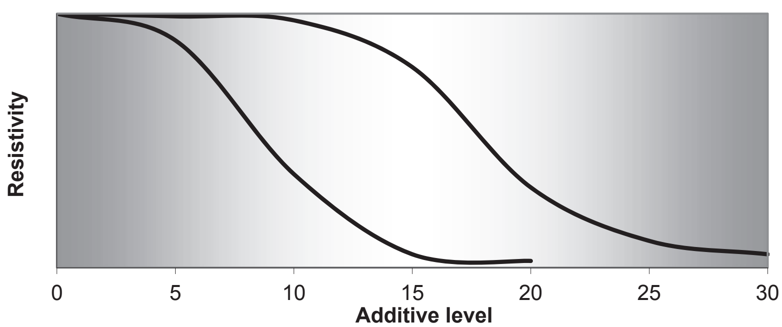

Figure 12.3 Percolation threshold.

Table 12.10 Property Examples of EMI Grades Compared to Neat Thermoplastics

		PA66		ABS		PPE	
		EMI	**GP**	**EMI**	**GP**	**EMI**	**GP**
Aluminum level	%	40	0	40	0	40	0
Specific gravity	g/cm^3	1.48	1.1	1.57	1.1	1.45	1.1
Elastic modulus	GPa	5	1–3.5	2.5	1–3	5.2	2.5
Tensile strength	MPa	41	40–85	23–29	30–65	45	45–65
Elongation break	%	4	>150	2–5	3–60	3	2–60
CTE	10^{-5}/°C	2.2	5–14	4	6–10	1.1	3–8
HDT 1.82 MPa	°C	190	85	95	100	110	110

acrylonitrile butadiene styrene (ABS), polyacetals… Generally, the surface resistivity is roughly in a range of 10^7–10^9.

The moisture trapped by the hydrophilic ends of molecules forms a thin conductive film at the surface of the plastic if the atmospheric moisture is sufficient. If the moisture level is too low, the antistatic additive becomes inefficient.

The antistatic agents migrate slowly to the surface at a controlled rate to maintain long-lasting conductivity.

The additive levels in the polymer are typically in a range of less than 1% to few percents.

Table 12.10 displays some comparative examples of properties for General purpose (GP) grades made electrically conductive, thanks to aluminum.

Table 12.11 displays some comparative examples of properties for GP grades made electrically conductive, thanks to conductive fibers.

Table 12.11 Examples of Conductive Fiber-Filled Polypropylenes

Fibers	**None**	**Stainless Steel**	**Carbon**
Resistivity, ohm cm	10^{16}	10^3	10^3
Tensile or flexural strength, MPa	20–40	41	41
Flexural modulus, GPa	1–1.4	1.4	4.3

12.8.3 Innovative Solutions

Among several industrial or experimental solutions, let us quote some examples without claiming to be exhaustive.

- Various conventional plastics including ABS, acrylics, composites, polyamides, polycarbonate, polyester, rubbers, thermoplastic elastomers… can be alloyed with ICPs and IDPs such as:
  - PEDOT (Poly(3,4-ethylenedioxythiophene) doped with poly(styrenesulfonate))
  - Polyaniline
  - Poly(3-hexylthiophene)
  - Poly(phenylene vinylene)
  - Polyarylene
  - Polypyrrole
  - Polyspirobifluorene
  - Polythiophene…
- CNT: The very low resistivity of CNT allows obtaining EMI polymers with levels of CNT inferior to 1%. This technique is, at the present time, handicapped by the cost and the difficulties to process them. The cost is fast decreasing.
- Graphene: Production of various electrically conductive thermoplastics including polyolefins and polyamides with graphene has been reported. The lowest electrical percolation

threshold was 0.1 vol.% reported by Stankovich and all for polystyrene-based composites.

Of course, the oldest and newest technologies can be combined.

Further Reading

Technical Guides, Newsletters, Web sites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, Borealis, BP Chemicals, Bryte, Ceca, Celanese, Chem Polymer, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cuming, EMS, Enichem, Epotecny, Eurotec, Eval, Exatec, Exxon, Ferro, Ferruzzi, Fiber-Cote, Framet Futura, General Electric Plastics, General Electric Silicones, GINAR Engineering Plastics, Grupo Repol, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Matweb, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, RTP, Sabic, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Taber, Technochemie GmbH, Teknor Apex, Telenor, The European Alliance for SMC, Thieme, Ticona, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vamptech, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

13 Sensory Issues: Optical Properties, Aesthetics, Odor, Taste, Touch

OUTLINE

The market appeal of plastics is of prime importance for numerous applications such as packaging, automotive, household appliances…Today, the concerned properties exceed the optical properties including features as diverse as esthetics, color, transparency, gloss, haze, surface aspect, touch, odor, NVH (noise, vibration, harshness), acoustics, taste transfer contributing to make a plastic part attractive, unappealing, or repulsive.

As the other properties, sensory characteristics degrade by aging, which can limit the lifetime of plastics parts still having satisfactory mechanical properties.

13.1 Refractive Index

As other products, thermoplastics may be characterized by their refractive indexes, which depend on the light wavelength.

Table 13.1 displays examples of refractive index (ranked in an ascending order) for about 40 grades including transparent ones. Used standard and wavelengths aren't indicated.

These data are not a rule and other characteristics can be found elsewhere. They cannot be used for designing any parts or goods. Used data for design must be measured on samples of the actual used compound processed according to the selected processing methods.

Results must be carefully examined:

- Those data aren't strictly comparable.
- Light wavelength isn't known.
- Grades taken into account are in limited number.
- Other data can be found elsewhere because of the broad variations of formulation.
- Use of nucleating agents, quenching, plasticization, impact modification, annealing, etc., aren't always pointed out.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Results should not be interpreted as an indication of the expected service life for any targeted application.

The range of refractive index of these more or less common thermoplastics is approximately 1.3 up to 1.8.

High-refractive index plastics are extremely useful for optical applications such as, for example, lenses, optical circuits, optical fibers, antireflective films and coatings, optical adhesives, LCD displays, waveguides, UV-reactive inks and varnishes…Heat or radiation (UV, EB, laser…) treatments, such as annealing, cross-linking, and high polymerization, contribute to a higher refractive index. More

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00013-1

Table 13.1 Refractive Index Examples

Extremum from the Examined Literature		**Minimum**	**Maximum**
FEP	Fluorinated Ethylene Propylene	1.34	1.34
PFA	Perfluoroalkoxy	1.34	1.34
PTFE	Polytetrafluoroethylene	1.32	1.38
ETFE	Ethylene Tetrafluoroethylene	1.40	1.40
PVDF	Polyvinylidene Fluoride	1.42	1.42
PE LD	Polyethylene, low density	1.42	1.53
PCTFE	Polychlorotrifluoroethylene	1.43	1.43
ECTFE	Ethylene Chlorotrifluoroethylene	1.44	1.45
PPO	Poly(propylene oxide)	1.45	1.46
PMP	Polymethylpentene	1.46	1.47
PVAC	Poly(vinyl acetate)	1.46	1.47
PPS	Polyphenylene Sulfide	1.46	1.76
CA	Cellulose acetate	1.47	1.48
CAB	Cellulose acetate butyrate	1.47	1.48
EVA	Ethylene–Vinylacetate copolymer	1.47	1.5
POM Homo	Polyacetal homopolymer	1.48	1.48
PVB	Poly(vinyl butyral)	1.48	1.49
PMMA	Poly(methyl methacrylate)	1.49	1.51
PP Homo	Polypropylene homopolymer	1.49	1.51
PVAL	Poly(vinyl alcohol)	1.50	1.50
EMA	Ethylene/methacrylic acid ionomer, sodium ion	1.51	1.51
PIB	Poly(isobutylene)	1.51	1.51
POM	Polyacetal	1.51	1.51
PAN	Poly(acrylonitrile)	1.51	1.52
ABS	Acrylonitrile–Butadiene–Styrene	1.52	1.52
EVOH	Ethylene–vinyl alcohol copolymer	1.52	1.53
PVC plasticized	Poly(vinyl chloride), plasticized	1.52	1.55
COC	Cyclic Olefin copolymer	1.53	1.53
PA6	Polyamide 6	1.53	1.53
PE HD	Polyethylene, high density	1.53	1.54
PVC rigid	Poly(vinyl chloride), rigid	1.53	1.55
PA transparent	Polyamide, transparent	1.53	1.57
PA66	Polyamide 66	1.53	1.57

Table 13.1 Refractive Index Examples—cont'd

Extremum from the Examined Literature		Minimum	Maximum
PA69 or 610 or 612	Polyamide 69 or 610 or 612	1.53	1.57
PS	Polystyrene	1.55	1.59
SAN	Styrene acrylonitrile copolymer	1.56	1.57
SMA	Styrene maleic anhydride copolymer	1.56	1.57
PET	Poly(ethylene terephthalate)	1.57	1.58
PC	Polycarbonate	1.58	1.59
PVDC	Polyvinylidene Chloride	1.60	1.60
PSU	Polysulfone	1.63	1.64
PEI	Polyetherimide	1.63	1.69
PEEK	Polyetheretherketone	1.65	1.77

sophisticated and scarce specialty thermoplastics can reach higher values up to 3.2 claimed for gelatin modified by the addition of Si-nanoparticles. Some producers or compounders market ready-to-use high-refractive index polymers.

On the other hand, low-refractive index plastics are also extremely useful for optical applications such as fiber optic core and cladding, optical lens coating, antireflective coatings, optical adhesives, encapsulation of various optical components such as light guides, patterning, or heterolayered device fabrication. Low-refractive index plastics are specialty fluorinated polymers possibly bearing chemical functions such as acrylate, propionate, acetate, or siloxane. So, refractive indices cannot fall below 1.3 but researchers develop more sophisticated ways allowing to obtain lower refractive index close to 1.

Plastics can be opaque, transparent without scattering, or translucent allowing light transmission but causing a noticeable scattering.

13.2 Transparent Thermoplastics

The most usual optical properties of transparent thermoplastics include:

- Light absorption: the percentage of light absorbed by the polymer versus the incident light.
- Light transmission: the percentage of light transmitted through the polymer versus the incident light.
- Haze induced by light scattering within the polymer. A water haze can be caused by absorbed moisture.
- Gloss: capacity of the polymer surface to reflect light in given directions.

Transparency and haze depend on, without claiming to be exhaustive:

- The used polymer and possible alloying (see Table 13.2). For the same designation, some grades can be transparent or translucent when others aren't. ABS copolymers can be transparent when compounds of SAN and polybutadiene are opaque.
- The actual crystallinity: transparency decrease when crystallinity increases.
- The compound recipe: Use of colors (see Table 13.3), fillers, reinforcements, nucleating agents, plasticizers, impact modifiers, and other additives.
- The possible treatments such as, stretching, quenching, annealing, etc. (see Table 13.3)
- The considered light wavelength.

Table 13.2 displays some transparent or translucent thermoplastics among others.

Tables 13.4 and 13.5 display statistical analysis of visible light transmission and haze for some

Table 13.2 Examples of Transparent or Translucent Thermoplastics

Family	Subfamily
Acrylic	Polymethylmethacrylate (PMMA)
	Styrene methyl methacrylate (SMMA)
	PMMA + PC blend
Polycarbonate	Polycarbonate (PC)
	Polycarbonate + polyester amorphous blends
Styrenic	Polystyrene (PS, HIPS, SB)
	Styrene acrylonitrile copolymer (SAN)
	Transparent ABS and methacrylate ABS (MABS)
	Styrene maleic anhydride (SMA)
	Styrenic block copolymer elastomers (SBC, SBS, SEBS, SIS)
	Polyphenylene oxide/polystyrene blends (PPO + PS)
Chlorinated thermoplastic	Polyvinyl Chloride (PVC)
Olefinic	Clarified polypropylene (PP)
	Polymethylpentene (PMP)
	Cyclic olefin (co)polymer (COC)
	Polyolefin elastomer/plastomer (POE/POP)
Polyester	Polyethylene terephthalate (PET)
	Polyethylene naphthalate (PEN)
	Polyester copolymers (PETG)
	Thermoplastic ether–ester copolymer elastomer (COPE or TPEE)
Cellulosic	Cellulose acetate, butyrate, propionate (CA, CAB, CAP)
Polyamide	Transparent PA (PA-T)
	Polyether block amide (PEBA)
Polyurethane	Thermoplastic polyurethane (TPU)
Ionomer	Acrylate copolymer
Acrylonitrile	Acrylonitrile copolymer (PAN)
Polyetherimide	Polyetherimide (PEI)
Polysulfone	Polysulfone (PSU)
	Polyethersulfone (PES)
	Polyphenylsulfone (PPSU)
Fluorinated thermoplastics	Fluorinated ethylene propylene (FEP)
	Ethylene Tetrafluoroethylene (ETFE)
	Polytetrafluoroethylene (PTFE)
	Polychlorotrifluoroethylene (PCTFE)
	Perfluoroalkoxy (PFA)
Thermoplastic polyimide	Polyimide, amorphous (TPI)
Biosourced thermoplastic	Poly lactic acid (PLA)
	Cellulosics

Table 13.3 Examples of Visible Light Transmission and Haze for GP, Colored, and Frost poly(methyl methacrylate)

Grade	Visible Light Transmission, %	Haze, %
General purpose	89	8
General purpose	89	4
General purpose	89	4
General purpose	88	8
General purpose	88	8
General purpose	88	8
Colored	83	
Colored	62	
Colored	60	
Colored	57	
Colored	56	
Colored	51	
Colored	50	
Frost	80	97
Frost	74	66

Table 13.4 Poly(methyl methacrylate) (PMMA): Examples of Visible Light Transmission (>90%) and Haze

	Visible Light Transmission, %	Haze, %
PMMA, clear: transmittance ≥ 90%		
Mean	92	1.5
Median	92	1
Standard deviation (SD)	0.8	0.87
Minimum	90	0.5
Maximum	93	4
Number of samples	27	27
Mean − 2.33 SD	90	−0.5
Mean + 2.33 SD	94	3.5

Table 13.5 Polycarbonate: Examples of Visible Light Transmission (>80%) and Haze

	Transmission, Visible, %	Haze, %
Mean	86.8	1.6
Median	86	1.5
Standard deviation	1.6	0.3
Minimum	85	1
Maximum	90	2
Number of samples	13	13
Mean − 2.33 SD	83	0.9
Mean + 2.33 SD	90	2.3

transparent grades of poly(methyl methacrylate) and polycarbonate.

Table 13.6 displays examples of maximum transmission and haze range for some thermoplastics. Minimum transmission is zero because all thermoplastics can be made opaque with fillers, reinforcements, colors, etc. Used standard and wavelengths aren't indicated. These data are not a rule and other characteristics can be found elsewhere. They cannot be used for designing any parts or goods. Used data for design must be measured on samples of the actual used compound processed according to the selected processing methods.

We can remark that fair transmission data can be linked to low or to high haze.

Results must be carefully examined:

- Only a few grades of each family are transparent or translucent.
- Those data aren't strictly comparable.
- Grade crystallinity degree is unknown.
- Wavelengths are unknown.
- Grades taken into account are in limited number.
- Other data can be found elsewhere because of the broad variations in formulation.
- Use of nucleating agents, quenching, plasticization, impact modification, annealing, etc., aren't pointed out.
- Errors, lack of accuracy, method uncertainty need to verify those data and to check the used compound.

Table 13.6 Examples of Visible Light Transmission and Haze

	Visible Light Transmission, %	Haze, %	
	Maximum	**Minimum**	**Maximum**
PFA	96	4	4
FEP	96		
ETFE	95		
SBC	93	1	2
CA	93	1	2
PAN	92	2	7
PMMA/Acrylate elastomer	92	1	1
PMMA	92	1	8
PTFE, amorphous	92		
SAN	91	2	3
COC	91	1	2
CAB	91	1	1
NAS	91	1	3
PETG	91	1	10
SMMA	91		
CAP	90	8	8
PP	90	7	17
PLA	90	2	85
PEI	90	2	2
POP	90	1	6
PMP	90	1	5
PC	90	1	2
PET	90	1	7
CP	90		
TPU	90		
PS	90		
PPSU	90		
PA SA	88	7	7
PA transparent	88	1	1
PC/PET	88	1	2
MABS	88		
ABS	86	3	10

Table 13.6 Examples of Visible Light Transmission and Haze—cont'd

	Visible Light Transmission, %	Haze, %	
	Maximum	Minimum	Maximum
PA	85	7	7
PVC	85	3	3
Ionomer (Surlyn)	85	2	2
PVC plasticized	85		
PEN	84	12	14
PPO/PS	83	7	8
PSU	80	5	5
PE	80	5	6
EVA	80	4	7
PEBA	80	1	1
PA11 PA12	80		
PC GF	80		
PPO nanoreinforced	80		
PESU	72	6	6
TPI amorphous	58		
CA matt	17		
PMMA+PC	0		
PB		25	55
PCTFE		2	3
SMA		2	3
EVOH		1	2
POE			21
SB			2
PLA/Copolyester			85

13.3 Aesthetics

Aesthetics is a complex characteristic depending on shape, color, gloss, surface quality, shaping defects, aging, and more generally people's opinion.

For example, impression inferred by gloss or mat aspect is partly objective and partly subjective depending on the reflected light, the individual, the purpose of the item, its shape and color, the targeted application. For example, generally speaking, in same car, it is preferred to have a glossy body part and a mat interior trim.

Polymers are naturally colored, grayish or yellowish, and so on, and are somewhat unappealing. The situation is even more disastrous with compounds incorporating additives leading to other undesired colors going up to the black color of some conductive thermoplastics. In addition, colors can evolve during storage and service life.

To obviate these drawbacks, it is necessary to carefully choose the polymer grade and additives and it is possible to use white fillers and other optically active additives. Generally, that is not sufficient and it is necessary to carefully process the materials and to preserve the obtained colors by carefully stabilizing the compound during all the service life.

Outdoor exposure is, perhaps the most severe aging condition but heat, neon light, or exposition to the north in cold climates can also be aggressive. For example, PVC compounds can turn to:

- Mat and possibly yellow by outdoor exposure
- Yellow for computer equipment including very soft compounds
- Yellow to red by discoloration under low irradiation, for example, neon lights
- Yellow to brown by discoloration under outdoor exposure in sunny climates
- Pink by outdoor exposure toward north in cold and humid climates
- Purple by thermal degradation
- Black by sulfur staining

Aesthetics during service life can be also damaged by physical injuries such as scratches or by optical phenomena such as fogging.

Scratch resistance can be enhanced by hard coatings or by overmolding with a harder plastic.

Fogging is a harsh issue for many application sectors including packaging, automobile, optical devices, electronic equipment, etc., accounting for a major share of the plastics market.

The word "fogging" relates to two different phenomena:

- Condensation of the air moisture on the cold plastic, formation of tiny droplets on the surface, light scattering, and obscuring of the polymer. This is an important problem for optical applications, packaging, horticulture, and so on. For a given difference in temperatures between the air and the plastic part, the duration of the fogging depends on the thermal conductivity of the polymer. Other materials as glass are subject to the same problem.
- Desorption of additives or low-molecular weight polymer from the plastic parts and their condensation on other cold parts: glazing of cars and particularly windscreens, optical lenses, or electronic devices. The deposit of additives can lead to electrical insulation. To avoid these troubles, two main ways are used: Choice of low outgassing additives and polymers without monomers or oligomers, spreading of a permanent barrier coating onto the surface of the plastic part.

Among several routes used to minimize the fogging due to the water condensation by internal or external technologies, let us quote:

- Use of special versions of plastics: Producers or compounders market antifog versions of several families.
- Choice of ingredients that:
  - Improve the wetting performances of the polymer
  - Improve water repellence.
- Spreading of a permanent or temporary coating onto the exposed surface.
- Modification of the design of the device if possible.

In the end, esthetics involves all the steps and parameters of the part life as we can see in Figures 13.1 and 13.2(a–e).

Aesthetics can be enhanced by optimization of the various steps of designing and fabrication: grade selection, drawing, modeling, simulation, prototyping, processing enhancement, coloration, decoration, overmolding…

13.3.1 Computer Tools Help Design Avoiding Many Defects

Modeling and simulation speeding up trials and enhancing processes are broadly used to design parts, molds, and dies. Software (see Table 13.7), commercialized or not, are legion, some of them being well known such as Moldflow.

Modeling and simulation help to:

- determine the manufacture ability of parts and avoid potential downstream problems
- optimize part and mold designs, processing, quality, waste level of injection, and other processing methods addressing subjects as diverse as warpage, shrinkage, gate location, number of

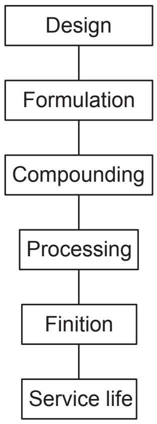

Figure 13.1 Direct and indirect aesthetics parameters.

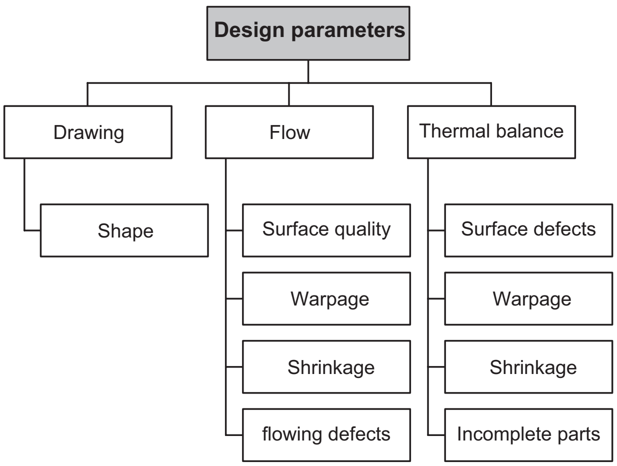

Figure 13.2a Design parameters.

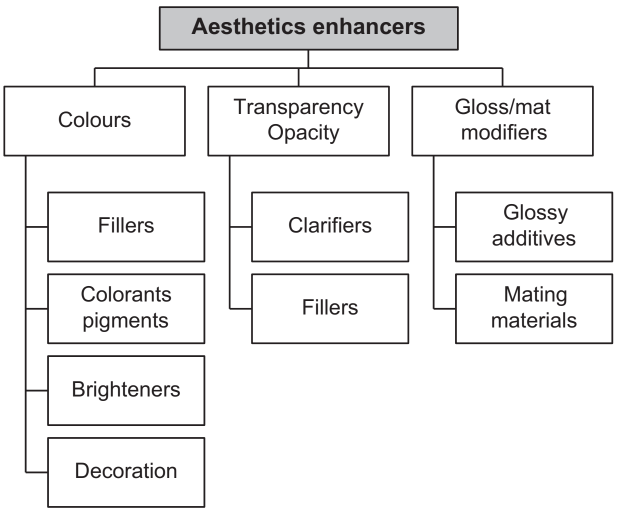

Figure 13.2b Aesthetics enhancers.

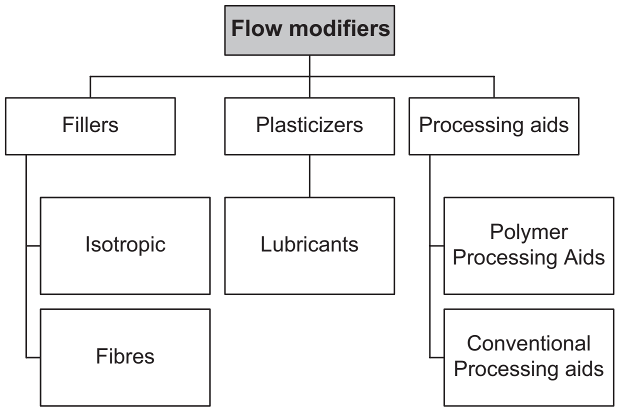

Figure 13.2c Flow modifiers.

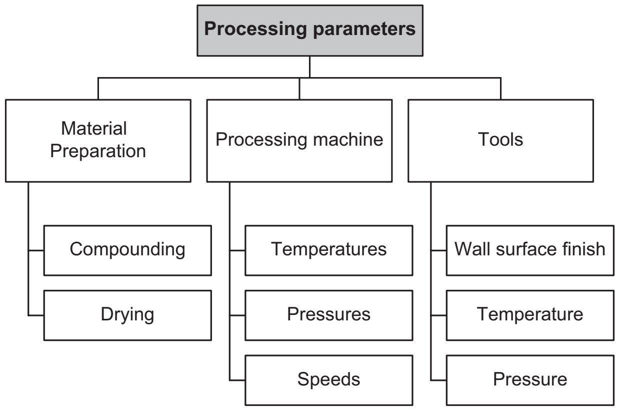

Figure 13.2d Processing parameters.

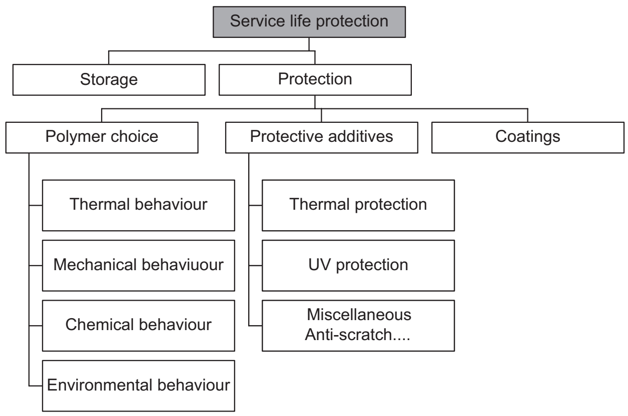

Figure 13.2e Service life parameters.

Table 13.7 Examples of Companies Dealing with Virtual Characterization

Company	Web Sites
Abaqus software	http://www.abaqus.com
Altair engineering	http://www.altair.com
Ansoft	http://www.ansoft.com
Ansys	http://www.ansys.com
Astek	http://www.groupeastek.com
Autodesk	http://www.autodesk.com
AVL	http://www.avl.com
CD Adapco	http://www.cd-adapco.com
Cetim	http://www.cetim.fr/
Cimpa (EADS)	http://www.cimpa.fr
Dassault systèmes	http://www.3ds.com
DeltaCad	http://www.deltacad.fr/
Digicad	http://www.digicad.fr
ESI	http://www.esi-group.com/
Flowmaster	http://www.flowmaster.com
Genoa	http://www.ascgenoa.com
Hyperworks	http://www.altair.com/
Intes	http://www.intes.fr
LS-Dyna	http://www.ls-dyna.com/
Marc	http://www.mscsoftware.com/product/marc
Mentor graphics	http://www.mentor.com
Moldflow	http://www.moldflow.com
MSC software	http://www.mscsoftware.com
Nastran	http://www.nenastran.com/
Principia	http://www.principia.fr/
Radioss	http://www.altair.com/
Samtech	http://www.samcef.com
Simulia	http://www.3ds.com/products-services/simulia/
Solid edge	http://www.plm.automation.siemens.com/en_us/products/solid-edge/index.shtml
SolidWorks	http://www.solidworks.fr

gates, molding window, clamping, wall thickness changes, weld lines, inserts, sink marks, production costs, cooling, runners, cavity numbers, molding cycles, molding pressure, flow behavior, mold filling, frictional heating, and many others

- avoid various defects and weaknesses frequently encountered when designing parts and molds, such as:
  - Air traps located usually in areas that fill last and resulting in voids and bubbles inside the

molded material, incomplete filling (short shot), or surface defects such as blemishes or burn marks. Software eases modifications of the filling pattern by reducing the injection speed, enlarging venting, or placing venting at the right place in the mold.
- Warpage and sink marks can be analyzed and reduced to acceptable levels by modification of wall thickness, ribs, bosses, and internal fillets.
- Voids caused by localized shrinkage of the material at thick sections without sufficient compensation when the part is cooling. Additional redesigning can avoid these defects.
- Weld lines or knit lines and meld lines formed when two melt fronts run into each other or join together can be improved by redesigning, relocation of holes, or inserts in the part.

Among the collateral benefits, let us quote:

- Improve part performance and durability
- Speed up designing allowing a fast study of multiple options
- Reduce the number and, of course, the cost of trials
- Reduce part cost by optimizing the consumption of material for a required performance level

Solutions must be adapted to the actual processing method:

- Conventional injection molding, gas-assisted injection molding, coinjection molding, and injection-compression molding: simulation of plastics flow, packing, mold cooling, shrinkage, and warpage
- Thermoforming
- Fiber-reinforced plastics

Prototyping is also of prime importance to detect misconceptions, assembly issues, etc.

Current methods used to make prototypes are subtractive manufacturing methodologies such as machining. Conversely, 3D printing and other additive manufacturing techniques make objects from 3D data generated from 3D computer-aided design or 3D scanning systems.

Several technologies compete (fused deposition modeling, deposition of liquid photopolymers or liquid binders, stacking and gluing of PVC foils…) to satisfy the same general objective:

- Affordability: financially accessible to small- and medium-sized businesses
- Ease of use for everyone
- Office friendly without polluting emissions
- Fast operating: short development time and low-end costs producing parts in hours instead of days.

13.3.2 Physical Defects Are Detectable at First Glance

Many physical defects detectable at first glance can be avoided thanks to:

- Use of special grades often marketed as Easy flow, Ultraflow, Easy processing…offering better flowing and processability.
- Processing aids that improve flowing of compounds.
- Plasticizers, lubricants, and extenders used to enhance low-temperature behavior also ease processing and surface quality.
- Use of isotropic reinforcements rather than anisotropic ones to minimize warpage and streaks.

Surface defects depend also on processing parameters: Surface quality of a fair compound processed on an adapted machine depends on numerous parameters such as, without claiming to be exhaustive: resin moisture; pressure, temperature, time and speed profiles of injection; molding parameters; mold design: venting; gate, sprue, and runner designs…

Warpage leads to bowed, warped, bent, or twisted surfaces. It is a complex phenomenon generally originated in variation of internal stresses in the material caused by variations in shrinkage and/or crystallinity and/or a strong chain orientation in thin walls, for example. Warped parts may not be functional or visually acceptable. In some cases, this phenomenon can be increased by:

- Nonuniform cooling: Temperature differences from one side of the mold to the other can lead to layers freezing and shrinking at different kinetics and generating internal stresses.
- Nonuniform shrinkage or nonuniform stress due to excessive anisotropic orientation in machine and transverse directions.

- Nonuniform packing, variations of mold and melt temperatures; low pressure, too high ejection temperature.
- Material variations such as moisture content, nonuniform melt, and pigmentation.
- Nucleating agents
- Unbalanced mold temperatures of both halves
- Unsuitable mold cooling time
- Unsuitable part and/or mold design…

Unaesthetic and weak weld lines result generally from the inability of two or more flow fronts to weld or knit together during the processing step. Holes, inserts, and other obstacles to the melt flow, multiple gate mold feeding can create visible flaws if the different flow fronts have cooled before meeting. In addition, weld lines can cause a color variation and weakness in the molded part. By nature, some materials tend to exhibit more visible weld lines and many fillers and additives such as glass fibers and metallic pigments also highlight weld lines. Weld lines can be minimized or suppressed by optimization of mold design and processing adjustments.

Short shots result from incomplete or inadequate filling of the mold. The main causes are an insufficient feeding, inadequate molding conditions, or resin flowability issues.

Structural foams and fluid-assisted injection molding can reduce unaesthetic surface defects.

13.3.3 Coloration, Decoration, Overmolding

The perceived color depends on numerous parameters such as:

- The right level of the right colorant or pigment
- The right shade of the used resin
- The suitable opacity/transparency balance
- The suitable gloss/mat balance
- The fillers and reinforcements used in the compound
- The surface aspect and surface morphology of the part
- The possible degradation of the compound due to unusual heat treatments during compounding or processing. Yellowing is well known but other discoloration types can appear such as greenish blue, brownish red, etc.

Colors, colorants, and pigments are chemicals that must require compliance to general and specific regulations and safety rules. The designer must be aware of the suitability of the polymer to be treated for the temperature and media needed for the coloring treatment.

Color may be obtained by adding colorants to compounds, or encapsulating the part with a continuous film of another colored or printed polymer: in-mold decoration (IMD), painting, multilayer sheets for thermoforming…

Color ages as other properties. Discoloration comes from overheating, light exposure, irradiation, or chemical attack…

Colorants and pigments, inorganic or organic, differ by:

- Their chemical nature
- Their form: powders eventually dust-free, masterbatches or concentrates in pellets, pastes, liquids, encapsulated…
- Their additional properties: pastel or bright colorants with eventual effects such as marble, speckle, phosphorescent or afterglow, pearlescent, metallic, photochromic, thermochromic…

Main problems for colorants and pigments relate to:

- The high temperatures during processing but now, high-temperature organic colorants stable up to 300 °C and complex inorganic color pigments with heat stability more than 900 °C are available.
- Preservation of end part dimensional stability without shrinkage and warpage.
- Innumerable variations for the same family of pigments. For example, metallic effects obtained with aluminum pigments can be varied thanks to the coloration and surface treatment, shape, size, surface aspect of the pigment:
  - A glitter effect—a bright metallic appearance with coarse grain sparkles. It is often used to enhance the three-dimensional appearance of an object by using a low enough concentration of metallic pigment to maintain some polymer transparency. It can be made even more

appealing by adding color with transparent pigments or dyes.

- A high sparkle effect—the traditional metallic effect obtained by using aluminum pigments in polymers. It is characterized by strong metallic sheen and often a noticeable grain. A variety of metallic pigment concentrations used in combination with transparent or opaque chromatic pigments can produce a broad spectrum of effects characterized by distinct metallic sheen and sparkle.
- A metallescent effect—a soft diffuse translucent metallic appearance similar to the effect obtained by using pearlescent pigments. This effect is developed only when using the proper aluminum pigment at very low loading levels in conjunction with transparent colorants.
- A pinpoint sparkle effect—due to the spherical shape and polished surface of the used aluminum pigments. The effect is seen as a cascade of shimmering pinpoint reflections of light. This effect can give "depth" to transparent polymers by producing sparkling reflections that come from below the polymer surface. When used with transparent colorants and viewed under bright light, this effect is quite dramatic.
- A liquid metal effect—a bright metallic effect producing the appearance of pure metal such as brushed aluminum or polished steel. It is characterized by a smooth liquid metallic sheen and controlled grain or no grain. The liquid metal look can also produce the appearance of anodized aluminum.

The choice of a solution depends on numerous parameters such as the nature of the polymer, the processing constraints (notably heat exposure, mixing technology), end product aesthetics, the durability under service conditions of the end product, relevant regulations, and cost.

Apart from adding colorants and pigments into compounds, color and decoration can be obtained by several techniques such as:

- Painting
- Metallization
- Printing
- Laser marking…
- Film insert molding—FIM
- Film profile cladding
- In-mold labeling
- In-mold graining
- In-mold coating—IMC
- Comolding, overmolding with protective coatings using conventional or proprietary processes.

Decoration hides the surface of the core with another material having other properties.

Painting is the oldest technique. The choice of the right paint depends on:

- The chemical and physical compatibility with the plastic
- The possibility to obtain the desired decorative effect
- The fair wetting and linking between the paint and polymer
- The preservation of all the functional properties during all the service life
- The suitability for the chosen application technique
- The ability of the thermoplastics to be painted to withstand the heat or UV radiation eventually needed for the paint curing.

The application processes are, for example, spraying, brushing, dipping, roller coating, electrostatic painting…

Metallization can be applied by batch or continuous vacuum metallizing, sputtering, and electroplating. Special polymer grades are marketed. The selected polymer grade must be able to withstand the selected metallization process.

Printing techniques are numerous, for example, silk screen printing, gravure or offset, hot stamping, hot stamping foil, fill and wipe process, pad printing, thermal transfer printing, ink-jet printing; hydrographics, laser marking…Special polymer grades are marketed for laser marking. The thermoplastics to be painted must withstand the heat printing material and the processing conditions.

IMD, the best known in-line decoration process, uses a decoration pattern bonded onto a special carrier film exactly located into the empty mold. During molding, the molten plastic adheres onto the film and the decoration pattern is released from the carrier film and transferred onto the part leading to a high surface quality. There are several techniques for a wide range of decoration options allowing fast changeovers of decorative patterns. Some postprocessing steps can be suppressed saving finishing costs and parts can be ready to assemble.

The same type of technique can be applied to manufacture parts with various materials, replacing the film with textile, wood, leather, etc.

FIM: An example is a glossy, aesthetic, and unpainted roof module on the Smart Roadster by DaimlerChrysler AG's Smart. The removable roof is surfaced with a thermoformable three-layer film (Lexan by Sabic Innovative Plastics) that can be comolded with either thermoplastic or thermoset substrates.

Film profile cladding: Window profile extruder and downline equipment manufacturers (Aluplast, Greiner Extrusionstechnik, and Fux) design an inline process of cladding PVC window profiles with decorative films. PVC profiles are clad directly after calibration and before coextrusion of elastomer seals.

In-mold graining developed by Johnson Controls is a covering process for large surfaces in which an ungrained thermoplastic polyolefin foam foil is wrapped onto a carrier and grained in a single process stage. The technique is used for a large surface in the production of the door panels for the Opel Astra.

IMC: In the conventional IMC method, the cavity surface of the injection molding tool is first sprayed with a coating and the cavity is then filled with the melted thermoplastic compound. Because the coating and the injection molding are performed consecutively, cycle times are substantially long. Bayer MaterialScience AG proposes a variant of this IMC process, which combines injection molding with reaction injection molding (RIM). In a two-step process, the part is first injection molded and then, with the aid of a turntable mold, is transferred to a second cavity. There, a reactive two-component polyurethane (PUR) system is injected using the RIM process. The PUR cures within the cooling time in the closed mold. For car interior applications, for example, IMC process could be used to apply a decorative finish to parts such as the glove compartment flap, add-on parts for the instrument panel, panels and mirror housings.

The CoverForm® process by Krauss Maffei and Evonik Rohm GMBH is developed for "one-shot" injection-molded scratchproof parts. A PMMA component is injection molded and a functional protective layer applied in the mold immediately afterward. A following compression molding sequence spreads the coating evenly over the PMMA surface.

The flow-coating/clearmelt process by Engel involves back injecting a wood design foil with a thermoplastic carrier and then covering the part with a transparent layer of PUR. The process is characterized in particular by a visually impressive 3D effect and excellent scratch resilience. The advantage of the process is that both back injection of the decor foil and flow coating with PUR occur in a single mold without interrupting the process.

Traditional characterization of plastics parts uses color matching cabinets, photocolorimeters, brightness meters, yellowing index, light transmission, and refractometers.

Unlike photocolorimeters and spectrophotometers that measure an average color and do not really assess what the human eye sees, Alpha MOS (http://www.alpha-mos.com) proposes its Visual Analyzer that would perform an overall visual evaluation of the different colors and shapes. This evaluation would be closer to the consumer vision thanks to a high-end technology based on in-depth image analysis.

Of course, if necessary, tests must be run after accelerated aging meeting the needs of the targeted application.

13.4 Odor and Taste Transfer

Anybody knows the unpleasant odors of "rubber" or "plastic" released by certain usual articles such as vinyl sheets for interiors of cars, PUR foams, raincoats, gloves…But there are also inverse facts as the leather perfume of vinyl sheets for wallets, purses, and other leather goods, etc. Odor can be tuned by the right choice of plastics and special additives.

Taste is another issue, one of the main problems for packaging industry and food contact requiring tasteless materials. In unusual applications, a specific taste can be obtained thanks to particular additives.

Note that odor and taste are induced by recognizable chemical entities but odor and taste perceptions are subjective features depending on each individual.

Some plastics can develop unpleasant odors during and after processing or after aging. To avoid or reduce this drawback, it is possible:

- To choose odorless virgin and recycled polymer grades and additives.

- To add deodorants or specific fragrances marketed for polymers: the odor isn't suppressed but is replaced by other odors.
- To add bactericides or preservatives avoiding development of microorganisms, fungi, and so on during service life.

Chemical entities responsible for odor and taste can be tested by traditional physicochemical instruments (e.g., gas chromatography, gas chromatography/mass spectrometry), and/or by specific instruments called electronic or e-nose and e-tongue (for example: Alpha-MOS, http://www.alpha-mos.com; Electronic Sensor Technology, http://www.estcal.com/; Sensigent, www.sensigent.com) The detection system of electronic noses consists of a sensor set measuring a change of physical properties when in contact with volatile organic compounds. As for chromatography, the correlation between analytical results and actual odor human perception is not direct.

Chemosensors, gas chromatography, and other instrumental analysis methods give quantitative data and information about volatile organic compounds but the correlation between analytical results and actual odor human perception is not direct due to potential interactions between several odorous components.

Perceived odor and taste may be appraised by sensory evaluation panels.

The ASTM Subcommittee E18.05 on Sensory Applications (see Chapter 1) focuses on test methods for the evaluation of molded polymer in terms of its perceived odor and the transfer of package-related odors or flavors, or both, to the food being packaged.

This evaluation may be carried out by panels of a small number of people or by several hundred depending on the type of information required. Sensory analysis panels can be grouped into four types: highly trained experts (1–3 people), trained laboratory panels (10–20 people), laboratory acceptance panels (25–50 people), and large consumer panels (more than 100 people).

Sensory panels lead to human evaluations expected to be representative of the satisfaction or dissatisfaction of plastics part users.

13.5 Touch

Touch can be as varied as rubber-like, metallic or mimicking cloth, wood, leather. Touch also depends on surface properties such as hardness and surface texture, for example, smooth, highly polished, ground, grained, or textured. Now a soft touch is particularly in fashion.

Touch may be modified by overmolding, surface treatments, FIM, etc.

Touch may be degraded by tackiness or stickiness of the plastic surface, scratches, cracks, and so on.

13.6 Acoustics, NVH

Generally speaking, conventional plastics have sound and vibration dampening properties but plastic parts can also initiate unwanted noises by vibration, friction, and impact. For example, certain automotive parts can vibrate at frequencies of engine rotation. Plastics rubbing on other plastics or various materials can also emit annoying noises.

The noise testing is very complex (see Chapter 1) due to its dependence on the frequency, the mode of propagation (air, transmission by solids…), the psychological aspects entering in the perception of noise. In addition, the diversity and heterogeneity of the standards, the application to specific areas having their own requirements such as automotive, building, aeronautic, household appliances, air conditioning, and others make the problem even harder. Noise measurements must be carried out by skill laboratories or staff thanks to special devices and according to various standards (see Table 1.10 for examples).

13.7 Sensory Testing Needs the Complementarity of Instrumental Measurements and Sensory Panel Evaluations

As said previously, esthetics is a complex characteristic depending on objective and subjective parameters. Many objective features can be tested by using various convenient standard test methods using various scientific devices whereas subjective parameters can be evaluated through more or less numerous people gathered in sensory analysis panels.

Analysis instruments have neither brains nor psychological faculties but they are never in a good or bad mood, tired, ill, and other human problems. They are perfect to identify or quantify chemical entities or physical properties but are unable to make the link between the obtained results and the satisfaction or dissatisfaction of plastics part users.

Human eyes can be used to test color if some precautions are observed. For example, ASTM D1729 "Standard Practice for Visual Appraisal of Colors and Color Differences of Diffusely Illuminated Opaque Materials" specifies the equipment and procedures for visual appraisal of the colors and color differences. This practice requires judgments by observers with normal color vision using color assessment cabinets.

Sensory evaluation by people panel aims to fill the gap between objective measurements and subjective appraisals.

Sensory evaluation was defined by the Sensory Evaluation Division of the Institute of Food Technologists (1975) as "the scientific discipline used to evoke, measure, analyze and interpret those reactions to characteristics of foods and materials as perceived through the senses of sight, smell, taste, touch and hearing." The complex sensation that results from the interaction of our senses is used to measure product quality in programs such as quality control and new product development.

Later, ASTM established the Subcommittee E18.05 on Sensory Applications, which focuses on test methods for the evaluation of molded polymer in terms of its perceived odor and the transfer of package-related odors or flavors, or both, to the food being packaged.

This evaluation may be carried out by panels of a small number of people or by several hundreds depending on the type of information required. Sensory analysis panels can be grouped into four types: highly trained experts (1–3 people), trained laboratory panels (10–20 people), laboratory acceptance panels (25–50 people), and large consumer panels (more than 100 people).

The first and simplest form of sensory analysis is made by the researcher who develops the new products making his own evaluation to determine the interest of designed products. Skilled laboratories and consumer panels develop sensory analysis in a more formal and scientific manner.

People being used as a measuring instrument, it is necessary to control all testing methods and conditions rigidly to overcome all kinds of extraneous influences caused by psychological factors. All precautions must be taken to provide the best physical and mental conditions of the panelists and minimize the influence of the testing environment affecting their sensory evaluations. According to ASTM STP 758 "Within both discrimination and descriptive sensory methods, performance records should be maintained for each panelist and should be periodically reviewed by the panel leader. The performance of each panel member should be compared with the performance of the panel as a whole. Panelists whose performance has declined should be interviewed by the panel leader in an attempt to determine the cause. Wherever possible, assistance should be offered in an attempt to restore performance."

Instrumental and panel sensory analyses complement each other:

- Instrumental analysis leads to precise data for chemical entities initiating odor, taste, vision… by use of traditional physical–chemical instruments or more specific devices such as electronic nose, electronic tongue, and visual analyzer.
- Sensory panel evaluation leads to human appraisals assumed to be representative of the satisfaction or dissatisfaction of the majority of plastics part users.

Further Reading

Technical guides, newsletters, websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, Borealis, BP Chemicals, Bryte, Ceca, Celanese, Chem Polymer, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eurotec, Eval, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, GINAR Engineering Plastics, Grupo Repol, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Matweb, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, RTP, Sabic, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Taber, Technochemie GmbH, Teknor Apex, Telenor, The European Alliance for SMC, Thieme, Ticona, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vamptech, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

14 Resistance to Chemicals, Light, and UV

OUTLINE

Polymers are sensitive to chemicals (as other materials) and also to light and ultraviolet (UV).

In addition to the family of the polymer and the general nature of the surrounding environment, the resistance is influenced by:

- The used grade, possible presence of a copolymer, and many features dependent on the processing such as morphology of the polymer, actual degree of crystallinity, molecular weight, molecular orientation, and possibly the cross-linking. To highlight the role of the used grade, losses of tensile strength of different grades of polybutylene terephthalate (PBT) immersed 90 days at room temperature in potash at 5% are about 7% for general purpose and FR grades when a glass fiber (GF)-reinforced grade losses more than 80%. Color is an important parameter for light resistance.

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00014-3

Many grades are designed for a better resistance to specific chemical environments or resistance to light and UV. Trade names may be, for example, stabilized to hydrolysis, soaps or detergents, acids, chlorine, UV-resistant, etc.

- The concentration, purity, and temperature of the surrounding environment.
  - A higher concentration of the active chemical generally increases the degradation. For example, after 1 year, acrylonitrile butadiene styrene (ABS) swelling is 2% in hydrochloric acid at 9% and 33% in concentrated hydrochloric acid.
  - Purity of the product: low levels of impurities can trigger degradation.
  - Temperature rising generally speeds up degradation. For example, for a polymethylmethacrylate (PMMA) immersed in potassium permanganate, loss of tensile strength after same durations is 16% at 20 °C and 86% at 60 °C.
  - The wavelength for light and UV.
- The duration of exposure, for example, a polyamide (PA) immersed in dilute acetic acid swells by 6% after 30 days and 12% after 365 days. Loss of tensile strength increases from 38% up to 100%.
- The shape of the part: thickness, sharp angles, grooves, roughness, threads, cuts, and significant variations in thickness. Parts must be designed to avoid stress concentrations. For the interpretation of test results and for the design of parts, the thickness must be taken into consideration. For example, for a given polyamide immersed 2 days in the same chemical, swelling is three times higher for a 1-mm thick sample than for a 3-mm thick sample.
- The possible mechanical loading can trigger or speed up environmental stress cracking (ESC) and cracking by light and UV.

14.1 Chemical Resistance of Unstressed Materials

For a database of 8445 assessments concerning 30 thermoplastics immersed in a diversified panel of chemicals at room temperature, 23% of thermoplastics are "not satisfactory," 13% are "limited," and fortunately 64% are "satisfactory."

When temperature increases, the category of "satisfactory" thermoplastics decreases down to 45% at 50 °C, a rather low temperature, and 22% at temperatures higher than 90 °C.

Those data point out the absolute need of a smart selection of the polymer adapted to the media and its temperature.

The action of a chemical on a plastic can induce four concomitant phenomena:

- Absorption of the liquid by the plastic, which leads to a swelling and possibly a plasticization of the part. In extreme cases, thermoplastics can be dissolved. That property is used to fabricate glues and adhesives.
- Extraction by the liquid of some material components (plasticizers, in particular, antidegradants, monomers and oligomers, colorants) leading to a weakening of the part. This extraction can reduce the apparent swelling of the part or even can lead to a retraction.
- Pollution of the liquid by the immersed polymer: desorption of particles and ingredients.
- Degradation of physical, mechanical, optical, and electrical properties, as well as the decrease in the lifetime.

It is crucial to examine the mechanical loading of the part. Most cases concern unstressed parts but sometimes parts are loaded, which lead to ESC much more aggressively. When a plastic exposed to air is subjected to a stress or a strain below its yield point, cracking can occur after a very long duration. The simultaneous exposure to a chemical environment under the same stress or strain can lead to a spectacular reduction of the failure time. The accelerated cracking in this way corresponds to the ESC. Specific tests are needed to study that phenomenon.

Please note that chemicals may be hidden but remain still hazardous. For example, for a water-resistant thermoplastic piping, solvents which are insoluble in water, such as aromatics, may be absorbed by thermoplastics over time, even when they are present at very low levels in the water. This leads to a decrease in the service life.

Chemical testing often consists of immersing the sample in the fluid under consideration for a given time at a given temperature. The test duration must be linked to the application. Often, duration is in the order of some days, which is overestimated for accidental splashes but is underestimated for continuous use during some years. Test temperature is often superior to the application temperature to accelerate aging but there is a risk to study differing chemical reactions.

The effects generated by chemicals can be highlighted in several manners:

- Evaluation of the volume, weight, or dimension swelling of the sample.
- Percentage of extracted materials.
- Degradation of the mechanical (or others including esthetics) characteristics, either immediately, or after drying.

For these tests, the service liquids (solvent, oil, hydraulic fluid, acid, base…) can be used but, to ease the establishment of specifications and comparative tests, reference solvents, oils, and fuels are often used. Tests on unstressed samples are not representative of ESC.

Some thermoplastics are more resistant than others, but for each chemical there are a limited number of suitable thermoplastics. The following deals with the behavior of a limited number of thermoplastics immersed in a limited number of chemicals. Assessments are subjective and relate to very diverse experiments. Durability requirements depend on the application. Targeted lifetime may evolve from some months up to 50 years for common applications such as construction industry.

Also take into account the synergistic effects for industrial chemicals containing impurities and for combinations of chemicals that are often more damaging than each component taken one by one.

14.1.1 Hydrocarbons

Table 14.1 displays some results concerning general assessments of behavior after prolonged immersion in a range of hydrocarbons at ambient temperature for given unstressed grades, which are not necessarily representative of all the hydrocarbon and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.1 displays assessments for some grades versus six aliphatic and aromatic hydrocarbons. The second part of Table 14.1 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined hydrocarbons. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for PA11 are 83% "S" and 17% "l" when in the first part of the table, PA11 is claimed "S" versus butane, hexane, isooctane, cyclohexane, toluene, and "l" versus benzene. That may be due to the aromatic structure of benzene (but toluene has also an aromatic structure) and versatility of assessments.

In a second example, polycarbonate (PC) is claimed "S" for 33%, "l" for 33%, and "n" for 33% of the assessments, which can be due to the versatility of assessments and/or the diversity of applications. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, aromatic hydrocarbons (benzene and toluene) are more damaging than aliphatic hydrocarbons.

To give a rough idea, behavior in heptane, an aliphatic hydrocarbon, can be illustrated by the following data related to arbitrarily chosen grades:

- PA: assessment "S"; after 30 days, swelling is 0% and loss of tensile strength is 6%
- ABS: assessment "l"; after 30 days, swelling is 7% and loss of tensile strength is 43%
- Polystyrene (PS): assessment "n"; after 7 days, loss of tensile strength is 86%.

Table 14.1 General Assessment of Estimated Behavior in Various Hydrocarbons at Room Temperature

Butane		**Hexane**		**Isooctane**		**Cyclohexane**		**Benzene**		**Toluene**	
CPE	I	ABS	I	ABS	I	ABS	I	ABS	n	ABS	n
PA11	S	CA	S	CA	S	CA	S	CA	S	CA	n
PA66	S	CPE	S	CPE	S	CPE	S	CPE	I	CPE	I
PC	S	CPVC	S	ECTFE	S	CPVC	S	CPVC	I	CPVC	n
PE-HD	S	ECTFE	S	EMA	S	ECTFE	S	ECTFE	S	ECTFE	S
PET	S	EMA	I	ETFE	S	EMA	S	EMA	I	EMA	S
PP	S	ETFE	S	EVA	n	ETFE	S	ETFE	S	ETFE	S
PSU	S	EVA	n	FEP	S	EVA	n	EVA	n	EVA	n
PTFE	S	FEP	S	PA11	S	FEP	S	FEP	S	FEP	S
PVC	S	PA11	S	PA66	S	PA11	S	PA_T	S	PA_T	S
		PA66	S	PAI	S	PA66	S	PA11	I	PA11	S
		PAI	S	PC	I	PAI	S	PA66	S	PA66	S
		PC	S	PEEK	S	PC	I	PAI	S	PAI	S
		PEEK	S	PE-HD	S	PEEK	S	PASA	S	PASA	S
		PE-HD	I	PE-LD	I	PE-HD	S	PC	n	PC	n
		PE-LD	I	PET	S	PE-LD	I	PEEK	S	PEEK	S
		PET	S	PFA	S	PET	S	PE-HD	I	PE-HD	I
		PFA	S	PMMA	S	PFA	S	PE-LD	n	PE-LD	n
		PMMA	S	PMP	I	PMMA	n	PET	I	PET	I
		PMP	I	POM	S	POM	S	PFA	S	PFA	S
		POM	S	PP	I	PP	I	PMMA	n	PMMA	n
		PP	I	PPE	n	PPE	n	PMP	n	PMP	I
		PPE	S	PPS	I	PPS	S	POM	S	POM	S
		PPS	S	PS	n	PS	n	PP	I	PP	I

		PS	n	PSU	S	PSU	S	PPE	n	PPE	n
		PSU	S	PTFE	S	PTFE	S	PPS	S	PPS	S
		PTFE	S	PVC	S	PVC	S	PS	n	PS	n
		PVC	S	PVDF	S	PVDF	S	PSU	I	PSU	I
		PVDF	S	SAN	S	SAN	S	PTFE	S	PTFE	S
		SAN	S			VINYL	S	PVC	n	PVC	n
		VINYL	S					PVDF	S	PVDF	S
								SAN	n	SAN	n
								VINYL	n	VINYL	n

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	% "S"	% "I"	% "n"
ECTFE	5	100	0	0
ETFE	5	100	0	0
FEP	5	100	0	0
PA_T	2	Not enough results		
PA66	6	100	0	0
PAI	5	100	0	0
PASA	2	Not enough results		
PEEK	5	100	0	0
PFA	5	100	0	0
POM	5	100	0	0
PTFE	6	100	0	0
PVDF	5	100	0	0
PA11	6	83	17	0
PPS	5	80	20	0

Continued

Table 14.1 General Assessment of Estimated Behavior in Various Hydrocarbons at Room Temperature—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "l"**	**% "n"**
CA	5	80	0	20
PET	6	67	33	0
PSU	6	67	33	0
PVC	6	67	0	33
EMA	5	60	40	0
SAN	5	60	0	40
CPE	6	50	50	0
PE-HD	6	50	50	0
CPVC	4	50	25	25
VINYL	4	50	0	50
PMMA	5	40	0	60
PC	6	33	33	33
PPE	5	20	0	80
PP	6	17	83	0
PMP	4	0	75	25
ABS	5	0	60	40
PE-LD	5	0	60	40
EVA	5	0	0	100
PS	5	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

Behavior in benzene, an aromatic hydrocarbon, can be illustrated by the following data:

- PA: assessment “S”; after 30 days, swelling is 1% and loss of tensile strength is 9%
- Polypropylene (PP): assessment “l”; after 30 days, swelling is 14% and loss of tensile strength is 30%
- PP: assessment “l”; after 365 days, swelling is 19%
- ABS: assessment “n”; after 30 days, sample is unusable.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.2 Oils and Fuels

Table 14.2 displays some results concerning general assessments of behavior after prolonged immersion in a range of oils and fuels at ambient temperature for given unstressed grades, which are not representatives of all the oils and fuels, and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.2 displays behavior assessments for some plastics grades versus six oils and undefined fuels. IRM or ASTM oils are reference oils generally more damaging from IRM 901 (formerly ASTM1) up to IRM 903 (formerly ASTM3).

The second part of Table 14.2 displays, for each quoted family, percentages of “satisfactory,” “limited,” and “nonsatisfactory” results concerning all the examined oils and fuels. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for polysulfone (PSU) are 75% “S” and 25% “l” when in the first part of the table, PSU is claimed:

- “S” versus each ASTM oil and vegetable oil,
- “S” and “l” versus industrial oils and fuels.

That may be due to the diversity of industrial oils and versatility of assessments.

In a second example, low-density polyethylene (LDPE) is claimed “S” for 33%, “l” for 44%, and “n” for 22% of the assessments, which can be due to the versatility of assessments. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule:

- Harshness of ASTM oils increases from ASTM1 up to ASTM3
- Industrial oils are very diverse, leading to various behaviors
- Vegetable oils are generally less damaging than mineral oils
- Fuels are diverse, leading to various behaviors.

To give a rough idea, behavior in motor oil can be illustrated by the following data related to arbitrarily chosen grades:

- Polyethylene (PE): assessment “S” and “l”; after 90 days, swelling is 1.9% and loss of tensile strength is 4%, increase in elongation at break is 22%
- Styrene acrylonitrile (SAN): assessment “S” and “l”; after 7 days, loss of tensile strength is 26%
- PS: assessment “l” and “n”; after 7 days, loss of tensile strength is 16%.

Table 14.2 General Assessment of Estimated Behavior in Various Oils at Room Temperature

ASTM1 Oil		ASTM2 Oil		ASTM3 Oil		Industrial Oils		Vegetable Oil		Fuels	
PEEK	S	ABS	S	ABS	I	ABS	S	ABS	S	ABS	n
PET	S	CA	S	CA	S	CA	S	ABS	n	ABS	S
PFA	S	CPE	S	CPE	S	CA	n	CA	S	CA	S
PMMA	S	CPVC	S	CPVC	S	COPE	S	CA	I	COPE	S
PMP	S	ECTFE	S	ECTFE	S	CPE	S	COPE	S	COPE	I
POM	S	EMA	S	EMA	S	CPE	I	COPE	I	COPE	S
PP	S	ETFE	S	ETFE	S	CPVC	S	COPE	S	ECTFE	S
PPE	S	EVA	I	EVA	I	ECTFE	S	CPE	S	ETFE	S
PPS	S	FEP	S	FEP	S	EMA	I	CPVC	S	EVA	n
PSU	S	PA11	S	PA11	S	EMA	S	ECTFE	S	EVOH	S
PTFE	S	PA66	S	PA66	S	ETFE	S	EMA	I	PA_T	S
PVC	S	PAI	S	PAI	S	EVA	n	EMA	S	PA11	S
PVDF	S	PC	S	PC	S	EVOH	S	ETFE	S	PA11	I
SAN	S	PE-LD	S	PE-LD	I	FEP	S	EVA	n	PA66	S
VINYL	S	PEEK	S	PEEK	S	PA_T	S	EVOH	S	PASA	S
		PE-HD	S	PE-HD	S	PA11	S	FEP	S	PC	I
		PET	S	PET	S	PA66	S	PA_T	S	PC	n
		PFA	S	PFA	S	PAI	S	PA11	S	PE-HD	S
		PMMA	S	PMMA	S	PC	S	PA66	S	PE-HD	I
		POM	S	PMP	I	PC	I	PAI	S	PE-LD	I
		PPE	S	POM	S	PEEK	S	PC	S	PE-LD	n
		PPS	S	PP	I	PE-HD	S	PC	n	PET	S
		PSU	S	PPE	S	PE-HD	I	PEEK	S	PET	I
		PTFE	S	PPS	S	PE-LD	I	PE-HD	S	PMMA	I
		PVC	S	PS	I	PE-LD	S	PE-HD	I	PMMA	S

		PVDF	S	PSU	S	PE-LD	n	PE-LD	S	PMP	n
		SAN	S	PTFE	S	PET	I	PE-LD	I	PMP	I
		VINYL	S	PVC	S	PET	S	PET	S	POM	S
				PVDF	S	PFA	S	PET	I	PP	n
				SAN	I	PMMA	I	PFA	S	PP	I
				VINYL	S	PMMA	S	PMMA	S	PPE	n
						PMP	I	PMP	I	PPE	I
						PMP	S	PMP	S	PPS	S
						POM	S	POM	S	PS	n
						PP	S	POM	I	PSU	I
						PP	I	PP	S	PSU	S
						PP	n	PP	n	PTFE	S
						PPE	I	PPE	S	PVAL	S
						PPE	n	PPE	I	PVC	S
						PPS	S	PPS	S	PVC	I
						PS	I	PS	I	PVDF	S
						PS	n	PS	n	SAN	S
						PS	S	PSU	S		
						PSU	I	PTFE	S		
						PSU	S	PVC	S		
						PTFE	S	PVDF	S		
						PVAL	S	SAN	S		
						PVC	S	VINYL	S		
						PVC	I				
						PVDF	S				
						SAN	S				
						VINYL	S				

Continued

Table 14.2 General Assessment of Estimated Behavior in Various Oils at Room Temperature—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "l"**	**% "n"**
COPE	3	100	0	0
CPVC	4	100	0	0
ECTFE	5	100	0	0
ETFE	5	100	0	0
EVOH	3	100	0	0
FEP	4	100	0	0
PA_T	3	100	0	0
PA66	5	100	0	0
PAI	4	100	0	0
PASA	1	Not enough results		
PEEK	5	100	0	0
PMMA	8	100	0	0
PPS	6	100	0	0
PTFE	6	100	0	0
PVAL	2	Not enough results		
PVDF	6	100	0	0
VINYL	5	100	0	0
CPE	7	86	14	0
PMP	8	86	14	0
PA11	6	83	17	0
SAN	6	83	17	0
PFA	5	75	25	0
PSU	8	75	25	0

PVC	8	75	25	0
CA	7	71	14	14
EMA	6	67	33	0
PET	9	67	33	0
PE-HD	8	63	38	0
ABS	7	57	14	29
PC	8	50	25	25
PPE	9	44	33	22
POM	7	38	50	13
PE-LD	9	33	44	22
PP	10	30	40	30
PS	7	14	43	43
EVA	5	0	40	60

S, satisfactory; l, limited; n, not satisfactory.

Behavior in gasoline can be illustrated by the following data:

- Polyethylene terephthalate (PET): assessment “S” and “l”; after 30 days, swelling is 1% and loss of tensile strength is 3%
- Polyphenylene ether (PPE): assessment “l” to “n”; after 30 days, the sample is unusable.

There is not a good agreement between assessments and data, which can be due to subjectivity of assessment, harshness of the considered application, formulation of the tested grades, broad diversity of “industrial oils,” “vegetable oil,” and “fuels.”

14.1.3 Mineral or Inorganic Acids

Table 14.3 displays some results concerning general assessments of behavior after prolonged immersion in a range of mineral acids at ambient temperature for given unstressed grades, which are not representative of all the mineral acids and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.3 displays behavior assessments for some plastics grades versus dilute and concentrate acids. The second part of Table 14.3 displays, for each quoted family, percentages of “satisfactory,” “limited,” and “nonsatisfactory” results concerning all the examined mineral acids. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for polyphenylene sulfide (PPS) are 80% “S” and 20% “l” when in the first part of the table, PPS is claimed:

- “S” versus sulfuric acid at 10% to >96%, nitric acid 10%, and hydrochloric acid >35%.
- “l” versus nitric acid, 50/65%, a concentrated and oxidizing acid.

That may be due to the diversity of industrial oils and versatility of assessments.

In a second example, ABS is claimed “S” for 33%, “l” for 17%, and “n” for 50% of the assessments, which can be due to the acid type and concentration and versatility of assessments. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule:

- For a same concentration, degradation depends on the acid type. Generally, hydrochloric acid is less harsh than sulfuric and nitric acids.
- For a same acid, degradation depends on the concentration. Generally, a low concentration is less harsh.

To give a rough idea, behavior in a dilute nitric acid can be illustrated by the following data related to arbitrarily chosen grades:

- PE: assessment “S”; after 28 days, no loss of tensile strength
- Polyoxymethylene (POM): assessment “n”; after 14 days, swelling is 12% and loss of tensile strength is 14%
- PA: assessment “n”; after 60 days, sample is unusable.

Behavior in hydrochloric acid can be illustrated by the following data:

- PPS: assessment “S”; after 14 days, swelling is 0% and loss of tensile strength is 0%
- ABS: assessment “l” and “n”; after 365 days, swelling is 33%
- POM: assessment “n”; after 14 days, sample is unusable.

Table 14.3 General Assessment of Estimated Behavior in Various Inorganic Acids

Sulfuric Acid, 10%		**Sulfuric Acid, 20/25%**		**Sulfuric Acid, >96%**		**Nitric Acid, 10%**		**Nitric Acid, 50/65%**		**Hydrochloric Acid, >35%**	
ABS	S	ABS	S	ABS	n	CA	n	ABS	n	ABS	l
CA	n	CA	n	CA	n	CPE	l	CA	n	ABS	n
CPE	S	CPE	S	CPE	l	CPVC	n	CPE	l	CA	n
CPVC	S	ECTFE	S	CPE	n	ECTFE	S	CPE	n	CPE	S
ECTFE	S	EVOH	n	CPVC	l	EMA	S	CPVC	S	CPVC	S
EMA	S	FEP	S	ECTFE	S	ETFE	S	ECTFE	S	ECTFE	S
ETFE	S	PA_T	S	EMA	n	EVA	S	EMA	n	EMA	S
EVA	S	PA11	S	ETFE	S	EVOH	n	ETFE	S	ETFE	S
EVOH	n	PA66	n	EVA	n	FEP	S	EVA	n	EVA	l
FEP	S	PAI	l	EVOH	n	PA_T	S	EVOH	n	EVOH	n
PA_T	S	PC	S	FEP	S	PA11	n	FEP	S	FEP	S
PA11	l	PE-HD	S	PA_T	n	PA66	n	PA_T	n	PA_T	n
PA66	n	PE-LD	S	PA11	n	PAI	l	PA11	n	PA11	n
PAI	l	PET	l	PA66	n	PC	S	PA66	n	PA66	n
PC	S	PFA	S	PAI	n	PEEK	S	PAI	n	PAI	n
PEEK	S	PMMA	S	PC	n	PE-HD	S	PC	n	PC	n
PE-HD	S	POM	n	PEEK	n	PE-LD	S	PEEK	n	PEEK	S
PE-LD	S	PP	S	PE-HD	S	PET	l	PE-HD	l	PE-HD	S
PET	l	PPE	S	PE-HD	n	PFA	S	PE-HD	S	PE-LD	S
PFA	S	PSU	S	PE-LD	S	PMMA	S	PE-LD	l	PET	n
PMMA	l	PTFE	S	PE-LD	l	PMP	S	PE-LD	S	PFA	S
PMP	S	PVAL	n	PE-LD	n	POM	n	PET	n	PMMA	S
POM	l	PVC	S	PET	n	PP	S	PFA	S	PMP	S
PP	S	SAN	S	PFA	S	PPE	S	PMMA	n	POM	n
PPE	S	VINYL	S	PMMA	n	PPS	S	PMP	l	PP	S

Continued

Table 14.3 General Assessment of Estimated Behavior in Various Inorganic Acids—cont'd

Sulfuric Acid, 10%		Sulfuric Acid, 20/25%		Sulfuric Acid, >96%		Nitric Acid, 10%		Nitric Acid, 50/65%		Hydrochloric Acid, >35%	
PPS	S			PMP	I	PS	I	POM	n	PPE	S
PS	I			PMP	S	PSU	S	PP	I	PPS	S
PSU	S			POM	n	PTFE	S	PP	S	PS	n
PTFE	S			PP	I	PVAL	n	PPE	I	PSU	I
PVAL	n			PP	n	PVC	S	PPS	I	PTFE	S
PVC	S			PPE	I	PVDF	S	PS	I	PVAL	n
PVDF	S			PPE	n	SAN	S	PSU	n	PVC	S
SAN	S			PPS	S	VINYL	S	PTFE	S	PVDF	S
VINYL	S			PS	n			PVAL	n	SAN	S
				PSU	n			PVC	S	VINYL	S
				PTFE	S			PVC	I		
				PVC	I			PVDF	S		
				PVC	n			SAN	I		
				PVDF	S			VINYL	n		
				PVDF	I						
				SAN	n						
				VINYL	n						

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	% "S"	% "I"	% "n"
ECTFE	6	100	0	0
ETFE	5	100	0	0
FEP	6	100	0	0
PFA	6	100	0	0
PTFE	6	100	0	0
PVDF	6	83	17	0

PPS	5	80	20	0
PE-HD	8	75	13	13
PMP	6	67	33	0
PE-LD	9	67	22	11
SAN	6	67	17	17
VINYL	6	67	0	33
PP	8	63	25	13
PVC	8	62	25	13
CPVC	5	60	20	20
EMA	5	60	0	40
PEEK	5	60	0	40
PPE	7	57	29	14
PMMA	6	50	17	33
PSU	6	50	17	33
PA_T	6	50	0	50
PC	6	50	0	50
CPE	9	44	33	22
EVA	5	40	20	40
ABS	6	33	17	50
PA11	6	17	17	67
PS	5	0	60	40
PAI	6	0	50	50
PET	6	0	50	50
POM	6	0	17	83
CA	6	0	0	100
EVOH	6	0	0	100
PA66	6	0	0	100
PVAL	5	0	0	100

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.4 Organic Acids

Table 14.4 displays some results concerning general assessments of behavior after prolonged immersion in a range of organic acids at ambient temperature for given unstressed grades, which are not representatives of all the organic acids and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.4 displays behavior assessments for some plastics grades versus dilute and concentrate organic acids. The second part of Table 14.4 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined organic acids. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for PP are 86% "S" and 14% "l" when in the first part of the table, PP is claimed:

- "S" versus all acids except oleic acid
- "S" and "l" versus oleic acid.

That may be due to the diversity of industrial oils and versatility of assessments.

In a second example, PA66 is claimed "S" for 19%, "l" for 19%, and "n" for 43% of the assessments, which can be due to the acid type and concentration and versatility of assessments. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule:

- Polymer behavior varies in the presence or absence of water.
- For a same concentration, degradation depends on the acid type.
- For a same acid, degradation depends on the concentration. Generally, a low concentration is less harsh.

To give a rough idea, behavior in acetic acid can be illustrated by the following data relating to arbitrarily chosen grades:

- PE: assessment "S"; after 90 days, swelling is 0.8%, loss of tensile strength is 0%, increase in elongation is 8%
- POM: assessment "l"; after 14 days, swelling is 1%, loss of tensile strength is 15%
- PA: assessment "n"; after 30 days, swelling is 5%, loss of tensile strength is negligible.

There is not a good agreement between assessments and data. That can be due to subjectivity of assessment, harshness of the considered application, too short test time or formulation of the tested grades.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.5 Bases

Table 14.5 displays some results concerning general assessments of behavior after prolonged immersion in a range of inorganic bases at ambient temperature for given unstressed grades, which are not representative of all the bases and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.5 displays behavior assessments for some plastics grades versus dilute and concentrate bases. The second part of Table 14.5

Table 14.4 General Assessment of Estimated Behavior in Various Organic Acids at Room Temperature

Acetic or Ethanoic Acid, 10%		Acetic Acid, 40/60%		Acetic Acid, 96%		Formic or Methanoic Acid, 85%		Oleic Acid, Unknown Conc.		Oxalic Acid, Unknown Conc.	
ABS	S	ABS	n	ABS	n	ABS	n	ABS	S	ABS	S
CA	n	ECTFE	S	CA	n	CA	n	CA	S	CA	n
CPE	S	ECTFE	S	CPE	S	CPE	S	CPE	S	CPE	S
CPVC	S	EVOH	n	CPVC	S	CPVC	S	CPVC	S	CPVC	S
ECTFE	S	PA_T	n	ECTFE	S	ECTFE	S	ECTFE	S	ECTFE	S
EMA	S	PA11	n	EMA	n	EMA	S	EMA	n	EMA	S
ETFE	S	PA66	n	ETFE	S	ETFE	S	ETFE	S	ETFE	S
EVA	S	PE-HD	S	EVA	n	EVA	S	EVA	n	EVA	l
EVOH	n	PE-LD	S	EVOH	n	FEP	S	FEP	S	EVOH	l
FEP	S	POM	l	FEP	S	PA_T	n	PA_T	S	FEP	S
PA11	l	PP	S	PA_T	n	PA11	n	PA11	S	PA_T	S
PA66	l	PTFE	S	PA11	n	PA66	n	PA66	S	PA11	l
PAI	S	PVAL	n	PA66	n	PAI	n	PC	S	PA66	l
PC	S	PVC	S	PAI	l	PC	n	PEEK	S	PAI	l
PC	l	PVC	n	PC	n	PEEK	l	PE-HD	S	PC	S
PEEK	S	SAN	S	PEEK	S	PE-HD	S	PE-LD	l	PE-HD	S
PE-HD	S			PE-HD	S	PE-LD	S	PE-LD	S	PE-LD	S
PE-LD	S			PE-LD	l	PET	l	PET	S	PET	l
PET	S			PET	l	PFA	S	PFA	S	PET	S
PFA	S			PFA	S	PMMA	n	PMMA	S	PFA	S
PMMA	S			PMMA	n	PMP	S	POM	S	PMMA	S
PMMA	l			PMP	l	POM	n	PP	l	PMP	S
PMP	S			POM	l	PP	S	PP	S	POM	l
POM	S			PP	S	PPE	S	PPE	S	PP	S

Continued

Table 14.4 General Assessment of Estimated Behavior in Various Organic Acids at Room Temperature—cont'd

Acetic or Ethanoic Acid, 10%		Acetic Acid, 40/60%		Acetic Acid, 96%		Formic or Methanoic Acid, 85%		Oleic Acid, Unknown Conc.		Oxalic Acid, Unknown Conc.	
PP	S			PPE	S	PPS	S	PPS	S	PPS	S
PPE	S			PPS	S	PS	I	PS	I	PS	S
PPS	S			PS	n	PSU	S	PSU	S	PSU	S
PS	S			PSU	S	PTFE	S	PTFE	S	PTFE	S
PSU	S			PTFE	S	PVC	S	PVC	S	PVC	S
PTFE	S			PVC	I	PVDF	S	PVDF	S	PVDF	S
PVAL	n			PVDF	S	VINYL	S	SAN	S	SAN	S
PVC	I			SAN	n			VINYL	S	VINYL	S
PVDF	S			VINYL	I						
SAN	S										
VINYL	S										

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	% "S"	% "I"	% "n"
CPE	5	100	0	0
CPVC	5	100	0	0
ECTFE	7	100	0	0
ETFE	5	100	0	0
FEP	5	100	0	0
PE-HD	6	100	0	0
PFA	5	100	0	0
PPE	4	100	0	0
PPS	5	100	0	0
PSU	5	100	0	0

PTFE	6	100	0	0
PVDF	5	100	0	0
PP	7	86	14	0
VINYL	5	80	20	0
SAN	5	80	0	20
PEEK	4	75	25	0
PMP	4	75	25	0
PE-LD	7	71	29	0
PVC	7	57	28	14
EMA	5	60	0	40
PC	6	50	17	33
PMMA	6	50	17	33
PET	6	50	50	0
ABS	6	50	0	50
PS	5	40	40	20
EVA	5	40	20	40
PA_T	5	40	0	60
POM	6	33	50	17
PA66	7	29	29	43
PAI	4	25	50	25
CA	5	20	0	80
PA11	6	17	33	50
EVOH	4	0	25	75
PVAL	2	Not enough results		

S, satisfactory; l, limited; n, not satisfactory.

Table 14.5 General Assessment of Estimated Behavior in Various Inorganic Bases at Room Temperature

NH_4OH, Dilute		NH_4OH, 30%		NaOH, 10%		NaOH, 20/25%		NaOH, 55%	
ABS	S	ABS	I	ABS	S	ABS	S	ABS	S
ECTFE	S	CA	n	CA	n	CA	n	CA	n
EVOH	n	CPE	S	CPE	S	ECTFE	S	CPE	S
PA66	S	CPVC	S	CPVC	S	EVA	S	CPVC	S
PC	n	ECTFE	S	ECTFE	S	EVOH	I	ECTFE	S
PE-HD	S	EMA	S	EMA	S	PA11	S	EMA	S
PE-LD	S	ETFE	S	ETFE	S	PE-HD	S	ETFE	S
PET	n	EVA	S	EVA	S	PE-LD	S	EVA	S
PMMA	S	EVOH	n	EVOH	I	PET	n	FEP	S
PMP	S	FEP	S	FEP	S	PMMA	S	PA11	I
POM	S	PA11	S	PA_T	S	POM	I	PA66	n
PP	S	PA66	S	PA11	S	PP	S	PAI	n
PS	S	PAI	n	PA66	I	PPS	S	PC	n
PSU	S	PC	n	PAI	n	PSU	S	PEEK	S
PTFE	S	PEEK	S	PC	S	PTFE	S	PE-HD	S
PVAL	n	PE-HD	S	PEEK	S	PVAL	n	PE-LD	S
PVC	S	PE-LD	S	PE-HD	S	PVC	S	PET	I
		PET	S	PE-LD	S	PVDF	I	PFA	S
		PFA	S	PET	S	SAN	S	PMMA	S
		PMMA	S	PFA	S			PMP	S
		POM	S	PMMA	S			POM	S
		PP	S	PMP	S			PP	S
		PPE	S	POM	S			PPE	I
		PPS	S	PP	S			PPS	S
		PS	S	PPE	S			PS	S

		PSU	S	PPS	S			PSU	S
		PTFE	S	PS	I			PTFE	S
		PVAL	n	PSU	I			PVAL	n
		PVC	S	PTFE	S			PVC	S
		PVDF	I	PVAL	n			PVDF	I
		SAN	S	PVC	S			SAN	S
		VINYL	S	PVDF	I			VINYL	S
				SAN	S				
				VINYL	S				

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	**% "S"**	**% "I"**	**% "n"**
CPE	3	100	0	0
CPVC	3	100	0	0
ECTFE	5	100	0	0
EMA	3	100	0	0
ETFE	3	100	0	0
EVA	4	100	0	0
FEP	3	100	0	0
PA_T	1	100	0	0
PEEK	3	100	0	0
PE-HD	5	100	0	0
PE-LD	5	100	0	0
PFA	3	100	0	0
PMMA	5	100	0	0
PMP	3	100	0	0
PP	5	100	0	0
PPS	4	100	0	0

Continued

Table 14.5 General Assessment of Estimated Behavior in Various Inorganic Bases at Room Temperature—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "l"**	**% "n"**
PTFE	5	100	0	0
PVC	5	100	0	0
SAN	4	100	0	0
VINYL	3	100	0	0
ABS	5	80	20	0
POM	5	80	20	0
PSU	5	80	20	0
PA11	4	75	25	0
PS	4	75	25	0
PPE	3	67	33	0
PA66	4	50	25	25
PET	5	40	20	40
PC	4	25	0	75
PVDF	4	0	100	0
EVOH	4	0	50	50
CA	4	0	0	100
PAI	3	0	0	100
PVAL	5	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined bases. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for ABS are 80% "S" and 20% "l" when in the first part of the table, ABS is claimed:

- "S" versus all bases except NH_4OH at 30%
- "l" versus NH_4OH at 30%.

That may be due to the diversity of industrial oils and versatility of assessments.

In a second example, PET is claimed "S" for 40%, "l" for 20%, and "n" for 40% of the assessments, which can be due to the base type and concentration and versatility of assessments. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

To give a rough idea, behavior in dilute ammonium hydroxide can be illustrated by the following data relating to arbitrarily chosen grades:

- POM: assessment "S"; after 365 days, swelling is 1% and loss of tensile strength is 16%, increase of elongation at break is 22%
- PET: assessment "n"; after 180 days, swelling is 4%, loss of tensile strength is 42%.

Behavior in soda can be illustrated by the following data:

- Polyvinylchloride (PVC): assessment "S"; after 30 days, swelling is 0.2% and loss of tensile strength is 5%
- PET: assessment "n" and "l"; after 365 days, swelling is 8% and loss of tensile strength is 60%.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.6 Amines

Table 14.6 displays some results concerning general assessments of behavior after prolonged immersion in a range of amines at ambient temperature for given unstressed grades, which are not representative of all the amines and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.6 displays behavior assessments for some plastics grades versus five amines. The second part of Table 14.6 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined amines. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for ABS are 0% "S," 20% "l," and 80% "n" when in the first part of the table, ABS is claimed:

- "n" versus all amines except triethylamine
- "l" versus triethylamine.

This may be due to the fact that it is a tertiary amine.

In a second example, high-density polyethylene (HDPE) is claimed "S" for 40%, "l" for 40%, and "n" for 20% of the assessments, which can be due to the amine type and versatility of assessments. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any

Table 14.6 General Assessment of Estimated Behavior in Various Amines

Butylamine		Dimethyl or Diethyl Amine		Triethylamine		Aniline		Pyridine	
ABS	n	ABS	n	ABS	l	ABS	n	ABS	n
CA	n	CA	n	CPE	S	CA	n	CA	n
CPE	l	CPE	S	ETFE	S	CPE	n	CPE	l
ECTFE	S	ECTFE	n	FEP	S	ECTFE	S	EMA	S
ETFE	S	EMA	n	PC	n	EMA	l	ETFE	S
FEP	S	ETFE	S	PEEK	S	EVA	n	EVA	n
PA11	l	EVA	l	PE-HD	l	FEP	S	FEP	S
PA66	S	EVA	n	PE-LD	l	PA_T	n	PA_T	n
PC	n	FEP	S	PFA	S	PA11	n	PA11	l
PE-HD	n	PA11	l	PMP	l	PA66	n	PA66	S
PE-LD	l	PA66	S	POM	S	PAI	n	PAI	n
PET	l	PAI	l	PP	l	PC	n	PC	n
PFA	S	PC	n	PPE	n	PE-HD	S	PE-HD	S
PMMA	n	PEEK	S	PPS	S	PE-LD	n	PE-LD	S
PMP	S	PE-HD	l	PTFE	S	PET	l	PET	n
POM	S	PE-LD	l	PVC	S	PFA	S	PFA	S
PP	S	PE-LD	n	PVDF	l	PMMA	n	PMMA	n
PPE	n	PET	l	VINYL	S	PP	S	PMP	n
PPS	l	PFA	S			PPE	n	POM	l
PS	n	PMMA	n			PS	n	POM	S
PSU	n	PMP	n			PSU	n	PP	l
PTFE	S	POM	n			PTFE	S	PPE	n
PVDF	l	PP	S			PVC	n	PPS	l
		PPE	n			SAN	n	PS	n

		PPS	n			VINYL	n	PSU	n
		PS	n					PTFE	S
		PSU	I					PVC	n
		PTFE	S					PVDF	I
		PVC	I					SAN	n
		PVDF	I					VINYL	n
		SAN	S						
		VINYL	n						
		VINYL	I						

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	**% "S"**	**% "I"**	**% "n"**
ETFE	4	100	0	0
FEP	5	100	0	0
PEEK	2	Not enough results		
PFA	5	100	0	0
PTFE	5	100	0	0
PA66	4	75	0	25
ECTFE	3	67	0	33
PP	5	60	40	0
POM	5	60	20	20
CPE	5	40	40	20
PE-HD	5	40	40	20
EMA	3	33	33	33
SAN	3	33	0	67
PPS	4	25	50	25
PMP	4	25	25	50

Continued

Table 14.6 General Assessment of Estimated Behavior in Various Amines—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "l"**	**% "n"**
PVC	4	25	25	50
VINYL	5	20	20	60
PE-LD	6	17	50	33
PVDF	4	0	100	0
PA11	4	0	75	25
PET	4	0	75	25
PAI	3	0	33	67
EVA	4	0	25	75
PSU	4	0	25	75
ABS	5	0	20	80
CA	4	0	0	100
PA_T	2	Not enough results		
PC	5	0	0	100
PMMA	4	0	0	100
PPE	5	0	0	100
PS	4	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule:

- Polymer behavior varies in the presence or absence of water
- For a same concentration, degradation depends on the amine type. Aromatic and heterocyclic products may be more aggressive than aliphatic amines.

To give a rough idea, behavior in aniline can be illustrated by the following data relating to arbitrarily chosen grades:

- PP: assessment “S”; after 30 days, swelling is 0.1%
- PVC: assessment “n”; after 30 days, loss of tensile strength is 26%, loss of elongation at break is 87%.

Behavior in aliphatic amines can be illustrated by the following data:

- Polyvinylidene fluoride (PVDF): assessment “l”; after 14 days, swelling is <1%, loss of tensile strength is 6% up to 10%, loss of elongation is 27% in one case and elongation is doubled in another case.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.7 Alcohols

Table 14.7 displays some results concerning general assessments of behavior after prolonged immersion in a range of alcohols at ambient temperature for given unstressed grades, which are not representative of all the alcohols and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.7 displays behavior assessments for some plastics grades versus six alcohols. The second part of Table 14.7 displays, for each quoted family, percentages of “satisfactory,” “limited,” and “nonsatisfactory” results concerning all the examined alcohols. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for PVC are 71% “S” and 29% “l” when in the first part of the table, PVC is claimed:

- “S” versus all alcohols except cyclohexanol
- “l” versus cyclohexanol.

That may be due to the special structure of cyclohexanol or versatility of assessments.

In a second example, PMMA is claimed “S” for 25%, “l” for 25%, and “n” for 50% of the assessments, which is partly due to versatility of assessments that are “S” and “n” for a same alcohol. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals

Table 14.7 General Assessment of Estimated Behavior in Various Alcohols at Room Temperature

Methanol		Ethanol		Propanol		Butanol		Cyclohexanol		Benzyl Alcohol	
ABS	I	ABS	I	ABS	S	ABS	n	ABS	I	ABS	n
CA	n	CA	n	CA	n	ABS	I	CA	I	CA	n
CPE	S	CA	I	CPE	S	CA	n	CPE	S	CPE	S
CPVC	S	CPE	S	ECTFE	S	CPE	S	ECTFE	S	ECTFE	S
ECTFE	S	CPVC	S	EMA	I	CPVC	S	EMA	S	ETFE	S
EMA	I	ECTFE	S	ETFE	S	ECTFE	S	ETFE	S	EVA	n
ETFE	S	EMA	I	EVA	S	EMA	I	EVA	n	FEP	S
EVA	I	ETFE	S	EVOH	S	ETFE	S	FEP	S	PA11	I
EVOH	n	EVA	I	FEP	S	EVA	I	PA11	I	PA66	I
FEP	S	FEP	S	PA11	I	FEP	S	PA66	I	PAI	S
PA_T	n	PA_T	n	PA66	S	PA11	I	PAI	S	PASA	S
PA11	S	PA11	S	PA66	I	PA66	S	PC	I	PC	n
PA66	I	PA11	I	PASA	S	PA66	I	PE-HD	S	PE-HD	S
PAI	S	PA66	I	PC	S	PAI	S	PE-LD	I	PE-LD	S
PC	I	PA66	S	PC	I	PC	S	PET	I	PET	I
PEEK	S	PAI	S	PEEK	S	PE-HD	S	PFA	S	PFA	S
PE-HD	S	PASA	S	PE-HD	S	PE-LD	S	PMMA	n	PMMA	n
PE-LD	S	PC	S	PE-LD	S	PET	S	PMP	S	PMP	n
PET	I	PEEK	S	PET	I	PET	I	POM	S	POM	S
PFA	S	PE-HD	S	PET	S	PFA	S	PP	S	PP	S
PMMA	n	PE-LD	I	PFA	S	PMMA	n	PPE	n	PPE	I
PMMA	S	PE-LD	S	PMMA	S	POM	S	PPS	S	PPS	I
PMP	S	PET	S	PMMA	I	PP	S	PS	I	PS	n
POM	S	PFA	S	PMP	S	PPE	S	PSU	S	PSU	I
PP	S	PMMA	I	POM	I	PPS	S	PTFE	S	PTFE	S
PPE	I	PMP	S	PP	S	PS	I	PVC	I	PVC	S

PPS	S	POM	S	PPE	I	PS	S	PVDF	S	PVDF	S
PS	I	PP	S	PPS	S	PSU	S	SAN	S	SAN	n
PSU	S	PPE	I	PS	S	PTFE	S			VINYL	S
PTFE	S	PPE	S	PS	I	PVC	S				
PVAL	n	PPS	S	PSU	S	PVC	I				
PVC	S	PS	I	PTFE	S	PVDF	S				
PVDF	S	PS	S	PVC	S	SAN	S				
SAN	n	PSU	S	PVDF	S	SAN	I				
VINYL	I	PTFE	S	SAN	S	VINYL	S				
		PVAL	n	VINYL	S						
		PVC	S								
		PVDF	S								
		SAN	S								
		SAN	I								
		VINYL	S								

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	% "S"	% "I"	% "n"
CPE	6	100	0	0
ECTFE	6	100	0	0
ETFE	6	100	0	0
FEP	6	100	0	0
PE-HD	6	100	0	0
PFA	6	100	0	0
PP	6	100	0	0
PTFE	6	100	0	0
PVDF	6	100	0	0
PAI	5	100	0	0

Continued

Table 14.7 General Assessment of Estimated Behavior in Various Alcohols at Room Temperature—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "I"**	**% "n"**
CPVC	3	100	0	0
PASA	3	100	0	0
PEEK	3	100	0	0
POM	6	83	17	0
PPS	6	83	17	0
PSU	6	83	17	0
VINYL	5	80	20	0
PMP	5	80	0	20
PE-LD	7	71	29	0
PVC	7	71	29	0
SAN	8	50	25	25
EVOH	2	Not enough results		
PC	7	43	43	14
PET	8	38	63	0
PA66	9	33	67	0
PA11	7	29	71	0
PPE	7	29	57	14
PS	9	33	56	11
ABS	8	25	50	25
EMA	5	20	80	0
EVA	6	17	50	33
PMMA	8	25	25	50
CA	7	0	29	71
PA_T	2	Not enough results		
PVAL	2	Not enough results		

- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule: For a same concentration, degradation depends on the alcohol type. Aromatic and heterocyclic products may be more aggressive than aliphatic alcohol.

To give a rough idea, behavior in ethanol, can be illustrated by the following data relating to arbitrarily chosen grades:

- PP: assessment "S"; after 365 days, swelling is 0.1%
- ABS: assessment "l"; after 28 days, loss of tensile strength is 77%.

Behavior in benzyl alcohol can be illustrated by the following data:

- PE: assessment "S"; after 55 days, swelling is 0.4%
- ABS assessment "n"; after 30 days, sample is unusable.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.8 Aldehydes

Table 14.8 displays some results concerning general assessments of behavior after prolonged immersion in a range of aldehydes at ambient temperature for given unstressed grades, which are not representative of all the aldehyde and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.8 displays behavior assessments for some plastics grades versus three aldehydes. The second part of Table 14.8 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined aldehydes. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for polymethylpentene (PMP) are 67% "S" and 33% "l" when in the first part of the table, PMP is claimed:

- "S" versus ethanol and methanal
- "l" versus benzaldehyde.

That may be due to the aromatic structure of benzaldehyde or versatility of assessments.

In a second example, PPE is claimed "S" for 33%, "l" for 33%, and "n" for 33% of the assessments, which is partly due to versatility of assessments that are "S" and "l" for a same aldehyde. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule:

- For a same concentration, degradation depends on the aldehyde type. Aromatic and heterocyclic products may be more aggressive than aliphatic aldehyde.
- Behavior depends on the presence of water and the concentration level.

To give a rough idea, behavior in formaldehyde at 36% can be illustrated by the following data relating to arbitrarily chosen grades:

- ABS: assessment "S"; after 30 days, swelling is 1%, loss of tensile strength is negligible.
- PPE: assessment "S" and "l"; after 14 days, swelling is 1% and loss of tensile strength is 11%.

Table 14.8 General Assessment of Estimated Behavior in Various Aldehydes at Room Temperature

Acetaldehyde or Ethanal		Formaldehyde or Methanal, 35%		Benzaldehyde	
ABS	n	ABS	S	ABS	n
CA	n	CA	n	CA	n
CPE	l	CPVC	S	CPE	l
ECTFE	S	ECTFE	S	ECTFE	S
EMA	l	ETFE	S	EMA	l
ETFE	S	EVA	S	ETFE	S
EVA	n	PA11	l	EVA	n
FEP	S	PA66	S	FEP	S
PA_T	l	PA66	l	PA11	l
PA11	S	PC	S	PA66	l
PA66	l	PE-HD	S	PAI	S
PAI	S	PE-LD	S	PC	n
PC	n	PET	S	PEEK	S
PE-HD	S	PMMA	S	PE-HD	S
PE-LD	l	PMP	S	PE-LD	l
PET	S	POM	S	PET	l
PFA	S	PP	S	PFA	S
PMMA	n	PPE	l	PMMA	n
PMP	S	PPE	S	PMP	l
POM	S	PPS	S	POM	S
PP	S	PS	n	PP	l
PPS	S	PSU	l	PPE	n
PS	n	PTFE	S	PPS	l
PSU	n	PVC	S	PS	n
PTFE	S	PVDF	S	PSU	n
PVAL	S	SAN	S	PTFE	S
PVAL	n			PVC	n
PVC	n			PVDF	S
PVDF	S			SAN	n
SAN	n			VINYL	n
VINYL	n				

Table 14.8 General Assessment of Estimated Behavior in Various Aldehydes at Room Temperature—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "l"**	**% "n"**
CPVC	1	Not enough results		
ECTFE	3	100	0	0
ETFE	3	100	0	0
FEP	2	Not enough results		
PAI	2	Not enough results		
PEEK	1	Not enough results		
PE-HD	3	100	0	0
PFA	2	Not enough results		
POM	3	100	0	0
PTFE	3	100	0	0
PVAL	2	Not enough results		
PVDF	3	100	0	0
PET	3	67	33	0
PMP	3	67	33	0
PP	3	67	33	0
PPS	3	67	33	0
PA11	3	33	67	0
PE-LD	3	33	67	0
PPE	3	33	33	33
ABS	3	33	0	67
EVA	3	33	0	67
PC	3	33	0	67
PMMA	3	33	0	67
PVC	3	33	0	67
SAN	3	33	0	67
PA66	4	25	75	0
CPE	2	Not enough results		
EMA	2	Not enough results		
PA_T	1	Not enough results		
PSU	3	0	33	67
CA	3	0	0	100
PS	3	0	0	100
VINYL	2	Not enough results		

S, satisfactory; l, limited; n, not satisfactory.

Behavior in benzaldehyde can be illustrated by the following data:

- PVDF: assessment “S”; after 14 days, swelling is negligible and loss of tensile strength is 9%
- ABS: assessment “n”; after 30 days, sample is unusable.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.9 Ketones

Table 14.9 displays some results concerning general assessments of behavior after prolonged immersion in a range of ketones at ambient temperature for given unstressed grades, which are not representative of all the ketone and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.9 displays behavior assessments for some plastics grades versus four ketones. The second part of Table 14.9 displays, for each quoted family, percentages of “satisfactory,” “limited,” and “nonsatisfactory” results concerning all the examined ketones. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for PVDF are 25% “S” and 75% “l” when in the first part of the table, PVDF is claimed:

- “S” versus acetophenone
- “l” versus other ketones.

That may be due to the ketone type or versatility of assessments.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals.
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule, for a same concentration, degradation depends on the ketone type. Aromatic and heterocyclic products may be more aggressive than aliphatic ketones.

To give a rough idea, behavior in acetone can be illustrated by the following data relating to arbitrarily chosen grades:

- PA: assessment “S”; after 30 days, swelling and loss of tensile strength are negligible.
- PC: assessment “n”; after 14 days, swelling is 8% and loss of tensile strength is 86%.

Behavior in acetophenone can be illustrated by the following data:

- PVDF: assessment “S”; after 14 days, swelling is 1.3%, loss of tensile strength is 11%, and elongation at break increases by 45%.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.10 Esters

Table 14.10 displays some results concerning general assessments of behavior after prolonged immersion in a range of esters at ambient temperature for given unstressed grades, which are not representative of all the ester and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.10 displays behavior assessments for some plastics grades versus five esters. The second part of Table 14.10 displays, for each quoted family, percentages of “satisfactory,” “limited,” and “nonsatisfactory” results concerning all the examined esters. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

Table 14.9 General Assessment of Estimated Behavior in Various Ketones at Room Temperature

Acetone or Propanone		MEK or Butanone		Acetophenone		Cyclohexanone	
ABS	n	ABS	n	ABS	n	ABS	n
CA	n	CA	n	CA	n	CA	n
COPE	l	CPE	l	CPE	S	CPE	S
CPE	l	ECTFE	S	ETFE	S	CPVC	n
CPVC	l	EMA	l	FEP	S	ECTFE	S
ECTFE	S	ETFE	S	PA11	S	EMA	l
ETFE	S	EVA	n	PA66	S	ETFE	S
EVA	n	FEP	S	PAI	S	EVA	n
FEP	S	PA11	S	PC	n	FEP	S
PA_T	l	PA66	l	PE-HD	S	PA_T	S
PA11	S	PAI	S	PE-LD	l	PA11	l
PA66	S	PC	n	PET	l	PA66	S
PAI	S	PEEK	S	PFA	S	PAI	S
PASA	S	PE-HD	S	PMMA	n	PC	n
PC	n	PE-LD	l	PMP	l	PE-HD	S
PEEK	S	PET	l	POM	l	PE-LD	l
PE-HD	l	PFA	S	PP	l	PET	l
PE-LD	l	PMMA	n	PPE	n	PFA	S
PET	l	PMP	l	PPS	S	PMMA	n
PFA	S	POM	l	PS	n	POM	S
PMMA	n	PP	S	PSU	n	PP	l
PMP	l	PPE	n	PTFE	S	PPE	n
POM	l	PPS	S	PVC	n	PPS	S
PP	S	PS	n	PVDF	S	PS	n
PPE	n	PSU	n	SAN	n	PSU	n

Continued

Table 14.9 General Assessment of Estimated Behavior in Various Ketones at Room Temperature—cont'd

Acetone or Propanone		MEK or Butanone		Acetophenone		Cyclohexanone	
PPS	S	PTFE	S	VINYL	n	PTFE	S
PS	n	PVC	n			PVC	n
PSU	n	PVDF	I			PVDF	I
PTFE	S	SAN	n			SAN	n
PVAL	n	VINYL	n				
PVAL	S						
PVC	n						
PVDF	I						
SAN	n						
VINYL	n						

Brief Result Analysis for Plastics Generating a Noticeable Number of Results

	Result Number	% "S"	% "I"	% "n"
ECTFE	3	100	0	0
ETFE	4	100	0	0
FEP	4	100	0	0
PAI	4	100	0	0
PASA	1	Not enough results		
PEEK	2	Not enough results		
PFA	4	100	0	0
PPS	4	100	0	0
PTFE	4	100	0	0
PA11	4	75	25	0
PA66	4	75	25	0
PE-HD	4	75	25	0

CPE	4	50	50	0
PA_T	2	Not enough results		
PP	4	50	50	0
PVAL	2	Not enough results		
POM	4	25	75	0
PVDF	4	25	75	0
COPE	1	Not enough results		
EMA	2	Not enough results		
PE-LD	4	0	100	0
PET	4	0	100	0
PMP	3	0	100	0
CPVC	2	Not enough results		
ABS	4	0	0	100
CA	4	0	0	100
EVA	3	0	0	100
PC	4	0	0	100
PMMA	4	0	0	100
PPE	4	0	0	100
PS	4	0	0	100
PSU	4	0	0	100
PVC	4	0	0	100
SAN	4	0	0	100
VINYL	3	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

Table 14.10 General Assessment of Estimated Behavior in Various Esters at Room Temperature

Ethyl Acetate		Butyl Acetate		Dibutyl Phthalate		Dioctyl Phthalate		Tricresyl Phosphate	
ABS	n	ABS	n	EVA	n	ABS	n	ABS	n
CA	n	CA	n	PA66	S	CA	S	CA	S
CPE	l	CPE	l	PC	n	CPE	l	CPE	S
CPVC	n	CPVC	n	PE-HD	l	CPVC	S	EMA	l
ECTFE	S	ECTFE	S	PET	l	ECTFE	S	ETFE	S
EMA	l	EMA	l	PMMA	n	EMA	l	EVA	n
ETFE	S	ETFE	S	POM	S	ETFE	S	FEP	S
EVA	n	EVA	n	PP	S	EVA	n	PA_T	S
EVOH	S	EVOH	S	PPE	n	FEP	S	PA11	S
FEP	S	FEP	S	PPS	S	PA_T	S	PA66	S
PA11	S	PA11	S	PSU	S	PA11	S	PC	n
PA66	l	PA66	S	PTFE	S	PA66	S	PE-HD	S
PAI	S	PAI	S	PVDF	l	PAI	S	PE-LD	S
PC	n	PC	n	SAN	n	PC	l	PET	S
PEEK	S	PE-HD	S			PC	n	PFA	S
PE-HD	S	PE-LD	l			PE-HD	S	PMMA	n
PE-LD	l	PET	l			PE-LD	l	PMP	S
PET	n	PFA	S			PET	l	POM	S
PFA	S	PMMA	n			PFA	S	PP	S
PMMA	n	PMP	l			PMMA	l	PS	n
PMP	n	POM	S			PMP	S	PTFE	S
POM	S	PP	l			POM	l	PVC	n
PP	l	PPE	n			PP	S	SAN	n
PPE	n	PPS	S			PPE	n	VINYL	n

PPS	S	PS	n			PPS	S		
PS	n	PSU	I			PS	n		
PSU	n	PTFE	S			PSU	S		
PTFE	S	PVC	n			PTFE	S		
PVC	n	PVDF	S			PVC	n		
PVDF	I	SAN	n			PVDF	S		
SAN	n	VINYL	n			SAN	n		
VINYL	n					VINYL	n		
Brief Result Analysis for Plastics Generating a Noticeable Number of Results									
		Result Number		**% “S”**		**% “I”**		**% “n”**	
ECTFE		3		100		0		0	
ETFE		4		100		0		0	
EVOH		2		Not enough results					
FEP		4		100		0		0	
PA_T		2		Not enough results					
PA11		4		100		0		0	
PAI		3		100		0		0	
PEEK		1		100		0		0	
PFA		4		100		0		0	
PPS		4		100		0		0	
PTFE		5		100		0		0	
PA66		5		80		20		0	
PE-HD		5		80		20		0	
POM		5		80		20		0	
PP		5		60		40		0	
PVDF		4		50		50		0	

Continued

Table 14.10 General Assessment of Estimated Behavior in Various Esters at Room Temperature—cont'd

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "l"**	**% "n"**
PMP	4	50	25	25
PSU	4	50	25	25
CA	4	50	0	50
CPVC	3	33	0	67
CPE	4	25	75	0
PE-LD	4	25	75	0
PET	5	20	60	20
EMA	4	0	100	0
PMMA	5	0	20	80
PC	6	0	17	83
ABS	4	0	0	100
EVA	5	0	0	100
PPE	4	0	0	100
PS	4	0	0	100
PVC	4	0	0	100
SAN	5	0	0	100
VINYL	4	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

For example, in the second part of the table, assessments for PA66 are 80% “S” and 20% “l” when in the first part of the table, PA66 is claimed:

- “S” versus all esters except ethyl acetate
- “l” versus other ethyl acetate.

That may be due to the ester type or versatility of assessments.

In a second example, chlorinated polyvinylchloride (CPVC) is claimed “S” for 33% and “n” for 67% of the assessments, which may be due to the difference of structure between acetates and phthalate.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

Generally speaking, but it is not a rule, for a same concentration, degradation depends on the ester type. The ester family is very heterogeneous with organic aliphatic products, organic semiaromatic products, and organic/inorganic entities.

To give a rough idea, behavior in ethyl acetate, can be illustrated by the following data relating to arbitrarily chosen grades:

- POM: assessment “S”; after 14 days, swelling and loss of tensile strength are negligible.
- PC: assessment “n”; after 14 days, swelling is 7% and loss of tensile strength is 87%.

Behavior in dioctyl phthalate can be illustrated by the following data:

- PP: assessment “S”; after 365 days, swelling is 0.2%.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.11 Ethers

Table 14.11 displays some results concerning general assessments of behavior after prolonged immersion in diethyl ether at ambient temperature for given unstressed grades, which are not representative of all the ether and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.11 displays behavior assessments for some plastics grades versus diethyl ether. The second part of Table 14.11 displays, for each quoted family, percentages of “satisfactory,” “limited,” and “nonsatisfactory” results.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- There is only one ether
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

To give a rough idea, behavior in diethyl ether can be illustrated by the following data relating to arbitrarily chosen grades:

- PA: assessment “S”; after 30 days, swelling and loss of tensile strength are negligible.
- PMMA: assessment “n”; after 30 days, samples are unusable.

Table 14.11 General Assessment of Estimated Behavior in Diethyl Ether at Room Temperature

ABS	n
CA	S
CPE	S
CPVC	n
ECTFE	S
EMA	S
ETFE	S
EVA	n
FEP	S
PA_T	S
PA11	S
PA66	S
PAI	S
PC	n
PEEK	S
PE-HD	l
PE-LD	n
PET	S
PET	l
PFA	S
PMMA	n
PMP	n
POM	S
PP	l
PPE	n
PPS	S
PS	n
PSU	S
PTFE	S
PVC	n
PVDF	S
SAN	n
VINYL	n

Table 14.11 General Assessment of Estimated Behavior in Diethyl Ether at Room Temperature—cont'd

Ranking by Expected Interest (Not Enough Results for Analysis)				
	Result Number	**% "S"**	**% "l"**	**% "n"**
CA	1	100	0	0
CPE	1	100	0	0
ECTFE	1	100	0	0
EMA	1	100	0	0
ETFE	1	100	0	0
FEP	1	100	0	0
PA_T	1	100	0	0
PA11	1	100	0	0
PA66	1	100	0	0
PAI	1	100	0	0
PEEK	1	100	0	0
PFA	1	100	0	0
POM	1	100	0	0
PPS	1	100	0	0
PSU	1	100	0	0
PTFE	1	100	0	0
PVDF	1	100	0	0
PET	2	50	50	0
PE-HD	1	0	100	0
PP	1	0	100	0
ABS	1	0	0	100
CPVC	1	0	0	100
EVA	1	0	0	100
PC	1	0	0	100
PE-LD	1	0	0	100
PMMA	1	0	0	100
PMP	1	0	0	100
PPE	1	0	0	100
PS	1	0	0	100
PVC	1	0	0	100
SAN	1	0	0	100
VINYL	1	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.12 Phenols

Table 14.12 displays some results concerning general assessments of behavior after prolonged immersion in phenol and cresol at ambient temperature for given unstressed grades, which are not representative of all the phenol and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.12 displays behavior assessments for some plastics grades versus phenol and cresol. The second part of Table 14.12 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning both phenols. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table. Generally, both phenols lead to corroborating assessments.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- There are only two phenols
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

To give a rough idea, behavior in phenol can be illustrated by the following data relating to arbitrarily chosen grades:

- PE: assessment "S"; after 30 days, swelling is 1% and loss of tensile strength is negligible.
- PPE: assessment "n"; after 14 days, swelling is 83% and samples are unusable.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.13 Chlorinated Hydrocarbons

Table 14.13 displays some results concerning general assessments of behavior after prolonged immersion in chlorinated hydrocarbons at ambient temperature for given unstressed grades, which are not representative of all the chlorinated hydrocarbons and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.13 displays behavior assessments for some plastics grades versus aliphatic and aromatic chlorinated hydrocarbons. The second part of Table 14.13 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined chlorinated hydrocarbons. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for PVDF are 83% "S" and 17% "l" when in the first part of the table, PVDF is claimed:

- "S" versus all chlorinated hydrocarbons except methylene chloride or dichloromethane
- "l" versus methylene chloride or dichloromethane.

That may be due to the chlorinated hydrocarbon type or versatility of assessments.

In a second example, PA11 is claimed "S" for 17%, "l" for 33%, and "n" for 50% of the assessments, which may be due to the difference between chlorinated hydrocarbons or versatility of assessments. In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals

Table 14.12 General Assessment of Estimated Behavior in Phenols at Room Temperature

Phenol		Cresol	
ABS	n	ABS	n
CA	n	CA	n
CPE	l	CPE	l
CPVC	S	EMA	n
ECTFE	S	ETFE	S
EMA	n	EVA	n
ETFE	S	FEP	S
EVA	n	PA11	n
FEP	S	PA66	n
PA_T	n	PAI	S
PA11	n	PC	n
PA66	n	PE-HD	S
PAI	S	PE-LD	l
PC	n	PET	n
PEEK	l	PFA	S
PE-HD	S	PMMA	n
PE-LD	S	POM	n
PE-LD	l	PP	S
PET	n	PPS	S
PFA	S	PS	l
PMMA	n	PSU	n
PMP	S	PTFE	S
POM	n	PVC	S
PP	S	PVC	l
PPE	n	PVDF	S
PPS	S	SAN	l
PS	l		
PSU	n		
PTFE	S		
PVC	l		
PVDF	S		
SAN	n		
VINYL	n		

Continued

Table 14.12 General Assessment of Estimated Behavior in Phenols at Room Temperature—cont'd

Ranking by Expected Interest (Not Enough Results for Analysis)				
	Result Number	**% "S"**	**% "I"**	**% "n"**
ETFE	2	100	0	0
FEP	2	100	0	0
PAI	2	100	0	0
PE-HD	2	100	0	0
PFA	2	100	0	0
PP	2	100	0	0
PPS	2	100	0	0
PTFE	2	100	0	0
PVDF	2	100	0	0
CPVC	1	100	0	0
ECTFE	1	100	0	0
PMP	1	100	0	0
PE-LD	3	33	67	0
PVC	3	33	67	0
CPE	2	0	100	0
PEEK	1	0	100	0
PS	2	0	100	0
SAN	2	0	50	50
ABS	2	0	0	100
CA	2	0	0	100
EMA	2	0	0	100
EVA	2	0	0	100
PA_T	1	0	0	100
PA11	2	0	0	100
PA66	2	0	0	100
PC	2	0	0	100
PET	2	0	0	100
PMMA	2	0	0	100
POM	2	0	0	100
PPE	1	0	0	100
PSU	2	0	0	100
VINYL	1	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

Table 14.13 General Assessment of Estimated Behavior in Chlorinated Hydrocarbons at Room Temperature

Chloroethane or Ethyl Chloride		Methylene Chloride or Dichloromethane		Chloroform or Trichloromethane		Carbon Tetrachloride or Tetrachloromethane		Benzyl Chloride	
ABS	n	ABS	n	ABS	n	ABS	n	ABS	n
CA	n	CA	n	CA	n	CA	n	CA	n
CPE	S	CPE	n	CPE	l	CPE	l	CPE	l
CPVC	n	ECTFE	l	ECTFE	S	CPVC	S	ECTFE	S
ECTFE	S	EMA	n	EMA	n	ECTFE	S	ETFE	S
EMA	n	ETFE	S	ETFE	S	EMA	n	EVA	n
ETFE	S	EVA	n	EVA	n	ETFE	S	EVOH	S
EVA	n	EVOH	S	EVOH	S	EVA	n	FEP	S
FEP	S	FEP	S	FEP	S	EVOH	S	PA11	l
PA11	S	PA_T	l	PA11	n	FEP	S	PA66	S
PA66	S	PA11	n	PA66	n	PA_T	S	PA66	l
PAI	S	PA66	n	PAI	S	PA11	l	PAI	S
PC	n	PAI	n	PC	n	PA11	n	PC	n
PE-HD	l	PASA	S	PEEK	S	PA66	l	PE-HD	l
PE-LD	l	PC	n	PE-HD	n	PA66	S	PE-LD	l
PET	n	PEEK	S	PE-LD	n	PAI	S	PE-LD	n
PFA	S	PE-HD	l	PET	l	PC	S	PET	S
PMMA	n	PE-LD	n	PFA	S	PEEK	S	PET	n
PMP	n	PET	n	PMMA	n	PE-HD	l	PFA	S
POM	l	PFA	S	PMP	l	PE-LD	n	PMMA	n
PP	n	PMMA	n	POM	n	PE-LD	l	PMP	n
PPE	n	POM	n	PP	l	PET	S	POM	S
PPS	S	PP	l	PPE	n	PET	l	POM	l
PS	n	PPE	n	PPS	S	PFA	S	PP	l
PSU	n	PS	n	PS	n	PMMA	n	PPE	n

Continued

Table 14.13 General Assessment of Estimated Behavior in Chlorinated Hydrocarbons at Room Temperature—cont'd

Chloroethane or Ethyl Chloride		Methylene Chloride or Dichloromethane		Chloroform or Trichloromethane		Carbon Tetrachloride or Tetrachloromethane		Benzyl Chloride	
PTFE	S	PSU	n	PSU	n	PMMA	I	PPS	S
PVC	n	PTFE	S	PTFE	S	PMP	n	PS	n
PVDF	S	PVC	n	PVC	n	POM	S	PSU	n
VINYL	n	PVC	I	PVDF	S	PP	I	PTFE	S
		PVDF	I	SAN	n	PP	n	PVC	n
		PVDF	S	VINYL	n	PPE	n	PVDF	S
		SAN	n			PPS	n	SAN	n
		VINYL	n			PS	I		
						PSU	S		
						PTFE	S		
						PVC	I		
						PVDF	S		
						SAN	I		
						VINYL	I		

Brief Result Analysis for Plastics Generating a Noticeable Number of Results				
	Result Number	**% "S"**	**% "I"**	**% "n"**
	Total	**% S**	**% I**	**% n**
ETFE	5	100	0	0
EVOH	4	100	0	0
FEP	5	100	0	0
PASA	1	Not enough results		
PEEK	3	100	0	0
PFA	5	100	0	0
PTFE	5	100	0	0
PVDF	6	83	17	0

ECTFE	5	80	20	0
PAI	5	80	0	20
PPS	4	75	0	25
PA_T	2	Not enough results		
CPVC	2	Not enough results		
PA66	7	43	29	29
POM	6	33	33	33
PET	7	29	29	43
CPE	5	20	60	20
PC	5	20	0	80
PSU	5	20	0	80
PA11	6	17	33	50
PE-HD	5	0	80	20
PP	6	0	67	33
PE-LD	7	0	43	57
PVC	6	0	33	67
PMP	4	0	25	75
SAN	4	0	25	75
VINYL	4	0	25	75
PS	5	0	20	80
PMMA	6	0	17	83
ABS	5	0	0	100
CA	5	0	0	100
EMA	4	0	0	100
EVA	5	0	0	100
PPE	5	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

To give a rough idea, behavior in carbon tetrachloride can be illustrated by the following data relating to arbitrarily chosen grades:

- PVDF: assessment "S"; after 14 days, swelling is 0.3%, loss of tensile strength is 5%, and loss of elongation is 27%.

Behavior in dichloromethane can be illustrated by the following data:

- Ethylene-tetrafluoroethylene (ETFE) assessment "S"; after 7 days, swelling is 4%, loss of tensile strength is 15%, elongation at break is unchanged.
- PP assessment "l"; after 365 days, swelling is 31%.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.1.14 Oxidants

Table 14.14 displays some results concerning general assessments of behavior after prolonged immersion in a range of oxidants at ambient temperature for given unstressed grades, which are not representative of all the oxidants and polymer families. A same polymer may appear on several lines with different assessments.

The first part of Table 14.14 displays behavior assessments for some plastics grades versus five oxidants. The second part of Table 14.14 displays, for each quoted family, percentages of "satisfactory," "limited," and "nonsatisfactory" results concerning all the examined oxidants. That is a complementary tool to roughly estimate the general behavior of polymers versus the chemicals examined in this table.

For example, in the second part of the table, assessments for ETFE are 80% "S" and 20% "l" when in the first part of the table, ETFE is claimed:

- "S" versus all oxidants except aqua regia
- "l" versus aqua regia, a very harsh oxidant.

That may be due to the unique highly corrosive feature of aqua regia or versatility of assessments.

In a second example, SAN is claimed "S" for 75% and "n" for 25% of the assessments, which may be due to the difference between aqua regia ("n") and other oxidants ("S"). In this case, the designer must be particularly cautious.

These general indications should be verified by consultation with the producer of the selected grades and by tests under operating conditions. These assessments are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods. Tests must be run on samples of the selected grade processed by the selected manufacturing method, according to procedures related to operating conditions.

Results must be carefully examined:

- Assessments are subjective
- Quoted assessments are not comparable
- Grades taken into account are limited in number
- Other assessments can be found elsewhere because of the broad variations of polymer formulation and impurities in industrial chemicals
- Errors, lack of accuracy, and method uncertainty require to verify those data and to run tests on the actually used compound.

To give a rough idea, behavior in chromic acid can be illustrated by the following data relating to arbitrarily chosen grades:

- PE: assessment "S"; after 90 days, swelling is 0% and loss of tensile strength and elongation are negligible.

Behavior in hydrogen peroxide can be illustrated by the following data relating to arbitrarily chosen grades:

- PE assessment "S"; after 365 days, swelling is negligible.

Behavior in potassium permanganate can be illustrated by the following data relating to arbitrarily chosen grades:

- PVC assessment "S"; after 30 days, swelling is 1%, elongation at break is unchanged.

Table 14.14 General Assessment of Estimated Behavior in Some Oxidants at Room Temperature

Sodium or Potassium Hypochlorite, 13/20%		Potassium Permanganate, 10/20%		Hydrogen Peroxide, 30/35%		Aqua Regia		Chromic Acid, 10–30%	
ABS	S	ABS	l	ABS	n	ABS	n	ABS	l
CA	n	CA	n	ABS	l	CA	n	ETFE	S
CPE	l	CPE	S	CA	n	CPE	n	PA11	n
CPVC	S	CPVC	S	CPE	S	CPE	l	PA66	n
CPVC	S	ECTFE	S	CPVC	S	ECTFE	S	PC	S
ECTFE	S	EMA	S	ECTFE	S	EMA	n	PE-HD	S
EMA	S	ETFE	S	ETFE	S	ETFE	l	PET	n
ETFE	S	EVA	n	EVA	S	EVA	n	PMMA	S
EVA	n	EVOH	n	EVOH	n	FEP	S	PP	S
EVA	l	FEP	S	FEP	S	PA11	n	PPE	S
FEP	S	PA11	n	PA11	n	PA66	n	PS	l
PA11	l	PA66	n	PA66	n	PAI	n	PSU	n
PA66	n	PAI	n	PAI	l	PC	n	PTFE	S
PAI	n	PC	S	PC	S	PEEK	l	PVC	S
PC	S	PEEK	S	PEEK	S	PE-HD	n	PVDF	S
PE-HD	S	PE-HD	S	PE-HD	S	PE-LD	n	SAN	S
PE-LD	S	PE-LD	S	PE-LD	S	PET	n		
PET	S	PET	S	PET	l	PFA	S		
PFA	S	PFA	S	PFA	S	PMMA	n		
PMMA	S	PMMA	S	PMMA	S	PMP	n		
PMP	S	PMP	S	PMP	S	POM	n		
POM	l	POM	S	POM	l	PP	n		
POM	n	PP	S	POM	n	PPE	l		
PP	S	PPE	S	PP	S	PPS	n		

Continued

Table 14.14 General Assessment of Estimated Behavior in Some Oxidants at Room Temperature—cont'd

Sodium or Potassium Hypochlorite, 13/20%		Potassium Permanganate, 10/20%		Hydrogen Peroxide, 30/35%		Aqua Regia		Chromic Acid, 10–30%	
PPE	S	PPS	S	PPE	S	PS	n		
PPS	S	PS	I	PPS	S	PSU	n		
PS	I	PSU	S	PS	S	PTFE	S		
PSU	S	PTFE	S	PSU	S	PVAL	n		
PTFE	S	PVAL	n	PTFE	S	PVC	I		
PVAL	n	PVC	S	PVAL	n	PVDF	I		
PVC	S	PVDF	S	PVC	S	SAN	n		
PVDF	S	SAN	S	PVDF	S	VINYL	n		
SAN	S	VINYL	S	TPU	I				
VINYL	S			VINYL	S				
Brief Result Analysis for Plastics Generating a Noticeable Number of Results									
		Result Number		**% "S"**		**% "I"**		**% "n"**	
CPVC		4		100		0		0	
ECTFE		4		100		0		0	
FEP		4		100		0		0	
PFA		4		100		0		0	
PTFE		5		100		0		0	
ETFE		5		80		20		0	
PPE		5		80		20		0	
PVC		5		80		20		0	
PVDF		5		80		20		0	
PC		5		80		0		20	
PE-HD		5		80		0		20	

PMMA	5	80	0	20
PP	5	80	0	20
PE-LD	4	75	0	25
PMP	4	75	0	25
PPS	4	75	0	25
SAN	4	75	0	25
VINYL	4	75	0	25
PEEK	3	67	33	0
EMA	3	67	0	33
PSU	5	60	0	40
CPE	5	40	40	20
PET	5	40	20	40
PS	5	20	60	20
EVA	5	20	20	60
ABS	6	17	50	33
POM	6	17	33	50
TPU	1	Not enough results		
PAI	4	0	25	75
PA11	5	0	20	80
CA	4	0	0	100
EVOH	2	0	0	100
PA66	5	0	0	100
PVAL	4	0	0	100

S, satisfactory; l, limited; n, not satisfactory.

- ABS assessment "l"; after 365 days, swelling is 22%.

As already said, these data are not a rule and others can be found elsewhere. They cannot be used for designing any parts or goods.

14.2 Environmental Stress Cracking

As already said, when a plastic exposed to air is subjected to a stress or a strain below its yield point, cracking can occur after a very long duration. The simultaneous exposure to a chemical environment under the same stress or strain can lead to a spectacular reduction of the failure time. The accelerated cracking in this way corresponds to the ESC. Specific tests are needed to study that phenomenon.

> Chemical resistance data from immersion tests on unstressed samples cannot be unconditionally applied to thermoplastic components subjected to continuous or dynamic mechanical stresses.

Stresses may be residual stresses after molding or may be originated from voluntary (or not) mechanical loading. According to the (plastic/chemical) couple, they can dramatically increase the degradation as we can see below.

For a given grade of PSU exposed to chromic acid 12% at room temperature:

- after 7 days, unstressed samples increase by 0.6% in weight and aspect is unchanged
- after less than 1 h, samples loaded under 13.8 MPa are broken.

This phenomenon, very important for designers, is complex and difficult to forecast. It can be detected by specific tests differing from the usual immersion tests under unstressed samples.

To improve the resistance to ESC, it may be useful to anneal residual stresses by gently heating unstressed parts: viscosities decrease allowing rearrangement of molecules and a reduction of stress. To avoid the distortion of parts, the treatment temperature must be lower than the temperature of deformation under load and away from the glass transition temperature. The recommended temperature is often 10°–15° below the temperature of deformation under load.

ESC is influenced by the factors already quoted for the chemical resistance. In addition to the family of the polymer and the general nature of the surrounding environment, designers must consider:

- The used grade, the morphology of the polymer, the actual degree of crystallinity, the molecular weight, the possible copolymer, molecular orientation, and possibly the cross-linking. Some grades are proposed for a better resistance to ESC, for example, "High environmental stress crack resistance (ESCR) grades," "outstanding ESCR," "Environmental Stress Crack Resistant," etc.
- The concentration, purity, and temperature of the surrounding environment.
  - A higher concentration increases the risk of cracking. For example, for a given PSU at room temperature, immersed in a 50/60 water/acetone solution, critical stress is 28 MPa. In pure acetone, the same stress level leads to breaking in 1 h.
  - Purity of the product: low levels of impurities can trigger cracking. For example, 0.1% of a surfactant can dramatically speed up ESC.
  - Temperature rising speeds up ESC.
- The level and the nature of the stress (internal or external).
- The duration of exposure: for example, for a polyetherimide (PEI) exposed to a brake fluid, the threshold of critical stress at room temperature is 9 MPa for cracking after 4 days and 13 MPa for cracking after 1 day.
- The shape of the part: sharp angles, grooves, roughness, threads, cuts, and significant variations in thickness. Parts must be designed to minimize stress cracking by avoiding large wall thickness variations, radiusing corners and edges, smoothening sharp intersections, threads, notches, and so on, avoiding stress concentrations.

ESC can be stopped by meeting less stressed regions. In the case of constant strain amplitude, relaxation results in a reduction of the stress over time and so a decrease in the ESC. Areas of different morphology of the polymer can also stop ESC.

ESC test results are influenced by the used methods relevant from two large families: at constant stress (load) or at constant strain (deformation). There are many procedures, for example, without claiming to be exhaustive:

ISO 8796:2004 Reviewed 2012 Polyethylene PE 32 and PE 40 pipes for irrigation laterals—Susceptibility to environmental stress cracking induced by insert-type fittings

ISO 16770:2004—Plastics—Determination of environmental stress cracking (ESC) of polyethylene—Full-notch creep test (FNCT)

ISO 22088:2006—Plastics—Determination of resistance to environmental stress cracking (ESC)

ASTM D 1693—Bent Strip ESCR Test

ASTM D1975-95(2010) Standard Test Method for Environmental Stress Crack Resistance of Plastic Injection Molded Open Head Pails

ASTM D2561-12 Standard Test Method for Environmental Stress-Crack Resistance of Blow-Molded Polyethylene Containers

ASTM D3929-03(2010)e1 Standard Test Method for Evaluating Stress Cracking of Plastics by Adhesives Using the Bent-Beam Method

ASTM D 5397 (2012) Appendix—Single Point Notched Constant Tensile Load (NCTL) Test

ASTM D5419-09 Standard Test Method for Environmental Stress Crack Resistance (ESCR) of Threaded Plastic Closures

ASTM D5571-94(2010) Standard Test Method for Environmental Stress Crack Resistance (ESCR) of Plastic Tighthead Drums Not Exceeding 60 Gal (227 l) in Rated Capacity

ASTM F 1248—Notched Pipe Ring ESCR Test

ASTM F 1473—13 The Polyethylene Notch Tensile (PENT) Test (constant load)

It is not possible to establish a direct correlation between the measured results of ESC tests and the actual behavior of parts, because the behavior of the latter may be more complex.

The following results must be taken into account more cautiously than for chemical resistance on unstressed samples:

- Tested grades are not cited, while resistance to ESC varies considerably from one grade to another. For example, for two ABS grades tested under the same conditions in the same chemical, cracks appear after 6 h for one, and 20 h for the other.
- There are few results in the published literature and cross-checks are not possible.
- Comparisons are hazardous or impossible because the testing conditions are different.

More absolutely than for chemical resistance without constraint, it is essential to check the used grade from the selected producer under procedures representative of the operating conditions.

14.2.1 Jumble of Published Results

The following information is not a scientific or technical study of ESC but a jumble of facts and figures more or less vague that are not comparable. It is not possible to find logical ways through these results and as already said, it is essential to check the used grade.

14.2.1.1 Polyolefins

The PEs are deemed sensitive to the ESC in the presence, in particular, of certain surfactants, alcohols, esters, ketones, ethers, and silicone oils. Cross-linking often improves behavior. For example, based on the same ESC test, failure time is about 50 times higher for XPE compared to HDPE for chemicals such as ketone, toluene, benzene, carbon tetrachloride, ethyl acetate, silicone oil, mineral oil, concentrated nitric acid…

In another test, for a 30% GF-reinforced PE immersed 7 days in heptane at room temperature without tension, on the one hand, under 0.25% strain, on the other hand, the loss of tensile strength is 19% for unstressed samples and 36% for stressed samples. For some other chemicals, both methods lead to identical results.

Polypropylenes are generally more resistant than PE but certain grades may be sensitive to oxidizing agents and strong acids, such as aqua regia, bromine, calcium hypochlorite, bleaching agents, and concentrated hydrofluoric acid.

For a PMP grade immersed 1 h in acetone, methyl isobutyl ketone or ethyl acetate… critical stress is in the range of 16 MPa up to 29 MPa. In contrast, in the same conditions there are no cracks by immersion in butyl acetate, methanol, and ethanol.

A polybutylene grade tested according to ASTM D 1693 with the detergent IGEPAL CO-630 at 50 °C presents no cracks after 15,000 h at a concentration of 10% or 2900 h at 25%.

14.2.1.2 Styrenics

Some PS may be sensitive to *n*-heptane, gasoline, methanol, vegetable oils, certain rubber, and soft PVC compounds. For 1 h to 1 day immersion, critical stress may vary from 2 MPa up to 17 MPa for common chemicals such as heptane, methanol, mixture of olive oil and oleic acid, detergent, acid for battery…

For 7 days of immersion at room temperature, a 30% GF-reinforced PS presents tensile strength losses between 9% and 43% for unstressed specimens versus 20–74% for specimen strained at 0.25%. Tested chemicals include ethylene glycol, bleaching agent, hydrochloric acid at 10%, motor oil, pure acetic acid, methanol, and detergent at 2%. In contrast, saturated solution of ammonia and some vegetable oils lead to similar results for both methods.

High-impact PS: For a given grade, under a stress of 7 MPa, cracks are visible after 1 h in *n*-butanol versus 2880 h (4 months) in air. For polystyrene/butadiene copolymers, oils and unsaturated fats may cause ESC.

ABS: For certain grades, after 7 days at room temperature, the critical strain is inferior to 0.5% for pure acetic acid, nitric acid at 70%, sulfuric acid at 98%, methanol, ethanol, acetone, cyclohexanone, methyl ethyl ketone, aniline, diethyl ether, benzene, hexane, pentane, carbon tetrachloride, chlorobenzene, perchloroethylene, chloroform, ethylene chloride, some freon, meta-cresol, phenol, some detergents, dibutyl phthalate, diethyl phthalate, ethylene acetate, methylene acetate, some silicone oils…

On the other hand, the following chemicals do not cause cracks in 7 days at room temperature under 1% strain: dilute acetic acid, hydrochloric acid at 25%, hydrofluoric acid at 12%, some detergents, antifreeze, some silicone grease, some machine grease, naphtha, some edible oils, and sodium hydroxide at 25%.

For immersion during 7 days at room temperature, a stressed (0.25% strain) 30 GF-reinforced ABS losses 12 up to 93% of its tensile strength when unstressed samples loss 0 up to 47%. Considered chemicals include vegetable oil, sulfuric acid at 10%, pure acetic acid, methanol, detergent at 2%, and brake fluid.

In contrast, concentrated solution of ammonia, heptane, hydrochloric acid at 10%, and some motor oils lead to similar results for both methods.

Acrylonitrile styrene acrylate (ASA): Certain grades may be more resistant than ABS versus some chemicals such as PVC plasticizers.

SAN: For immersion during 7 days at room temperature, a stressed (0.25% strain) SAN losses 11% up to 30% of its tensile strength when unstressed samples loss 0% up to 22%. Considered chemical include sulfuric acid at 10%, pure acetic acid, detergent at 2%, and ethylene glycol.

In contrast, saturated solution of ammonia and heptane leads to similar results for both methods.

14.2.1.3 Polyamides

PA6 and PA66 may be sensitive to concentrated solutions of salts of lithium, nickel, zinc, barium, cobalt, copper, iron, and heavy metals. In practice, galvanized parts can cause ESC and grades specially stabilized for this purpose are available. Concentrated aqueous solution of zinc chloride is used for the detection of internal stresses.

Some acids and oxidants in concentrated solutions can also quickly lead to stress cracking of certain grades.

PA610, PA11, and PA12 are claimed more resistant to ESC than PA66 or PA66.

14.2.1.4 Polymethylmethacrylate

PMMAs are sensitive to ESC but certain grades more resistant are proposed with possibly different mechanical properties.

For certain grades, after 3 min at room temperature, the critical strain is in the range of 0.1% up to 0.4% for methanol, isopropanol, ethyl acetate, butyl acetate, tetrachloroethylene, trichloroethylene, toluene, and xylene. The critical stress at 1 h at room temperature is in the range of 14 MPa up to 28 MPa for immersion in methanol, ethanol, ethyl acetate, butyl acetate, toluene, acetone, and methyl isobutyl ketone.

14.2.1.5 Polyoxymethylene

After 7 days of immersion at room temperature in heptane or sulfuric acid at 10%, a 30% GF-reinforced POM exhibits tensile strength losses of 0% and 24% for unstressed specimens versus 28% and 40% for specimen strained at 0.25%. In contrast, both methods lead to similar results for pure acetic acid, brake fluid, petrol, hydrochloric acid at 10%, some vegetable oils, and engine oils.

A test on curved samples does not show cracks for certain grades immersed 7 days at room temperature, in acetic acid at 5%; carbon tetrachloride, ethyl acetate, formaldehyde at 37%; engine oil, toluene, sodium chloride at 10%.

14.2.1.6 Polycarbonate

PCs are sensitive to ESC but certain grades more resistant are proposed with possibly different mechanical properties.

For certain grades, the critical stress at 1 h at room temperature is in the range of 9 MPa up to 24 MPa for ethyl acetate, butyl acetate, toluene, ethanol, acetone, and methyl isobutyl ketone.

After 7 days of immersion in ethylene glycol or heptane at room temperature, a given PC grade exhibits tensile strength losses of 0% and 9% for unstressed specimens versus 22% and 56% for specimen strained at 0.25%.

In contrast, both methods lead to similar tensile stress losses after immersion in pure acetic acid, brake fluid, gasoline, hydrochloric acid at 10%, methanol, motor oil, and sulfuric acid at 10%.

In a series of tests under strain, cracks appear after a maximum of 7 days at room temperature, for deformations of 1% maximum, in the following products: dilute acetic acid, some bleach and cleaning agents, some fruit juices and cola drinks, photo development products, heptane, isopropanol, methanol, and certain release agents.

On the other hand, under the same conditions, the same grade has not cracked under deformations of 1.6% in pure acetic acid, some adhesives, dilute citric acid, some fruit juices, some detergents, ketchup, potash at 10%.

On specimens in contact with various rubbers, the critical thresholds of stress were 26–30 MPa at room temperature and 8–12 MPa at 80 °C.

14.2.1.7 Polyphenylene Ether

Certain PPEs may be sensitive to certain chemicals such as tributylphosphate, some brake fluids, and some vegetable oils.

After 7 days of immersion at room temperature, a 30% GF-reinforced PPE exhibits tensile strength losses of 1–9% for unstressed specimens versus 19–23% for specimen strained at 0.25%. Tested chemicals are brake fluid and some vegetable oils. In contrast, both methods lead to similar results for pure acetic acid, hydrochloric acid at 10%, some detergents at 2%, ethylene glycol, heptane, methanol, motor oil, and sulfuric acid at 10%.

After 5 h under a stress of 83 MPa, a GF-reinforced grade exhibits no cracks in the following fluids: gasoline at 60 °C, ethylene glycol at 93 °C, transmission oil at 93 °C, brake fluid at 60 °C, Skydrol at 23 °C, mixture of benzene, toluene, and xylene at 23 °C.

In another series of tests, it was not found significant differences in tensile strength losses after 7 days at room temperature between unstrained and strained (0.25% strain) samples. Tested chemicals include ammonium hydroxide, detergent at 2%, pure ethylene glycol, heptane, hydrochloric acid at 10%, methanol, and sulfuric acid at 10%.

14.2.1.8 Polyvinylchloride and Chlorinated Polyvinyl Chloride

PVC: Methanol is reported as causing the ESC of some grades.

CPVC: Some authors inform that prolonged high stresses and absorption of certain hydrocarbon contaminants may cause stress cracking.

14.2.1.9 Polyvinylidene Fluoride

Stress cracking can occur on some PVDF grades when simultaneously exposed to mechanical stress and an environment with pH ≥ 12, or when operating in a medium which is likely to generate atomic chlorine.

Samples submitted to ASTM D 1693 during 1 year, saw their resistance at yield decrease less than 5% in contact with the following products: hydrochloric acid at 36% at 130 °C, sulfuric acid 80% at 90 °C, nitric acid 32% at 90 °C, acetic acid 50% at 130 °C, soda 45% at 90 °C, ethylene glycol at 130 °C, perchloroethylene at 90 °C, and crude oil at 130 °C.

14.2.1.10 Polysulfones

PSU as a lot of amorphous polymers are sensitive to ESC but certain grades or derivatives are more resistant. For example, time to cracking by immersion under 1% strain in ethyl acetate or toluene may be, respectively, 65 and 45 h for some grades and 10 and 3 h for other grades.

Time to cracking of given grade samples stressed at 14 MPa may be inferior to 1 h by immersion at room temperature in ethyl acetate; pure or dilute (60%)

acetone; methyl ethyl ketone; isopropanol; dioctyl phthalate; certain freon; naphthalene; dichlorobenzene; turpentine; toluene; chromic acid 12% and 60%; Skydrol 500 A; certain gasolines; some hydraulic fluids; some detergents; cleaning and disinfection agents; some products for welding, sealing, or gluing.

For the same test, there are no cracks after 500 h of immersion at room temperature in ethanol, methanol, pure oleic acid, some vegetable oils, heptane, hydrochloric acid at 20%, sulfuric acid at 10%, fuel JP4, some detergents, some antifreeze, some oils and greases, ASTM1 oil, coffee at 96 °C, and certain cleaning agents or disinfectants.

14.2.1.11 Polyetherether Ketone

In a 1-h immersion test, under a 3% strain at room temperature, acetone causes a slight cracking, while isopropyl alcohol, ethyl acetate, and toluene cause no apparent alteration.

In a shorter test, 20 min under 3% strain, trichloroethylene, hexane, Skydrol, and JP 5 fuel do not lead to ESC.

14.2.1.12 Polyetherimide

As a lot of amorphous polymers, PEIs are sensitive to ESC.

In a series of tests at room temperature, cracking appeared in less than 24 h for critical stresses in the range of 4–17 MPa during immersion in acetone, certain brake fluids, chloroform, ethyl acetate, methylene chloride, methyl ethyl ketone, saturated solution of phenol, trichloroethane, triethylphosphate, toluene, and xylene.

On the other hand, in the same tests, cracking was not occurred after 14 days at room temperature for lower applied stresses during immersion in acetone, some brake fluids, some antifreezes, butanol, carbon tetrachloride, cyclohexane, some detergents, ethyl ether, certain gasolines, hexane, some hydraulic fluids, methanol, methyl ethyl ketone, saturated solution of phenoltriethylphosphate, toluene, and xylene.

14.3 Photooxidation: Weathering, Light, and UV Behavior

Weathering covers very different situations:

- climate varies according to the regions and time for a given area
- exposure mode: direct or indirect light, sunlight duration, irradiation angle
- other combined factors: humidity, rain, ozone
- Pollution: acid rain, industrial pollution… Some studies have shown that degradation due to weather could be stronger in moderately sunny industrial areas than in very sunny but less polluted regions.

Light can also be artificial with more or less broad spectrum including UVs.

14.3.1 Overview of Light and UV Resistance

Polymers are organic materials and are sensitive to natural or artificial UV sources.

This is of primary importance for outdoor exposure of unprotected parts and for some industrial applications such as electrical welding, photocopier, light exposure devices…

Additives such as special fillers (for example, carbon blacks), UV stabilizers, and so on can enhance the basic resistance of the matrix to UV.

Under quite precise conditions (angle of incidence, positioning, temperature, water vapor, surface water…), tests can be done by exposure:

- to the natural light of the sun or
- to the radiation of xenon lamps (Xenotest, Weather-Ometer) or others.

Outdoor suitability: Underwriter Laboratories (UL) consider a material suitable for outdoor if it has gone through testing in accordance with UL 746C, “the Standard for Safety of Polymeric Materials—Use in Electrical Equipment Evaluations.” Exposure may be UV light exposure for 720 h of twin-enclosed carbon or 1000 h of xenon-arc Weather-Ometer conditioning, and/or water exposure or immersion for 7 days at 70 °C. The material is tested before and after exposure to these conditions for flammability, mechanical impact, and mechanical strength.

The results may lead to one of the following outcomes:

- (f1)—Suitable for outdoor use with respect to exposure to UV light, water exposure, and immersion in accordance with UL 746C. The

Table 14.15 Example of Property Variations after Irradiation

	Natural Light	Xenon Lamp with Anti-UV Glass	Duration Factor
Duration, h	15,000	1500	10
Elongation at break, %	700	80	
Oxygen absorption, mmol/kg	300	1400	

(f1) footnote indicates that the material has met both UV and water exposure or immersion requirements as called out in UL 746C.

- (f2)—Subjected to one or more of the following tests: UV, water exposure, or immersion in accordance with UL 746C, where the acceptability for outdoor use is to be determined by UL. The (f2) footnote indicates that the material has only met or has been tested partially for UV or water exposure or immersion.

The problem of light sources is obviously crucial for accelerated light aging tests. Table 14.15 (Gijsman P., Polymer Degradation and Stability, 46, 1994, p. 63) illustrates the influence of source on degradation. Unfortunately, the acceleration factor is not the same for all properties. In this example, versus natural exposure, the artificial exposure divides elongation at break by a factor of 9 in round number and at the opposite multiplies oxygen absorption by a factor of 4 in round number.

The effects of light aging first affect the surface appearing in several ways:

- Surface degradation, chalking, crazing, cracking, hardened surface layer.
- Mainly for clear grades, aspect modification, loss of gloss and discoloration, chalking, yellowing, browning…
- Decrease in the mechanical properties that can lead to inability to the function.
- Retraction, loss of mass.
- Embrittlement.
- Desorption and consumption of protective additives leading to an acceleration of the aging.
- Modification of flow properties and other characteristics, which may prevent recycling.

The degradation depends on:

- The nature of the polymer, its color and opacity, presence of impurities and structural irregularities, use of protection additives.
- The nature of the spectrum (UV are the most aggressive) and the angle of the rays. The solar spectrum varies with geographical locations, the period of the year, and the local circumstances. In general, spectrum begins around 300 nm. The overall intensity, already highly variable, cannot be a sufficient criterion since only a small portion of the spectrum is known to be aggressive. The intensity of radiation for each of the wavelengths is very important.
- The thickness of the test piece or part. Irradiation damages the exposed surface but warming damages the part more or less deeply.
- The ambient temperature and the temperature of the part itself which heats up because of the absorption of light energy. For example, for a same polymer, a same air temperature, black samples have a surface temperature of 50 °C versus 33 °C for white samples.
- Moisture of air, rain, and sea spray that add their hydrolytic action to the action of UV.
- The presence of ozone and air pollutants.
- The possible mechanical stresses applied to the samples, which favor cracking creating new surfaces for light attack and new sites for oxygen uptake. These elements contribute to the acceleration of degradation.

The interpretation of natural or artificial exposures is difficult because of:

- climate diversity
- the risks of industrial or domestic pollution in real life
- the lack of correlation between artificial and natural aging

- the different degradation kinetics of the various properties. For example, half-life of a given PA exposed to artificial UV light is 6000 h based on brilliance or 11,000 h based on tensile strength.

Weathering is difficult to quantify because the weather covers a complex, variable, and poorly defined context. Exposure conditions vary greatly geographically and even locally:

- annual hours of sunshine, from less than 1200 up to more than 4000 h per year
- energy of irradiation. For example, natural radiation energy may be 85 kL y in Central Europe, 140 kL y in Florida, and 190 kL y in Arizona.
- spectral composition
- average and extreme temperatures
- humidity, rain, sea spray
- ozone
- industrial pollution…

For the USA only, let us quote three climate examples:

- Miami: mean temperature of 24.4 °C, total annual precipitation averages 1420 mm, hours of sunshine per year 2943.
- Barrow (Alaska): mean annual temperature −12.5 °C, total annual precipitation averages 114 mm.
- Yuma (Arizona): annual average temperature is 23.4 °C, total annual precipitation averages 80.6 mm, and hours of sunshine per year 4127.

So, it is impossible to determine standard conditions: some polymers can be resistant to UV and behave properly in a dry and sunny climate but on the other hand polymers sensitive to hydrolysis, age quickly in a hot and humid climate.

With regard to time alone, it should be noted that an induction period during which the loss of property is low or negligible. Then the degradation is accelerating more or less brutally (curve in "knee"). So extrapolation of lifetimes must be cautious.

14.3.2 Elements of Appraisal

Table 14.16 approximately classifies some thermoplastics on the basis of their inherent weather resistance. Formulation can greatly improve this ranking by using anti-UV additives, fillers absorbing light, surface coatings. So, ranking of compounds may be very different. For example, PVC can get 10-year warranty for outdoor applications, painted PPE can be used for car body, ABS protected by a PVDF film is proposed for outdoor applications.

14.3.2.1 Effect of Color

For a natural polypropylene taken as base 1 for UV resistance under specified conditions, the different colored compounds prepared from this polypropylene have relative UV resistances in the range of 1 up to 12 (see Table 14.17).

Obviously, in addition to the color, the nature of the pigment is of importance explaining that the three red grades are in the broad range of 1 up to 3.3. The white grade has a good rank because it is obtained with an opaque pigment that stops the radiation at the surface, avoiding the degradation of the deeper layers. Two blues behave differently because the used pigments are different. The outstanding behavior of black polypropylene should be noted.

Table 14.16 Ranking Proposal for Light Resistance

Good behavior	PVDF
	PTFE
Fair behavior	PC
	PET
	PMMA
	PPE
	PVDC
Limited behavior	PS
	ABS
	POM
	PA
	PE
	PP
	PVC

14.3.2.2 Effect of Anti-UV Additives

Table 14.18 displays property retentions after 1 year of exposure for stabilized and unstabilized polymers: UV protections are effective but do not systematically improve all properties. For example, for the white PC, elongation at break is drastically increased when tensile strength and impact resistance aren't significantly changed.

Table 14.19 displays another face of UV protection efficiency concerning embrittlement times of PP protected with six different systems. Efficiency factor linked to unstabilized PP varies from 1.06 up to 5.2.

Allen N.S. and Coll. (Polymer Degradation and Stability, 61, 1998, p. 183).

Table 14.17 UV Resistance of PP Compounds: Examples of Color Effect

Color	Relative Resistance to UV
Natural	1
Red	1
Magenta	1
Blue	1.8
Yellow	2
White	2.3
Red	2.8
Brick red	3.3
Blue	3.5
Green	3.5
Black	12

14.3.3 Examples of Published Assessments Relating to Light and UV Behavior of Compounds

The following information is not a scientific or technical study but a jumble of more or less vague facts and figures that are not comparable. The following results relate to a few grades tested or basically assessed under particular conditions and cannot be generalized. As already said, it is essential to check the used grade in convenient conditions.

14.3.3.1 Polyolefins and Derivatives

Polyolefins resist hydrolysis well but are more or less naturally sensitive to light and UV. They must be protected by efficient protective systems.

PE must be protected by addition of anti-UV and other protective agents and/or by 2–3% of an adequate carbon black. In such cases, after weathering of test bars for several years in various climates, the retention of tensile strength is generally good but the elongation at break retention can be as low as 10%.

PP must be protected by the addition of anti-UV and other protective agents and/or by 2–3% of a suitable carbon black.

After weathering of test bars (3 mm thick) for 1 year in a sunny climate, the retention of properties is, for example:

- 56% for tensile strength, 59% for elongation at break, and 62% for impact strength for a natural unstabilized grade

Table 14.18 Property Retentions after 1 year of Exposure

			Retentions, %		
		Location	Tensile Strength	Elongation at Break	Impact
PC	Unstabilized	Arizona			7
	Stabilized				97
PC-white	Unstabilized	Florida	96	22	91
	Stabilized		93	78	85
PE	Unstabilized	Florida	56	59	52
	Stabilized		76	78	95

Table 14.19 Embrittlement Times of PP Protected with Six Different Systems

UV Protection System	Embrittlement Time, h	Efficiency Factor
None	384	
A	408	1.06
B	912	2.4
C	1032	2.7
D	1512	3.9
E	1944	5.1
F	2004	5.2

- 76% for tensile strength, 78% for elongation at break, and 95% for impact strength for a natural UV-protected grade.

PMP must be protected by the addition of specific anti-UV and other protective agents.

Cyclic olefin copolymer is proposed in light and UV stabilized grades.

Ethylene-vinyl acetate copolymers (EVAs) are naturally resistant to light, UV, ozone, and weathering and, even more, they can be protected by addition of specific anti-UV and other protective agents. Under identical conditions, lifetimes of films exposed outdoors are 3 years for a protected EVA versus less than 1 year for an LDPE film. Increasing vinyl acetate content improves light, UV, ozone, and weathering resistance.

Ethylene-vinyl alcohol copolymer is sufficiently resistant to light and UV to be used in packaging but it is sensitive to water and must be protected.

EMA ionomers must be protected for long exposures to light and UV such as in exterior automotive parts.

14.3.3.2 PVC and Other Chlorinated Thermoplastics

PVC resists hydrolysis well but is naturally sensitive to light and UV. It must be protected by addition of anti-UV and other protective agents. Well-optimized compounds and grades stabilized against heat, UV, light, and weathering resist to weathering and long warranty periods can be allowed, for example, 10 years and more. For a protected, white rigid PVC, after natural weathering for 3 years in Michigan, the retention of impact strength is 68% and the yellowness index increases by 5.

Chlorinated PVC (PVC-C) resists hydrolysis well but is naturally sensitive to light and UV. It must be protected by addition of anti-UV and other protective agents. In these cases, PVC-C can be used for long-lasting exterior parts.

Chlorinated polyethylene (CPE): Suitable compounds exhibit good property retention after 6 years of exposure in Arizona, for example:

- 120% for 100% modulus
- 110% for tensile strength
- 90% for elongation at break, which is the most sensitive property to UV and weathering.

PVDC resists hydrolysis well but is naturally sensitive to light and UV. It must be protected.

14.3.3.3 Styrenics

PS resists hydrolysis well but is naturally sensitive to UV, light, and weathering especially when alloyed with a UV sensitive rubber such as polybutadiene. It must be protected by the addition of anti-UV and other protective agents and/or by a suitable carbon black.

After weathering, the retention of properties for test bars (3-mm thick) is, for example:

- 85% for tensile strength after 6-month outdoor exposure in Los Angeles for a protected GF-reinforced grade
- 89% for tensile strength after 12-month outdoor exposure in Los Angeles for another protected GF-reinforced grade.

ABS resists hydrolysis well but is naturally sensitive to light and UV the more as the amount of polybutadiene increases. It must be protected by the addition of anti-UV and other protective agents or by an outer film of UV-resistant polymer such as PVDF.

Methylmethacrylate–acrylonitrile–butadiene–styrene (MABS) has a butadiene-containing elastomer component. Its behavior on exposure to heat or UV light can therefore be compared with that of ABS. Intense UV radiation or outdoor weathering can damage the rubber component, leading to yellowing and reduced impact strength. Finished parts made from MABS in pale transparent colors are particularly susceptible to color change on weathering or heat aging. MABS is therefore preferably used in indoor applications.

SAN resists hydrolysis well but may be sensitive to light and UV. It must be protected by the addition of anti-UV and other protective agents.

ASA resists hydrolysis well and is naturally much less sensitive to light and UV than ABS. Retention of mechanical performances is far better and yellowing is far lower. Even after long-term weathering, suitable ASA grades do not show the graying typical of even UV-stabilized ABS. ASA has applications in exterior parts for automotive construction. ASA may be alloyed with PC.

Acrylonitrile-EPDM-styrene (AES or AEPDS), and acrylonitrile-chlorinated polyethylene–styrene are more resistant to weathering than ABS, EPDM (ethylene propylene diene terpolymer) and CPE being more weathering resistant than polybutadiene.

14.3.3.4 Polyamides

PA6 or PA66 is naturally sensitive to light and UV. It must be protected by the addition of anti-UV and other protective agents.

After weathering of test bars (3 mm thick) in a sunny climate, the property retentions are, for example:

- 50% for tensile strength and 3% for elongation at break after 6 months for a natural unprotected grade
- 32% for tensile strength and 2% for elongation at break after 5 years for a natural unprotected grade
- 99% for tensile strength and 38% for elongation at break after 6 months for a UV-protected grade
- 89% for tensile strength and 22% for elongation at break after 5 years for a UV-protected grade.

PA11 and PA12 must be protected by the addition of anti-UV and other protective agents.

Optimized PA12 grades are resistant to weathering and suitable for many exterior applications. Resistance to weathering can be further improved by suitable UV stabilization and pigmentation with carbon black. This allows the use in applications under climates with high UV radiation.

For two grades of PA12, one in natural color, the other in black, the half-life of 1-mm-thick test based on:

- gloss would be in the range of near 1 year (natural color) up to near 3 years (black sample).
- tensile impact strength would be in the range of near 1 year (natural color) up to much more than 5 years (black compound).

Transparent PA exhibits generally fair resistance to weathering. Some UV-stabilized grades can satisfy stringent specification requirements, harsher than f1 according to UL 746 C and are, therefore, suitable for use in exterior applications.

Even after 20,000 h of exposure to xenon light at 65 °C with dry/water cycling, no noticeable change can be seen in the mechanical and optical properties (transparency, color) of suitable UV-stabilized grades.

By comparison, some general purpose transparent PA grades have half-lives based on tensile strength of the order of more or less 1000 h.

14.3.3.5 Thermoplastic Polyesters

Polyesters are sensitive to hydrolysis and UV. They must be protected by addition of anti-UV and other protective agents.

Generally, black grades are more resistant than neat ones. In these cases, after weathering of test bars for 1 year in various sunny climates, the retention of tensile strength or notched impact strength is generally good.

For 3-year outdoor exposures of 3-mm-thick samples, the retention of tensile or impact strengths can be, for example:

- 50% up to 97% for natural-unreinforced PBTs, depending on the UV stabilization
- 65% up to 97% for black-unreinforced PBTs, depending on the UV stabilization
- 84% up to 100% for black-reinforced PBTs, depending on the UV stabilization.

14.3.3.6 Polymethylmethacrylate

The weathering resistance is one of the most interesting features of PMMA, along with its transparency. The inherently UV resistance can be further improved by addition of protective agents.

Optical properties are not greatly affected by long outdoor exposures. For example, after 3-year exposure in a sunny climate, the light transmittance of given grades is superior to 90%, and the yellowing and haze are slight.

For 3-mm-thick samples exposed in the same conditions, the retention of mechanical performances can be, for example:

- 70–85% for tensile strengths
- 40–70% for elongations at break
- 70–90% for impact strengths.

14.3.3.7 Polycarbonate

PCs are inherently sensitive to hydrolysis and UV. They must be protected by addition of anti-UV and other protective agents. Generally, black grades are more resistant than neat ones. In these cases, after weathering of test bars for 1 year in various sunny climates, the retention of tensile strength or notched impact strength is generally good.

For a 2-year outdoor exposure of transparent PCs, the retention of impact strengths can be, for example:

- 4% for an unstabilized grade
- 100% for a UV-stabilized grade.

Under the same conditions, the optical properties after exposure are:

- unstabilized grade: 82% for transmittance, 20% for the haze, and 20 for the yellowing index
- UV-stabilized grade: 87% for transmittance, 15% for the haze, and 6 for the yellowing index.

Very different data can be obtained with other grades under different conditions.

14.3.3.8 Polyacetal

Polyacetals (POM) are UV-sensitive and must be protected by the addition of anti-UV and other protective agents. Generally, black grades are more resistant than natural ones. In these cases, after weathering of test bars for 1 year in various sunny climates, the retention of tensile strength or notched impact strength is generally good.

For 3- and 10-year outdoor exposures of 3-mm-thick samples, retentions of tensile strength and elongation at break can be, for example:

- nearly 100% of tensile strength for UV-stabilized acetals
- 45% up to 75% for elongation at break, depending on the UV stabilization.

14.3.3.9 Polyphenylene Ether

PPE is moderately UV-sensitive and must be protected by addition of anti-UV and other protective agents. Generally, black grades are more resistant than natural ones.

14.3.3.10 Fluorinated Thermoplastics

Perfluorinated thermoplastics are not sensitive to moisture or UV. Generally, stabilization is not needed.

Polytetrafluoroethylene: After 1-year outdoor exposures of 3-mm-thick samples, retentions of tensile strengths and elongation at break are near 100%.

After 15-year outdoor exposures of 0.1- to 0.15-mm-thick films in a sunny and humid climate, the retentions of tensile strengths and elongations at break are in the range of 91% up to 125% without visible change.

ETFEs are inherently insensitive to moisture and UV. Generally, stabilization is not needed. However, GF-reinforced grades can be altered by long outdoor exposures.

Polychlorotrifluoroethylenes are insensitive to moisture and UV. Generally, stabilization is not needed.

Ethylene monochlorotrifluoroethylenes are inherently insensitive to moisture and UV. Generally, stabilization is not needed.

PVDF is inherently insensitive to moisture and UV. Generally, stabilization is not needed.

PVFs are inherently resistant to weathering. After 6 years of outdoor exposure in a sunny climate, retentions of properties are about:

- 80% for tensile strength
- 55% for elongation at break.

14.3.3.11 Cellulosics

Cellulosics are inherently moisture and UV-sensitive, requiring efficient stabilization. CA is particularly sensitive to water and weathering.

14.3.3.12 Polysulfone

PSUs are inherently UV-sensitive and must be protected by the addition of anti-UV and other protective agents. Black compounds are generally more resistant.

14.3.3.13 Polyphenylene Sulfide

PPS are inherently resistant to UV, weathering, and hydrolysis. Black compounds are the most UV-resistant.

The mechanical characteristics of a PPS grade remain fair after an exposure of 10,000 h in a Weather-Ometer.

14.3.3.14 Polyetherimide

PEIs are inherently resistant to UV and hydrolysis.

14.3.3.15 Liquid Crystal Polymer

Typically, liquid crystal polymers (LCPs) have a good weatherability. In a series of experiments, certain LCPs are slightly altered by 1 year of outdoor exposure with a light surface chalking, but after a 2000 h exposure in a Weather-Ometer, retention of mechanical properties is superior to 90%.

14.3.3.16 Polybenzimidazole

Polybenzimidazole resistance to weathering is estimated by certain sources to be limited.

14.3.3.17 Alloys

ABS/PC: sensitivity to heat, UV, light, and weathering, requires efficient protections for outdoor exposure (stabilized grades are marketed).

ABS/PA: sensitivity to heat, UV, light, and weathering, requires efficient protection for long-term outdoor exposure (stabilized grades are marketed).

ASA/PC alloys are appreciated for their behavior and low yellowing with UV, light, and weathering but UV protection is needed for long-term outdoor exposures (stabilized grades are marketed).

ABS/PA: sensitivity to heat, UV, light, and weathering, requires efficient protection for long-term outdoor exposure (stabilized grades are marketed).

PP/PA: sensitivity to heat, UV, light, and weathering, requires efficient protection for outdoor exposure (stabilized grades are marketed).

Thermoplastic polyester alloys exhibit a certain sensitivity to heat, UV, light, and weathering, requiring efficient protection for outdoor exposure (stabilized grades are marketed).

ABS/PVC: sensitivity to heat, UV, light, and weathering, requires efficient protection for outdoor exposure (stabilized grades are marketed).

14.3.3.18 Thermoplastic Elastomer and Thermoplastic Vulcanizate

TPS (styrenics thermoplastic elastomer): styrene–butadiene–styrene, as well as all elastomers rich in double bonds, is not suited to exposure to light, UV, and ozone, whereas styrene ethylene/butylene styrene shows good behavior.

Thermoplastic olefin resists hydrolysis well but is naturally sensitive to light and UV. It must be protected by the addition of anti-UV and other protective agents and possibly by a few percent of an appropriate carbon black.

PP/EPDM-V resists hydrolysis well but is naturally sensitive to light and UV. It must be protected by addition of anti-UV and other protective agents and possibly by a few percent of an appropriate carbon black.

TPE/PVC resists hydrolysis well and is naturally sensitive to light and UV, but special grades are marketed with a sufficient weathering resistance to allow exterior applications in the automotive industry and construction.

Thermoplastic polyurethanes are naturally sensitive to light, UV, and hydrolysis but special grades are marketed. Specific grades target applications in tropical climates.

Copolyester TPEs are naturally sensitive to light, UV, and hydrolysis but special weathering-resistant grades are marketed. Polyester-esters are more UV-resistant but more sensitive to hydrolysis.

Polyether bloc amides are naturally sensitive to light, UV, and hydrolysis but special grades are marketed. Half-lives corresponding to a 50% decay of elongation at break after Xenotest exposure are roughly:

- 5 months for UV-stabilized grades with 25–40 Shore D hardness
- 6 months for UV-stabilized grades with 55–70 Shore D hardness.

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, Borealis, BP Chemicals, Bryte, Ceca, Celanese, Chem Polymer, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cuming, EMS, Enichem, Epotecny, Eurotec, Eval, Evonik, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, GINAR Engineering Plastics, Grupo Repol, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Matweb, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem, Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, RTP, Sabic, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Taber, Technochemie GmbH, Teknor Apex, Telenor, The European Alliance for SMC, Thieme, Ticona, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vamptech, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
[5] Reinforced Plastics, Elsevier Ltd.

15 EcoDesign

OUTLINE

Material Selection for Thermoplastic Parts. http://dx.doi.org/10.1016/B978-0-7020-6284-1.00015-5

All the industrial activities consume resources and energy, pollute, and compromise the future of the planet by global warming, atmospheric ozone depletion, accumulation of pollutants often under organic forms particularly harmful for human, animal, vegetal, and aquatic life. To preserve the essential needs of future generations during a maximum time, it is essential to think all our actions and to design all the products and goods for a better sustainability. There are no perfect answers to this grave problem but several more or less easy ways allow more or less improvement of sustainability. Figure 15.1 schematically displays, without claiming to be exhaustive, total and partial ways toward greener products and strategies.

EcoDesign, Green Design, Sustainable Design, Environmental Design, and so on are new ways of designing aiming to comply with the principles of social, economic, and ecological sustainability. They are based on principles concerning the native resource preservation, renewable source uses avoiding competition with food crops, energy saving, ban of toxic elements and molecules, carbon footprint reduction, effectiveness of recycling, end cost optimization…

Main actions are among others:

- Basic and usual measures aiming to:
  - Enhance durability
  - Save energy, weight etc.
  - Reduce pollution
  - Recycling and use of recycled plastics
  - Reuse, repair, remanufacture used parts
- Replacement of fossil materials (polymers, reinforcements, and additives) by renewable materials:
  - Partial ways
  - Total ways
- Promotion of solution systems leading to better sustainable use:
  - Lightening of cars, planes, packaging etc.
  - Function integration
  - Thermal and sound isolation.

From a practical point of view, a poll organized by SpecialChem (www.specialchem.com) identifies the most commonly used ways for the production phase of more environment-friendly products:

- Bio-based polymers for 34% of the voters
- Higher recycled resin level for 21% of the voters
- Lower energy to produce for 17% of the voters
- Lower part weight for 17% of the voters
- Higher mineral loading for 9% of the voters
- Biofiller and Biofiber use for 2% of the voters

The use phase isn't included in this poll.

15.1 Well-Established Routes

Some good practices are known but sometimes they are forgotten leading to brittle, heavy, costly,

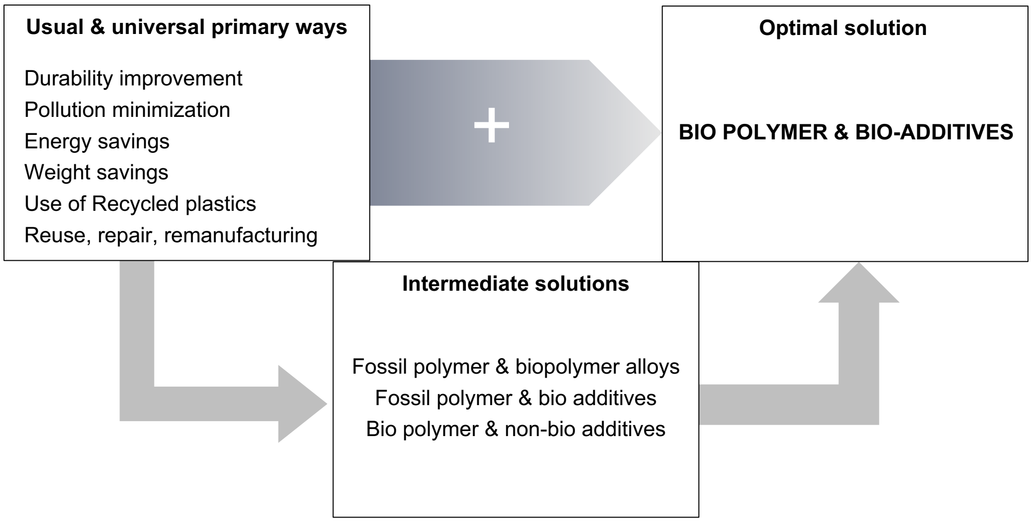

Figure 15.1 Main ways toward green design.

and environmentally harmful parts. Of course, you aren't in this situation but for others it may be useful to reminder these obvious facts.

15.1.1 Enhance Durability Thanks to Long-Lasting Parts

Times to failure during service life for a given part obey a Gaussian distribution. It is possible to improve lifetime by acting on the average value, thanks to an upgrading of the polymer compound or/and fight against the lowest values, which reduces premature failures. According to various sources, origins of premature part failures during service life are generated, depending on the type of polymer (plastics, elastomers, or composites), by the following:

- Misconceptions for 10 up to 70% of the cases
- Processing defects for 20 up to 50% of the cases
- Abnormal service conditions for 10 up to 40% of the cases.

Design issues must be detected as soon as possible to avoid exploding inflation of costs. At the third European Plastics News Sustainable Plastics Packaging conference, Mark Shayler, managing director of UK-based environmental and eco-design consultancy, "eco3" told delegates:

"For every £100 spent solving a problem in production, it would cost £10 to solve it in development and just £1 to solve at the design stage."

Designers can't act on abnormal service conditions but can improve design and processing to decrease or suppress the 60 up to 90% failures due to misconceptions and processing defects. Minimization of stresses and stress concentrations, broadening of the processing windows, suppression of weak spots are the first answers to premature failures.

Longer average service life can be obtained by:

- Use of a more performing thermoplastic
- Use of additives lengthening the lifetime of the polymer
- Use of additives enhancing the original properties of the compound
- Better designing to favor a higher original level of performance
- Better control of processing.

Figure 15.2 schematically shows some tracks to improve durability.

15.1.1.1 Switching to Another Thermoplastic

The solution is the best balance of end properties/processing ease/end cost for the studied case. Let us quote some very different examples but there isn't a universal answer.

Sabic claims using PC (Lexan Light) to replace PVC/PMMA products on seating frames could help reduce weight by approximately 121.6 kg based on an aircraft with average of 190 seats, which can help the total commercial fleet save roughly 206,720 tons of fuel and 656,640 tons of carbon dioxide (CO_2) a year.

Volkswagen (VW) switched from glass-reinforced polyamide (PA) to polypropylene (PP) for its air intake manifolds application, now used in a variety of its car models with engine sizes from 1.4 to 1.6 l. Borealis Xmod™ GB306SAF is claimed to lead to lower system costs without significant changes in tooling, part design, or equipment investment as well as improving acoustic part behavior.

Viking, a producer of ice skates completely made in plastic—except for the metal blade selected 60%

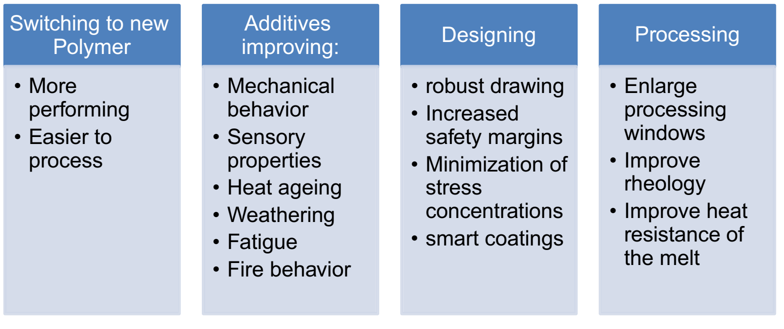

Figure 15.2 Schematic ways toward long-lasting parts.

glass-filled Akulon Ultraflow K-FG12 BLK PA material for various components of the new skates. The material is claimed providing a right balance of design freedom, flow performance, lower processing temperatures, easier coloring, surface appearance, high stiffness, and end cost.

15.1.1.2 Protective Additives for Long-Lasting Compounds

Oxygen, heat, light and UV, shear, dynamic stresses tackle polymers, damaging mechanical, electrical, optical performances and sensorial properties. Actual consequences of aging are generally:

- Mechanical property degradations, weakening, embrittlement…
- Sensorial degradation, discoloration, chalking, crazing, loss of gloss and transparency, unpleasant odors…
- Weight loss, shrinkage.
- Desorption and consumption of additives which speed up aging.
- Pollution of environment…

Main protective additives can be arbitrarily classified as follows:

- Processing stabilizers: antioxidants incorporated into the polymer to avoid heat degradation during processing. For example, thermal stabilizers in PVC formulation are essential to help PVC to withstand higher temperatures, which enlarge processing temperature windows and save costs. These stabilizers also provide the necessary stabilization required for all the service life.
- Antioxidants added into the polymer compound to decrease thermo-oxidation during the service life avoiding molecular weight changes, and loss of mechanical, physical, and aesthetic properties.
- Light stabilizers decreasing degradations initiated by sunlight or UV exposure. Certain fillers and organic UV-absorbers act as filters protecting the polymer from UV.
- Hydrolysis stabilizers: Chemicals added to the polymer to avoid hydrolysis degradation during service life.

Often, two or three protective additives are combined to reinforce their efficiency but polymer degradation can never be totally inhibited. This is just a question of time of exposure to heat, light, water, and other aggressive environments.

Figure 15.3 shows an example of the efficiencies of five antioxidant systems incorporated in the same polymer. The system 1 is the initial formulation with a good thermal resistance. Systems 2–5 lead to increases of about 70% up to slightly more than 100% of the embrittlement times by aging at 130 °C. Table 15.1 displays other examples relating to degradations following weathering of unstabilized

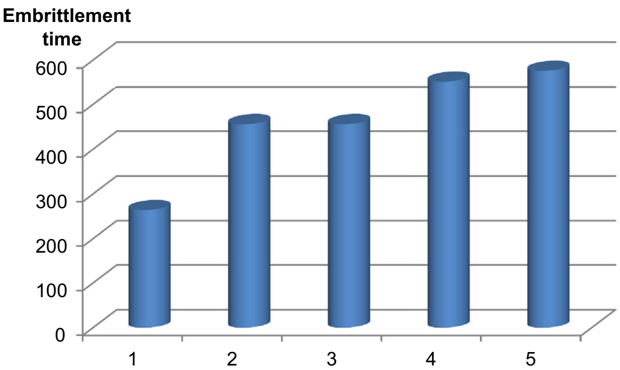

Figure 15.3 Improvement of lifetime by four protective systems.

Table 15.1 Examples of the Efficiencies of Anti-UV Stabilization

		% Degradation		
		Tensile Strength	Elongation at Break	Impact Strength
PC white	Unstabilized	4	78	9
	UV stabilized	7	22	15
PE	Unstabilized	44	41	48
	UV stabilized	24	22	5

and UV-stabilized polycarbonate and polyethylene. Results and efficiency of the anti-UV protection depend on the examined property and polymer. For the PC grade, elongation at break is dramatically improved but the other properties are slightly decreased in a generally reasonable proportion. For the PE grade, all the properties are substantially or dramatically improved.

The other additives into the compound can also act on the aging and, for example, a right carbon black grade can be the most efficient anti-UV but color is gray or black.

15.1.1.3 Design Long-Lasting Parts

Some simple rules can avoid premature failures of parts sometimes used in abnormal conditions. A good example is the drawing of large radii to link two walls of different thicknesses or different directions. Figure 15.4 shows an example for two perpendicular walls of 2 mm thickness linked by a radius evolving from less than 0.1 mm up to 0.4 mm. Simultaneously, the stress concentration ratio drops from more than 5 down to 2.4, which is an acceptable value.

15.1.2 Simulation and Modeling Tools Optimize Design and Save Time, Weight, Energy

Part design is a difficult exercise carried out by skilled technical staff and leading to technical and economic consequences. The designers, mold makers, and engineers through simulation setup, modeling, and result interpretation can more or less easily test design efficiency and changes linked to wall thickness, gate location, material, geometry, and more generally can evaluate manufacturability of thermoplastic materials.

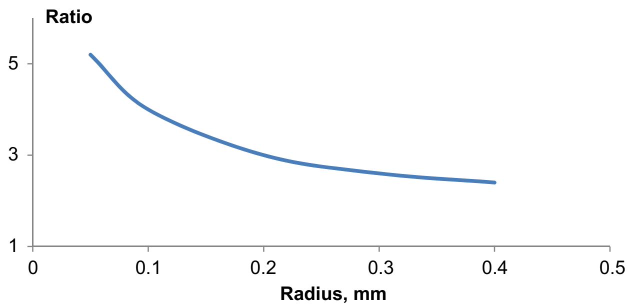

Figure 15.4 Effect of radius on the stress concentration ratio.

Software provides simulation and modeling tools for:

- plastic part design
- mechanical performance analysis
- development of preprocessing models
- injection molding and a wide range of specialized process applications i.e., gas-assist, co-injection…
- filling, heating, cooling of thermoplastic materials
- fiber orientation and breakage in plastic part designs
- failure analysis and optimization studies
- optimization of NVH performance…

Software can help:

- Avoid costly mold rework: ensure molds will work right the first time to avoid time-consuming, costly, and unnecessary rework.
- Optimize feed system design: sprues, runners, and gates to balance runner systems; optimize gate type, size, and location; determine the best runner layout, size, and cross-sectional shape.
- Estimate cycle time, clamp tonnage, and shot size: quote tooling projects quickly and accurately; size the injection molding machine for a given mold, optimize cycle time, and reduce plastics material scrap…

Solutions depend on the specific conditions of the real case study, varying with the used grade, the part geometry, the molding tools, the tolerances etc. Consequently, software editor, independent organizations or societies; plastics producers propose more or less specialized software, services, and guides. Table 15.2 displays some examples without claiming to be exhaustive and without any warranty.

Modeling and simulation adapted to the actual processing method speed up design, trials, and enhance processes. They are broadly used to design parts, molds, and dies allowing to:

- Save material weight
- Determine the manufacturability of parts
- Avoid potential downstream problems

Table 15.2 Examples of CAD Software

Society or Brand Name	Web Site
Abaqus Software (Dassault Systèmes)	http://www.3ds.com/products-services/simulia/overview/
Altair Engineering	http://www.altair.com
Ansoft(Ansys)	http://www.ansys.com/
Ansys	http://www.ansys.com
Astek	http://www.groupeastek.com
Autodesk	http://www.autodesk.com
Cetim	http://www.cetim.fr/
Cimpa (EADS)	http://www.cimpa.fr
Dassault Systèmes	http://www.3ds.com
DeltaCad	http://www.deltacad.fr/
ESI	http://www.esi-group.com/
Flowmaster	http://www.mentor.com/products/mechanical/flowmaster-landing/
Genoa	http://www.ascgenoa.com
Hyperworks	http://www.altair.com/
Intes	http://www.intes.de/
LS-Dyna	http://www.ls-dyna.com/
Marc	http://www.mscsoftware.com/product/marc
Mentor Graphics	http://www.mentor.com
Moldflow	http://www.autodesk.com/products/simulation-moldflow/overview
MSC Software	http://www.mscsoftware.com
Nastran	http://www.mscsoftware.com/product/msc-nastran
Principia	http://www.principia.fr/
Radioss	http://www.altair.com/
Samtech	http://www.plm.automation.siemens.com/en_us/products/lms/samtech/index.shtml
Simulia	http://www.3ds.com/products-services/simulia/
Solid Edge	http://www.plm.automation.siemens.com/en_us/products/solid-edge/index.shtml
SolidWorks	http://www.solidworks.com/

- Avoid various defects and weaknesses frequently encountered when designing parts and molds, such as:
  - Air traps located in areas that fill last and resulting in voids and bubbles inside the molded material, incomplete filling (short shot), or surface defects such as blemishes or burn marks. Software eases modifications of the filling pattern by reducing the injection speed, enlarging venting, or placing venting at the right place in the mold.
  - Warpage and sink marks that can be analyzed and reduced to acceptable levels by modification of wall thickness, ribs, bosses, and internal fillets.

   - Voids caused by localized shrinkage of the material at thick sections without sufficient compensation when the part is cooling. Additional redesigning can avoid these defects.
   - Weld lines or knit lines and meld lines formed when two melt fronts run into each other or join together. These defects can be improved by redesigning, relocation of holes or inserts in the part.
- Improve part performance and durability
- fast study of multiple options, which speeds up and enhance designing
- Reduce the number and, of course, the cost of trials
- Save processing energy
- Reduce part cost by optimizing the consumption of material for a required performance level…

15.1.3 Smart Coatings

The application field of a polymer can be limited by its behavior versus some environmental parameters, from chemical or friction nature, for example. A coating making a barrier between the polymer and its environment can drastically change its features. So, coatings are often performing and cost-effective solutions to enhance the performance of a polymer by completing its properties with those of another organic or mineral material. For example, natural rubber is very elastic but isn't resistant to ozone. A thick part based on natural rubber can be made ozone resistant by coating it with another ozone-resistant rubber and the whole part can remain elastic.

Coating allows one to obtain surface properties completely different from those of the core and vice versa. Coating cannot protect against heat but can avoid the contact of the core material with oxygen in air.

One of the issues inherent to coatings is the permanent cohesion between the treated part and the coating, which depends on the adhesion between the two polymers and also on the compatibility of the coefficients of thermal expansion, elongations at break, and other physical properties.

Additional properties are as diversified as, for example, aesthetics, antifriction, aging resistance, anticorrosion, electrical conductivity, antifogging behavior, self-healing paints and topcoats, oxygen barrier, carbon dioxide barrier, migration barrier, scratch resistance, controlled wettability, antistatic behavior, antireflective properties, IR absorption or reflection, thermal dissipation, antimicrobial or antifouling activity, decontamination properties, super-hydrophobic or super-hydrophilic behavior, chromophore…

Coating techniques are also very diversified from simple methods such as painting, soaking, spraying, powdering, dipping, extrusion, printing… up to sophisticated processes such as plasma torch spraying, plasma-assisted chemical vapor deposition, ion beam deposition, sputter deposition, RF plasma deposition, or plasma polymerization-deposition consisting of polymerize monomer or oligomer onto the parts to be protected by vapor phase deposition.

The matter of this subchapter isn't to talk about paints and other well-known coatings but to examine some examples of high-tech or unusual polymer coatings allowing to extend the application field of polymers by adding them new basic properties, thanks to the functional features of the polymer shell.

All the following information is theoretical and must be verified. Processing of coating is difficult and subject to numerous parameters. Moreover certain processes are patented and the user must verify the following information and carefully check its interest, suitability, and applicability for his or her own problems, material, and final requirements.

15.1.3.1 Silicon Oxide coating Thanks to the Ceramis® Technology

By which a SiOx (Silicon oxide) coating is applied to various types of substrates (including PLA films) used for demanding applications in both packaging and technical markets. AMCOR has received the BRC/IoP (British Retail Consortium/Institute of Packaging) certificate for its Ceramis® Barrier Films used by leading producers of packaging for the food, pharmaceutical, cosmetics, and technical markets. The electron beam evaporation allows a controlled and constant evaporation of the coating material.

15.1.3.2 Diamond-like Coating

Diamond-like carbon (DLC) coatings exist in several different forms of amorphous carbon materials that display some of the unique properties of diamond. DLC coatings can be amorphous, more or less flexible, hard, strong, and slick according to the composition and processing method. Film formation can be obtained by plasma-assisted chemical vapor deposition, ion beam deposition, sputter deposition, and RF plasma deposition.

For example, Morgan Technical Ceramics proposes Diamonex DLC coatings deposited at temperatures below 150 °C by ion beam direct deposition or RF

Plasma CVD and offering a wear-resistant chemical barrier for plastics. Benefits include wear and abrasion resistance, low Friction, high hardness, antireflective properties, corrosion resistance, gas barrier effect.

Some commercial and industrial applications of Diamonex DLC protective coatings concern sectors as diversified as aerospace, automotive, cosmetics, bearings, electronics, industrial wear parts, textiles…

15.1.3.3 Acetylene Plasma Coating for an Effective Gas Barrier Effect

To meet the requirements of carbonated and/or oxide-sensitive beverages packaged in polyethylene terephthalate (PET), Sidel has developed acetylene plasma coatings, the Actis™ and Actis Lite™ (amorphous carbon treatment on internal surface) barrier solutions, depositing ultrathin layers of hydrogenated amorphous carbon on the inside of PET bottles making a barrier to gases.

15.1.3.4 Graphene-Based Coatings: The Promising Ultraperforming Coating for the Near Future?

Suitable grades of graphene can be dispersed in water or solvents for applications in coatings, paints, inks, and linings to add electrical conductivity, barrier effect, and surface durability. Quoted applications are conductive coatings, transparent conductive coatings for solar cells and displays, electrostatic coatings, nylon fuel tank, and fuel line coatings imparting high barrier properties coupled with electrical conductivity; plastic containers that keep food fresh for weeks…

15.1.3.5 Polyimide Coatings

(Dow Corning) for organic light-emitting diodes (OLEDs). These products require protective materials that are resistant to high temperatures, wear and corrosion, which can cause cracks and electrical shorts. The polyimide coating acts as an insulation layer and is designed to protect against cracks and electrical shorts in the circuitry. The polyimide coating offers stable mechanical, electrical, and chemical properties; low temperature cure (230 °C/30 min/air) and the ability to utilize current processes.

15.1.3.6 Siloxane Coating

The Exatec multilayer coating system (EXATEC) is developed for polycarbonate automotive glazing protection. The Exatec multilayer coating system combines a proprietary siloxane coat, a plasma-enhanced chemical vapor deposition (PECVD), and printing steps in which inks and dyes can be applied for additional functionalities such as light control, decorative effects, defrosting systems, and radio antennas.

15.1.3.7 Engineering and Specialty Plastics

Virtually all the other engineering and specialty plastics can be used as coating, for example, polybenzimidazole (PBI), divinylsiloxane-benzocyclobutene (DVS-CBC), polyamide-imide (PAI), polyethersulfone (PESU), polyetheretherketone (PEEK), polyphenylsulfone (PPSU), liquid crystal polymer (LCP), PTFE, FEP, PFA, ECTFE, PVDF, PAs (PA11 and PA12), parylenes, hyperbranched polymers, polyurethanes for self-healing topcoats…

15.1.4 Weight Saving and Induced Benefits

Reinforcement, function integration, and drawing optimization are the most used ways to gain weight for a defined function. Induced benefits include directly thermoplastic material weight saving, processing cost savings if part walls are thinner, and indirectly energy savings during service life and disposal at end-of-life.

15.1.4.1 Raw Material Weight Saving: Example of Mechanical Performance Upgrading

The most frequent improvements concern the reinforcement of rigidity and mechanical properties, which can be obtained with various fibers among other solutions.

The goal is:

- To increase the mechanical properties
- To improve the HDT
- To reduce the tendency to creep under continuous loading
- To save costs in decreasing the material cost used to obtain the same stiffening

The main problems are:

- The risk of shortened length of the fibers broken during processing.
- The anisotropy due to the fiber orientation and settling.

The glass fibers are the most popular with 95% of the consumption of the fibers used for the reinforcement of plastics.

The aramid fibers and the carbon fibers account for nearly the other last 5%.

Numerous other fibers have specific uses:

- Steel fibers and steel cords for tires, conveyor belts, ESD compounds.
- Mineral fibers as boron, quartz, and whiskers.
- Natural fibers such as jute, flax, and so on are developing to meet environmental concerns and sustainable development policy.
- Textile fibers as nylon, polyesters…
- Industrial fibers as polyethylene, PTFE, PEI, PPS, PEEK, LCP, melamine, PBO…

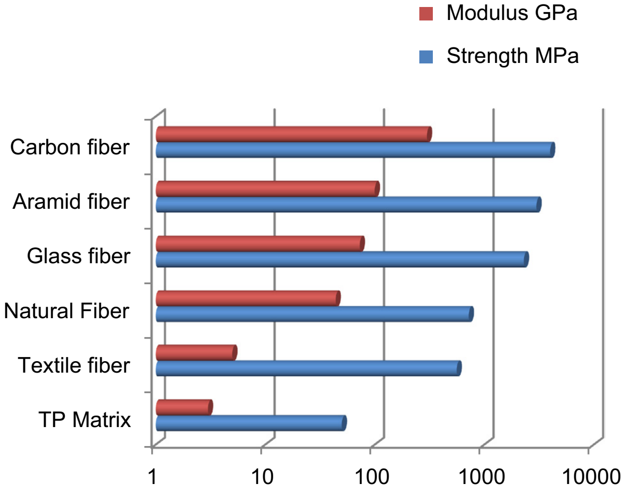

Figure 15.5 Strength (MPa) and modulus (GPa) of various fibers.

Figure 15.5 shows examples of tensile strength and modulus of various fibers and the same properties for an average thermoplastic (TP) matrix. Obviously, composite performances are intermediate between those of the used fiber and matrix (see Table 15.3).

Apart from fibers, mineral fillers, glass beads, nanofillers, carbon nanotubes (CNTs) among others are also used for special reinforcements or for cost saving.

Reinforcement with Mineral Fillers and Glass Beads

Reinforcement with mineral fillers is not as noteworthy as the fiber reinforcement. Often the cost is significantly decreased but only a few properties are improved and others can be damaged.

Table 15.3 shows some examples (not a rule) of the reinforcement ratios for mineral fillers, glass beads and, for comparison glass fiber-reinforced thermoplastics. The reinforcement ratio is the performance of the reinforced polymer divided by the performance of the unfilled polymer. A reinforcement ratio inferior to one corresponds to the reduction of the considered property. For example, tensile strength of the mineral-filled compound is reduced by 30%.

Table 15.3 Examples of the Effect of Mineral Fillers and Glass Beads on the Reinforcement Ratios of Thermoplastics

	Reinforcement Ratios		
	Mineral	**Glass Beads**	**Glass Fiber**
Tensile strength	0.7	1	1.5
Tensile modulus	2.2	1.5	3.2
Notched impact strength	0.3	0.4	0.3
HDT A	1.1	1.2	2.0
Thermal conductivity	1.9	1.7	1.4
Coefficient of thermal expansion	0.4	0.6	0.5
Density	1.2	1.2	1.1
Shrinkage	0.4	0.6	0.3

For mineral and glass bead-filled thermoplastics versus neat and glass fiber reinforced ones:

- Tensile strength decreases below that of the neat polymer.
- Elongation at break is intermediate between neat and glass fiber-reinforced polymer.
- Modulus increases and becomes intermediate between neat and glass fiber-reinforced polymer.
- Impact strength decreases.
- HDT increases and becomes intermediate between neat and glass fiber-reinforced polymers.
- Coefficient of thermal expansion and shrinkage are reduced while thermal conductivity increases.
- Price decreases but density increases.

Reinforcement with Nanofillers

To exceed the usual filler reinforcement and to obtain a real nanocomposite, it is necessary to destroy the primary particle structure of the nanofiller during processing:

- Either completely by dispersing the elementary particles into the macromolecules—delaminated nanocomposite.
- Either partially, by intercalating macromolecules between the elementary particles—intercalated nanocomposite.

The most popular nanofiller is a natural layered silicate, the montmorillonite, that is subjected to specific treatments. The properties of the final nanocomposite depend on the nanocomposite treatments and the mixing efficiency.

Reinforcement with CNTs

CNTs are hollow carbon cylinders with hemispherical endcaps of less than 1 nm to a few nanometers in diameter and several micrometers in length. The aspect ratios are in the order of 1000 and more. CNTs can be categorized based on their structures:

- Single-wall nanotubes (SWNT)
- Multiwall nanotubes (MWNT)
- Double-wall nanotubes (DWNT).

The elementary nanotubes agglomerate in bundles or ropes that are difficult to disaggregate. Some technologies are patented by producers to exfoliate, disperse, and compatibilize the nanoparticles in polymer matrices.

The main properties are:

- Very high modulus of the order of 1000 GPa and more.
- Very high tensile strength of 50,000 MPa and more.
- A low density: 1.33 g/cm^3.
- High electrical conductivities with a very high current density of the order of 109 A/cm^2.
- High thermal conductivities of the order of 6000 W/mK, better than that of diamond and 35 times and more than that of CFs.
- Insensitivity to heat degradation in the range of engineering polymer applications.
- Reinforcement efficiency at very low levels in plastics.
- Very high cost quickly decreasing.

Table 15.4 displays comparative theoretical performances of various composites reinforced with various additives. Glass fiber-reinforced thermoplastics (GFRTP) are the most common and carbon fiber reinforced thermoplastics (CFRTP) are the most performing.

Raw material saving, yes but…

- Apart from the actual weight of material, the raw material saving is difficult and uncertain to judge when polymers and additives are dissimilar. Monomers, energy, pollution are not identical and a lower weight doesn't inevitably lead to sustainable and economic advantages. To lighten that, we quote estimations of costs of commodity, engineering, and high-tech polymers.
- Commodity polymers are a homogeneous family with prices of one or some euros per kilogram
- Engineering polymers are more heterogeneous with costs from 2 €/kg up to €10/kg, gathering mechanical performing polymers, gas proofing materials, transparent polyamides…
- High-tech polymers with costs up to nearly €100/kg gather high-tech matrices, carbon fiber-reinforced plastics, fluoropolymers and top of the range thermoplastic elastomers.

Table 15.4 Examples of the Effect of Mineral Fillers and Glass Beads on the Reinforcement Ratios of Thermoplastics

	Reinforcement Ratios					
	Mineral Fillers	**Glass Beads**	**Nanocomposites**	**CNT Composites**	**GFRTP**	**CFRTP**
Density	1.2	1.2	1	1	1.1	
Tensile strength	0.7	1	1.25	0.8–1.3	1.5	2–3
Tensile modulus	2.2	1.5	1.3	1.03–1.4	3.2	3–6
Notched impact strength	0.3	0.4			0.3	1–2

It can be noticed that the glass fiber reinforcement improves thermomechanical performances without increasing the cost. Carbon fibers enhance the mechanical performances more effectively but the cost increases significantly.

15.1.4.2 Processing Cost Savings Induced by Weight Saving

Material cost is an important part of the end cost and, if the performances of the part are reached, any material weight saving leads to a substantial cost saving. In addition, for a defined material, it is sure that the downgauging decreases the processing energy because of the lower compound weight to be worked, melt, heated, and cooled. Furthermore, weight saving is generally due to thinner walls improving the thermal behavior with faster heating and cooling times, which leads to faster cycle times and processing cost savings.

15.1.4.3 Weight Saving Saves Energy during the Whole Service Life

Lightening in Transport: Fuel Savings

It is obvious that a lower weight of material needs less fuel for its transport. The three following examples deal with automobile and aeronautics for which transport is the main purpose and packaging for occasional transport.

For transport, it must be noticed that the direct weight saving on polymer parts induces other gains on the engine, the structure, and the suspension which are less loaded and can be adapted.

Automobile

The multiplying coefficient of weight part saving, including induced effects, can be estimated in the order of 1.5. The weight reduction constitutes an invaluable asset for running energy saving. For a mid-range car model, a reduction by 100 kg of the running mass can lead to a reduction of a few percent of fuel consumption, for example, 0.4 up to 0.6 l/100 km. If the weight saving is 300 kg, one can estimate a fuel saving of about 2500 l after 160,000 km, the average mileage of a European vehicle at its end of life. Extended to the European park, the economy is 5 million tons of petroleum, that is to say 25–30 million tons of CO_2.

Aeronautics

Kerosene is expensive and the fuel expenditure of airline companies, members of the International Air Transport Association (IATA), was estimated to 149 billion dollars in 2008 (135 billion in 2007), which represents 30% of their total expenditure.

The use of composites on the A380 Airbus makes it possible to have a weight saving evaluated to 1.5 tons. For the Boeing 787 Dreamliner, the weight saving is even more significant, as much as 50% of the primary structure. Consequently, Airbus and Boeing announce to their customers fuel savings of about 20%with their new planes.

Generally speaking, these advantages coming from weight saving lead the constructors to tolerate overspendings for the shift from a traditional solution to a lighter one. Tolerated cost overruns are about some hundred euros per saved kilogram for a helicopter and more than 1000 € per kg for a satellite.

Lightening in Packaging: Fuel Savings

The plastic packaging industry does not cease to reduce the weights of unit packaging. For example, for the last 20 year period, the weight reductions are estimated to:

- 70% for the carrier bags, from 20 g down to 6 g;
- 45% for bottles for cleaning products, from 69 g down to 38 g;
- 30% for 1.5 l bottles, from 43 g down to 30 g.

Fuel savings correspond to the weight reduction of the carried packaging.

15.1.5 Use of Recycled Plastics: Save Energy, Resources, Pollution, and Money

Recycled plastics include in-house regrind, postindustrial regrind, and postconsumer regrind. Origin is more or less identified and upgrading treatments may be applied such as addition of protective agents, plasticizers, impact modifiers, and eventually low levels of glass fibers, colors, etc.

Recycled polymer properties are more or less different from those of the corresponding virgin polymer but suitably recycled plastics can have properties that are good enough for many applications, with a noticeable economic advantage. Table 15.5 compares properties of virgin and recycled PAs. These data are examples only and cannot be considered as representative.

Some regulations can restrict the use of recyclates. For example, the UL Recognition program for recycled plastics uses proven scientific analysis and testing to evaluate plastic compounds with postconsumer or postindustrial content for compliance to UL 746D (Standard for Safety for Polymeric Materials—Fabricated Parts). This rigorous and innovative testing approach enables a recognized resin to have the same level of acceptability in an end-product application as a virgin compound. In essence, it allows for a resin which has been made with a certain percentage of recycled plastics to be substituted for a virgin plastic in end-use applications where compliance to UL 746C (Standard for Safety of Polymeric Materials—Use in Electrical Equipment Evaluations) is required.

The Certification Process for recycled plastics includes three parts: the initial certification, quality assurance (QA) program, and follow-up services.

The Initial Certification for compliance to requirements described in UL 746D. There are two paths for evaluating a recycle plastic according to its origin.

Path 1: Recycled Plastics with Consistent Identification. This is typically postindustrial regrinds that are traded between different companies. Several batches are required with the following properties tested: IR—infrared analysis, TGA—thermogravimetric analysis, DSC—differential scanning calorimetry, flammability, short-term properties (i.e., HAI, HWI, CTI, etc.), colors, elevated relative thermal index (RTI) through long-term thermal aging (LTTA); a generic RTI can be assigned based on a positive IR comparison to a generic plastic.

Path 2: Recycled Plastics without Consistent Identification. This is typically postconsumer plastics that have been used in consumer products that are considered waste. The plastic in these products is recovered and reprocessed to be reused again in consumer products. Several batches are required with the following properties tested: flammability, impact strength, tensile strength, heat deflection temperature, dielectric strength, hot wire ignition (HWI) or glow wire ignition, infrared analysis (IR), short-term properties (i.e., HAI, HWI, CTI, etc.), colors, elevated RTI through LTTA; a generic RTI can be assigned based on a positive IR comparison to a generic plastic.

The QA program involves establishing the traceability of plastic sources. Traceability is a very important part of producing a high quality, safe, reliable recycled plastic because this program ensures that the manufacturer is maintaining good control of their many plastic sources. In the QA program, a number of tests can be conducted as indicated in UL 746D. Several tests are required based on the flammability rating. These tests are to be conducted on an ongoing base as deemed required by the quality management system. During follow-up inspection visits, the inspector will review records for compliance with these test methods.

The follow-up services verifies compliance with safety requirements as it is being produced on an ongoing basis through regular manufacturing visits and sample selection with testing.

In order to complete the UL recognition, a recycled plastic manufacturer must have a registered quality management system that is compliant with ISO 9001 or an equivalent internationally recognized standard.

Regrind from reclaimed scrap from molding, such as sprues or runners that are reused in-house at a molding facility can be reintroduced into the molding hopper; with up to 25% where the rest of the 75%

Table 15.5 Performance Examples of Virgin and Recycled PA 6

	Virgin Neat PA 6	Recycled Neat PA 6	Variation (%)
Density	1.13	1.13	=
Shrinkage, %	1.6	1.6	=
Water absorption saturation, %	9.4	9.5	=
Rockwell R hardness	119	119	=
Tensile stress at yield, MPa	85	80	–6
Tensile strain at yield, MPa	5	3.5	–30
Tensile modulus, GPa	3.3	3.2	=
Flexural modulus, GPa	3	2.8	–7
Notched Izod, –30 °C	5	4	–20
Notched Izod, 23 °C	5.5	4.5	–18
HDT B, °C	184	175	–5
HDT A, °C	67	60	–10
Coefficient of thermal expansion (10^{-5}/K)	7.5	7.5	=
	33% GF PA 6	**33% GF PA 6**	**Variation (%)**
	Virgin	**Recycled**	
Density	1.39	1.38	=
Shrinkage, %	0.2–0.9	0.2–1	=
Water absorption saturation, %	6.7	6.6	=
Rockwell R hardness	121	121	=
Tensile stress at break, MPa	200	165	–17
Tensile strain at break, MPa	3	3	=
Tensile modulus, GPa	10.7	9.5	–11
Flexural modulus, GPa	9.4	9.3	=
Notched Izod, –30 °C	11	8	–27
Notched Izod, 23 °C	15	12	–20
HDT B, °C	218	215	=
HDT A, °C	203	208	=

is comprised of the same virgin grade that was used to mold the parts where the regrind came from.

As some properties are affected by recycling, the designer must be vigilant, notably concerning ultimate mechanical performances such as tensile and impact strengths, and also sensory properties such as color, odor and taste, and fire behavior, fire retardancy, and smoke emission. Rheology changes, less known, can disturb processing and increase processing costs. Table 15.5 displays property examples of PA recycled in laboratories.

Table 15.6 displays examples of PS, PP, and PA industrially recycled and marketed by recyclers or plastics producers.

Table 15.6 Examples of Industrially Recycled PS, PP, and PA

Polystyrene Examples			
	Impact modified virgin PS	**AXPOLY® rPS01 3039 Black or White Impact Modified PS Produced from 100% Postconsumer Raw Materials**	
Property	Range	Specification	Typical properties
MFI (5 kg at 200 °C), g/10 min		5–8	6
Density	1.03–1.06	1.03–1.06	1.03
Tensile Strength, MPa	20–45	15–25	22
Impact Strength, kJ/m^2		6–10	8
Moisture content, %	0.05–0.30	<0.25	0.17
Elongation at break, %	20–65	25–50	35

Polypropylene Examples					
PP	**Virgin**		**Recycled from End-of-Life Vehicle**		
Filler level	**None**	**10–40% Talc**	**Undefined, Low**	**20% Talc**	**40% Talc**
MFI (2.16 kg at 230 °C), g/10 min			6	9	5
Density	0.9–0.91	0.97–1.25	0.93	1.09	1.22
Tensile Strength, MPa	20–35	21–28	19.6	23	25
Impact Strength, kJ/m^2			11.9	10	5
Moisture, %	0.01–0.1	0.01–0.03			0.19
Elongation at break, %	200–500	20–30	33	25	

Example of Virgin and Recycled PP Mixture Filled with 20% Mineral		
Physical Properties		**Daplen™ MD250SY PP**
Density	Unit	1.080
Melt flow rate (230°C/2.16 kg)	g/10 min	6
Flexural modulus (2 mm/min)	GPa	2.4
Flexural strength	MPa	37
Charpy impact strength, notched (+23 °C)	kJ/m²	3
Charpy impact strength, notched (–20 °C)	kJ/m²	1.3
Heat deflection temperature (1.80 MPa)	°C	61

Example of Polyamide 6: Nypel (BASF) Heat Stabilized, 30% Glass Fiber Reinforced Compound Based on Recycled Nylon 6		
Density	g/cc	1.36
Moisture absorption at equilibrium	%	1.9
Linear mold shrinkage	%	0.3
Mechanical Properties		
Hardness, Rockwell R	Rockwell R	121

Table 15.6 Examples of Industrially Recycled PS, PP, and PA—cont'd

Tensile strength at break		
RT	MPa	155
120 °C	MPa	65
80 °C	MPa	80
−40 °C	MPa	220
Elongation at break	%	3
Tensile modulus		
RT	GPa	9.6
120 °C	GPa	2.7
80 °C	GPa	3.8
−40 °C	GPa	8.7
Flexural strength	MPa	230
Flexural modulus	GPa	8.1
Izod impact, notched	J/cm	0.85
Izod impact, notched (ISO)		
RT	kJ/m²	8
−40 °C	kJ/m²	6.5
Charpy impact unnotched	J/cm²	5.4
Charpy impact, notched	J/cm²	0.86
Electrical Properties		
Volume resistivity	Ohm-cm	≥1.00e + 13
Thermal Properties		
CTE, linear	10–5	3.8
CTE, linear, parallel to flow	10–5	2.5
CTE, linear, transverse to flow	10–5	6.7
Melting point	°C	220
Deflection temperature at 0.46 MPa (66 psi)	°C	219
Deflection temperature at 1.8 MPa (264 psi)	°C	205
Flammability, at thickness 0.810 mm	UL94	HB

Of course, a recycled polymer is cheaper than the same virgin polymer. Figure 15.6 displays examples of ratios (recycled cost/virgin GP polymer cost) without indications concerning the polymer type and the level of purity and upgrading. Obviously other figures may be found elsewhere. The range of recycled polymer costs is broader than the range of homologous virgin polymer costs depending on recyclate quality, upgrading, demand on defined grades, polymer type, general economic situation. According to this graph, the cost saving evolves between 50% and 90% of the virgin material cost with usually a 20% advantage. The polymer cost is an important parameter but lower recyclate quality and processing troubles or adaptations can partially or totally annihilate this advantage. So, two polls show that more than 10% of voters are not economically satisfied by recyclate use.

Often recycled material is mixed with virgin polymer. Producers' recommendations vary with the polymers and the reinforcement. For example, recycled engineering thermoplastics can be used from 15 up to 30% and TPE from 10 up to 50%. Recycled LFRT use is the most limited, for example 5%. These levels are not rules and certain products can be entirely made out from recycled materials.

Most used recyclates are commodities but engineering plastics are marketed or in-house recycled. For example:

- SoRPlas by Sony is made from recycled DVDs and optical sheets from TVs. Sony claims "Combined together they make an extremely versatile recycled plastic containing sodium sulfate flame retardant. Only 1% of SoRPlas is made from non-recycled materials cutting CO_2 emissions by 77.3% over the manufacture of conventional plastic materials."
- For production of bottles, by using 100% postconsumer recycled (PCR) resin, the cradle-to-gate energy consumption of the resin compared to virgin is reduced by 52% and the carbon footprint is lowered by 57%. In addition, an on-site production of PCR bottles keeps over 600 truckloads of bottles off the road each year and eliminates over 200 metric tons of carbon dioxide equivalent emissions, according to Amcor.
- US-based Nestlé Waters, manufacturer of the Arrowhead brand bottled water, has committed to using 50% recycled content in its water bottles
- For recycling of PET, the carbon cost of producing food grade rPET 78 pellet in 2010 was 254 kg/t, while the cost of producing virgin PET was 681 kg/t.

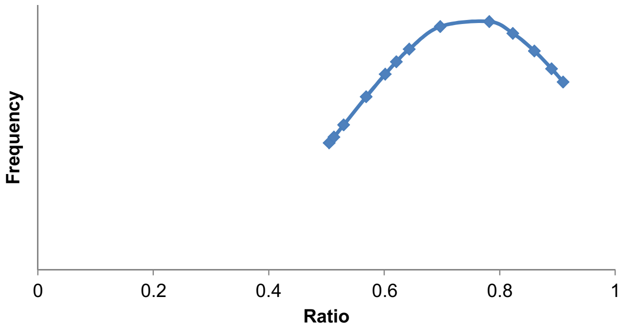

Figure 15.6 Ratio (recycled cost/virgin cost).

According to two polls (see Table 15.7) launched by Omnexus (http://www.omnexus.com/), "Which factor limits the increase in the use of post-consumer recycled polymers, the most?" and "What is the most critical issue in using recycled engineering thermoplastics?" The main issues are the "reliability of supply, the variation of performances" and "limited processing stability" for 60% and 72% of voters. The cost is also an issue for 11% and 17% of voters.

Table 15.7 Issues Limiting the Use of Recycled Polymers

	Commodity & Engineering	Commodity	Engineering
Reliability of supply	22–27%		
Variation of performances	26–41%		
Cost	11–17%		
Limited processing stability	9.3–9.1%		
Limited performances			9.3%
Ban by some specifications			6.8%
Risk of polluting substances		14%	
Lack of regulations		8%	

15.1.6 Promote Repairing of Used Parts

Large thermoplastic-made parts have the significant economical advantage of being rather easy to repair.

A skilled professional can correctly repair the most-common thermoplastic parts, such as piping, geomembranes, inflatable boats and structures, by welding or gluing patches after removal of the soiled and damaged part.

Designer must ease repairing of large and costly parts using, for example, a single material tolerating the repairing products and processes, and a simple geometry.

Let us quote some repairing examples without claiming to be exhaustive:

- Conveyor belts: repairing is systematic for units of some importance and specificity.
- Pipes, pipelines: repairing is often possible and is used for expensive items.
- Roll recovering: systematically used for units of some importance.
- Coated fabrics: Repairing is used for important devices.
- Flooring: Repairing is possible after accidental damages.
- Cables and jackets: repairing is industrially applied.
- Inflatable boats: Small damages can be repaired by the owners. Major damages can be repaired by specialists.
- Tank relining: systematically used for industrial large installations.

Welding and gluing are often used to put in place a new part or a patch replacing a damaged section of the old device. Particular care must be taken of cleanliness: one should not hesitate to clean and even refresh by abrasion, the surfaces to be joined. For old parts, it is necessary to remove the surface to reach unpolluted, noncorroded, and nonoxidized matter. In the repair of tanks, pipes, etc., it can be impossible to rejoin if thermoplastics are bulk impregnated with chemicals or if degradation is too severe.

Some basic and good sense precautions must be taken. Repairing is a serious operation that must be entrusted to a specialist. The following remarks are only generalities:

- It isn't possible to repair anything and everything: apart from the damaged section, the rest of the part must satisfy the requirements for a standard working.
- Too big a damage can't be repaired: decisions must be taken by a professional.
- Damages in a high-loaded location can't be repaired: decisions must be taken by a professional.
- Some defects are hidden and may be unnoticed for (in)expert eyes. Nondestructive inspection tests must be applied by specialists to help to their detection.

15.2 Replacement of Fossil Materials by Renewable Materials

Bio-sourced polymers are directly or indirectly derived from renewable biomass sources, such as vegetable oil, cornstarch, pea starch, sugar, wastes etc., in contrast to fossil plastics which are derived from petroleum. Industry can use physical means, conventional, or green chemistry or biosynthesis to convert biomass into feedstocks, building blocks, or usable end forms of plastics. Bioplastics are not a single class of polymers but rather a family of products which can differ considerably from one another. Let us point out that the needed energy to produce these polymers is mainly produced by conventional ways including fossil fuels and nuclear energy.

Bioplastics are probably one of the smartest forms of plastics to satisfy sustainability concepts developed and then normalized (ISO 14000) to help the economic and industrial actors to think about ways able to improve or minimize the degradation of our Earth.

15.2.1 Renewable Polymers

Most bio-sourced thermoplastics are recent and all the following characteristics and features are those claimed by bioplastics producers.

Classification of bio-sourced thermoplastics is a difficult exercise because of the diversity of sources, treatments, formulations, and possible combinations with fossil polymers.

Among resins more or less directly derived from natural raw materials, we can quote for example:

- Starch, produced by all green plants as an energy store, is a major food source for humans and industrial utilization can compete food uses. Starch-based plastics, modified with flexibilizers and plasticizers such as sorbitol and glycerin, constitute an important part of the bioplastics market, mainly for the packaging but there are also various engineering applications.

- Polylactides and polylactic acid (PLA) plastics are another important family of bioplastics resembling conventional-clear polystyrene with good aesthetics (gloss and clarity), but stiff and brittle, which needs their formulation and plasticization for most practical applications. Generally, they can be processed on existing standard equipment. Compared to a competitive oil-based polymer, dependency from fossil resources is reduced by 25–55%, and exhaust gases influencing global warming are reduced by 10–70%.
- Cellulose, the most spread natural polymer, usable after simple physical processing or convertible by chemical treatments. It is present in all wild or cultivated vegetal products: wood, cotton, and other natural fibers. Chemical modifications lead to cellulosics, acetate, and other esters. Of course, new applications are in competition with existing ones, except if they use wastes. Let us remember that industrial cellulosics are esters of natural cellulose coming from wood. The most common are:
  - Cellulose acetobutyrate, CAB
  - Cellulose acetate, CA
  - Cellulose propionate, CP

Cellulosics are appreciated for their easy processability, esthetics, transparency, high gloss, pleasant touch, aptitude for coloring and decoration, low electrostatic built up, balance of fair mechanical properties and chemical resistance to oils, greases, and aliphatic hydrocarbons; fair electrical insulating properties, fair performance/cost ratio, food contact possibilities. However, cellulosics are handicapped by their density and sensitivity to heat, water, and several common chemicals.

- Polyhydroxyalkanoate (PHA), polyhydroxybutyrate (PHB), and other polyesters are produced via microbial routes. According to the used raw materials and polymerization methods, their behavior can evolve from a rigid plastic up to a soft material with melting points from about 40 °C up to 180 °C.
- Lignin, a complex chemical compound most commonly derived from wood, is one of the most abundant organic polymers on Earth, constituting from 25 up to 33% of the dry mass of wood. Lignin is unusual as a biopolymer, because of its heterogeneity and imprecise composition. However, as a wood constituent, it is indirectly used in WPC, a fast-growing line of plastics.
- Natural rubber, a polymer of isoprene including exclusively carbon and hydrogen with the formula (C5H8)n, consists of a linear chain with a molecular weight of 100,000 up to 1,000,000. It must be noted that natural rubber has very few applications as a thermoplastic resin and must be vulcanized for most applications.
- SORONA by DuPont, based on renewable raw material, is derived from glucose coming from cornstarch. Fossil resource consumption for the production process is reduced by 50%.

For more indirect routes, let us quote for example:

- Polyethylene and polypropylene synthesized from alcohol obtained by fermentation of sugars leading to ethanol, itself leading to ethane. Biopolyethylene is among important and fast-growing bioplastics.
- Polystyrene and PVC could be produced according to the ethanol route.
- Soranol and copolyester thermoplastic elastomers (Hytrel) can be synthesized from propanediol.
- Polyamides: Rilsan® Polyamide 11, Pebax®, and Platamid® are bio-based, high-performance polymers produced from renewable resources. Polyamide 10.10 can have a very high level of biocarbon and PA6.10 can be based to the extent of about 60% on sebacic acid, a renewable raw material derived from castor oil.
- Bio-based polyethylene terephthalate (PET) is a special case of partially bio-based plastics boosted by companies such as The Coca Cola Company, Heinz & Co., Ford Motors, Nike Co. and Proctor & Gamble. This first step is intended to be followed by 100% bio-based PET.
- Thermoplastic polyurethanes can include biopolyols.
- Acrylics and styrenics: Vegetable Oil Polymer Network (VOPNet) studies their production

from renewable resources. A grade of Altuglas PMMA includes 20% of bio-derived carbon.

15.2.1.1 Ready-to-Use Thermoplastic Starch

The oldest industrial product is Mater-Bi® (by Novamont), a thermoplastic starch that can be processed by injection, extrusion, thermoforming, foaming. It can be colored using Mater-Bi-based biodegradable masterbatches, which are available from Clariant and other manufacturers.

According to Novamont, properties of ready-to-use grades are in the range of those of polyolefins, not basically different from commodity petroleum-based resins, particularly low-density polyethylene, (see Table 15.8). These data are not a rule and other characteristics can be found elsewhere. They cannot be used for designing any parts or goods.

Injection grades of Mater-Bi® can be molded using standard injection molding machines. The maximum injection temperature must be inferior to 200 °C and the residence time must be as short as possible. Parts have the advantage of being antistatic, eliminating the accumulation of electrical charges. About 10% of the scraps can be reused. Many parts can be injection molded such as pencil sharpeners, rulers, cartridges, toys, combs, plant pots, bones, and other toys for pets.

Extrusion grades can be processed into film using traditional LDPE extruders but at lower extrusion temperatures. Productivity and scrap level are similar and scraps can be recycled using the same techniques as those used for PE. Different film grades are available for specific applications, e.g., bags, shopping bags, mulching films, packaging, and hygiene products. Films can be printed on using water- or solvent-based inks, with any type of printing technique and without the need for surface treatment. Sealing is similar to that of PE with a competitive speed.

Thermoforming: Starch-based films and sheets can be used to manufacture non-transparent, rigid, thermoformed trays, which are used for fresh food packaging. This packaging can be disposed of in a composting plant with the food scraps.

Foaming: The Mater-Bi® Wave foam sheet is an alternative to polystyrene, polyurethane, and polyethylene foams commonly used in protection packaging. Starch is expanded using water, extruded into sheets and then assembled into blocks that can be cut into any shape. Mater-Bi® Wave has a robust and resilient closed-cell structure. Sheets and blocks are available in different sizes, with densities from 30 to 400 kg/m^3.

From an environmental standpoint Gaïalene® (by Roquette Group), another thermoplastic starch brings 40% CO_2 emission cuts compared to polyolefins. The environmental footprint is even better if ones take into account the CO_2 removed from the atmosphere to grow the Gaïalene® raw materials: corn, wheat, potatoes, and peas.

15.2.1.2 Ready-to-Use PLA Grades

Polylactides and polylactic acid (PLA) plastics, one of the most used family of bioplastics, are resembling conventional clear polystyrene with good aesthetics (gloss and clarity), but stiff and brittle, which needs their formulation and plasticization for most practical applications. Generally, they can be processed on existing standard equipment. According to NatureWorks, ready-to-use Ingeo grades are stiffer but not basically different from commodity petroleum-based resins, particularly polystyrene.

Table 15.9 displays some examples of properties of neat and reinforced PLA (according to NatureWorks and RTP company) for injection, extrusion and bioriented film. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

Table 15.8 Starch-Based and Petroleum-Based Resin Property Examples

	MATER-BI®		PP	PS	LDPE
	Injection	Film			
MFI, g/10 min	6–30	2–4	6–30	19–24	0.1–6
Tensile strength, MPa	15–35	20–50	20–40	20–60	10–30
Elongation at break, %	20–150	200–600	100–500	1–5	150–600
Young's modulus, GPa	0.6–5	0.1–0.6	0.6–1.6	2.5–3.5	0.15–0.3

Table 15.9 Property Examples of PLA Resins

			Durable Goods	Durable Goods
Unreinforced Injection Grades	**GP**	**GP**	**Amorphous**	**Semicrystalline**
Specific gravity	1.24–1.25	1.24	1.24	1.24
Melt index, g/10 min (210°C/2.16 kg)	10–85	14–22	65	65
Melt index, g/10 min (190°C/2.16 kg)	10–40			
Clarity	Transparent		Transparent	Opaque
Tensile strength, MPa	48		63	63
Tensile modulus, GPa	3.8	3.6	3.6	3.6
Flexural strength, MPa		108	108	108
Flexural modulus, GPa		3.6	3.6	4.3
Tensile elongation, %	2.5	3.5	3.5	1.3
Notched Izod impact, J/m	16	16	16	16
HDT 0.45 MPa, °C		55–56	55–56	151
Unreinforced Extrusion Grades	**Thermoforming**		**BOPLA**	
Specific gravity	1.24		1.24	
Melt index, g/10 min (210 °C/2.16 kg)	5–7		2.1	
Melt index, g/10 min (190 °C/2.16 kg)				
Clarity			Transparent	
Haze			2.1	
Gloss, 20°			90	
Tensile strength, MPa	53		103–110 (MD)	
			144 (TD)	
Modulus, GPa	3.5		3.3–3.4 (MD)	
			3.8–3.9 (TD)	
Tensile elongation, %	6		160 (MD)	
			100 (TD)	
Notched Izod impact, J/m	13			
Reinforced Grades				
Glass fiber, %	10	20	30	40
Specific gravity	1.32	1.39	1.48	1.57
Izod impact strength, notched, J/m	43	48	53	48
Izod impact strength unnotched, J/m	320	320	320	320
Tensile strength, MPa	79	97	110	110
Tensile elongation, %	1.5	1.5	1.5	1.0

Table 15.9 Property Examples of PLA resins—cont'd

Reinforced Grades				
Tensile modulus, GPa	6.9	8.3	10.2	13.8
Flexural strength, MPa	93	117	145	145
Flexural modulus, GPa	6.6	8.6	11.2	13.8
HDT at 1.8 MPa, °C	106	148	149	149
HDT at 0.46 MPa, °C	143	152	160	160

MD, machine direction; TD, transverse direction.

Table 15.10 Property Comparison of 30% Glass Fiber-Reinforced PLA and Fossil Plastics

	PLA	**PP**	**PLA**	**PBT**
Glass fiber; %	**None**	30	**30**	30
Tensile strength, MPa	**48**	76	**109**	124
Flexural strength, MPa	**83**	112	**145**	190
Flexural modulus, GPa	**3.8**	4.8	**11**	8.2
Impact resistance, Izod, notched, J/m	**16**	107	**53–59**	96
Heat deflection temperature at 0.46 MPa, °C	**51**	157	**164**	224

Table 15.10 displays some properties of 30% glass fiber-reinforced PLA and two reinforced fossil plastics, PP, and PBT. Data are only given to provide a rough idea of the PLA performance, which is halfway between fossil PP and PBT. Data cannot be used for designing any parts or goods.

Processing conditions are more or less comparable to those of commodity resins. However, it is necessary to take into account the following:

- The sensitivity to water and humidity as far as the temperature is higher. Drying is essential for the stability of the material in the molten state. A moisture content of less than 0.025% (250 ppm) is recommended to prevent viscosity degradation. It is necessary to keep sealed the foil-lined boxes or bags initially dried. The resin should not be exposed to atmospheric conditions after drying. Pellets that have been exposed to the atmosphere for extended time periods will require additional drying time.
- The incompatibility with other resins. All the processing machinery and lines must be properly cleaned before feeding and purged to prevent any cross contamination.
- PLA regrind is not compatible with other regrind products. It is necessary to carefully clean the grinding equipment and transfer lines or to have dedicated systems for PLA. Some grinding systems can require additional cooling to efficiently grind PLA. Amorphous regrind must be crystallized prior to drying at low temperature (for example below 50 °C), to assure efficient and effective drying.
- The thermal stability: processing temperatures must be as low as possible and the residence times must be as short as possible.

Injection: Suitable PLA grades can be processed on conventional injection molding equipment. The material is stable in the molten state, provided that the drying procedures are carefully followed. Rheology is highly dependent on melt temperature.

Extrusion: PLA can be processed on conventional extrusion equipment with a suitable general-purpose screw.

Thermoforming: PLA extruded sheets must be stored in a dry and temperate environment, below 40 °C and 50 RH, which avoids drying before thermoforming, haze parts, blocking and unwinding issues, molecular weight breakdown, and loss of

Table 15.11 Property Examples of Biograde

		C 6509 CL	C 7500	C9550
Density	(g/cm³)	1.29	1.31	1.67
Tensile modulus of elasticity	(GPa)	2.7	3	4.2
Tensile strength	(MPa)	62.5	66	41
Tensile strain at break	(%)	12.6	12.5	6.5
Flexural modulus	(GPa)	2.9	2.9	4
Flexural stress at 3.5% strain	(MPa)	69	70	63
Notched impact strength (Charpy), RT	(kJ/m²)	5	6.5	2
Impact strength (Charpy), RT	(kJ/m²)	No break	No break	37
Hardness	Shore D	78	80	83
Melt temperature	°C	180–190	>180	>180
Vicat A softening temperature	°C	104	110	118
Melt flow rate (230 °C/5 kg)	(g/10 min)	38–42	17–21	11–15

physical strength. PLA is highly polar and has an electrostatic behavior needing the use of antielectrostatic bars. Generally, PLA can be processed using forming ovens, molds, and trim tools designed for PET or polystyrene, HIPS, and OPS.

Corona or flame surface treatment can be used to ensure high-quality printed graphics.

Application examples: cutlery, cups, plates and saucers, dairy containers, food serviceware, transparent food containers, blister packaging, cold drink cups, outdoor novelties, consumer goods, electronics, cosmetics, housewares, toys, biaxially oriented films…

A special form of PLA (Stereocomplex PLA) is developed by Teijin Limited as BIOFRONT™, a heat-resistant PLA, which initially will be used for the manufacture of a high-quality, highly durable car-seat fabric combining polymer from nonoil materials and from petroleum origin. The melting point of BIOFRONT fibers is 210 °C, more than 40 °C higher melting temperature than conventional PLA.

BIOFRONT™ is a stereocomplex with a special crystal structure in which the poly L-lactic (PLLA) acid and poly D-lactic (PDLA) acid are arranged alternately leading to a substantial increase of the melting temperature. In addition, by developing a new additive that controls the hydrolysis of a polymer, Teijin succeeded in improving the hydrolysis durability of PLA. Allowing to produce durable engineering plastics widening application of PLA in uses such as automobile, electronic equipment, and apparel that require resistance to hydrolysis, as well as to uses where hydrolysis is desirable such as medical care, packages, civil engineering and construction, and oil fields (the drilling phase in shale gas extraction, etc.).

15.2.1.3 Ready-to-Use Cellulose-Based Plastics

FKuR Plastics Corp. launched several heat-resistant cellulose-based polymers with the brand name BIOGRADE®. Developed particularly for technical applications, Biograde® can be processed on conventional plastics processing machines without the need for modifications. Mainly composed of natural resource materials, these biodegradable resins are especially designed for injection molding applications.

FKuR Plastics Corp. claims Biograde® resins have been successfully used in the production of heat-resistant cutlery and for the production of technical electronic parts and household equipment.

Table 15.11 displays some properties of Biograde. Data are only given to provide a rough idea of their performance and cannot be used for designing any parts or goods.

15.2.1.4 Various Aliphatic Polyesters: Polyhydroxyalkanoate (PHA), Polyhydroxybutyrate (PHB), Polyhydroxyvalerate (PHV), Polyhydroxybutyrate-*co*-hydroxyvalerate (PHBV), Polyhydroxybutyrate-hexanoate (PHBH) Copolymer

According to the used raw materials and polymerization methods, their behavior can evolve from a rigid plastic up to a soft material with melting points from about 40 °C up to 180 °C.

The properties of PHA vary with the composition, but generally speaking the more common grades resemble polyolefins.

Polyhydroxybutyrate (PHB) resembles PP with higher modulus and lower impact resistances.

Polyhydroxybutyrate-valerate (PHBV) is less rigid and more elastic.

- **Polyhydroxyalkanoate, PHA:** For instance, Mirel by Metabolix is a family of bioplastic materials that are both bio-based and biodegradable in natural soil and water environments, home composting systems, and industrial composting facilities. The rate and extent of biodegradability depend on the size and shape of the articles made from it. Mirel is not designed to biodegrade in conventional landfills.

Table 15.12 displays some characteristics of PHA (Mirel and MVera by Metabolix). Data are only given to provide a general idea and cannot be used for designing any parts or goods.

Table 15.12 PHA (Mirel): Property Examples

	Molding Grades	Film
Miscellaneous Properties		
Density, g/cm^3	1.2–1.6	1.3
Shrinkage, %	1.3–1.55	
Mechanical Properties		
Tensile strength, MPa	20–25	22–25
Elongation at break, %	4–7	250–450
Tensile modulus, GPa	1.6–3	0.1–0.7
Flexural strength, MPa	33–40	
Flexural modulus, GPa	1.3–2	
Notched impact strength ASTM D256, J/m	26–37	
Thermal Properties		
HDT B (0.46 MPa), °C	110–132	
HDT A (1.8 MPa), °C	36–77	
Vicat softening point B10, °C	110–133	
Melting point, °C		170

- **Polyhydroxybutyrate (PHB) and Polyhydroxybutyrate-valerate (PHBV) derivatives:** Tg of pure PHB is 5 °C and its melting point is 170–180 °C. Hydroxyvalerate (HV) units act to lower the melting point, increase impact strength and flexibility, and reduce tensile strength. The copolymers are semicrystalline but when the HV content increases, the rate of crystallization reduces, and nucleating agents are routinely added to accelerate crystallization during processing. Plasticizers are also used to improve processability and flexibility. According to the HV content, polymers could be tough like polypropylenes or softer and more like polyethylenes. This has led to applications in packaging such as films and bottles where their degradability brings sufficient added value to offset their high cost. PHB/PHV copolymers are used in preference to PHB homopolymer for general purposes (e.g., molding containers) in order to obtain a better balance of stiffness and toughness. PHV contents of 5–20% give properties broadly similar to those of the polyolefins. They melt at lower temperatures than the homopolymer, giving a useful improvement in melt-processability.

They are being used for biodegradable containers (of which shampoo bottles are the most high-profile example) and other articles difficult to recycle, e.g., disposable razors or medically contaminated articles.

Table 15.13 displays some characteristics of PHB and PHBV (Goodfellow). Data are only given to provide a general idea and cannot be used for designing any parts or goods.

- **Polyhydroxybutyrate-hexanoate, PHBH:** The Kaneka company proposes bio-based, biodegradable and compostable copolymer

Table 15.13 Examples of PHBV Properties

	PHB Goodfellow	PHB/PHV 92/8	PHB/PHV 88/12
Physical Properties			
Density	1.25	1.25	1.25
Mechanical Properties			
Tensile strength, yield, MPa	40	28	40
Tensile modulus, GPa	3.5	0.9	0.5
Elongation at break, %		15	35
Izod impact, unnotched, J/m	35–60	100	200
Electrical Properties			
Electrical resistivity, ohm-cm	1 E+16	1 E+16	1 E+16
Dielectric constant, 1 MHz	3.0	3.0	3.0
Thermal Properties			
Maximum service temperature, air, °C	95		
Specific heat, J/g-°C		1.4	1.40
Thermal conductivity, W/mK		0.15	0.15

(Polyhydroxybutyrate-hexanoate, PHBH). PHBH is obtained by a defined fermentation process where plant oils are digested to produce PHBH which is stored in microorganisms. PHBH is then extracted from these microorganisms. Its biodegradation can take place in both aerobic and anaerobic conditions (For example, it can biodegrade at 35 °C under anaerobic conditions in 20 days and, under 52 °C and anaerobic conditions, biodegradation of PHBH is above 60%.

Thanks to a controlled balance of hard segments (butyrate) and soft segments (hexanoate) the final material hardness can be tailor-made. Flexible grades target films and other packaging uses. Rigid grades are developed for disposable cutlery and thermoformed blisters.

Table 15.14 displays some characteristics of PHBH (by Kaneka). Data are only given to provide a general idea and cannot be used for designing any parts or goods.

Cost remains a severe handicap for these specialty polymers. For example, some prices were quoted in 2008 at $4.4 per kg or more recently at 5€ per kg. As for all potential applications of "sustainable" polymers, legislation or customer diktat can change the economics to some extent.

15.2.1.5 Liquid Wood Based on Lignin—Arboform by Tecnaro

Researchers at the Fraunhofer Institute for Chemical Technology (ICT) and the Fraunhofer spin-off Tecnaro GmbH have developed a bioplastic, known as Arboform® or liquid wood, made of the lignin syrup discarded by the cellulose industry. After mixing with fine natural fibers made of wood, hemp, or flax and natural additives such as wax, the produced thermoplastic can be melted and injection-molded in car parts, urns, and other durable components which can, at the end of their life, be biodegraded. In addition, Arboform® makes use of lignin which would otherwise be burnt or used in low-value animal feeds.

Table 15.15 displays some characteristics of Arboform (by Tecnaro) depending on the used formulation. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

Arboform is priced around €5/kg in 2014 for orders of 100 kg. It has drawn interest from the automotive industry for its ability to replicate the finish and feel of wood in three-dimensional parts. It has also been used to produce loudspeaker casings and golf tees.

Table 15.14 Examples of PHB and PHBH Properties

Examples of PHB Properties				
Physical Properties				
Density	1.2	1.2	1.25	1.17
Moisture absorption at equilibrium, %		0.75	0.4	0.4
Linear mold shrinkage, %		1.3	1.3	1.3
Mechanical Properties				
Tensile strength, yield, MPa	40			
Tensile strength, ultimate, MPa		15–20	24–27	18–20
Tensile modulus, GPa		0.9–1.2	1.7	1–1.22
Elongation at break, %		11–18	6–9	10–17
Flexural strength, MPa		18	35	17
Hardness, Shore D		57	67	56
Izod impact, unnotched, J/m	35–60			
Charpy impact unnotched, J/cm^2		2.1	3	8
Charpy impact notched, J/cm^2		0.21	0.27	0.86
Electrical Properties				
Electrical resistivity, ohm-cm	1 E+16			
Dielectric constant, at 1 MHz	3.0			
Thermal Properties				
Maximum service temperature, °C	95	120	120	120
Minimum service temperature, °C		–30	–30	–30

Examples of PHBH Properties (Kaneka)		
Physical Properties		
Density	1.2	1.19
Water vapor transmission g/m^2/day at Thickness 0.0600 mm	80–120	80–120
Oxygen transmission cc-mm/m^2-24h-atm at thickness 0.0600 mm	0.300–0.900	0.300–0.900
Mechanical Properties		
Tensile strength, ultimate, MPa	28	25
Tensile modulus, GPa	1.24	0.665
Elongation at break	26	331
Flexural modulus, GPa	1.53	0.9
Izod impact, notched, J/m	33	39
Thermal Properties		
Glass transition temperature (Tg), °C	2	0
Vicat softening point, 1 kg, °C	117	104

Continued

Table 15.14 Examples of PHB and PHBH Properties—cont'd

Examples of PHBH Properties (Kaneka)		
Melting point, °C	142	136
HDT 0.46 MPa	100	87
Optical Properties		
Haze, thickness 0.100 mm, %	40	27

Table 15.15 Characteristic Examples of Arboform

	Unit	Range
Density	g/cm^3	1.3–1.4
Mold shrinkage	%	0.1–0.3
Water content	%	2–8
Mechanical Properties		
Tensile strength	MPa	10–22
Ultimate elongation	%	0.3–0.7
Tensile modulus	GPa	1–5
Flexural modulus	GPa	1–5
Flexural strength	MPa	10–50
Impact strength	kJ/m^2	2–5
Hardness	Shore D	50–80
Thermal Properties		
Coefficient of thermal expansion	10^{-5}/°C	1–5
Vicat temperature	°C	80
Thermal conductivity	W/(m*K)	0.384
Hot-wire test	–	650 °C passed
Electrical Properties		
Conductivity, surface	Ohm	$5*10^9$

15.2.1.6 Miscellaneous Proprietary Alloys and Compounds

There are two main ways investigated by researchers, producers, and compounders: on the one hand, alloying of several natural-sourced polymers and on the other hand alloying of natural and fossil products.

Proprietary alloys and compounds are announced as the answer to the market needs for higher performing bio-based materials. Quote, for example, without claiming to be exhaustive:

- PolyOne's reSound™ biopolymer compounds incorporating up to 50% bio-derived content by weight by using high-performance engineering resins compounded with biopolymers like PLA, PHB, PHBV, and other biopolyesters. They offer increased sustainability without sacrificing performance. In addition, reSound compounds are claimed to have a fair balance of temperature, impact, and cost performance that enables manufacturers to reduce the environmental impact of their products, while delivering performance of the same order than conventional engineering resins.

Table 15.16 displays some characteristics of PolyOne reSound based on PLA depending on the used formulation. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

- BIOP (Biopolymer Technologies) receives Frost & Sullivan award for BIOPAR® a starch-based bioplastic polymer produced through a proprietary technology. BIOPAR® consists of aliphatic copolyesters, starch, and a patented proprietary compatibilizer. It is a soft polymer with an elastic modulus inferior to 0.12 GPa and an elongation at break up to 600%. It targets application in the food packaging, consumer goods, landscape gardening, agriculture, caps, closures, shopping bags, automobile parts, and interiors. BIOPAR® reduces the quantity of synthetic material being used in the polymer. Its water vapor rate and gas barrier properties provide it with the ability to replace polyethylene in several applications. It enables energy and cost savings for processors and end-users.
- Remember the previously cited Stereocomplex PLA: Teijin Limited proposes BIOFRONT™, a heat-resistant PLA, which initially will be used for the manufacture of a high-quality, highly durable car-seat fabric combining polymer from nonoil materials and from petroleum origin. The

Table 15.16 Examples of Properties of PolyOne reSound Based on PLA

Renewable resource content	%	45–50
Density	g/cm³	1.210
Mold shrinkage	%	0.7
Melt flow Index, 250 °C, 5 kg	g/10 min	10–14
Mechanical Properties		
Tensile modulus	GPa	2
Tensile strength at yield	MPa	53–55
Tensile strength at break	MPa	31–39
Elongation at yield	%	3–3.5
Elongation at break	%	60
Flexural modulus	GPa	2.8–2.9
Flexural strength	MPa	90
Izod impact notched	J/m	534–641
Thermal Properties		
DTUL at 0.46 MPa	°C	108–115

melting point of BIOFRONT fibers is 210 °C, more than 40 °C higher melting temperature than conventional PLA.

- BASF develops ECOVIO® consisting of polylactic acid obtained from corn and ECOFLEX®, which is derived from petrochemicals. Ecovio® can be used to produce flexible films or items such as mobile phone housings and yoghurt cups.

Table 15.17 displays some characteristics of Ecovio (BASF) based on PLA depending on the used formulation. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

- BASF also develops ECOBRAS, a blend of Ecoflex aliphatic aromatic co-polyester and a "vegetable polymer" derived from corn flour.
- BIOGRADE® (by FKuR) previously quoted (see Table 15.11) has been especially designed for injection molding applications. BIOGRADE® is predominantly composed of natural resource materials and does not contain starch or starch derivatives. Furthermore BIOGRADE® is claimed to having the following advantages:
  - high content of natural resource materials

Table 15.17 Examples of Properties of Ecovio Based on PLA and LDPE for Comparison

Property	**Unit**	**Ecovio®F Film C2203**	**Ecovio®F Blend C2203**	**LDPE For Comparison**
Density	g/cm³	1.24–1.26	1.24–1.26	0.922–0.925
Melt flow rate MFR 190 °C, 2.16 kg	g/10 min	<2	<2.5	0.6–0.9
Melting temperature	°C	110–155	110–155	114
Hardness	Shore D	59	59	48
Light transmission	%	85		8
Haze	%		85	8
Tensile modulus	MPa	840/280	750/520	260/300
Tensile strength	MPa	39/30	35/27	26/20
Ultimate strength	MPa	39/29	35/27	–
Ultimate elongation	%	330/430	320/250	300/600
Failure Energy (dyna test)	J/mm	42	38	5.5
Permeation Rates				
Oxygen	cm³/(m²·d·bar)	670	860	2900
Water vapor	(g/(m²·d))	84	98	1.7

- heat resistance up to 115 °C
- injection moldable on conventional injection molding equipment
- flat sheet/film suitable for thermoforming on conventional deep drawing machinery
- Food contact approved
- Biodegradability certified by independent organizations.

- In addition to Biograde FKuR Kunststoff GmbH has developed a wide range of biodegradable plastics primarily made from natural resources, BIO-FLEX® and FIBROLON® lines. They can be converted using conventional plastics processing machines and methods such as injection molding, extrusion, coextrusion, thermoforming, blow molding, injection blow molding, lamination, extrusion coating, sheet extrusion. Bio-Flex® can be processed on standard LDPE-blown film lines and converting equipment.

  Transparent grades offer high content of renewable resource material, for example, between 60% and 80%. The transparency of a 20 µm film, for example, is close to 91% (light transmission).

  Table 15.18 displays some characteristics of BIO-FLEX®.

- Researchers at the Industrial Material Institute in Quebec reported that if blends of PLA with thermoplastic starch are properly plasticized and compatibilized through reactive extrusion, then the starch phase can considerably increase the blend ductility. Compatibilization by grafting maleic anhydride onto PLA prior to blending leads to elongation at break in excess of 200%, compared to 5–20% for unmodified blends and pure PLA.
- BioHybrid from Cardia Bioplastics combines thermoplastic starch and traditional or biodegradable polymers, for example, among others:
  - Cardia BiohybridTM BL-F is made of 66% of renewable starch and PE
  - Cardia Biohybrid™ BL-M is made of 66% of renewable starch and PP
  - Cardia Compostable B-M based on biodegradable polyesters has a biodegradability (ISO14855) higher than 98%.

Table 15.19 displays some characteristics of BioHybrid (Cardia Bioplastics) depending on the used formulation. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

- Researchers at the Michigan State University modify PLA with nanoscopic hyperbranched polymers to improve the material balance of stiffness and toughness. The modified material will provide an ideal matrix for nano-clays, talc, and natural fiber reinforcements.
- Koffi L. Dagnon, Nandika A. D'Souza (Antec 2008) study blends of polycaprolactone and a starch-based material prepared by compounding with a twin-screw Brabender. Table 15.20 displays some mechanical performances for PCL contents higher than 60%. Data are only given to provide a general idea and cannot be used for designing any parts or goods.
- Other examples are Starch-loaded PE, Starch-loaded PEAA (PE/acrylic acid), alloys of cellulose or starch acetates with PE, PP, PS; PHBV at 30% into PE or PVC recyclate; Starch-based polyester copolymer; ternary alloys of polyester (20–60%), starch (20–40%), and polycaprolactone (11–16 %); PVAL and starch; PLA and starch.

Table 15.21 displays some characteristics for three examples. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

15.2.1.7 Bio-Sourced Composites

Composites can be completely produced from renewable raw materials, the bio-sourced matrix including up to 40% by weight of natural fibers such as cotton, hemp, kenaf, or man-made cellulose fibers. Of course, fossil matrix can be also reinforced with natural fibers (see Section 15.2.3). The high strength renewable and biodegradable composite materials have a variety of commercial applications. Following another way, routinely used for fossil polymers, bioplastics can also be reinforced with glass or carbon fibers. For example:

- NEC uses kenaf as a natural fiber reinforcement providing enhanced stiffness for PLA. The impact strength of a 20% kenaf fiber-reinforced PLA composite is in the order of that of a 20% glass reinforced ABS. This has been achieved by compounding at low shear in a single screw extruder to prevent fiber shortening and by adding flexibilizers. Mass production of these bioplastic composites is expected for housings of electronic products.

Table 15.18 Examples of Properties of BioFlex by FKuR

		Bio-FlexR F 1110 Film Extrusion	Bio-FlexR F 2110 Film Extrusion	Bio-FlexR F 6510 Film Extrusion	Bio-FlexR F S5630 Thermoforming Injection
Tensile modulus of elasticity	MPa	230	730	2.6	2.2
Tensile strength	MPa	16	20	47	32
Tensile strain at tensile strength	%	>300	>300	4	6
Tensile stress at break	MPa			23	29
Tensile strain at break	%			19	9
Flexural modulus	MPa	215	680	2.65	2.4
Flexural strain at break	%	No break	No break	No break	No break
Flexural stress at 3.5% strain	MPa	6	17	64	46
Notched impact strength (Charpy), RT	kJ/m^2	No break	83	7	3
Impact strength (Charpy), RT	kJ/m^2	No break	No break	No break	51
Density	g/cm^3	1.28	1.27	1.3	1.55
Thermal Properties					
Melt temperature	°C	>155	145–160	150–170	140–160
Vicat A softening temperature	°C	68	78	60	105
Heat distortion temperature HDT B	°C				68
Melt volume rate (190 °C/2.16 kg)	cm^3/10 min	1.5–3.5	3–4	2.5–4.5	8–10
Melt flow rate (190 °C/2.16 kg)	g/10 min	2–4	3–5	2.5–4.5	10–12
Barrier Properties (20 μm)					
Water vapor	g/(m^2·d)			130	
Oxygen	cm^3/(m^2·d·bar)			1.060	
Nitrogen	cm^3/(m^2·d·bar)			150	

- A halogen- and phosphorus-free flame retardant PLA/kenaf version using a metal hydroxide flame retardant system has already been developed and will be used for personal computer housings.
- NEC develops a PLA–carbon fiber composite achieving high heat conductivity. Used in the housings of electronic products, the material releases the heat generated from electronic parts through whole housing surfaces. NEC says that with a carbon fiber content of 10% the heat diffusion is comparable to stainless steel, and with 30% carbon fiber loading, heat diffusion is twice as important as that of stainless steel.

The quoted materials are only examples and many other products are developed or proposed.

Table 15.19 Examples of Biohybrid Properties

		Biohybrid BL-F	Biohybrid BL-M	Biohybrid B-M
Traditional polymer		PE	PP	Biodegradable polyester
Properties	**Unit**			
Melt flow index (2.16 kg/190 °C)	g/10 min	1.2	3.6	9
Density		1.18	1.11	1.2
Melting temperature range	°C	90–100	90–100	
Moisture content	%	<0.6	<0.6	<0.6
		Film	**Molding**	**Molding**
Properties		**50BLF/30LLDPE/20LDPE**	**30BL-M/70PP**	
Tensile strength at yield	MPa	>25	>23	19.8
Tensile strength at break	MPa	>20	>23	
Tensile modulus	GPa			1.3
Elongation at break	%	>330	>150	
Izod notched impact strength	kJ/m^2		3.4	
Charpy impact strength	J/m			23.5

Table 15.20 Mechanical Performance Examples for PCL/Starch-Based Blends

	Modulus (GPa)	Tensile Strength (MPa)
PCL	0.2	13.8
PCL70/Starch30	0.3	12.8
PCL60/Starch 40	0.3	12.0
PCL30/Starch70	0.2	7.30

15.2.2 Conventional Polymers Synthesized from Bio-Sourced Chemical Bricks

Natural-sourced chemicals such as ethanol, sorbitol, isosorbide, succinic acid, adipic acid, glycol, and many others can be used for the polymer synthesis instead of fossil equivalents. Main characteristics of the obtained polymers are virtually identical.

15.2.2.1 Polyolefins

Braskem inaugurated one of the largest ethylene-from-ethanol plant that will enable the production of 200,000 tons of green polyethylene per year (I'm green™ Polyethylene). The process used to produce each ton of polyethylene from the primary raw material removes 2.5 tons of carbon dioxide from the atmosphere through sugarcane photosynthesis. The final product is claimed to have the same properties

Table 15.21 Performance Examples of Some Compounds of PVAL or PLA and Starch

Recipe Examples			
PVAL	30–60		
PLA		50	70
Starch	30–60	50	30
Glycerin	12–18	NA	NA
Urea	4–8	NA	NA
Property Ranges			
Tensile strength, MPa	10–25		
Flexural strength, MPa		40–60	70
Flexural modulus, GPa		3	3.5
Elongation at break, %	50–200		

and characteristics as conventional polyethylene and can be processed by clients' equipment without the need for any adjustments. Braskem has stepped up its research into the development of other polymers, especially green PP.

The Dow Chemical Company and Crystalsev, one of Brazil's largest ethanol players, have announced plans for a world-scale facility to manufacture polyethylene from sugarcane.

Total Petrochemicals, IFP Energies nouvelles (IFPEN) and its subsidiary Axens announced an alliance with the objective to develop a new optimized technology for the production of bio-ethylene by dehydration of ethanol. This technology will pave the way to a competitive production of bio-ethylene from renewable resources with lower energy consumption and lower CO_2 emissions. Bio-ethylene could be integrated in various polymer applications such as polyethylene (PE), polyethyleneteraphthalate (PET), polystyrene (PS), polyvinyl chloride (PVC) and acrylonitrile–butadiene–styrene (ABS) in existing unmodified downstream polymerization installations.

15.2.2.2 Polyamides

Among many examples (see Table 15.22 for properties), let us quote:

- Polyamide 11 (PA 11), marketed by Arkema and other companies is a technical polymer used in high performance applications such as automotive fuel lines, pneumatic airbrake tubing, electrical anti-termite cable sheathing, oil and gas flexible pipes and control fluid umbilicals, sports shoes, electronic device components, catheters, etc. For example, transparent Bio-based Rilsan® Clear Rnew has a 54% bio-sourced carbon content.
- Ultramid® BALANCE (by BASF), Zytel RS (by DuPont), Grilamid 2S (by EMS) and VESTAMID Terra (by EVONIK) include bio-sourced polyamides. PA 6.10 can be based to the extent of about 60% on sebacic acid, a renewable raw material derived from castor oil.
- Renewably sourced polyamide 10.10 is claimed 60% up to nearly 100% bio-based. Examples are Zytel® RS, Grilamid 1S (by EMS), Hiprolon® 200 (by Suzhou HiPro Polymers Co.), VESTAMID® Terra (by Evonik)…
- DSM proposes PA4.10 high performance polyamides (EcoPaXX™ grades) with 70% bio-based content from nonfood biomass. Thanks to the castor oil chemistry, EcoPaXX™ grades show zero carbon footprint from cradle to gate, which means the CO_2 generated during the manufacturing processes is compensated for by the amounts of CO_2 consumed during the growth of castor beans. EcoPaXX™ can be used in very demanding applications like automotive under the hood parts, automotive structural parts, industrial castor wheels, household equipment components.
- Solvay is collaborating with Mitsubishi Gas Chemical (MGC) on the development of renewably sourced specialty polymers. The work is initially focused on high-temperature bio-polyamides derived from castor oil-based sebacic acid.
- Some polyphthalamides such as Grivory HT3 (PA10T/X) having a renewable content have main features of PPA, i.e., high peak temperature and heat resistance, resistance to chemicals and hydrolysis. Certain grades are suitable for lead-free soldering.
- Some amorphous transparent polyamides have a renewable content such as Grilamid TR.

15.2.2.3 Thermoplastic Polyesters

Bio-based polyethylene terephthalate (PET) is a special case of partially bio-based plastics boosted by companies such as The Coca Cola Company, Heinz & Co., Ford Motors, Nike Co. and Proctor & Gamble. This first step is intended to be followed by 100% bio-based PET. In 2010, Coca Cola rolled out its bio-based PET PlantBottle® concept. According to the company, 2.5 billion PlantBottle® bottles were manufactured in 2010. Coca Cola is partnering with Gevo, Virent, and Avantium on a method for synthesis of paraxylene using bio-based materials. Coca Cola aims a 100% plant-based PET PlantBottle® by 2020.

DuPont engineering polymers has launched Hytrel® RS thermoplastic elastomers providing all the performance characteristics of traditional Hytrel® materials, while offering a more environment-friendly solution than products that are entirely petroleum-based. Hytrel® RS has been developed using a renewably sourced polyol derived from corn sugar or other renewable sources. It contains between 20 and 60% renewably sourced material. One of the

Table 15.22 Examples of Totally or Partially Natural-Sourced Engineering Plastics

Performance Examples of Totally or Partially Natural-Sourced Polyamides								
	PA 11		PA1010		PA610		PA410	
Polyamides	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Miscellaneous Properties								
Density (g/cm^3)	1.01	1.06	1.05		1.07	1.1	1.05	1.05
Shrinkage (%)	0.7	1.5			0.8	1.3	1.8	2.8
Absorption of water (%)	0.2	0.4	0.7	1.3	0.4	0.6	1.7	
Mechanical Properties								
Shore hardness, D	58	80			70	85	72	
Rockwell hardness, M	<10	30			<10	50		
Stress at yield (MPa)	50	65	35	40	50	70	35	50
Strain at yield (%)							6	20
Tensile strength (MPa)	50	65			45	90		
Elongation at break (%)	250	400	<50	>50	150	300		
Tensile modulus (GPa)	0.9	1.2	0.6	0.8	1	2.1	0.9	1.8
Flexural modulus (GPa)	0.9	1.2			1	2.4		
Notched impact strength ASTM D256 (J/m)	70	NB			30	80		
Thermal Properties								
HDT B (0.46 MPa) (°C)	130	155	125	125	160	175	140	
HDT A (1.8 MPa) (°C)	50	60	55	55	75	85	75	
Continuous use temperature (°C)	80	150			80	150		
Melting temperature (°C)	175	190	197	197	210	220	250	
Brittle point (°C)	–120	–70						
Thermal conductivity (W/m·K)	0.33	0.33			0.21	0.23		

Specific heat (cal/g/°C)	0.50	0.60			0.4	0.4		
Coefficient of thermal expansion (10^{-5}/°C)	9	15	11	17	6	14	12	14
Electrical Properties								
Volume resistivity (ohm·cm)	10^{14}	10^{14}	10^{10}	10^{11}	10^{12}	10^{15}		
Dielectric constant	3	9			3	6		
Loss factor (10^{-4})	200	2000			70	900		
Dielectric strength (kV/mm)	25	30	37	39	16	26		
Fire behavior								
Oxygen index					23	27		
UL94 fire rating	HB	HB	HB	HB	HB	V2		

Performance Examples of Bio and Conventional Merquinsa TPU						
Film and Sheet	**Pearlbond®**		**Pearlthane®**			
Origin	ECO	Fossil	ECO	Fossil	ECO	Fossil
Hardness (Shore A or D)	52D	92A	81A	83A	91A	94A
Crytallization rate	Extremely high	Very high	Medium	Very low	Medium	Medium
Melting range (°C)	70–80	65–85	180–190	130–140	185–195	150–160
Bonding temp (°C)	80–100	90–100	190–200	150–160	205–215	180–190
Dry cleaning resistance	None	None	Excellent	Excellent	Excellent	Excellent

first uses worldwide of DuPont™ Hytrel® RS thermoplastic elastomer in sporting goods applications is the collar of the Salomon "Ghost" freerider alpine ski-boot.

Gevo, Inc. has announced that it has successfully produced fully renewable and recyclable PET with its potential customer, Toray Industries. Gevo employed prototypes of commercial operations from the petrochemical and refining industries to make para-xylene from isobutanol. This renewable para-xylene was sent to Toray for conversion into bio-based PET. Toray employed its existing technology and new technology jointly developed with Gevo and used Gevo's para-xylene and commercially available renewable monoethyleneglycol (MEG) to produce fully renewable PET (all of the carbon in this PET is renewable).

Toyota Motor Corporation has announced it plans to make vehicle liner material and other interior surfaces from an ecological PET consisting of 70% terephthalic acid and 30% monoethylene glycol, by weight; bio-PET is made by replacing monoethylene glycol with a biological raw material derived from sugarcane.

Virent announced that it has successfully made Paraxylene from 100% renewable plant sugars. The Paraxylene, when combined with existing PET technology, allows manufacturers to offer customers 100% natural, renewable, plant-based PET. Virent's Paraxylene, which has been trademarked BioFormPX™, is made through a patented, catalytic process.

Avantium Research and Technology, a Netherlands company develops YXY chemical catalytic technology leading to a new bio-based plastic, PEF, to make 100% bio-based bottles that could be a replacement for today's PET bottles.

15.2.2.4 Thermoplastic Polyurethanes

For example, Merquinsa has developed, via its own ECO proprietary technology, a new range of bifunctional polyols with different molecular weights, made from raw materials derived from renewable sources. Standard reaction conditions are used with isocyanates resulting in an innovative Bio-TPU family (Pearlthane® & Pearlbond® ECO) with mechanical properties close to those of standard TPU product families. For example, Pearlbond® ECO D900 has a 75% bio content as certified by ASTM D6866. Table 15.22 displays, among other engineering thermoplastics, a short comparison between bio and fossil TPUs. Data are only given to provide a general idea and cannot be used for designing any parts or goods.

RadiciSpandex Corp., engaged in the production of RadElast® spandex, is developing an eco-friendly Elastane using a renewably sourced material. This innovative product line will be the world's first spandex consisting of 80% biomaterial made from a renewable source (corn).

15.2.2.5 Acrylics

Altuglas® Rnew, is a PMMA grade containing 25% of carbon that is derived directly from biomass. This product offers properties comparable to those of conventional grades produced entirely from fossil carbon.

15.2.3 Reinforcement with Natural Fibers for Polymer Composites

After a long period of disinterest, the composite industry shows a renewed interest for natural fibers because of:

- Fossil energy savings resulting from biomass use instead of crude oil.
- The low energy consumption for their production.
- The renewable origin.
- The lower industrial means, investments, and technical knowledge.
- The biodegradability except some cases.
- The burning possibility of wastes.

There are also some drawbacks, for example:

- Moisture absorption,
- Sensitivity to high temperatures and UV limiting outdoor exposure and/or high-temperature applications.
- The natural origin of vegetal fibers leading to higher variations of quality according to growing areas, batches, years, and seasons.

For some technical properties, natural fibers are not as performing as glass fibers as we can see in Table 15.23 that displays some examples of physical and mechanical properties for some natural fibers. Other data can be found elsewhere because of the natural origin, the differences in treatments, processing and quality of the fibers.

Table 15.23 Examples of Physical and Mechanical Properties for Some Natural Fibers

	Modulus GPa	Density g/cm^3	Tensile Strength MPa	Elongation at Break %	Moisture Absorption %
Glass fibers	70	2.5	3000	2.5	0
Ramie	60–130		400–900	4	15
Nettle	60–110	1.5	900–1800	1–3	
Hemp	70	1.5	550–900	2	8
Flax	28	1.5	350–1000	3	7
Jute	27	1.3	400–800	2	12
Lyocell	22	1.3	750	12	
Sisal	9–22	1.5	500–600	2	11
Cotton	12	1.5	400	7	17
Viscose	12	1.3	310	8	
Coconut or coir	5–6	1.2	175–220	20–30	10

Table 15.24 Properties of Natural Fiber Reinforced and WPC Grades Compared to Neat Polymers

	Unreinforced TP		Natural Fiber Reinforced TP and WPC		GF-Reinforced TP	
	Engineering Data	Specific Data	Engineering Data	Specific Data	Engineering Data	Specific Data
Tensile strength, MPa	40	37	36.5	33	120	82
Elongation at break, %	186		6.5		6	
Tensile modulus, GPa	2.1	1.9	4.9	4.4	9	6
Flex modulus, GPa	2.1	1.9	4.1	3.7	9	6
Notched Izod impact, J/m	117	107	75.5	67	120	82
HDT A 1.85 MPa, °C	64		84		183	
Density	1.09		1.12		1.46	
CTE 10**5/°C	11.2		7.4		3.5	

Table 15.24 compares engineering and specific properties of natural fiber (NF) reinforced grades and wood plastic composites (WPCs), on the one hand, and short glass fiber-reinforced thermoplastic grades on the other hand. Specific properties are ratios of engineering data divided by density. Even for specific data, properties evolve similarly to those of glass fiber-reinforced thermoplastics but the reinforcement is far lower. These data relate to a few grades and are only examples that cannot be used for designing, computing, or to make economic predictions. Other properties can be found elsewhere.

Properties of NF composites and WPC fall between those of neat and glass reinforced thermoplastics. The lower density of NF versus GF cannot fill the gap between specific properties of NF and GF reinforced grades. Compared to neat TPs, NFTPs and WPCs offer:

- Similar tensile strength
- Far lower elongation at break

- Approximately doubled tensile and flexural modulus
- Lower notched Izod impact strength
- Higher HDT A
- Slightly increased density
- Lower CTE.

15.2.4 Additives from Renewable Resources

The oldest and most common additives based on renewable resources are:

- Fatty acids, their salts, esters, and amides used as lubricants, processing aids, PVC heat stabilizers, emulsifiers,…
- Pine derivatives: pine tar, rosin, terpene used as tackifiers and processing aids.
- Vulcanized vegetable oils or factices used in rubber formulations
- Phenol derivatives used as antioxidants
- Liquid depolymerized natural rubber used as a cross-linkable polymeric plasticizer
- Epoxidized soya bean oil used as a plasticizer…

Table 15.25 displays some examples of natural and seminatural additives without claiming to be exhaustive.

15.3 Take Advantage of Thermoplastics Versatility for a More Sustainable Use Phase

Using plastics can help reduce operational energy use and greenhouse gas emissions throughout the life of manufactured products as diverse as packaging, automotive and transportation, building and construction, appliances and electronics, wind turbines, etc.

Savings of operational energy use may be very much higher than energy used for the product or part manufacture. Following examples relating to the three most important markets consuming thermoplastics demonstrate the importance of the use phase. Of course energy is linked to GHG emissions and pollution.

15.3.1 Example of an Energy-Efficient House

Gregory A. Keoleian, Steven Blanchard, Peter Reppe (Journal of Industrial Ecology—"Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House") compare an energy-efficient house (EEH) and a similar standard house (SH). Among many parameters, the EEH, designed to minimize heating and cooling energy, uses 4500 kg of polymer in addition to the polymers used in SH. Table 15.26 displays energy and GHG assessments. EEH saves total energy of 9640 GJ. The use phase accounted for 91% of the total life-cycle energy consumption over a 50-year home life for the standard habitation. The equivalent EEH led to a dramatic reduction in the EEH total life-cycle energy, about 40%. The overspending for the EEH is quickly paid off by the heating and cooling cost savings.

Life-cycle greenhouse gas emissions are in line with the energy scenario. Of course, all the savings are not induced by a higher use of polymers but relate to the whole solution.

Table 15.25 Natural and Seminatural Additive Examples

Fatty Acids	
Saturated Fatty Acids	**Carbon Atoms**
Butyric or butanoic	4
Caproic or hexanoic	6
Caprylic or octanoic	8
Capric or decanoic	10
Lauric or dodecanoic	12
Myristic or tetradecanoic	14
Palmitic or hexadecanoic	16
Stearic or octadecanoic	18
Unsaturated Fatty Acids	
Sebacic	10
Myristoleic	14
Palmitoleic	16
Oleic	18
Linoleic	18
Ricinoleic	18

Table 15.25 Natural and Seminatural Additive Examples—cont'd

Unsaturated Fatty Acids	
Erucic	22
Metal Salts of Fatty Acids	
Ba, Ca, Cd, Zn stearates	
Ca, K, Na, Zn oleate	
Amides of Fatty Acids	
Erucamide	
Oleamide	
Stearamide	
Behenamide	
Oleyl palmitamide	
Stearyl erucamide	
Ethylene bis-stearamide	
Ethylene bis-oleamide	
Esters of Fatty Acids	
Glycerol monostearate	
Pine Derivatives	
Rosin	
Pine tar	
Terpene	
Vulcanized Vegetable Oils	
White factices	
Brown factices	
Phenol Derivatives	
Vitamin E	
Cardamol	
Cashew oil	
Liquid Depolymerized Natural Rubber	
Epoxidized Soya Bean Oil	

15.3.2 Automotive Industry

Weight saving is a highway for reducing fuel consumption. Generally, it is expected that every 10% reduction in vehicle mass improves fuel economy by about 7%. Reducing vehicle mass by 30% directly results in about a 21% MPG increase. In addition, for 1 kg primary mass reduction, there is up to 0.5–0.7 kg of secondary mass reduction. Of course, reduced fuel consumption reduces CO_2 emissions.

Mass reduction has also positive effects on vehicle performance.

Lifetime of cars is on the order of 100,000 miles up to 150,000 miles with fuel consumption on the order of 8 up to 20 l/100 miles that is to say 8,000 l up to 30,000 l for the use phase. If 1 l of fuel produces 30 MJ, use phase energy can be appraised to 240,000 up to 900,000 MJ. 10% weight saving reducing fuel consumption by 7%, use phase energy consumption can be reduced by 16,800 up to 63,000 MJ for a 10% weight saving. Of course, GHG emissions are also reduced.

Table 15.27 displays some results of GHG emissions for four conventional cars. Results are broadly spread depending on retained methods of assessment, type of car, lifetime hypothesis, etc., but it is sure that use phase is by far of the prime importance.

Taking out a specific plastic part, Claire Boland's thesis "Life Cycle Energy and Greenhouse Gas Emissions of Natural Fiber Composites for Automotive Applications: Impacts of Renewable Material Content and Lightweighting" values GHG emissions for a part weighing approximately 3 kg used for a conventional car (see Table 15.28). These data confirm the supremacy of the use phase (80% and more) and the interesting results of natural fiber-reinforced thermoplastic.

Some opposite ways toward weight saving can be:

- Combining carbon fiber-reinforced thermoplastic, Direct Compounding technology and injection: Zoltek Automotive, KraussMaffei, and Lanxess have developed carbon fiber-reinforced polyamide front ends molded in the 1960 s. Continuous operation and reproducibility of process was demonstrated using a complex front end module tool.
- Reinforcement by olefin/carbon fiber hybrid. Innegra S by Innegra Technologies (www.innegratech.com/) is a high performance olefin fiber which is lightweight, tough, durable, hydrophobic, and recyclable. When existing high-modulus carbon fibers are combined with Innegra S fiber, part weight can be reduced, impact resistance and damage tolerance improved, and electrical behavior fine-tuned.

Table 15.26 Examples of Energy Consumption and GHG Emission for EEH and SH

	EEH		SH		Savings Thanks to EEH
Energy for construction, GJ	1669	26%	1509	9%	–160
50 years energy, GJ consumption	4700	74%	14,500	91%	9800
Total energy, GJ	6369	100%	16,009	100%	9640
GWP, tons of CO_2 equivalents	370		1010		640

Table 15.27 Examples of GHG Emissions for Diverse Cars

	GHG for Production, kg CO_2 eq.	GHG for Use Phase, kg CO_2 eq.	Total GHG, kg CO_2 eq.
Mean	4790	44,500	49,290
Median	5000	45,000	48,900
Minimum	2870	15,000	20,000
Maximum	6300	73,000	79,300
	% GHG for Production	**% GHG for Use Phase**	**% Total GHG**
Car A	5	95	100
Car B	8	92	100
Car C	15	85	100
Car D	25	75	100

Table 15.28 Examples of Energy Consumption and GHG Emission for a Component (about 3 kg)

	Glass Fiber Composite		Natural Fiber Composite		Savings NF versus GF
Energy for production, MJ	250	17%	230	17%	8%
Energy consumption for use phase	1250	83%	1120	83%	10%
Total energy,	1500	100%	1350	100%	10%
GHG for production, kg CO_2 eq.	20	20%	12	14%	40%
GHG for use phase, kg CO_2 eq.	80	80%	74	86%	8%
Total GHG	100	100%	86	100%	14%

- The MuCell process (microcellular foam injection molding process) has already been used successfully in Ford vehicles in Europe for valve covers, along with heating, ventilating and air conditioning (HVAC) systems. The Society of Plastics Engineers awarded Ford's use of the MuCell process (Grand Award at the association's 41st Auto Innovation Awards Competition). By creating the instrument panel structure for the Ford Escape in microcellular foam, weight is reduced more than 1 lb., mechanical properties are improved, molding cycle time is reduced 15%, and molding clamp tonnage is reduced 45%, saving an estimated \$3 US/vehicle versus solid injection.

- Glass replacement for glazing offers up to 50% potential weight savings. An automotive backlight prototype, featuring SABIC's EXATEC® plasma coating system shows the benefits of this multilayer system. At its core is LEXAN™ polycarbonate resin, with additional layers of UV protection and EXATEC coating, which provides glasslike abrasion resistance. The EXATEC system can provide up to 50% weight reduction versus glass, with design freedom that enables unique styling and part integration. Additional potential benefits include increased safety when compared to glass and better thermal management. The first application of polycarbonate (PC) glazing in rear fixed and roll-down side windows in a production automotive vehicle relates to the Fiat's new 5001 multipurpose vehicle, which reduces weight by about 35%.
- Air resistance optimization, thanks to drag reduction: About 50% of a vehicle fuel consumption at 50 mph is in overcoming air resistance. Air resistance increases as the square of the speed, the fuel consumption increases with speed and accordingly, the effect of reducing aerodynamic drag increases with speed. Thermoplastics and composites offer many advantages for manufacturing of complex devices leading to aerodynamic drag and noise reduction.

Among a multitude of parts for mass production vehicles up to sports or F1 cars, let us quote some examples:

- Fenders
- Engine and Body Undershields, Side body under shields
- Wheel Arch Liners and Ram Air Lips
- Spoilers
- Fairings
- Acoustic side panels
- Splitters, Front splitters and air dams
- Canards
- Rear diffusers
- Side skirts
- Vortex generators
- Drag Reduction System or rear movable wing

Some actual examples selected from 2014 SPE's Auto Division Finalists of Automotive Innovation Awards Competition point out the interest of automakers and the diversity of used means:

- Cellulose Fiber Composite Console Armrest: This application represents the first time glass fiber-reinforced PP has been replaced by a natural fiber-reinforced PP with equivalent performance but improved environmental impact. This armrest console uses 20% renewably sourced cellulose fiber obtained from sustainably harvested forestry by-products. The resulting part is cost neutral but 6% lighter, reduces tool abrasion, and lowers process energy by 10%, thanks to lower temperature and faster process cycles. From a life-cycle analysis standpoint, it reduces CO_2 emissions by 11% and saves 2500 gal of fuel over the vehicle's life.
- Gap Hider: By combining postconsumer inorganic manufacturing scrap, reclaimed polyester fiber from carpet, wood flour from postconsumer wood fiber scrap, and both virgin and reclaimed polypropylene, a gap-hider panel with 25% recycled content is produced. Additionally, the zero-waste vacuum forming blow molding manufacturing process returns all scrap and offcuts to the raw materials supplier to be re-recycled into raw material stock again. The resulting panel is thinner than alternatives, saves 5% weight and 10% costs versus virgin material while reducing the waste stream and lowering the carbon footprint.
- Crankshaft Cover with Integrated Oil Seal: This is the world's first sustainable crankshaft cover, which is molded in a PA 4.10 formulated from 70% renewable resources and certified to be 100% carbon neutral from cradle to grave. The design itself features a friction-optimized dynamic seal in polytetrafluoroethylene (PTFE), which replaced a wet chemistry surface treatment and is activated via a vacuum-plasma process. The entire production process is eco-driven with no net waste. The CAE-optimized design enables a plastic flange to be used as a torque support for assembly operations during vehicle manufacture. The resulting part is 40% lighter than the incumbent aluminum part it replaced.

15.3.3 Packaging

A recent European study (Denkstatt GmbH. The impact of plastics on life cycle energy consumption and greenhouse gas emissions in Europe. Vienna, Austria. June 2010, p. 11) found that replacing plastics with other materials would require the use of 57% more energy and result in a 61% increase in greenhouse gas emissions.

For the United States, Table 15.29 displays weight, energy, and pollution initiated by US Packaging according to a hypothesis of replacement of plastics with substitutes.

Table 15.29 US Packaging: Hypothesis of Replacement of Plastics with Substitutes

Weights (Million kg) of Plastic and Example of Substitute Materials			
	Plastics, Million kg	Substitute Materials, Million kg	Overweight of Substitute Solutions, Million kg
Other rigid	4264	23,079	18,815
Other flexible	4188	16,830	12,642
Beverage containers	3095	14,568	11,473
Carrier bags	1297	2436	1139
Caps and closures	779	769	–10
Stretch and Shrink	748	6418	5670
Total	14,371	64,100	49,729
GWP Results for Plastics and Examples of Substitute Materials (Million Metric Tonnes CO_2 eq)			
	Plastics	**Substitute Materials**	**Over Pollution of Substitute Solutions**
Caps and closures	3.28	3.1	–0.17
Beverage containers	13.73	23.4	9.67
Stretch and shrink	2.54	13.3	10.8
Carrier bags	4.21	13.8	9.6
Other flexible	14.52	46.8	32.28
Other rigid	20.31	40.9	20.59
Total	58.6	141.3	82.7
Cumulative Energy Demand for Plastics and Example of Substitute Materials (billion MJ)			
	Plastics	**Substitute Materials**	**Over Energy Demand of Substitute Solutions**
Caps and closures	80.7	41.8	–38.9
Beverage containers	274	391.5	117.5
Stretch and Shrink	66.4	245	178.6
Carrier bags	116	188	72
Other flexible	362	1081.5	719.5
Other rigid	458	510.5	52.5
Total	1357	2458	1101

Considered plastic materials are:

- Low-density polyethylene (LDPE)
- High-density polyethylene (HDPE)
- Polypropylene (PP)
- Polyvinyl chloride (PVC)
- Polystyrene (PS)
- Expanded polystyrene (EPS)
- Polyethylene terephthalate (PET)

Alternative materials include:

- coated and uncoated paper and paperboard
- glass
- steel
- aluminum
- textiles
- rubber
- cork

Except for caps and closures, substitutes are heavier (average overweight of 346%), emit more CO_2 (+142%) and consume more energy (+81%). Obviously those data are hypotheses and results depend on the methods of production of raw materials, the processing methods, the type of the used energy, logistics, and transport issues etc. For example, it is possible to modify end results playing on type of the used energy, location of manufacturing, lifetime, transport of raw material, semifinished and finished products, running time, efficiency of the manufactured part or product, end-of-life scenario… Results of Life cycle assessments (LCAs) must be carefully examined and comparisons must take into account all the used hypotheses and parameters. It is not possible to compare apples and oranges, such as water pollution for cultivated natural fibers and chemical pollution for glass fiber production.

Going into further detail, some examples of LCAs illustrate diverse situations. The following data are not rules but very few examples. Results are briefly expressed as some ratios concerning the nonrenewable energy, the greenhouse effect or CO_2 emission, the pollution (sulfur oxides - SOx), carbon dioxide, carbon monoxide, nitrogen oxide (Nox) emissions), acidification and carcinogenicity indicators, water emissions (phosphates, nitrates); terrestrial ecotoxicity, and human toxicity.

Table 15.30 Life Cycle of a Natural Fiber Compared to a Glass Fiber

	Glass Fiber (GF)	Natural Fiber (NF)	
	Data	**Data**	**Saving, %**
Energy use (MJ/kg)	48.33	3.64	92
Carbon dioxide emissions (kg/kg)	2.04	0.66	68
COD to water (mg/kg)	18.81	2.27	88
SOx emissions (g/kg)	8.79	1.23	86
BOD to water (mg/kg)	1.75	0.36	79
Particulate matter (g/kg)	1.04	0.24	77
NOx emissions (g/kg)	2.93	1.07	63
CO emissions (g/kg)	0.80	0.44	45
			Loss, %
Phospates to water (mg/kg)	43.06	233.6	442
Nitrates to water (mg/kg)	14.00	24,481	175,000

According to S.V. Joshia, L.T. Drzal, A.K. Mohanty, S. Arora, Are natural fiber composites environmentally superior to glass fiber reinforced composites?

Table 15.30 displays an example of differences between a glass and a natural fiber. The natural fiber has a unique balance of ecoperformances except for water pollution with nitrates and phosphates due to their cultivation.

The same type of balance affects the composites (see Tables 15.31 and 15.32), more or less influenced by the used plastic matrix with a unique balance of ecoperformances except for water pollution with nitrates and phosphates due to the natural fiber cultivation.

Table 15.31 Example of Life Cycle of a Natural Fiber-Reinforced Composite Compared to Neat ABS

	ABS	Hemp Reinforced Plastic	
		Data	**Saving, %**
Total energy (MJ)	132	73	45
CO_2 emissions (kg)	4.97	4.19	16
CO (g)	4.44	2.14	52
SO_2 (g)	17.54	10.70	39
Methane (g)	17.43	16.96	3
			Loss, %
Nox (g)	14.14	18.64	32
Nitrate emissions to water (g)	0.08	12.05	15,000
Phosphate emissions to water (g)	0	0.09	Very high

K. Wotzel, R. Wirth, R. Flake, Life cycle studies on hemp fiber reinforced components and ABS for automotive parts, Angewandte Makromolekulare Chemie 272 (4673) (1999) 121–127.

15.4 Overview of Some Environmental Indicators and Benchmarks Relating to LCA

LCAs are complex concepts depending on the methods of production of raw materials, the processing methods, the type of the used energy, logistics, and transport issues, etc. So, when examining results, it is necessary to clearly understand what the used methods are and what is measured or assumed.

15.4.1 Clarification Concerning Some Terms

Life cycle assessment or life cycle analysis (LCA) assesses environmental impacts resulting from all the stages of a product or part life including raw material extraction, material processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. LCA is also known as ecobalance, and cradle-to-grave analysis.

Life Cycle Inventory (LCI) is the inventory of the total energy use, raw material use, air and water emissions, and the total solid waste produced from the cradle-to-grave (grave being the ultimate disposal). The LCI gives the basic data for the LCA. It is equivalent to the eco-profile covering the complete life cycle. In the strict sense of the term, the LCI of resins, pellets, new films, or tubes… does not exist because the pellets and new parts or products aren't usually thrown away.

Eco-Profile: assessment of the total energy use, raw material use, air and water emissions, and the total solid waste produced from the cradle to the factory gate. An eco-profile always ends with the production of the considered part or product.

Cradle to Factory Gate: cycle beginning with raw material extraction from the earth and ending with the product leaving the factory.

Cradle to Grave: complete cycle beginning with raw material extraction and ending with the final disposal of the product or part (recycling, compost, landfill, etc.).

The tonne of oil equivalent (toe) is defined as the amount of energy released by burning one tonne of crude oil. It is approximately 42 GJ.

Abiotic depletion refers to the depletion of nonliving (abiotic) resources such as fossil fuels, minerals, clay, and peat. Abiotic depletion is measured in kilograms of Antimony (Sb) equivalents.

Global warming potential is an appraisal of greenhouse gas (for example, CO_2, methane, nitrous oxide…) contribution to global warming. Global warming comes from an increase in the atmospheric concentration of greenhouse gases which changes the absorption of infra-red radiation in the atmosphere leading to changes in climatic patterns and higher global average temperatures. Global warming potential is measured in terms of CO_2 equivalents.

Photochemical oxidation. The formation of photochemical oxidant smog is the result of complex reactions between NOx and VOCs under the action of sunlight (UV radiation) which leads to the formation of ozone in the troposphere. The smog phenomenon is very dependent on meteorological conditions and the background concentrations of pollutants. Photochemical oxidation is measured using photooxidant creation potential (POCP) which is normally expressed in ethylene equivalents.

Table 15.32 Life Cycle Environmental Performance of China Reed Reinforced, and Glass Fiber-Reinforced Transport Pallets

	Glass Fiber Pallet	China Reed Pallet	
			Saving, %
Cumulative nonrenewable energy use MJ	1400	717	49
CML—Green house effect (kg CO_2 eq)	75.3	40.4	46
Sulfur oxides (SOx) air emissions (g)	289	163	44
Carbon dioxide emissions (kg)	73.1	42	43
Eco-indicator 95—carcinogenicity (1027 kg PAHeq)	7.11	4.48	37
Eco-indicator 95—acidification (kg SO_2 eq)	0.65	0.41	37
Water emission—BOD (mg)	414	266	36
NOx air emissions (g)	513	349	32
Carbon monoxide (g)	74.3	54.6	27
CML—terrestrial ecotoxicity (kg 1,4 dichleq)	5250	4480	15
			Loss, %
Water emissions—phosphates (g)	0.59	1.67	183
CML—human toxicity (kg 1,4 dichleq)	21.2	9.04	57
Water emissions—nitrates (g)	1.72	153	8800

According to S.V. Joshia, L.T. Drzal, A.K. Mohanty, S. Arora, Are natural fiber composites environmentally superior to glass fiber reinforced composites? Composites: Part A 35 (2004) 371–376.

Eutrophication is caused by the addition of nutrients to a soil or water system which leads to an increase in biomass, damaging other life forms. Water acquires a high concentration of nutrients, especially phosphates and nitrates promoting excessive growth of algae. Eutrophication is measured in terms of phosphate $\left(PO_4{}^{3-}\right)$ equivalents.

Acidification results from the deposition of acids which leads to a decrease in the pH and increase of potentially toxic elements. The major acidifying pollutants are SO_2, NOx, HCl, CO_2, and NH_3. Acidification is measured in terms of SO_2 equivalents.

Toxicity is the degree to which something is able to produce illness or damage to an exposed organism. There are four different types of toxicity; human toxicity, terrestrial ecotoxicity, marine aquatic ecotoxicity, and freshwater aquatic ecotoxicity. Toxicity is measured in terms of dichlorobenzene equivalents.

Biochemical oxygen demand (BOD) measures the amount of dissolved oxygen needed by aerobic biological organisms present in the water to break down organic material. The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20 °C.

Chemical oxygen demand (COD) measures the amount of organic compounds in water. COD measures everything that can be chemically oxidized.

CML, Eco-Indicator 95, Eco-Indicator99 are methods used for LCA.

15.4.2 Examples of Environmental Indicators and Benchmarks Relating to LCA

LCAs depend on the methods of production of raw materials, the processing methods, the type of the used energy, logistics, and transport issues etc. The following data are not rules but very few examples. Most often results are briefly expressed as ratios concerning the energy consumption and the greenhouse effect or CO_2 emission. Exceptionally, results can relate to more detailed pollution such as sulfur oxides

(SOx), carbon dioxide, carbon monoxide, nitrogen oxide (NOx) emissions, acidification and carcinogenicity indicators, water emissions (phosphates, nitrates); terrestrial ecotoxicity, and human toxicity. Of course results highly depend on the cycle end: resin, pellet, new part or product, used part or product, use of recycled polymer, end-of-life scenario.

Results of LCAs must be carefully examined and comparisons must take into account all the used hypotheses and parameters. For example, it is possible to modify end results playing on type of the used energy, location of manufacturing, lifetime, transport of raw material, semifinished and finished products, running time and number of reuses, efficiency of the manufactured part or product, end-of-life scenario… It is not possible to compare apples and oranges, such as water pollution for cultivated natural fibers and chemical pollution for glass fiber production.

Most used indicators are:

- Energy requirement expressed, for example, in MJ/kg of polymer, part or others
- Net carbon footprint expressed in kg CO_2 equivalent per kg plastic.

Tables 15.26–15.33 display examples of environmental indicators.

15.4.2.1 Environmental Impact of Polymer Production

The following information comes from technical literature and is expected to be related to resins ready for processing but it cannot be excluded that some data concern molded products. When the number of results is convenient, means, medians, standard deviations, minimum, and maximum are displayed. These data are not a rule and other figures can be found elsewhere. They cannot be used for designing any parts or goods.

Energy requirement can be sliced in:

- Energy needed for operation up to the desired level of production: pellets, product or part, etc.
- Energy equivalent to the chemical feedstock needed to build the polymer chain. Of course this item is very high for fossil polymers.

Table 15.33 displays some examples of energy consumptions. For instance, statistically speaking, total energy equivalent consumed for biopolymers is claimed about 50% of that consumed for fossil polymer. For fossil polymer, energy for chemical feedstock use can be equal or higher than energy use for operation. Several figures can be displayed for a same polymer when there are several samples.

For the following information it is expected that energy consumption relates to the total energy but it is possible that some sources take account only of the energy used for operation.

Table 15.34 displays examples of energy requirements expressed in MJ/kg of polymer. When there are sufficient data for a family, statistical results are reported. Generally, these data confirm lower energy consumptions for bio-sourced thermoplastics with some exceptions concerning PAs 1010 and 610. These figures are slightly different from those of Table 15.33, which probably comes from different samples and methods.

Table 15.35 displays examples of Net carbon footprint expressed in kg CO_2 equivalent per kg plastic. When there are sufficient data for a family, statistical results are reported. Negative results come from the consumption of CO_2 during plant growing. Generally these data confirm lower carbon footprints for bio-sourced thermoplastics with some exceptions.

15.4.2.2 Environmental Impact of Fibers

Reinforcement with fibers impacts nonrenewable energy requirements according to energy consumption for the fiber production (see Table 15.36). When there are sufficient data for a family, statistical results are reported. Effect of fiber is also expressed for composites. Generally these data confirm lower carbon footprints for bio-sourced fibers. However, definitive figures for composites depend also of the actual weight saving according to the effective performance of the reinforced compound.

Table 15.37 displays examples of net carbon footprint expressed in kg CO_2 equivalent per kg fiber or composite. Generally these data confirm lower carbon footprints for natural fiber-reinforced thermoplastics versus glass fiber-reinforced thermoplastics.

15.4.2.3 Environmental Impact of Processing

Previous data relate to polymers or composites. For parts and products, energy consumption for processing must be added. Generally levels are much lower, for example:

- Injection molding: 5–30 MJ/kg

Table 15.33 Examples of Consumed Energy, MJ per kg Polymer

Statistical Analysis		
Polymers	**Fossil Polymers, MJ/kg**	**Biomass Sourced, MJ/kg**
Mean	84	43
Median	80	43
Standard deviation	20	16
Minimum	52	3
Maximum	140	70
Samples	42	28

Detailed Examples				
Energy Use/kg	**Total, MJ/kg**	**Feedstock, MJ/kg**	**Operation, MJ/kg**	**Feedstock/ Operation, %**
Fossil Thermoplastics				
PA66	142	47	95	49
PA6	120	40	80	50
PC	118	40	78	51
HIPS	90	45	45	100
GPPS	85	45	40	113
PET	80	40	40	100
PET	80	40	40	100
PE	80	50	30	167
PP	78	48	30	160
Bio-Sourced Thermoplastics				
PLA	55	0	55	0
Cellulose	90	0	90	0

- Film extrusion: 3–6 MJ/kg
- Film calendaring: 6 MJ/kg
- Pipe extrusion: 3–7 MJ/kg
- Blow molding: 5–19 MJ/kg.

GHG emissions coming from processing are coherent with energy consumption, for example:

- Injection molding: 0.5–1.6 kg CO_2 equivalent per kg plastic
- Blow molding: 1.1–1.2 kg CO_2 equivalent per kg plastic
- Extrusion pipe: 0.4–1 kg CO_2 equivalent per kg plastic

15.4.2.4 Environmental Impact of End-Product Type

Table 15.38 displays examples of fossil energy requirement in MJ and net carbon footprint expressed in kg CO_2 equivalent per item. For a given polymer, broad property ranges are reported. Generally these data confirm lower carbon footprints for natural fiber-reinforced thermoplastics versus glass fiber-reinforced thermoplastics.

Table 15.34 Examples of Energy Requirements Expressed in MJ/kg of Polymer

Fossil Thermoplastics	**PP**	**PE**	**PET**	**PVC**
Mean	72	78	75	61
Median	76.5	80	78	57
Standard deviation	9.8	6.3	5.5	11
Minimum	53	69	69	52
Maximum	78	87	80	77
Samples	6	9	7	4
Fossil thermoplastics	**Styrenics**	**PC**	**PA6 and PA66**	**PMMA**
Mean	90	113	132	207
Median	86			
Standard deviation	6.7			
Minimum	82	103	120	
Maximum	104	120	140	
Samples	11	3	3	1
Bio-Sourced thermoplastics	**PLA**	**Undefined Bioplastic**	**PA1010 100% Bio-Sourced**	**PA1010 100% Bio-Sourced 30 GF**
Mean	45	55	231	182
Median	42			
Standard deviation	12.6			
Minimum	17			
Maximum	70			
Samples	17	1	1	1
Bio-sourced thermoplastics	**PHA**	**PA610 63% Bio-Sourced**	**PA610 30 GF**	**PHB**
Mean	39	175	143	45
Median	42			
Standard deviation	22			
Minimum	3			
Maximum	66			
Samples	10	1	1	1
Bio-Sourced thermoplastics	**TP Starch**			
Mean	25			
Median				
Standard deviation				
Minimum				
Maximum				
Samples	1			

Table 15.35 Examples of Net Carbon Footprint Expressed in kg CO_2 Equivalent per kg Plastic

Statistical Analysis				
	Fossil Polymers		Biomass-Sourced Polymers	
Mean	2.8		0.6	
Median	2.5		0.77	
Standard deviation	1.5		1.5	
Minimum	0.681		–3	
Maximum	8		2.8	
Samples	42		34	
Defined Polymers				
Fossil Thermoplastics	**PP**	**PE**	**PET**	**PVC**
Mean	2.1	1.8	2.5	2.3
Median	2	1.9	2.7	2.2
Standard deviation	0.57	0.57	0.85	0.46
Minimum	1.3	1	0.7	1.9
Maximum	3.14	3.2	3.1	2.9
Samples	8	9	7	4
Fossil Thermoplastics	**Styrenics**	**PC**	**PA**	**PMMA**
Mean	3	4.6	6.7	14.7
Median	3.1			
Standard deviation	0.56			
Minimum	2.1	4.1	4.5	
Maximum	3.9	5.2	8	
Samples	13	2	3	1
Bio-Sourced Thermoplastics	**PLA**	**Undefined Bioplastic**	**Bioplastic from Wheat**	**PA1010 100% Bio-Sourced**
Mean	1.2	3.2	1.2	4
Median	1.1			
Standard deviation	0.9			
Minimum	–0.7			
Maximum	2.8			
Samples	16	1	1	1

Continued

Table 15.35 Examples of Net Carbon Footprint Expressed in kg CO_2 Equivalent per kg Plastic—cont'd

Defined Polymers				
Bio-Sourced Thermoplastics	**PHA**	**PA610 63% Bio-Sourced**	**Thermoplastic Starch**	**PHB**
Mean	0.12	4.1	1.1	2.6
Median	0.1			
Standard deviation	1.5			
Minimum	−2			
Maximum	2			
Samples	10	1	1	1

Table 15.36 Examples of Energy Use for Production of Different Fibers and composites (MJ/kg)

Fiber		
Synthetic Fiber	**Glass Fiber**	**Carbon Fiber**
Mean	36	253
Median	35	
Standard deviation	14	
Minimum	13	183
Maximum	51	290
Samples	7	2

Natural Fiber	Hemp Fiber	Flax Fiber	Reed Fiber
	5–13	9–12	4

Mat		
	Glass Fiber Mat	**Flax Fiber Mat**
	55	9–12

Composites		
	Glass Fiber Reinforced	**Natural Fiber Reinforced**
PP 30 GF	62–91	
PA610 30 GF	175	
PA1010 30 GF	182	
PP 40 kenaf fiber		52–96
PP 30 cellulose fiber		70–105

Table 15.37 Examples of Net Carbon Footprint Expressed in kg CO_2 Equivalent per kg Plastic

Fibers	
GF	2.04
China reed fiber	0.66
Composites	
PP 30 GF	2.4
PP 30 cellulose fiber	1.7
PP 60 GF	2.6
PP 60 cellulose fiber	1.2
PA610	4.1
PA610 30 GF	4.6

Table 15.39 displays examples of environmental impact of fossil and natural products. Generally these data confirm the interest of bio-sourced products with some drawbacks related to phosphate and nitrate emissions to water. Caution: some results are per pallet weighing several kg.

15.4.2.5 Environmental Impact of Recycling

For the United States in 2008, it is estimated that use of recycled PET and recycled HDPE has saved $75*10^9$ MJ of fossil energy and $2.1*10^9$ kg CO_2 equivalent.

For example, carbon dioxide emitted by recycling of PET is approximately 10 times lower than carbon dioxide emitted by production of virgin PET.

Table 15.38 Fossil Energy Requirement in MJ and Net Carbon Footprint Expressed in kg CO_2 Equivalent

Product	Fossil Energy Requirement, MJ	Net Carbon Footprint, kg CO_2 Equivalent
Clamshell, Per 1000 Parts		
PS	765	77
PET	1228	93
PP	858	63
PLA5	900	48
PLA6		26
PLA	930	49
PLA	720	62
Bottle 0.5 l, Per 1000 Bottles		
PLA		10
PLA		14
PLA		110
PLA		128
PET		78
Pipes, Per Given Length		
PVC	90	
PVC	216	
PE	288	

Table 15.39 Life Cycle Examples of Fossil and Bio-Sourced Products

Fibers				
	Glass Fiber (GF)		Natural Fiber(NF)	
Results Per	**kg**		**kg**	
Energy use (MJ/kg)	48.33		3.64	
Carbon dioxide emissions (kg/kg)	2.04		0.66	
COD to water (mg/kg)	18.81		2.27	
SOx emissions (g/kg)	8.79		1.23	
BOD to water (mg/kg)	1.75		0.36	
Particulate matter (g/kg)	1.04		0.24	
NOx emissions (g/kg)	2.93		1.07	
CO emissions (g/kg)	0.80		0.44	
Phosphates to water (mg/kg)	43.06		233.6	
Nitrates to water(mg/kg)	14.00		24,481	
Composites				
	ABS	**ABS/Hemp**	**GF Pallet**	**China Reed Pallet**
Results Per	**kg**	**kg**	**Pallet**	**Pallet**
Energy use (MJ)	132	73	1400	717
Carbon dioxide emissions (kg)	4.97	4.19	75.3	40.4
SOx emissions (g)	17.54	10.70	289	163
BOD to water (mg)			414	266
NOx emissions (g)	14.14	18.64	513	349
CO emissions (g)	4.44	2.14	74.3	54.6
Methane (g)	17.43	16.96		
Phosphates to water (mg)	0	0.09	0.59	1.67
Nitrates to water(mg)	0.08	12.05	1.72	153

Further Reading

Technical Guides, Newsletters, Websites

3M, Akzo Plastics, Allied Signal, Allrim, Amcel, APC (AmericanPlasticsCouncil.org), Amoco, Arkema, Arco Chemical, Astar, Atochem, Atofina, Bakelite GmbH, BASF, Bayer, BF Goodrich, BIP, Bisco, Borealis, BP Chemicals, Bryte, Ceca, Celanese, Chem Polymer, Ciba, Cray Valley, Culver City Corp, Degussa, Devcon, Dow, DSM, Du Pont de Nemours, DuPont Dow, Dynamit Nobel, Eleco, Emerson & Cumming, EMS, Enichem, Epotecny, Eurotec, Eval, Evonik, Exatec, Exxon, Ferro, Ferruzzi, FiberCote, Framet Futura, General Electric Plastics, General Electric Silicones, GINAR Engineering Plastics,Grupo Repol, Hexcel, Hoechst, Hüls, ICI, Irathane, Isomeca, Kommerling, Kuraray, La Bakélite, Loctite, Lohmann, Matweb, Mecelec, Menzolit, Mitsui Chem, Monsanto, Montedison, Naphtachimie, Neste, Nief Plastic, Nippon Gohsei, Nippon Mitsubishi, Nonacor, Norflys, Orkem,

Owens Corning, Perstop, Phillips Petroleum, PlasticsEurope, PPG, PRW, Raschig, Recticel, Repsol, Rhodia, Rhône Poulenc, Rohm, RTP, Sabic, Schulman, Scott Bader, Shell, Sika, Sintimid, SNIA Tecnopolimeri, SNPE, Solvay, spmp, Stratime, Symalit, Synres, Synthésia, T2L, Taber, Technochemie GmbH, Teknor Apex, Telenor, The European Alliance for SMC, Thieme, Ticona, Toray, Tramico, Tubize Plastics, Tubulam, Ube, Union Carbide, Uniroyal, Vamptech, Vetrotex, Vyncolit, Wacker, Wilson Fiberfil, YLA.

Reviews

[1] Plastics Additives & Compounding, Elsevier Ltd.
[2] Modern Plastics Encyclopaedia, McGraw-Hill Publications.
[3] Modern Plastics International, Canon Communications LLC, Los Angeles, CA, USA.
[4] Plastics News.com, Crain Communications.
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Conclusion

Engineers who work in many industrial segments that utilize plastic parts are not plastics experts. According to recent studies, about 60% of plastics failures come from a wrong selection of the used grade. Time-dependent properties, environmental stress cracking, chemical resistance, notched rupture, thermal degradation, dynamic fatigue, creep, and UV resistance are the main issues. This book is not a fount of science for a definitive selection of thermoplastics, but aims to provide easy-to-understand and easy-to-use tools for a systematic approach of a preliminary material selection. Of course, this solution has the disadvantages of its simplicity and cannot replace the knowledge and experience of plastics specialists.

Today, despite their limitations, plastics are an industrial and economic reality competing with traditional materials, in particular, metals among which steel is the most important.

Global consumption of plastics comes close to 300 million tons per annum, growing consistently by an average annual rate of 5%, superior to steel and aluminum rates.

Generally speaking, a solution strictly limited to the replacement of metal, glass, or other traditional material leads to a failure for economic or technical reasons. To succeed in plastics selection, it is necessary to think about complete solution systems taking advantage of all the properties of plastics, which allow overcoming their general higher cost than steel, aluminum, paper, cardboard, glass, wood, and other alternative materials.

Additional cost due to polymer use must be compensated for by designing, processing, finishing, assemblage, setup, operating and maintenance costs, and by integration of a maximum of functions reducing the number of subparts.

Among plastics, the freedom of the thermoplastic chains increases their mobility and possibilities of relative displacement, which brings certain advantages and disadvantages:

- easier processing
- shorter processing cycles
- suitability for welding
- repair possibilities
- easier recycling
- fusibility
- lower modulus retention when the temperature rises
- trend to creep.

So, thermoplastics are well positioned to provide solution systems if the designers tackle the problem as a whole with its economic, technical, and environmental points of view. The choice of the used polymer must be envisaged according to technical points of view (main features including aesthetics, collateral properties, durability), economics (cheap up to costly raw materials, processing and finishing costs), processability (common or special processing methods, composites…), and recycling. Of course, the selected thermoplastic(s) must meet the relevant regulations of the various countries of processing, application, and disposal. Last but not least, rising trends toward more sustainable products must be carefully studied.

To solve these issues, thermoplastics offer:

- design freedom: realization of all shape and size parts sometimes unfeasible with metals, wood, or other traditional materials
- weight savings, lightening of structures, and miniaturization
- reduction of the costs of finishing, construction, setup, assembling, and handling

- ease and reduction of maintenance operations
- integration of functions thanks to a smart exploitation of collateral properties such as damping, sound absorption, aesthetics, electrical and heat insulation, translucence or transparency, and other properties inaccessible for metals, wood, cardboard, etc.
- aesthetics, the possibilities of bulk coloring or in-mold decoration to take the desired appearance of wood, metal, or stone, which avoids or reduces finishing operations. Smart processing methods allow direct commercialization of parts out of injection press
- durability, absence of rust, and corrosion (but beware of aging)
- ease of formulation to prioritize specific properties
- use of dedicated design packages (modeling and simulation) to optimize the geometry at each point where it is possible according to the chosen processing method
- possibility to combine two polymer materials to ensure several functionalities
- possibility of selective reinforcement in the direction of the stresses
- production flexibility: processing adaptability from the prototype to mass production. Adaptation to "niche" products
- possibility to refresh or to renew the product lines more frequently thanks to the easier replacement and modification of tools with plastic than with metals
- reduction or suppression of the periodic painting of metals, which contributes to a reduction in pollution.

So, no engineer or designer can be ignorant of plastics, but the decision to use a new material is difficult and leads to huge implications. For projects already based on plastics, the selection among some tens of thousands grades coming from very diversified families may be a real headache. It is essential to objectively define realistic specifications taking into account the regulatory framework, and technical, economic, and environmental consequences.

As for other materials, the first step is to define specifications in an objective way:

- an undervaluation of the constraints leads to issues during use
- an overvaluation involves an overcharge due to part oversizing and/or the selection of materials that have unnecessarily high performance levels and costs.

The following factors, among others, must be carefully examined:

- targeted lifespan, end-of-life criteria
- mechanical properties: instantaneous, permanent or cyclic stresses, impact, etc.
- temperature: extremes and average
- compliance with the relevant regulations
- aesthetics
- dimensional tolerances
- environment: outdoor exposure, light, moisture, ozone, corrosion, radiation…
- physical properties: transparency, thermal and electrical conductivity, gas permeability, tribological properties…
- chemical properties: risks of polymer corrosion, risks of environmental pollution by the plastic, food contact, desorption of ingredients in space vacuum, pollution of chemical and electrochemical baths, migration…
- electrical properties: influence of moisture, temperature, and aging
- weight
- price: must be considered, not only per weight or volume, but also according to the fundamental properties. The total lifetime cost, taking account of the expenses of assembly, maintenance, use, etc., is the true criterion.

It is necessary to remember that the combination of several factors often has a synergistic effect: a plastic resistant to a chemical in the absence of mechanical stress at ambient temperature can crack quickly when simultaneously exposed to moderate mechanical loading and can be degraded more or less quickly in the event of a moderate temperature rise.

Once the specification is established, a first screening of the materials having the required minimal properties can be made, starting with the most important properties, and keeping in mind some essential parameters including among others:

- the actual penetration of the material category in the industrial area
- the functionalities of the device to be designed and the function integration opportunities created by thermoplastic use
- the performances of selected thermoplastic(s) versus those of the competing material
- the abundance or scarcity of the thermoplastic material and the process targeted
- the cost
- the processing possibilities
- the environmental constraints.

The intrinsic mechanical properties of plastics and composites are different from those of conventional materials:

- Expressed in the same units, the hardness of engineering materials covers a vast range broader than 1 to 100. Plastics are at the bottom end of the range but are of a wide diversity and offer decisive advantages compared to metals, glass, ceramics, wood, and others.
- The properties of unidirectional composites in the fiber direction can compete with those of current metals and alloys but in the transverse direction, performances are limited, at the best, to those of the used polymer matrix.
- Polymers are electrical and thermal insulators but have high coefficients of thermal expansion.
- Polymers are not sensitive to rust but are sensitive to thermo-oxidation, photodegradation, and, for some of them, to moisture degradation.
- Polymers present a more or less plastic behavior under stresses, leading to lower modulus and ultimate strength retentions, and higher long-term creep or relaxation when the temperature rises.
- Many polymers, including the commodities, are resistant to chemicals usually met in industry or at home and displace the metals previously used for applications such as domestic implements, gas and water pipes, factory chimneys, and containers for acids and other chemicals.

The final choice of the design team results from many iterations concerning the functional properties, the environmental constraints, the possibility to produce the part in the required quantities, the regulation compliance, and the price. According to the market acceptance, the price taken into consideration may be the part cost, but can also include assembling, delivery, setup, and end-of-life costs, taking account of durability, and various savings in maintenance, running costs, etc.

In a few words, succeeding in plastics design needs to develop an innovative frame of mind taking into account, on the one hand, the main requirements briefly clarified in Figure 1 for some of them and a chart suggesting main possible interactions between parameters of production and requirements helping to result in the best solution system (see Figure 2).

Thermoplastics are relatively new materials provoking endless research and development efforts, which lead to a significant number of new compounds, processes, and solution systems. So, designers must continuously scrutinize the market to detect, among others:

- improvement of the cost/performance ratios
- improvement of the immediate and long-term characteristics, to win structural parts
- better thermal resistance
- better weathering behavior
- enhancement of coloring, surface aspect, and more generally aesthetics
- improvement of the surface properties
- adaptability of the grades, which must satisfy the requirements of the market and develop specific properties and better combinations of properties
- halogen-free fire-retardant grades
- improvement of the adherence of paints, printing inks, and adhesives

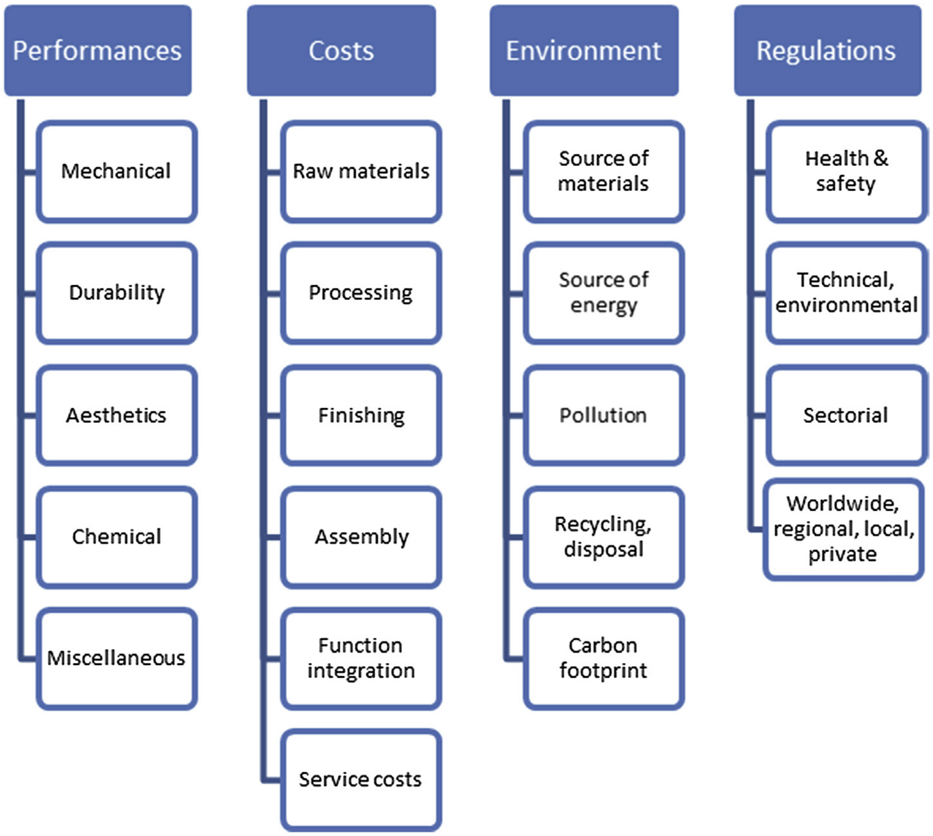

Figure 1 Main requirements concerning plastics solutions.

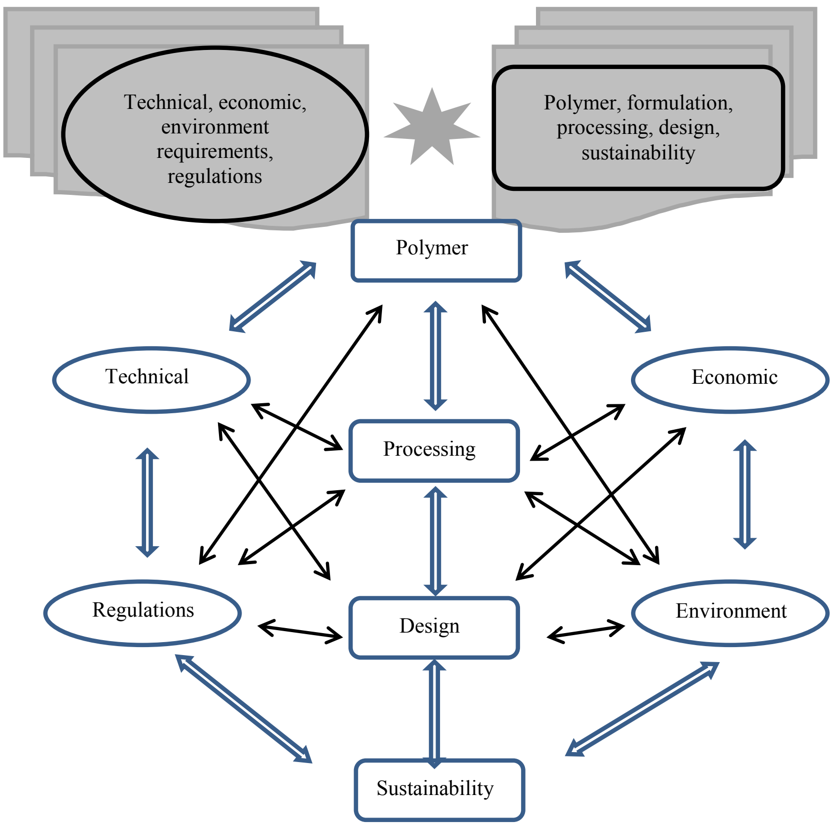

Figure 2 Main possible interactions between parameters of production and requirements.

- better performance, particularly impact resistances, at low temperature
- improved ease of processing
- improvement of the mold productivity
- automation of the process equipment
- better control of the processes by SPC (statistical process control)
- development of new manufacturing methods
- online compounding to reduce costs and thermal degradation
- hybrid associations with nonplastic materials
- use of wastes and recycled materials to satisfy environmental requirements and lower the costs

All the developmental routes are being investigated:

- New materials are being introduced, including:
  - new polymers, for example, cyclic resins
  - new reinforcements ranging from the more-or-less conventional to the highly sophisticated, such as graphene or carbon nanotubes.
- Evolution of processing: globalization, automation, industrialization, simplification, low-cost tools.
- Popularization of high-performance products such as carbon fibers to compete glass fibers and 3D reinforcements to compete with their 2D counterparts.
- Sustainable standard and high-performance reinforcements, sustainable and biodegradable components for matrices, sustainable composites.
- New combinations of known products or techniques such as the low weight reinforced thermoplastics (LWRT).

The above comments are only a superficial overview of the immense possibilities of young thermoplastic materials, which could be "The Materials of the 21st Century."

This book is not a fount of science for a definitive selection of thermoplastics but is only one of the tools aiming to help the preselection of thermoplastics. Of course, it is imperative to cooperate with polymer specialists for the selection of the definitive solution system.

Glossary

Abiotic depletion Abiotic depletion refers to the depletion of nonliving (abiotic) resources such as fossil fuels, minerals, clay, and peat. Abiotic depletion is measured in kilograms of antimony (Sb) equivalents.

Accelerated heat aging Conventional accelerated heat aging tests consist in exposing defined samples to controlled temperature air in ovens protected from light, ozone, and chemicals, for one or more given times. The degradation is measured by the variation at room temperature of one or several physical, mechanical, or esthetic characteristics during aging. The variations of impact resistance, hardness, tensile, or flexural strength are the most frequently studied. Accelerated aging is an arbitrary measurement that must be interpreted and must constitute only one of the elements used in making a judgment.

Acidification Acidification results from the deposition of acids which leads to a decrease in the pH and increase in potentially toxic elements. The major acidifying pollutants are SO_2, NO_x, HCl, CO_2, and so on. Acidification is measured in terms of SO_2 equivalents.

Acoustic emission (AE) Sound generated by defects such as crack initiation or crack growth when a sample or part is mechanically stressed.

Additive Adding additives to raw polymer(s) optimizes durability, reinforcement, plasticity, processing, esthetics, impact resistance, optical or electrical properties, fire resistance, etc. Reinforcement uses glass, aramid, carbon fibers, natural fibers, textile fibers, mineral fillers, glass beads, nanofillers, and carbon nanotubes. Other mineral or organic additives are as diverse as plasticizers, colorants and pigments, impact modifiers, processing stabilizers, antioxidants, light stabilizers, hydrolysis stabilizers, tribological agents, antirodents, microbicides, low-cost fillers, matting agents, foaming additives, etc.

Alloy Thermoplastic families are diverse but their number is limited and often there are wide gaps between the properties of two basic polymer types. To bridge the gap, two polymer families can be mixed if they are compatible or if it is possible to compatibilize them with a third material. For a suitable mixing of two components, the properties of an alloy, including the cost, are generally intermediate between those of each component.

Amorphous Chains of an amorphous polymer are randomly arranged. Amorphous polymers slowly soften when heated above their glass transition temperature. Generally, amorphous polymers have lower chemical resistance than semicrystalline ones but may be transparent.

Anisotropic A polymer or composite is anisotropic if its properties depend on the test direction. When measured along different axes, physical and/or mechanical properties (modulus, refractive index, conductivity, etc.) are different. Unidirectional tapes are highly anisotropic.

Annealing Heating and keeping a polymer part at a temperature near, but below, its melting point to relax internal stresses without distortion of its shape.

Aspect ratio The ratio of length to diameter of a fiber or the ratio of the thickness to the planar sizes of a particle.

ASTM standards ASTM International, formerly known as the American Society for Testing and Materials (ASTM), is a globally recognized leader in the development and delivery of international voluntary consensus standards. Today, some 12,000 ASTM standards are used around the world to improve product quality, enhance safety, facilitate market access and trade, and build consumer confidence. The main technical committee (TC) dealing with plastics is the

D20—Plastics but other standards can be classified in C03—Chemical-Resistant Nonmetallic materials; D07—Wood; D08—Roofing and Waterproofing; D09—Electrical and Electronic Insulating Materials; D13—Textiles; D14—Adhesives and others.

Balanced laminate All plies of a balanced laminate are placed in plus/minus pairs, for example, ±45° symmetrically about the layup centerline.

Biochemical oxygen demand (BOD) Biochemical oxygen demand (BOD) measures the amount of dissolved oxygen needed by aerobic biological organisms present in the water to break down organic material. The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20 °C.

Biodegradation Biodegradation is the chemical decomposition of polymers by bacteria or other biological means in the presence of oxygen (aerobically biodegradation), or in the absence of oxygen (anaerobically biodegradation).

For the nonbiodegradable polymers, degradation can be obtained by using high levels of biodegradable additives. These ones are sources of nutrients for microorganisms but the conventional polymer, polyethylene particularly is not biodegraded; Only the biodegradable additives are completely biodegraded but:

- The skeleton of conventional polymer becomes weak and brittle and can disappear more easily.
- The surface area is highly increased and promotes the chemical and bacterial attacks.

It is possible to degrade polymers by:

- photodegradation obtained by the addition of small levels of UV degradation promoters or photoinitiators.
- Oxydo-degradation: Prooxidants accelerate the thermooxidation of the polymers.
- Hydrolysis: Polyesters are sensitive to hydrolysis that cuts the macromolecules. The fragments are more or less biodegradable.
- Water solubility: The polymer disappears from the view but the chemical species can pollute the environment. Generally, final uses are specific because of the solubility.

Biothermoplastics from renewable sources Bioplastics are not a single class of polymers but rather a series of products that can vary considerably the one from the other. They are directly or indirectly based on renewable biomass sources, such as vegetable oil, cornstarch, pea starch, sugar, etc.

Brittle plastic When mechanically stressed, the break point of brittle plastics arises immediately after the yield point or coincides with it.

Carbon footprint Carbon footprint can be featured by the total amount of carbon dioxide (CO_2) and methane (CH_4), directly or indirectly emitted by a defined system or activity. Calculated as carbon dioxide equivalent (CO_2e). Carbon footprint of various forms of energy generation can be, for example:

- Coal 900–1000 g/kW h
- Gas 450–600
- Photovoltaic 50–100
- Wind, nuclear, hydro less than 50

Cast film Film made by casting a layer of plastic onto a surface. After solidification, the film is removed for use. The plastic can be in molten state, in solution, or dispersion.

Chemical oxygen demand (COD) Chemical oxygen demand (COD) measures the amount of organic compounds in water. COD measures everything that can be chemically oxidized.

Composites Composites combine a polymer matrix, thermoset, or thermoplastic, and a nonmiscible reinforcement closely linked with the matrix: fibers of significant length compared to the diameter, yarns, mats, fabrics, foams, honeycombs, etc. The matrix (or binder) ensures the cohesion of the composite, and distributes and damps the impacts or stresses to protect the composite from the environment. The cohesion of the matrix and reinforcements is of vital importance. The reinforcement bears the stresses. When these reinforcements are not randomly distributed, the properties are anisotropic, being enhanced in the reinforcement direction.

Compound Compounds are obtained by mixing of raw polymer(s) with additives leading to a broad range of characteristics for the same raw polymer.

Consolidation Compression of a heated composite to reduce voids and achieve a better cohesion and strength.

Copolymer or heteropolymer Copolymers (or heteropolymers) are polymerized from two or more monomers arranged in various structures: statistical copolymers with a random arrangement of comonomers, alternating copolymers with a regular distribution of the comonomers, block copolymers alternating blocks of each monomer. Copolymers can be linear, branched, or hyperbranched. Branched copolymers include star copolymers, brush copolymers, and comb copolymers.

Cradle to factory gate Cycle beginning with raw material extraction from the earth and ending with the product leaving the factory.

Cradle to grave Complete cycle beginning with raw material extraction and ending with the final disposal of the product or part (recycling, compost, landfill, etc.).

Crazing Tiny cracks near or on the surface of plastic materials.

Creep Creep is the time-dependent strain induced by a constant mechanical loading. The strain is a function of the stress level, the time for which the stress is applied, and the temperature. The results can be presented graphically in various ways by combining these three parameters or in quantified forms: creep modulus and creep strength, for example. Creep can lead to breaking for levels of stress much lower than ultimate stresses measured by dynamometry.

Cross-linking or curing Building of a 3D network thanks to chemical reactions linking several polymer chains. Cross-linking can be achieved by heating, UV, or electron beam irradiation, etc. Some thermoplastics are cross-linkable and are industrially used in their two forms—thermoplastic and thermoset.

Crystallinity Polymers can be amorphous, crystalline, or semicrystalline. Semicrystalline polymers contain regions of three-dimensional ordering and amorphous regions without any order. The degree of crystallinity is the weight fraction or the volume fraction of crystalline material. It is ranging from zero for a completely amorphous polymer to one for a completely crystalline polymer. Semicrystalline polymers are generally tougher than totally amorphous polymers but are opaque when some amorphous polymers are transparent. The crystallinity of a polymer can be measured by DSC, density, or X-ray diffraction.

Ductile plastic A plastic is ductile when the break point is far from the yield point.

e-Manufacturing Polymer parts can be produced by e-Manufacturing, an additive manufacturing (AM) technique building up objects from 3D data generated from 3D computer-aided design (CAD) or 3D scanning systems. e-Manufacturing or Direct digital manufacturing is suitable for limited-run production of certain parts, being a cost-effective alternative to traditional manufacturing methods for low production volume, high design complexity, probability of near-term design changes.

Eco-profile Assessment of the total energy use, raw material use, air and water emissions, and the total solid waste produced from the cradle to the factory gate. An eco-profile always ends with the production of the considered part or product.

End cost The end cost include processing, assembling, delivery, set up, operating, and end-of-life costs, taking account of durability and savings in maintenance, operating costs, etc. End costs must be taken into account to decide to design with plastics or conventional materials.

Environmental stress cracking—ESC When a plastic exposed to air is subjected to a stress or a strain below its yield point, cracking can occur after a very long duration. The simultaneous exposure to a chemical environment under the same stress or strain can lead to a spectacular reduction of the failure time. The accelerated cracking in this way corresponds to “environmental stress cracking” (ESC).

Eutrophication Eutrophication is caused by the addition of nutrients to a soil or water system which leads to an increase in biomass, damaging other life forms. Water acquires a high concentration of nutrients, especially phosphates and nitrates promoting excessive growth of algae. Eutrophication is measured in terms of phosphate $\left(PO_4^{3-}\right)$ equivalents.

Face sheet or skin Surface material of sandwich structures.

Fire behavior Polymers are based on organic matter more or less combustible. They emit smokes and drip. Fire behavior depends on the nature of the polymer, the use of fire-proofing agents, special plasticizers, and specific fillers. Tests relate to:

- the tendency for combustion: UL94 ratings, oxygen index
- the smoke opacity
- the toxicity and corrosivity of the smoke.

The main categories of UL rating are:

- V0: The most difficult to burn, extinguished after 10 s, no drips
- V1: Extinguished after 30 s, no drips
- V2: Extinguished after 30 s, flaming particles or drips permitted
- 5V: Extinguished after 60 s, flaming particles or drips permitted
- HB: Burning horizontally at a 76 mm/min maximum rate.

The UL rating depends on the exact grade and the sample thickness.

The oxygen index is the minimum percentage of oxygen in an atmosphere of oxygen and nitrogen that sustains the flame of an ignited polymer sample.

Flow line or weld line A flow line is a mark on a molded part resulting from the meeting of two flow fronts during molding. Generally, this spot has weaker properties.

Fogging The word relates to two different phenomena:

- Condensation of the air moisture on a cold material, formation of tiny droplets on the surface, light scattering and obscuring of the material.
- Desorption of additives or low-molecular weight polymer from the plastic parts and their condensation on other cold parts: glazing of cars and particularly windscreens, optical lenses or electronic devices where the deposit of additives can also make electrical insulation.

Glass transition temperature (Tg) For amorphous polymers or amorphous domains of semicrystalline polymers, the glass transition temperature (Tg) is a reversible transition from a hard and brittle state into a molten or rubber-like state. There are sudden and significant changes in the physical properties including the coefficient of thermal expansion and specific heat. The transition temperature value depends on the testing conditions, notably the cooling or heating rate and the frequency of the measured parameter.

Global warming potential (GWP) Global warming potential is an appraisal of greenhouse gas (for example, CO_2, methane, nitrous oxide, etc.) contribution to global warming. Global warming comes from an increase in the atmospheric concentration of greenhouse gases which changes the absorption of infrared radiation in the atmosphere leading to changes in climatic patterns and higher global average temperatures. Global warming potential is measured in terms of CO_2 equivalents, comparing the amount of heat trapped by a certain mass of the studied gas to the amount of heat trapped by a similar mass of carbon dioxide.

Greenhouse gases (GHG) Greenhouse gases are often expressed in terms of the amount of carbon dioxide, or its equivalent of other GHGs, emitted through transport, land clearance, and the production and consumption of food, fuels, manufactured goods, materials, wood, roads, buildings, and services.

Haze Haze refers to the cloudy appearance of a transparent polymer caused by light scattering. Haze may appear after long exposition to moisture.

Heteropolymer or copolymer Heteropolymers or copolymers are polymerized from two or more monomers arranged in various structures: statistical copolymers with a random arrangement of comonomers, alternating copolymers with a regular distribution of the comonomers, and block copolymers alternating blocks of each monomer. Copolymers can be linear, branched, or hyperbranched. Branched copolymers include star copolymers, brush copolymers, and comb copolymers.

Homopolymer Homopolymers are based on a single monomer. They can be linear (a single chain) or branched (with side chains).

Hybrid materials Hybrid materials are not really a clearly defined material category but result from a design method that associates, by integrating them closely, one or more polymers on the one hand and, generally, one or more other materials, which provide one or more functionalities difficult or impossible to obtain with only one polymer.

Impact behavior Impact tests measure the energy absorbed during a specified impact of a standard weight striking, at a given speed, a test sample clamped with a suitable system. The hammer can be a falling weight or, more often, a pendulum. In this case, the samples can be smooth or notched. The results depend on the molecular orientation and the degree of crystallization of the material in the sample, its size, the clamping system, the possible notch and its form, the mass and the strike speed. The values found in the literature, even for instrumented multiaxial impact (ISO 6603-2:2000), can only be used to help choosing and do not replace tests on real parts. The Izod and Charpy impact tests are mostly used.

ISO standards ISO (International Organization for Standardization) is the world's largest developer and publisher of International Standards. ISO is a network of the national standards institutes of 163 countries with a Central Secretariat in Geneva, Switzerland, that coordinates the system. ISO is a nongovernmental organization that forms a bridge between the public and private sectors.

Two main technical committees (TC) deal with plastics and rubbers: TC 61 for plastics and TC 45 for rubber and rubber products. Standards can also be emitted by other TCs such as, for example, TC 138 for plastics pipes, fittings, and valves for the transport of fluids or TC 20 for aircraft and space vehicles.

Isomer Isomers have the same molecular formula but different atom and function arrangements. Structural isomers have different monomer arrangements.

Stereoisomers have same monomer arrangement but different spatial distributions of chemical functions.

Polymers can be *cis* or *trans* according to the relative position of substituent on either side of a double bond.

Isotropic Isotropic polymers have equal properties in all directions. Carefully molded glass bead-filled thermoplastics are isotropic.

Laminate A laminate is made of several stacked plies (or laminae) with diverse orientations chosen to achieve required properties. These plies are hold together thanks to the resin. Among other parameters, the laminate performance depends on the properties of each ply, the orientations of the reinforcements, the order in which the plies are stacked, and the cohesion between the plies.

Life-cycle assessment or life-cycle analysis (LCA) Life-cycle assessment or life-cycle analysis (LCA) assesses environmental impacts resulting from all the stages of a product or part life including raw material extraction, material processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. LCA is also known as ecobalance and cradle-to-grave analysis.

Life-cycle inventory (LCI) Life-cycle inventory (LCI) is the inventory of the total energy use, raw material use, air and water emissions, and the total solid waste produced from the cradle-to-grave (grave being the ultimate disposal). The LCI gives the basic data for the LCA. It is equivalent to the eco-profile covering the complete life cycle. In the strict sense of the term, the LCI of resins, pellets, new films or tubes, and so on does not exist because the pellets and new parts or products are not usually thrown away.

Light and UV resistance Polymers are based on organic materials and are sensitive to natural or artificial UV sources. This is of primary importance for outdoor exposure of unprotected parts and for some industrial applications such as electrical welding, photocopier light exposure devices … The UV resistance can be tested thanks to specific devices including irradiation by artificial UV light of various UV sources or by direct sunlight exposition.

The interpretation of the test results is difficult because of climate diversity, risks of industrial or domestic pollution in real life, lack of correlation between artificial and natural aging, and the different degradation kinetics of the various properties.

Molecular weight Molecular weight can be expressed in:

- Number average molecular weight (Mn)
- Weight average molecular weight (Mw)

The ratio of the weight average to the number average (Mw/Mn) is the polydispersity index giving an indication on the molecular weight distribution.

Molecular weight distribution—MWD Most polymers have a unimodal distribution but for specific purposes some have a bimodal distribution. The MWD influences the strength of solid plastics and the rheology of molten polymers.

Orthotropic Properties of orthotropic polymers are different along two orthogonal directions. For example, balanced laminates having same properties along X- and Y-axis but different properties along Z-axis (thickness).

Photochemical oxidation The formation of photochemical oxidant smog is the result of complex reactions between NO_x and VOCs under the action of sunlight (UV radiation) which leads to the formation of ozone in the troposphere. The smog phenomenon is very dependent on meteorological conditions and the background concentrations of pollutants. Photochemical oxidation is measured using photo-oxidant creation potential (POCP) which is normally expressed in ethylene equivalents.

Placement Process to set reinforcements in a composite part to maximize required properties. For example, fiber placement or tape placement.

Ply or lamina A ply (or lamina) is a flat or curved elementary arrangement of unidirectional or woven fibers embedded in the polymer matrix. Its thickness depends on the used reinforcement. For example, a carbon fiber ply may be in the order of 0.127-mm thick. Usually, several plies are stacked to build a laminate.

Polymer A polymer is a long chain or macromolecule built by polymerization of one or several monomer(s). Homopolymers are made from only one monomer and comonomers from two or more monomers.

Polymers can be linear or branched. Branched copolymers include star copolymers, brush copolymers, and comb copolymers.

Post cure Additional curing achieved by heating, UV, or electron beam irradiation, etc., to optimize the 3D network. Some thermoplastics are cross-linkable and are industrially used in their two forms—thermoplastic and thermoset.

Pot life Period of time a paint or an adhesive stay usable.

Preform Blow molding: Preform or parison is the crude part molded or extruded before blowing. Composites: Reinforcements shaped before addition of the resin or before molding.

Prepreg Reinforcements of all forms such as fabrics, rovings, tapes, ribbons, etc. (made of aramid, glass or carbon fibers) are impregnated with thermoplastic or thermoset resins to give prepregs. The resin level can be as high as 85%. After or during shaping, part consolidation is achieved by heating under pressure.

REACH (Registration Evaluation Authorization and Restriction of Chemicals) REACH can be a European directive but also a China regulation dealing with new chemical substance notification to the Chemical Registration Centre (CRC) of the Ministry of Environmental Protection (MEP) for the new chemicals irrespective of annual tonnage, i.e., chemicals other than the approximately 45,000 substances currently listed on the Inventory of Existing Chemical Substances Produced or Imported in China (IECSC). Failure to register will mean the substance cannot be manufactured or imported into the EU market.

Recycling Three main ways can be used:

- reuse with virgin material in the same or another application
- conversion into basic chemicals by chemolysis or thermolysis
- energy production by combustion.

Relaxation Relaxation is the time-dependent stress resulting from a constant strain. The stress is a function of the strain level, the application time, and the temperature. The results of tests at a defined temperature can be presented as a load versus time curve or a stress retention versus time curve.

The stress retention for a defined time and temperature is the actual measured stress divided by the original stress at time zero.

Residual internal stresses Thermoplastic injection moldings may contain residual stresses that are the consequence of differential cooling rates through the molded parts. They depend upon a wide range of variables including the mold design, material, and processing parameters. These stresses can significantly reduce the lifetime of parts and can reduce the dimensional stability by warpage. They also contribute to environmental stress-cracking damages.

Residual monomer Residual monomers are the nonreacted monomers remaining after polymerization. There is an obligation to comply with limits of residual monomer levels.

Rheology Rheology studies the flow and deformation of materials in both solid and fluid states applying the laws of elasticity and viscosity initially proposed by Hooke and Newton. Today, there are many mathematical models.

Molten thermoplastics are pseudoplastic fluids with a viscosity decreasing when shearing increases, which is an advantage in injection molding when the material flows through small cross-section gates. Processing temperature, rate of flow, residence time, etc. affect the rheology.

Rheology of thermosetting resins is more complex, the cross-linking or curing affecting more or less abruptly the rheology during processing.

RoHS (Restriction of Hazardous Substances) The RoHS directive restricts certain hazardous substances commonly used in electrical and electronic equipment. Do not confuse EU RoHS and China RoHS: Both target similar goals but approaches are different concerning the product categories, the restrictions, the application schedule.

Sandwich structure A sandwich structure is fabricated by firmly linking a thick core and two thin and stiff outer skins or faces. Often, the core material is foam, honeycomb, or balsa with a low density.

Foams are prefabricated or cast in place.

Normally, sandwich composites are lightweight and stiff depending on type and thickness of core, stiffness of faces, and binding performance. If the adhesive bond between the various elements is too weak, there are risks of delamination.

Skin or face sheet Surface material (composites, plastics, metals) of sandwich structures. Generally, thickness of the two faces is inferior to core thickness.

Stress concentration The stress concentration is the high increase in stress near a notch, void, hole, inclusion, or other discontinuity of a plastic part.

Sustainability The concept of sustainability was developed and then normalized (ISO 14000) to help the economic and industrial players to think about ways able to improve or minimize the degradation of our Earth. Sustainability can be schematized as a tripod based on:

1. Environmental requirements: the basis axiom can be simplified as follows "Today acts mustn't compromise the environment of the planet for tomorrow" or "present acts mustn't compromise the needs of future generations."
2. Economic growth: sustainable products must be efficient, competitive, cost-effective, and beneficial for everybody.
3. Social progress including fair labor standards, equal treatment of women and minorities.

Tape Unidirectional prepreg, generally of limited width.

Thermal behavior Polymers are temperature-sensitive. A fall in temperature has only physical effects: increase in the modulus and rigidity, reduction in the impact resistance; the material can become brittle. Semicrystalline polymers crystallize.

A temperature rise causes immediate and long-term effects:

- Immediate physical effects: decay of the modulus and other mechanical and physical properties, softening, reversible thermal expansion, and, eventually, irreversible shrinkage and warpage.
- Long-term effects: irreversible creep and relaxation, irreversible chemical degradation of the material, decrease in mechanical properties, even after a return to the ambient temperature.

Thermoplastics Thermoplastics have the simplest molecular structure, with chemically independent macromolecules. By heating, they are softened or melted, which allows shaping, molding, extrusion, thermoforming, welding. After cooling, they solidify again.

Multiple cycles of heating and cooling can be repeated without severe damage, allowing reprocessing and recycling.

Thermosets Thermosets before hardening, like thermoplastics, are independent macromolecules. But in their final state, after hardening, they have a three-dimensional structure obtained by chemical cross-linking produced after (spray-up molding or filament winding) or during the processing (compression or injection molding, for example).

Tonne of oil equivalent (toe) Tonne of oil equivalent (toe) is defined as the amount of energy released by burning 1 tonne of crude oil. It is approximately 42 GJ.

Toxicity Toxicity is the degree to which something is able to produce illness or damage to an exposed organism. There are four different types of toxicity—

human toxicity, terrestrial ecotoxicity, marine aquatic ecotoxicity, and fresh water aquatic ecotoxicity. Toxicity is measured in terms of dichlorobenzene equivalents.

Tow A tow is an untwisted bundle of continuous filaments. The number of filaments is expressed in thousands followed by a K (for kilo). For example, a xyK tow has 1000xy filaments.

TPE or Thermoplastic elastomer Thermoplastics having elastic properties in a defined range of temperatures. TPEs combine the ease of thermoplastic processing without curing, and ease of recycling but their mechanical properties decrease as the temperature rises because of their thermoplasticity.

TPV TPE having a vulcanized phase.

UL fire rating The UL94 fire rating provides basic information on the material's ability to extinguish a flame, once ignited. The samples can be tested horizontally (H) or vertically (V) and the burning rate, the extinguishing time, and dripping are considered. The main categories are:

- V0: The most difficult to burn, extinguished after 10 s, neither dripping nor flaming particles.
- V1: Extinguished after 30 s, neither dripping nor flaming particles.
- V2: Extinguished after 30 s, flaming particles or drips permitted.
- 5V: Extinguished after 60 s, flaming particles or drips permitted.
- HB: Burning horizontally at a 76 mm/min maximum rate.

The UL rating depends on the sample thickness. For the same grade of polyethylene, the UL ratings are:

- V2 for a 1.6 mm thickness
- V0 for a 6 mm thickness.

UL temperature index The temperature index is the maximum temperature that causes a 50% decay of the studied characteristics in the very long term. It is derived from long-term oven-aging test runs. The UL temperature index depends on the properties considered:

- electrical only
- electrical and mechanical, impact excluded
- electrical and mechanical, impact included.

The UL temperature indices increase with the thickness of the samples. Like all laboratory methods, the temperature index is an arbitrary measurement that must be interpreted and must constitute only one of the elements by which judgment is made.

Weld line or flow line A weld line is a mark on a molded part resulting from the meeting of two flow fronts during molding. Generally, this spot has weaker properties.

Yield point The yield point is the first point of the stress–strain curve for which there is an increase in the strain without an increase in the stress. Parts must always operate well below this stress–strain level during service.

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