

CHAPTER 8

PLASTICS AND ELASTOMERS

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8.1 INTRODUCTION

The use of plastics has increased almost 20-fold in the last 30 years. Plastics have come on the scene as the result of a continual search for man-made substances that can perform better or can be produced at a lower cost than natural materials such as wood, glass, and metal, which require mining, refining, processing, milling, and machining. Plastics can also increase productivity by producing finished parts and consolidating parts. Thus, an item made from several metal parts that require separate fabrication and assembly can often be consolidated into one or two plastic parts. Such increases in productivity have led to fantastic growth.

Plastics can be classified in several ways. The two major classifications are thermosetting materials and thermoplastic materials. As the name implies, thermosetting plastics or thermosets are set, cured, or hardened into a permanent shape. The curing that usually occurs rapidly under heat or UV light leads to an irreversible cross-linking of the polymer. Thermoplastics differ from thermosetting materials in that they do not set or cure under heat. When heated, thermoplastics merely soften to a mobile, flowable state where they can be shaped into useful objects. Upon cooling, the thermoplastics harden and hold their shape. Thermoplastics can be repeatedly softened by heat and shaped.

Thermoplastics can be classified as amorphous or semicrystalline plastics. Most polymers are either completely amorphous or have an amorphous component even if they are crystalline. Amorphous polymers are hard, rigid glasses below a fairly sharply defined temperature, which is known as the glass transition temperature. Above the glass transition temperature, the amorphous polymer becomes soft and flexible and can be shaped. Mechanical properties show profound changes near the glass transition temperature. Many polymers are not completely amorphous but are semicrystalline. Semicrystalline polymers have melting points that are above their glass transition temperatures. The degree of crystallinity and the morphology of the crystalline phase have an important effect on mechanical properties. Crystalline plastics will become less rigid near their glass transition temperature but will not flow until the temperature is above the crystalline melting point. At ambient temperatures, crystalline/semicrystalline plastics have greater rigidity, hardness, density, lubricity, creep resistance, and solvent resistance than amorphous plastics.

From a cost and performance standpoint, polymers can be classified as either commodity or engineering plastics.

Another important class of polymeric resins are elastomers. Elastomers have glass transition temperatures below room temperature. Thus, elastomeric materials are rubber-like polymers at room temperatures, but below their glass transition temperature they will become rigid and lose their rubbery characteristics.

8.2 COMMODITY THERMOPLASTICS

The commodity thermoplastics include polyolefins and side-chain-substituted vinyl polymers.

8.2.1 Polyethylene

Polyethylenes (PEs) have the largest volume use of any plastic. They are prepared by the catalytic polymerization of ethylene. Depending on the mode of polymerization, one can obtain a high-density (HDPE) or a low-density (LDPE) polyethylene polymer. LDPE is prepared under more vigorous conditions, resulting in short-chain branching. Linear low-density polyethylene (LLDPE) is prepared by introducing short-branching via copolymerization with a small amount of long-chain olefin.

Polyethylenes are crystalline thermoplastics that exhibit toughness, near-zero moisture absorption, excellent chemical resistance, excellent electrical insulating properties, low coefficient of friction, and ease of processing. Their heat deflection temperatures are reasonable but not high. The branching in LLDPE and LDPE decreases the crystallinity. HDPE exhibits greater stiffness, rigidity, improved heat resistance, and increased resistance to permeability than LDPE and LLDPE. Some typical properties of PEs are listed in Table 8.1.

Uses. HDPE's major use is in blow-molded bottles, drums, carboys automotive gas tanks; injection-molded material-handling pallets, trash and garbage containers, and household and automotive parts; and extruded pipe.

LDPE/LLDPEs find major applications in film form for food packaging, as a vapor barrier film, plastic bags; for extruded wire and cable insulation; and for bottles, closures and toys.

8.2.2 Polypropylene

Polypropylene (PP) is prepared by the catalyzed polymerization of propylene. PP is a highly crystalline thermoplastic that exhibits low density, rigidity, excellent chemical resistance, negligible water absorption, and excellent electrical properties. Its properties appear in Table 8.2.

Table 8.1 Typical Property Values for Polyethylenes

Property	HDPE	LLDPE/LDPE
Density (Mg/m ³)	0.96–0.97	0.90–0.93
Tensile modulus (GPa)	0.76–1.0	—
Tensile strength (MPa)	25–32	4–20
Elongation at break (%)	500–700	275–600
Flexural modulus (GPa)	0.8–1.0	0.2–0.4
Vicat soft point (°C)	120–129	80–98
Brittle temperature (°C)	–100 to –70	–85 to –35
Hardness (Shore)	D60–D69	D45–D55
Dielectric constant (10 ⁶ Hz)	—	2.3
Dielectric strength (MV/m)	—	9–21
Dissipation factor (10 ⁶ Hz)	—	0.0002
Linear mold shrinkage (in./in.)	0.007–0.009	0.015–0.035

Table 8.2 Typical Property Values for Polypropylenes

Density (Mg/m ³)	0.09–0.93
Tensile modulus (GPa)	1.8
Tensile strength (MPa)	37
Elongation at break (%)	10–60
Heat deflection at 0.45 MPa (°C)	100–105
Heat deflection at 1.81 MPa (°C)	60–65
Vicat soft point (°C)	130–148
Linear thermal expansion (mm/mm·K)	3.8×10^{-5}
Hardness (Shore)	D76
Volume resistivity (Ω -cm)	1.0×10^{17}
Linear mold shrinkage (in./in.)	0.01–0.02

Uses. End uses for PP are in blow-molding bottles and automotive parts; injection-molding closures, appliances, housewares, automotive parts, and toys. PP can be extruded into fibers and filaments for use in carpets, rugs, and cordage.

8.2.3 Polystyrene

Catalytic polymerization of styrene yields polystyrene (PS), a clear, amorphous polymer with a moderately high heat deflection temperature. PS has excellent electrical insulating properties, but, it is brittle under impact and exhibits very poor resistance to surfactants and solvents. Its properties appear in Table 8.3.

Uses. Ease of processing, rigidity, clarity, and low cost combine to support applications in toys, displays, and housewares. PS foams can readily be prepared and are characterized by excellent low thermal conductivity, high strength-to-weight ratio, low water absorption, and excellent energy absorption. These attributes have made PS foam of special interest as insulation boards for construction, protective packaging materials, insulated drinking cups, and flotation devices.

8.2.4 Impact Polystyrene

Copolymerization of styrene with a rubber, polybutadiene, can reduce brittleness of PS, but only at the expense of rigidity and heat deflection temperature. Impact polystyrene (IPS) or high-impact polystyrene (HIPS) can be prepared, depending on the levels of rubber. These materials are translucent to opaque and generally exhibit poor weathering characteristics. Typical properties appear in Table 8.3.

8.2.5 SAN (Styrene/Acrylonitrile Copolymer)

Copolymerization of styrene with a moderate amount of acrylonitrile provides a clear, amorphous polymer (SAN) with increased heat deflection temperature and chemical resistance compared to polystyrene. However, impact resistance is still poor. Typical properties appear in Table 8.3

Uses. SAN is utilized in typical PS-type applications where a slight increase in heat deflection temperature and/or chemical resistance is needed, such as housewares and appliances.

Table 8.3 Typical Properties of Styrene Thermoplastics

Property	PS	SAN	IPS/HIPS	ABS
Density (Mg/m ³)	1.050	1.080	1.02–1.04	1.05–1.07
Tensile modulus (GPa)	2.76–3.1	3.4–3.9	2.0–2.4	2.5–2.7
Tensile strength (MPa)	41–52	65–76	26–40	36–40
Elongation at break (%)	1.5–2.5	—	—	15–25
Heat deflection temperature at 1.81 MPa (°C)	82–93	100–105	80–87	80–95
Vicat soft point (°C)	98–107	110	88–101	90–100
Notched Izod (kJ/m)	0.02	0.02	0.1–0.3	0.1–0.5
Linear thermal expansion (10^{-5} mm/mm·K)	5–7	6.4–6.7	7.0–7.5	7.5–9.5
Hardness (Rockwell)	M60–M75	M80–M83	M45, L55	R69–R115
Linear mold shrinkage (in./in.)	0.007	0.003–0.004	0.007	0.0055

8.2.6 ABS

ABS is a terpolymer prepared from the combination of acrylonitrile, butadiene (as polybutadiene), and styrene monomers. Compared to PS, ABS exhibits good impact strength, improved chemical resistance, and similar heat deflection temperature. ABS is also opaque. Properties are a function of the ratio of the three monomers. Typical properties are shown in Table 8.3.

Uses. The previously mentioned properties of ABS make it suitable for tough consumer products; automotive parts; business machine housings; telephones; appliances; luggage; and pipe, fittings, and conduits.

8.2.7 Polyvinyl Chloride

The catalytic polymerization of vinyl chloride yields polyvinyl chloride. It is commonly referred to as PVC or vinyl and is second only to polyethylene in volume use. Normally, PVC has a low degree of crystallinity and good transparency. The high chlorine content of the polymer produces advantages in flame resistance, fair heat deflection temperature, good electrical properties, and good chemical resistance. However, the chlorine also makes PVC difficult to process. The chlorine atoms have a tendency to split out under the influence of heat during processing and heat and light during end use in finished products, producing discoloration and embrittlement. Therefore, special stabilizer systems are often used with PVC to retard degradation.

There are two major sub-classifications of PVC: rigid and flexible (plasticized). In addition, there are also foamed PVC and PVC copolymers. Typical properties of PVC resins appear in Table 8.4.

Rigid PVC

PVC alone is a fairly good rigid polymer, but it is difficult to process and has low impact strength. Both of these properties are improved by the addition of elastomers or impact modified graft copolymers, such as ABS and impact acrylic polymers. These improve the melt flow during processing and improve the impact strength without seriously lowering the rigidity or the heat deflection temperature.

Uses. With this improved balance of properties, rigid PVCs are used in such applications as door and window frames; pipe, fittings, and conduit; building panels and siding; rainwater gutters and down spouts; credit cards; and flooring.

Plasticized PVC

Flexible PVC is a plasticized material. The PVC is softened by the addition of compatible, nonvolatile, liquid plasticizers. The plasticizers, which are usually used in > 20 parts per hundred resins, lower the crystallinity in PVC and act as internal lubricants to give a clear, flexible plastic. Plasticized PVC is also available in liquid formulations known as plastisols or organosols.

Uses. Plasticized PVC is used for wire and cable insulation, outdoor apparel, rainwear, flooring, interior wall covering, upholstery, automotive seat covers, garden hose, toys, clear tubing, shoes, tablecloths, and shower curtains. Plastisols are used in coating fabric, paper, and metal; and rotationally cast into balls, dolls, and so on.

Table 8.4 Typical Property Values for Polyvinyl Chloride Materials

Property	General Purpose	Rigid	Rigid Foam	Plasticized	Copolymer
Density (Mg/m ³)	1.40	1.34–1.39	0.75	1.29–1.34	1.37
Tensile modulus (GPa)	3.45	2.41–2.45	—	—	3.15
Tensile strength (MPa)	8.7	37.2–42.4	> 13.8	14–26	52–55
Elongation at break (%)	113	—	> 40	250–400	—
Notched Izod (kJ/m)	0.53	0.74–1.12	> 0.06	—	0.02
Heat deflection temperature at 1.81 MPa (°C)	77	73–77	65	—	65
Brittle temperature (°C)	—	—	—	–60 to –30	—
Hardness	D85 (Shore)	R107–R122 (Rockwell)	D55 (Shore)	A71–A96 (Shore)	—
Linear thermal expansion (10 ⁻⁵ mm/mm·K)	7.00	5.94	5.58	—	—
Linear mold shrinkage (in./in.)	0.003	—	—	—	—

Foamed PVC

Rigid PVC can be foamed to a low-density cellular material that is used for decorative moldings and trim.

Uses. Foamed plastisols add greatly to the softness and energy absorption already inherent in plasticized PVC, giving richness and warmth to leather-like upholstery, clothing, shoe fabrics, handbags, luggage, and auto door panels; and energy absorption for quiet and comfort in flooring, carpet backing, auto headliners, and so on.

PVC Copolymers

Copolymerization of vinyl chloride with 10–15% vinyl acetate gives a vinyl polymer with improved flexibility and less crystallinity than PVC, making such copolymers easier to process without detracting seriously from the rigidity and heat deflection temperature. These copolymers find primary applications in flooring and solution coatings.

8.2.8 Poly(vinylidene chloride)

Poly(vinylidene chloride) is prepared by the catalytic polymerization of 1,1-dichloroethylene. This crystalline polymer exhibits high strength, abrasion resistance, high melting point, better than ordinary heat resistance (100°C maximum service temperature), and outstanding impermeability to oil, grease, water vapor, oxygen, and carbon dioxide. It is used for packaging films, coatings, and monofilaments.

When the polymer is extruded into film, quenched, and oriented, the crystallinity is fine enough to produce high clarity and flexibility. These properties contribute to widespread use in packaging film, especially for food products that require impermeable barrier protection.

Poly(vinylidene chloride) and/or copolymers with vinyl chloride, alkyl acrylate, or acrylonitrile are used in coating paper, paperboard, or other films to provide more economical, impermeable materials.

A small amount of poly(vinylidene chloride) is extruded into monofilament and tape that is used in outdoor furniture upholstery.

8.2.9 Poly(methyl Methacrylate)

The catalytic polymerization of methylmethacrylate yields poly(methyl methacrylate) (PMMA), a strong, rigid, clear, amorphous polymer. PMMA has excellent resistance to weathering, low water absorption, and good electrical resistivity. PMMA properties appear in Table 8.5.

Uses. PMMA is used for glazing, lighting diffusers, skylights, outdoor signs, and automobile taillights.

8.2.10 Poly(ethylene Terephthalate)

Poly(ethylene terephthalate) (PET) is prepared from the condensation polymerization of dimethyl terephthalate and ethylene glycol. PET is a crystalline polymer that exhibits high modulus, high strength, high melting point, good electrical properties, and moisture and solvent resistance. PET crystallizes slowly, hence blow-molded and extruded objects are clear. Injection-molding grades are nucleated to facilitate crystallization and shorten the molding cycle. Nucleated PET resins are opaque.

Uses. Primary applications of PET include blow-molded beverage bottles; fibers for wash and wear, wrinkle-resistant fabrics; and films that are used in food packaging, electrical applications (capacitors, etc.), magnetic recording tape, and graphic arts.

Table 8.5 Typical Properties of Poly(methyl Methacrylate)

Property	PMMA
Density (Mg/m ³)	1.18–1.19
Tensile modulus (GPa)	3.10
Tensile strength (MPa)	72
Elongation at break (%)	5
Notched Izod (kJ/m)	0.4
Heat deflection temperature at 1.81 MPa (°C)	96
Continuous service temperature (°C)	88
Hardness (Rockwell)	M90–M100
Linear thermal expansion (10 ⁻⁵ mm/mm·K)	6.3
Linear mold shrinkage (in./in.)	0.002–0.008

8.3 ENGINEERING THERMOPLASTICS

Engineering thermoplastics comprise a special high-performance segment of synthetic plastic materials that offer premium properties. When properly formulated, they may be shaped into mechanically functional, semiprecision parts or structural components. "Mechanically functional" implies that the parts may be subjected to mechanical stress, impact, flexure, vibration, sliding friction, temperature extremes, hostile environments, etc., and continue to function.

As substitutes for metal in the construction of mechanical apparatus, engineering plastics offer advantages such as transparency, light weight, self-lubrication, and economy in fabrication and decorating. Replacement of metals by plastic is favored as the physical properties and operating temperature ranges of plastics improve and as the cost of metals and their fabrication increases.

8.3.1 Polyesters (Thermoplastic)

Poly(butylene terephthalate) (PBT) is prepared from the condensation polymerization of butanediol with dimethyl terephthalate. PBT is a crystalline polymer that has a fast rate of crystallization, which facilitates rapid molding cycles. It seems to have a unique and favorable balance of properties between polyamides and polyacetals. PBT has low moisture absorption, extremely good self-lubricity, fatigue resistance, solvent resistance, and good maintenance of mechanical properties at elevated temperatures. PBT resins are often used with reinforcing materials like glass fiber to enhance strength, modulus and heat deflection temperature. Properties appear in Table 8.6.

Uses. Applications of PBT include gears, rollers, bearing, housings for pumps, and appliances, impellers, pulleys, switch parts, automotive components, and electrical/electronic components. A high-density PBT is used in countertops and sinks.

8.3.2 Polyamides (Nylon)

The two major types of polyamides (PA) are nylon 6 (PA6) and nylon 66 (PA66). Polycaprolactam or nylon 6 is prepared by the polymerization of caprolactam. Poly(hexamethylene adipamide) or nylon 66 is derived from the condensation polymerization of hexamethylene diamine with adipic acid. Polyamides are crystalline polymers. Nylon's key features include a high degree of solvent tolerance, toughness, and fatigue resistance. Nylons do exhibit a tendency to creep under applied load. Glass fibers or mineral fillers are often used to enhance the properties of polyamides. In addition, the properties of nylon are greatly affected by moisture, which acts as a plasticizer. Properties of nylon 6 and 66 with and without glass fiber appear in Table 8.7.

Uses. The largest application of nylons is in fibers. Molded applications include automotive components, related machine parts (gears, cams, pulleys, rollers, boat propellers, etc.), appliance parts, and electrical insulation.

Modified Polyamides

Moisture has a profound effect on the properties of polyamides. Water acts as a plasticizer in polyamides, lowering their rigidity and strength while increasing their ductility. Moreover, an increase in moisture has a negative effect on dimensional stability. Polyamides have been modified by blending with poly(phenylene ether) (PPE) in order to minimize the effect of moisture. In PA/PPE alloys, the polyamide is the continuous phase and imparts good solvent resistance. The PPE is a dispersed phase and acts as a reinforcement of the crystalline nylon matrix, giving improved stiffness and toughness versus the unfilled nylon resin. Since PPE does not absorb any significant amount of moisture, the

Table 8.6 Typical Properties of Poly(butylene Terephthalate)

Property	PBT	PBT + 40% Glass Fiber
Density (Mg/m ³)	1.300	1.600
Flexural modulus (GPa)	2.4	9.0
Flexural strength (MPa)	88	207
Elongation at break (%)	300	3
Notched Izod (kJ/m)	0.06	0.12
Heat deflection temperature at 0.45 MPa (°C)	154	232
Heat deflection temperature at 1.81 MPa (°C)	54	232
Hardness (Rockwell)	R117	M86
Linear thermal expansion (10 ⁻⁵ mm/mm·K)	9.54	1.89
Linear mold shrinkage (in./in.)	0.020	< 0.007

Table 8.7 Typical Properties of Polyamides

Property	PA6	PA6 + 40% Glass Fiber	PA66	PA66 + 40% Glass Fiber
Density (Mg/m ³)	1.130	1.460	1.140	1.440
Flexural modulus (GPa)	2.8	10.3	2.8	9.3
Flexural strength (MPa)	113	248	—	219
Elongation at break (%)	150	3	60	4
Notched Izod (kJ/m)	0.06	0.16	0.05	0.14
Heat deflection temperature at 0.45 MPa (°C)	170	218	235	260
Heat deflection temperature at 1.81 MPa (°C)	64	216	90	250
Hardness (Rockwell)	R119	M92	R121	M119
Linear thermal expansion (10 ⁻⁵ mm/mm-K)	8.28	2.16	8.10	3.42
Linear mold shrinkage (in./in.)	0.013	0.003	0.0150	0.0025

effect of moisture on properties and dimensional stability is reduced in PPE/PA blends versus polyamides. In addition, heat deflection temperatures are enhanced. Properties are shown in Table 8.8.

Uses. PA/PPE alloys are used in automotive body panels (fenders and quarter panels), automotive wheel covers, exterior truck parts, under-the-hood automotive parts (air intake resonators, electrical junction boxes and connectors), fluid handling applications (pumps, etc.).

8.3.3 Polyacetals

Polyacetals are prepared via the polymerization of formaldehyde or the copolymerization of formaldehyde with ethylene oxide. Polyacetals are crystalline polymers that exhibit rigidity, high strength, solvent resistance, fatigue resistance, toughness, self-lubricity, and cold-flow resistance. They also exhibit a tendency to thermally depolymerize and, hence are difficult to flame-retard. Properties are enhanced by the addition of glass fiber or mineral fillers. Typical properties appear in Table 8.9.

Uses. Applications of polyacetals include moving parts in appliances and machines (gears, bearings, bushings, etc.), in automobiles (door handles, etc.), and in plumbing (valves, pumps, faucets, etc.).

8.3.4 Polyphenylene Sulfide

The condensation polymerization of dichlorobenzene and sodium sulfide yields a crystalline polymer, polyphenylene sulfide (PPS). It is characterized by high heat resistance, rigidity, excellent chemical resistance, low friction coefficient, good abrasion resistance, and electrical properties. PPS is somewhat difficult to process due to the very high melting temperature, relatively poor flow characteristics, and some tendency for slight cross linking during processing. PPS resins normally contain glass fibers for mineral fillers. Properties appear in Table 8.10.

Uses. The unreinforced resin is used only in coatings. The reinforced materials are used in aerospace applications, pump components, electrical/electronic components, appliance parts, and in automotive applications.

Table 8.8 Typical Properties of PPE/Polyamide 66 Alloys

Property	Unfilled		10% Glass Fiber		30% Glass Fiber	
	PA	PPE/PA	PA	PPE/PA	PA	PPE/PA
Density (Mg/m ³)	1.14	1.10	1.204	1.163	1.37	1.33
Flexural modulus (GPa)						
Dry as molded	2.8	2.2	4.5	3.8	8.3	8.1
100% relative humidity at 150°C	0.48	0.63	2.3	2.6	4.1	5.8
	0.21	0.70	0.9	1.6	3.2	4.3
Flexural strength (MPa)						
Dry as molded	96	92	151	146	275	251
100% relative humidity at 150°C	26	60	93	109	200	210
	14	28	55	60	122	128

Table 8.9 Typical Properties of Polyacetals

Property	Polyacetal	Polyacetal + 40% Glass Fiber
Density (Mg/m ³)	1.420	1.740
Flexural modulus (GPa)	2.7	11.0
Flexural strength (MPa)	107	117
Elongation at break (%)	75	1.5
Notched Izod (kJ/m)	0.12	0.05
Heat deflection temperature at 0.45 MPa (°C)	170	167
Heat deflection temperature at 1.81 MPa (°C)	124	164
Hardness (Rockwell)	M94	R118
Linear thermal expansion (10 ⁻⁵ mm/mm·K)	10.4	3.2
Linear mold shrinkage (in./in.)	0.02	0.003

8.3.5 Polycarbonates

Most commercial polycarbonates are derived from the reaction of bisphenol A and phosgene. Polycarbonates (PCs) are transparent amorphous polymers. PCs are among the stronger, tougher, and more rigid thermoplastics. Polycarbonates also show resistance to creep and excellent electrical insulating characteristics. Polycarbonate properties are shown in Table 8.11.

Uses. Applications of PC include safety glazing, safety shields, non-breakable windows, automotive taillights, lenses, electrical relay covers, various appliance parts and housings, power tool housings, automotive exterior parts, and blow-molded bottles.

Polycarbonate/ABS Alloys

PC/ABS blends are prepared by extruder blending of PC and ABS resins and offer a unique balance of properties. The addition of ABS improves the melt processing of the blend, which facilitates filling large, thin-walled parts. The toughness (especially at low temperatures) of PC is enhanced by the blending with ABS while maintaining the high strength and rigidity. The properties are a function of the ratio of ABS to polycarbonate. Properties appear in Table 8.12.

Uses. PC/ABS is used in automotive body panels (doors), housewares (small appliances). PC/ABS has become the resin of choice for business equipment because of the combination of processing ease and toughness.

8.3.6 Polysulfone

Polysulfone is prepared from the condensation polymerization of bisphenol A and dichlorodiphenyl sulfone. The transparent, amorphous resin is characterized by excellent thermo-oxidative stability, hydrolytic stability, and creep resistance. Properties appear in Table 8.13.

Uses. Typical applications of polysulfones include microwave cookware, medical equipment where sterilization by steam is required, coffee makers, and electrical/electronic components.

Table 8.10 Typical Properties of Poly(phenylene Sulfide)

Property	PPS + 40% Glass Fiber
Density (Mg/m ³)	1.640
Tensile modulus (GPa)	7.7
Tensile strength (MPa)	135
Elongation at break (%)	1.3
Flexural modulus (GPa)	11.7
Flexural strength (MPa)	200
Notched Izod (kJ/m)	0.08
Heat deflection temperature at 1.81 MPa (°C)	> 260
Constant service temperature (°C)	232
Hardness (Rockwell)	R123
Linear thermal expansion (10 ⁻⁵ mm/mm·K)	4.0
Linear mold shrinkage (in./in.)	0.004

Table 8.11 Typical Properties of Polycarbonates

Property	PC	PC + 40% Glass Fiber
Density (Mg/m ³)	1.200	1.520
Tensile modulus (GPa)	2.4	11.6
Tensile strength (MPa)	65	158
Elongation at break (%)	110	4
Flexural modulus (GPa)	2.3	9.7
Flexural strength (MPa)	93	186
Notched Izod (kJ/m)	0.86	0.13
Heat deflection temperature at 0.45 MPa (°C)	138	154
Heat deflection temperature at 1.81 MPa (°C)	132	146
Constant service temperature (°C)	121	135
Hardness (Rockwell)	M70	M93
Linear thermal expansion (10 ⁻⁵ mm/mm·K)	6.74	1.67
Linear mold shrinkage (in./in.)	0.006	0.0015

8.3.7 Modified Polyphenylene Ether

Poly(2,6-dimethyl phenylene ether) (PPE) is prepared by the polymerization of 2,6-dimethylphenol. This amorphous polymer has a very high glass transition temperature, high heat deflection temperature, and no hydrolyzable bonds. PPE is usually blended with styrenics (i.e., HIPS, ABS, etc.) to form a family of modified polyphenylene ether-based resins (and with polyamides, as described earlier). These amorphous blends cover a wide range of heat deflection temperatures, depending on the ratio of PPE to HIPS. They are characterized by high toughness, outstanding dimensional stability at elevated temperatures, outstanding hydrolytic stability, long-term stability under load, and excellent dielectric properties over a wide range of frequencies and temperatures. Their properties appear in Table 8.14.

Uses. Applications include automotive (instrument panels, trim, etc.), TV cabinets, electrical connectors, pumps, plumbing fixtures, and small appliances.

8.3.8 Polyimides

Polyimides are a class of polymers prepared from the condensation reaction of a dicarboxylic acid anhydride with a diamine. Thermoplastic and thermoset grades of polyimides are available. The thermoset polyimides are among the most heat-resistant polymers; they can withstand temperatures up to 250°C. Thermoplastic polyimides, which can be processed by standard techniques, fall into two main categories — polyetherimides (PEI) and polyamideimides (PAI).

In general, polyimides have high heat resistance, high deflection temperatures, very good electrical properties, very good wear resistance, superior dimensional stability, outstanding flame resistance, and very high strength and rigidity. Polyimide properties appear in Table 8.15.

Uses. Polyimide applications include gears, bushings, bearings, seals, insulators, electrical/electronic components (printed wiring boards, connectors, etc.), cooking utensils, microwave oven components, and structural components.

Table 8.12 Typical Properties of Polycarbonates/ABS Blends

Properties	PA/ABS Ratio (wt/wt)			
	0/100	50/50	80/20	100/00
Density (Mg/m ³)	1.06	1.13	1.17	1.20
Tensile modulus (GPa)	1.8	1.9	2.5	2.4
Tensile strength (MPa)	40	57	60	65
Elongation at break (%)	20	70	150	110
Notched Izod:				
at 25°C (kJ/m)	0.30	0.69	0.75	0.86
at -20°C (kJ/m)	0.11	0.32	0.64	0.15
Heat deflection temperature at 1.81 MPa (°C)	80	100	113	132

Table 8.13 Typical Properties of Polysulfone

Property	Polysulfone
Density (Mg/m ³)	1.240
Tensile modulus (GPa)	2.48
Tensile strength (MPa)	70
Elongation at break (%)	75
Flexural modulus (GPa)	2.69
Flexural strength (MPa)	106
Notched Izod (kJ/m)	0.07
Heat deflection temperature at 1.81 MPa (°C)	174
Constant service temperature (°C)	150
Hardness (Rockwell)	M69
Linear thermal expansion (10 ⁻⁵ mm/mm-K)	5.6
Linear mold shrinkage (in./in.)	0.007

8.4 FLUORINATED THERMOPLASTICS

In general, fluoropolymers or fluoroplastics are a family of fluorine-containing thermoplastics that exhibit some unusual properties. These properties include inertness to most chemicals, resistance to high temperatures, extremely low coefficient of friction, and excellent dielectric properties. Mechanical properties are normally low, but can be enhanced with glass or carbon fiber or molybdenum disulfide fillers. Properties are shown in Table 8.16.

8.4.1 Poly(tetrafluoroethylene)

Poly(tetrafluoroethylene) (PTFE) is a crystalline, very heat-resistant (up to 250°C) chemical-resistant polymer. PTFE has the lowest coefficient of friction of any polymer. It does not soften like other thermoplastics, and has to be processed by unconventional techniques (PTFE powder is compacted to the desired shape and sintered).

Uses. PTFE applications include non-stick coatings on cookware; non-lubricated bearings; chemical-resistant pipe, fittings, valves, and pump parts; high-temperature electrical parts; and gaskets, seals, and packings.

8.4.2 Poly(chlorotrifluoroethylene)

Poly(chlorotrifluoroethylene) (CTFE) is less crystalline and exhibits higher rigidity and strength than PTFE. Poly(chlorotrifluoroethylene) has excellent chemical resistance and heat resistance up to 200°C. Unlike PTFE, CTFE can be molded and extruded by conventional processing techniques.

Table 8.14 Typical Properties of Modified Polyphenylene Ether Resins

Property	190 Grade	225 Grade	300 Grade
Density (Mg/m ³)	1.080	1.090	1.060
Tensile modulus (GPa)	2.5	2.4	—
Tensile strength (MPa)	48	55	76
Elongation at break (%)	35	35	—
Flexural modulus (GPa)	2.2	2.4	2.4
Flexural strength (MPa)	57	76	104
Notched Izod (kJ/m)	0.37	0.32	0.53
Heat deflection temperature at 0.45 MPa (°C)	96	118	157
Heat deflection temperature at 1.81 MPa (°C)	88	107	149
Constant service temperature (°C)	—	95	—
Hardness (Rockwell)	R115	R116	R119
Linear thermal expansion (10 ⁻⁵ mm/mm-K)	—	—	5.9
Linear mold shrinkage (in./in.)	0.006	0.006	0.006

Table 8.15 Typical Properties of Polyimides

Property	Polyimide	Polyetherimide		Polyamideimide	
		Unfilled	30% Glass Fiber	Unfilled	30% Glass Fiber
Density (Mg/m ³)	—	1.27	1.51	1.38	1.57
Tensile modulus (GPa)	2.65	2.97	10.3	4.83	10.7
Tensile strength (MPa)	195	97	193	117	205
Elongation at break (%)	90	60	3	10	5
Notched Izod (kJ/m)	—	0.6	0.11	0.13	0.11
Heat deflection temperature at 0.45 MPa (°C)	—	410	414	—	—
Heat deflection temperature at 1.81 MPa (°C)	—	392	410	260	274
Constant service temperature (°C)	—	R109	M125	E78	E94
Hardness (Rockwell)	—	R109	M125	E78	E94
Linear thermal expansion (10 ⁻⁵ mm/mm-K)	—	5.6	2.0	3.60	1.80
Linear mold shrinkage (in./in.)	—	0.5	0.2	—	0.25

Uses. CTFE applications include electrical insulation, cable jacketing, electrical and electronic coil forms, pipe and pump parts, valve diaphragms, and coatings for corrosive process equipment and other industrial parts.

8.4.3 Fluorinated Ethylene-Propylene

Copolymerization of tetrafluoroethylene with some hexafluoropropylene produces fluorinated ethylene-propylene polymer (FEP), which has less crystallinity, lower melting point, and improved impact strength than PTFE. FEP can be molded by normal thermoplastic techniques.

Uses. FEP applications include wire insulation and jacketing, high-frequency connectors, coils, gaskets, and tube sockets.

8.4.4 Polyvinylidene Fluoride

Polyvinylidene fluoride (PVDF) has high tensile strength and better ability to be processed but less thermal and chemical resistance than FEP, CTFE, and PTFE.

Table 8.16 Typical Properties of Fluoropolymers

Property	PTFE	CTFE	FEP	ETFE	ECTFE
Density (Mg/m ³)	2.160	2.100	2.150	1.700	1.680
Tensile modulus (GPa)	—	14.3	—	—	—
Tensile strength (MPa)	27.6	39.4	20.7	44.8	48.3
Elongation at break (%)	~ 275	~ 150	~ 300	100–300	200
Notched Izod (kJ/m)	—	0.27	0.15	—	—
Heat deflection temperature at 0.45 MPa (°C)	—	126	—	104	116
Heat deflection temperature at 1.81 MPa (°C)	—	75	—	71	77
Constant service temperature (°C)	260	199	204	—	150–170
Hardness	D55–65 (Shore)	D75–80 (Shore)	D55 (Shore)	D75 (Shore)	R93 (Rockwell)
Dielectric strength (MV/m)	23.6	19.7	82.7	7.9	19.3
Dielectric constant at 10 ² Hz	2.1	3.0	2.1	2.6	2.5
Dielectric constant at 10 ³ Hz	2.1	2.7	—	2.6	2.5
Linear thermal expansion (10 ⁻⁵ mm/mm-K)	9.9	4.8	9.3	13.68	—
Linear mold shrinkage (in./in.)	0.033–0.053	0.008	—	—	< 0.025

Table 8.17 Properties of General Purpose Elastomers

Rubber	ASTM Nomenclature	Outstanding Characteristic	Property Deficiency	Temperature Use Range (°C)
Butadiene rubber	BR	Very flexible; resistance to wear	Sensitive to oxidation; poor resistance to fuels and oil	-100 to 90
Natural rubber	NR	Similar to BR but less resilient	Similar to BR	-50 to 80
Isoprene rubber	IR	Similar to BR but less resilient	Similar to BR	-50 to 80
Isobutylene-isoprene rubber (butyl rubber)	IIR	High flexibility; low permeability to air		-45 to 150
Chloroprene	CR	Flame resistant; fair fuel and oil resistance; increased resistance toward oxygen, ozone, heat, light	Poor low temperature flexibility	-40 to 115
Nitrile-butadiene	NBR	Good resistance to fuels, oils, and solvents; improved abrasion resistance	Lower resilience; higher hysteresis; poor electrical properties; poorer low temperature flexibility	-50 to 80
Styrene-butadiene rubber	SBR	Relatively low cost	Less resilience; higher hysteresis; limited low temperature flexibility	-50 to 80
Ethylene-propylene copolymer	EPDM	Resistance to ozone and weathering	Poor hydrocarbon and oil resistance	-50 to < 175
Polysulfide	T	Chemical resistance; resistance to ozone and weathering	Creep; low resilience	-45 to 120

Table 8.18 Properties of Specialty Elastomers

Elastomer	ASTM Nomenclature	Temperature Use Range (°C)	Outstanding Characteristic	Typical Applications
Silicones (polydimethylsiloxane)	MQ	-100 to 300	Wide temperature range; resistance to aging, ozone, sunlight; very high gas permeability	Seals, molded and extruded goods; adhesives, sealants; biomedical; personal care products
Fluoroelastomers	CFM	-40 to 200	Resistance to heat, oils, chemical	Seals such as O-rings, corrosion resistant coatings
Acrylic	AR	-40 to 200	Oil, oxygen, ozone, and sunlight resistance	Seals, hose
Epichlorohydrin	ECO	-18 to 150	Resistance to oil, fuels; some flame resistance; low gas permeability	Hose, tubing, coated fabrics, vibration isolators
Chlorosulfonated	CSM	-40 to 150	Resistance to oil, ozone weathering, oxidizing chemicals	Automotive hose, wire and cable, linings for reservoirs
Chlorinated polyethylene	CM	-40 to 150	Resistance to oils, ozone, chemicals	Impact modifier, automotive applications
Ethylene-acrylic		-40 to 175	Resistance to ozone, weathering	Seals, insulation, vibration damping
Propylene oxide		-6- to 150	Low temperature properties	Motor mounts

Uses. Polyvinylidene fluoride applications include seals and gaskets, diaphragms, and piping.

8.4.5 Poly(ethylene chlorotrifluoroethylene)

The copolymer of ethylene and chlorotrifluoroethylene is poly(ethylene chlorotrifluoroethylene) (ECTFE). It has high strength and chemical and impact resistance. ECTFE can be processed by conventional techniques.

Uses. Poly(ethylene chlorotrifluoroethylene) applications include wire and cable coatings, chemical resistant coatings and linings, molded lab ware, and medical packing.

8.4.6 Poly(vinyl fluoride)

Poly(vinyl fluoride) films exhibit excellent outdoor durability. It is the least chemical-resistant fluoropolymer.

Uses. Poly(vinyl fluoride) uses include glazing, lighting, and coatings on presurfaced exterior building panels.

8.5 THERMOSETS

Thermosetting resins are used in molded and laminated plastics. They are first polymerized into a low molecular weight, linear or slightly branched polymer or oligomer that is still soluble, fusible, and highly reactive during final processing. Thermoset resins are generally highly filled with mineral fillers and glass fibers. Thermosets are generally catalyzed and/or heated to finish the polymerization reaction, which cross links them to almost infinite molecular weight. This step is often referred to as curing. Such cured polymers cannot be reprocessed or reshaped.

The high filler loading and the high cross-link density of thermoset resins result in very high densities and very low ductility, but very high rigidity and good chemical resistance.

8.5.1 Phenolic Resins

Phenolic resins combine the high reactivity of phenol and formaldehyde to form pre-polymers and oligomers called resoles and novolaks. These materials are combined with fibrous fillers to give a phenolic resin, which when heated provides rapid, complete cross linking to cured structures. The highly cross-linked aromatic structure has high hardness, rigidity, strength, heat resistance, chemical resistance, and good electrical properties.

Uses. Phenolic applications include automotive uses (distributor caps, rotors, brake linings), appliance parts (pot handles, knobs, bases, electrical/electronic components (connectors, circuit breakers, switches), and adhesive in laminates (e.g., plywood).

8.5.2 Epoxy Resins

The most common epoxy resins are prepared from the reaction of bisphenol A and epichlorohydrin to yield low molecular weight resins that are liquid either at room temperature or on warming. Each polymer chain usually contains two or more epoxy groups. The high reactivity of the epoxides with amines, anhydrides, and other curing agents provides facile conversion into highly cross-linked materials. Cured epoxy resins exhibit hardness, strength, heat resistance, electrical resistance, and broad chemical resistance.

Uses. Epoxy resins are used in glass-reinforced, high-strength composites in aerospace, pipes, tanks, pressure vessels; encapsulation or casting of various electrical and electronic components (printed wiring boards, etc.); adhesives; protective coatings in appliances, flooring, and industrial equipment; and sealants.

8.5.3 Unsaturated Polyesters

Unsaturated polyesters are prepared by the condensation polymerization of various diols and maleic anhydride to give a very viscous liquid that is then dissolved in styrene monomer. The addition of styrene lowers the viscosity to a level suitable for impregnation and lamination of glass fibers. The low molecular weight polyester has numerous fumarate ester units that provide easy reactivity with styrene monomer. In combination with reinforcing materials like glass fiber, cured resins offer outstanding strength, high rigidity, high strength-to-weight ratio, impact strength, and chemical resistance. Properly formulated, reinforced unsaturated polyesters are commonly referred to as sheet molding compound (SMC) or reinforced plastics. SMC typically is formulated with 50% calcium carbonate filler, 25% long glass fiber (> 1 in.), and 25% unsaturated polyester. The highly filled nature of SMC results in high density and a brittle, easily pitted surface.

Bulk molding compound (BMC) is formulated similarly to SMC except that 1/4-inch chopped glass is used. The shorter glass length gives easier process but lower strength and impact.

Uses. The prime use of unsaturated polyesters is in combination with glass fibers in high-strength composites and in SMC and BMC materials. The applications include transportation markets (large body parts for automobiles, trucks, trailers, buses, and aircraft), marine markets (small to medium-sized boat hulls and associated marine equipment), building panels, housing and bathroom components (bathtub and shower stalls), appliances, and electrical/electronic components.

8.5.4 Alkyd Resins

Alkyd resins are based on branched pre-polymers from glycerol, phthalic anhydride, and glyceryl esters of fatty acids. Alkyds have excellent heat resistance, are dimensionally stable at high temperatures, and have excellent dielectric strength (> 14 MV/m), high resistance to electrical leakage, and excellent arc resistance.

Uses. Alkyd resin applications include drying oils in enamel paints, lacquers for automobiles and appliances; and molding compounds when formulated with reinforcing fillers for electrical applications (circuit breaker insulation, encapsulation of capacitors and resistors, and coil forms).

8.5.5 Diallyl Phthalate

Diallyl Phthalate (DAP) is the most widely used compound in the allylic family of thermosets. The neat resin is a medium viscosity liquid. These low molecular weight pre-polymers can be reinforced and compression molded into highly cross-linked, completely cured products.

The most outstanding properties of cured DAP are excellent dimensional stability and high insulation resistance. In addition, DAP materials have high dielectric strength and excellent arc resistance and chemical resistance.

Uses. DAP applications include electronic parts, electrical connectors, bases, and housings. DAP is also used as a coating and impregnating material.

8.5.6 Amino Resins

The two main members of the amino family of thermosets are the melamine- and urea-based resins. They are prepared from the reaction of melamine and urea with formaldehyde. In general, these materials exhibit extreme hardness, scratch resistance, electrical resistance, and chemical resistance.

Uses. Melamine resins find use in colorful, rugged dinnerware; decorative laminates (countertops, tabletops, and furniture surfacing); electrical applications (switchboard panels, circuit breaker parts, arc barriers, and armature and slot wedges); and adhesives and coatings.

Urea resins are used in particle board binders, decorative housings, closures, electrical parts, coatings, and paper and textile treatment.

8.6 GENERAL-PURPOSE ELASTOMERS

Elastomers are polymers that can be stretched substantially beyond their original length and will retract rapidly and forcibly to essentially their original dimensions upon release of the force.

The optimum properties and/or economics of many rubbers are obtained through formulating with reinforcing agents, fillers, extending oils, vulcanizing agents, antioxidants, pigments, and so on. End-use markets for formulated rubbers include automotive tire products (including tubes, retread applications, valve stems, and inner liners), adhesives, cements, caulks, sealants, latex foam products, hose (automotive, industrial, and consumer applications), belting (V-conveyor and trimming), footwear (heels, soles, slab stock, boots, and canvas), and molded, extruded, and calendered products (athletic goods, flooring, gaskets, household products, O-rings, blown sponge, thread, and rubber sundries). A list of general-purpose elastomers and properties is summarized in Table 8.17.

8.7 SPECIALTY ELASTOMERS

Specialty rubbers offer higher performance than general-purpose rubbers and find use in more demanding applications. They are more costly and hence are produced in smaller volumes. Properties and uses are summarized in Table 8.18.