SECTION 10
POLYMERS, RUBBERS, FATS, OILS, AND WAXES

10.1 POLYMERS

Polymers are mixtures of macromolecules with similar structures and molecular weights that exhibit some average characteristic properties. In some polymers long segments of linear polymer chains are oriented in a regular manner with respect to one another. Such polymers have many of the physical characteristics of crystals and are said to be *crystalline.* Polymers that have polar functional groups show a considerable tendency to be crystalline. Orientation is aided by alignment of dipoles on different chains. Van der Waals' interactions between long hydrocarbon chains may provide sufficient total attractive energy to account for a high degree of regularity within the polymers.

Irregularities such as branch points, comonomer units, and cross-links lead to *amorphous* polymers. They do not have true melting points but instead have glass transition temperatures at which the rigid and glasslike material becomes a viscous liquid as the temperature is raised.

Elastomers. Elastomers is a generic name for polymers that exhibit rubberlike elasticity. Elastomers are soft yet sufficiently elastic that they can be stretched several hundred percent under tension. When the stretching force is removed, they retract rapidly and recover their original dimensions.

Polymers that soften or melt and then solidify and regain their original properties on cooling are called *thermoplastic.* A thermoplastic polymer is usually a single strand of linear polymer with few if any cross-links.

Thermosetting Polymers. Polymers that soften or melt on warming and then become infusible solids are called *thermosetting.* The term implies that thermal decomposition has not taken place. Thermosetting plastics contain a cross-linked polymer network that extends through the finished article, making it stable to heat and insoluble in organic solvents. Many molded plastics are shaped while molten and are then heated further to become rigid solids of desired shapes.

Synthetic Rubbers.   Synthetic rubbers are polymers with rubberlike characteristics that are prepared from dienes or olefins. Rubbers with special properties can also be prepared from other polymers, such as polyacrylates, fluorinated hydrocarbons, and polyurethanes.

Structural Differences.   Polymers exhibit structural differences. A *linear* polymer consists of long segments of single strands that are oriented in a regular manner with respect to one another. *Branched* polymers have substituents attached to the repeating units that extend the polymer laterally. When these units participate in chain propagation and link together chains, a *cross-linked* polymer is formed. A *ladder* polymer results when repeating units have a tetravalent structure such that a polymer consists of two backbone chains regularly cross-linked at short intervals.

Generally polymers involve bonding of the most substituted carbon of one monomeric unit to the least substituted carbon atom of the adjacent unit in a *head-to-tail* arrangement. Substituents appear on alternate carbon atoms. *Tacticity* refers to the configuration of substituents relative to the backbone axis. In an *isotactic* arrangement, substituents are on the same plane of the backbone axis; that is, the configuration at each chiral center is identical.

$$
\begin{array}{cccc}
Y & Y & Y & Y \\
| & | & | & | \\
-C- & C- & C- & C-
\end{array}
$$

In a *syndiotactic* arrangement, the substituents are in an ordered alternating sequence, appearing alternately on one side and then on the other side of the chain, thus

$$
\begin{array}{cccc}
Y & & Y & \\
| & & | & \\
-C- & C- & C- & C- \\
& | & & | \\
& Y & & Y
\end{array}
$$
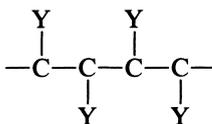
In an *atactic* arrangement, substituents are in an unordered sequence along the polymer chains.

Copolymerization.   Copolymerization occurs when a mixture of two or more monomer types polymerizes so that each kind of monomer enters the polymer chain. The fundamental structure resulting from copolymerization depends on the nature of the monomers and the relative rates of monomer reactions with the growing polymer chain. A tendency toward alternation of monomer units is common.

$$-X-Y-X-Y-X-Y-$$

Random copolymerization is rather unusual. Sometimes a monomer which does not easily form a homopolymer will readily add to a reactive group at the end of a growing polymer chain. In turn, that monomer tends to make the other monomer much more reactive.

In *graft copolymers* the chain backbone is composed of one kind of monomer and the branches are made up of another kind of monomer.

$$
\begin{array}{cccccc}
-X- & X- & X- & X- & X- & X- \\
| & & & | & & \\
Y & & & Y & & \\
| & & & | & & \\
Y & & & Y & &
\end{array}
$$
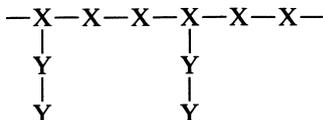
The structure of a *block copolymer* consists of a homopolymer attached to chains of another homopolymer.

$$-XXXX-YYY-XXXX-YYY-$$

Configurations around any double bond give rise to *cis* and *trans* stereoisomerism.

10.2 ADDITIVES TO POLYMERS

10.2.1 Antioxidants

Antioxidants markedly retard the rate of autoxidation throughout the useful life of the polymer. Chain-terminating antioxidants have a reactive —NH or —OH functional group and include compounds such as secondary aryl amines or hindered phenols. They function by transfer of hydrogen to free radicals, principally to peroxy radicals. Butylated hydroxytoluene is a widely used example.

Peroxide-decomposing antioxidants destroy hydroperoxides, the sources of free radicals in polymers. Phosphites and thioesters such as tris(nonylphenyl) phosphite, distearyl pentaerythritol diphosphite, and dialkyl thiodipropionates are examples of peroxide-decomposing antioxidants.

10.2.2 Antistatic Agents

External antistatic agents are usually quaternary ammonium salts of fatty acids and ethoxylated glycerol esters of fatty acids that are applied to the plastic surface. Internal antistatic agents are compounded into plastics during processing. Carbon blacks provide a conductive path through the bulk of the plastic. Other types of internal agents must bloom to the surface after compounding in order to be active. These latter materials are ethoxylated fatty amines and ethoxylated glycerol esters of fatty acids, which often must be individually selected to match chemically each plastic type.

Antistatic agents require ambient moisture to function. Consequently their effectiveness is dependent on the relative humidity. They provide a broad range of protection at 50% relative humidity. Much below 20% relative humidity, only materials which provide a conductive path through the bulk of the plastic to ground (such as carbon black) will reduce electrostatic charging.

10.2.3 Chain-Transfer Agents

Chain-transfer agents are used to regulate the molecular weight of polymers. These agents react with the developing polymer and interrupt the growth of a particular chain. The products, however, are free radicals that are capable of adding to monomers and initiating the formation of new chains. The overall effect is to reduce the average molecular weight of the polymer without reducing the rate of polymerization. Branching may occur as a result of chain transfer between a growing but rather short chain with another and longer polymer chain. Branching may also occur if the radical end of a growing chain abstracts a hydrogen from a carbon atom four or five carbons removed from the end. Thiols are commonly used as chain-transfer agents.

10.2.4 Coupling Agents

Coupling agents are molecular bridges between the interface of an inorganic surface (or filler) and an organic polymer matrix. Titanium-derived coupling agents interact with the free protons at the inorganic interface to form organic monomolecular layers on the inorganic surface. The titanate-coupling-agent molecule has six functions:

$$\overset{1}{}\qquad\qquad\overset{2\ \ 3\ \ 4\ \ 5\ 6}{}$$
$$(RO)_m—Ti—(O—Y—R^2—Z)_n$$
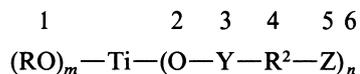
where

Type	m	n
Monoalkoxy	1	3
Coordinate	4	2
Chelate	1	2

Function 1 is the attachment of the hydrolyzable portion of the molecule to the surface of the inorganic (or proton-bearing) species.

Function 2 is the ability of the titanate molecule to transesterify.

Function 3 affects performance as determined by the chemistry of alkylate, carboxyl, sulfonyl, phenolic, phosphate, pyrophosphate, and phosphite groups.

Function 4 provides van der Waals' entanglement via long carbon chains.

Function 5 provides thermoset reactivity via functional groups such as methacrylates and amines.

Function 6 permits the presence of two or three pendent organic groups. This allows all functionality to be controlled to the first-, second-, or third-degree levels.

Silane coupling agents are represented by the formula

$$Z\!-\!R\!-\!SiY_3$$

where Y represents a hydrolyzable group (typically alkoxy); Z is a functional organic group, such as amino, methacryloxy, epoxy; and R typically is a small aliphatic linkage that serves to attach the functional organic group to silicon in a stable fashion. Bonding to surface hydroxy groups of inorganic compounds is accomplished by the $-SiY_3$ portion, either by direct bonding of this group or more commonly via its hydrolysis product $-Si(OH)_3$. Subsequent reaction of the functional organic group with the organic matrix completes the coupling reaction and establishes a covalent chemical bond from the organic phase through the silane coupling agent to the inorganic phase.

10.2.5 Flame Retardants

Flame retardants are thought to function via several mechanisms, dependent upon the class of flame retardant used. Halogenated flame retardants are thought to function principally in the vapor phase either as a diluent and heat sink or as a free-radical trap that stops or slows flame propagation. Phosphorus compounds are thought to function in the solid phase by forming a glaze or coating over the substrate that prevents the heat and mass transfer necessary for sustained combustion. With some additives, as the temperature is increased, the flame retardant acts as a solvent for the polymer, causing it to melt at lower temperatures and flow away from the ignition source.

Mineral hydrates, such as alumina trihydrate and magnesium sulfate heptahydrate, are used in highly filled thermoset resins.

10.2.6 Foaming Agents (Chemical Blowing Agents)

Foaming agents are added to polymers during processing to form minute gas cells throughout the product. Physical foaming agents include liquids and gases. Compressed nitrogen is often used in

injection molding. Common liquid foaming agents are short-chain aliphatic hydrocarbons in the C_5 to C_7 range and their chlorinated or fluorinated analogs.

The chemical foaming agent used varies with the temperature employed during processing. At relatively low temperatures (15 to 200°C), the foaming agent is often 4,4′-oxybis-(benzenesulfonylhydrazide) or p-toluenesulfonylhydrazide. In the midrange (160 to 232°C), either sodium hydrogen carbonate or 1,1′azobisformamide is used. For the high range (200 to 285°C), there are p-toluenesulfonyl semicarbazide, 5-phenyltetrazole and analogs, and trihydrazinotriazine.

10.2.7 Inhibitors

Inhibitors slow or stop polymerization by reacting with the initiator or the growing polymer chain. The free radical formed from an inhibitor must be sufficiently unreactive that it does not function as a chain-transfer agent and begin another growing chain. Benzoquinone is a typical free-radical chain inhibitor. The resonance-stabilized free radical usually dimerizes or disproportionates to produce inert products and end the chain process.

10.2.8 Lubricants

Materials such as fatty acids are added to reduce the surface tension and improve the handling qualities of plastic films.

TABLE 10.1   Plastic Families

Acetals	Fluorocarbons (*continued*)
Acrylics	Poly(vinylidene fluoride) (PVDF)
Poly(methyl methacrylate) (PMMA)	Ethylene-chlorotrifluoroethylene copolymer
Poly(acrylonitrile)	Ethylene-tetrafluoroethylene copolymer
Alkyds	Poly(vinyl fluoride) (PVF)
Alloys	Melamine formaldehyde
Acrylic-poly(vinyl chloride) alloy	Melamine phenolic
Acrylonitrile-butadiene-styrene-poly(vinyl chloride) alloy (ABS-PVC)	Nitrile resins
Acrylonitrile-butadiene-styrene-polycarbonate alloy (ABS-PC)	Phenolics
Allyls	Polyamides
Allyl-diglycol-carbonate polymer	Nylon 6
Diallyl phthalate (DAP) polymer	Nylon 6/6
Cellulosics	Nylon 6/9
Cellulose acetate resin	Nylon 6/12
Cellulose-acetate-propionate resin	Nylon 11
Cellulose-acetate-butyrate resin	Nylon 12
Cellulose nitrate resin	Aromatic nylons
Ethyl cellulose resin	Poly(amide-imide)
Rayon	Poly(aryl ether)
Chlorinated polyether	Polycarbonate (PC)
Epoxy	Polyesters
Fluorocarbons	Poly(butylene terephthalate) (PBT) [also called polytetramethylene terephthalate (PTMT)]
Poly(tetrafluoroethylene) (PTFE)	Poly(ethylene terephthalate) (PET)
Poly(chlorotrifluoroethylene) (PCTFE)	Unsaturated polyesters (SMC, BMC)
Perfluoroalkoxy (PFA) resin	Butadiene-maleic acid copolymer (BMC)
Fluorinated ethylene-propylene (FEP) resin	Styrene-maleic acid copolymer (SMC)
	Polyimide

TABLE 10.1 Plastic Families (*Continued*)

Poly(methylpentene)	Sulfones (*continued*)
Polyolefins (PO)	Poly(ether sulfone)
Low-density polyethylene (LDPE)	Poly(phenyl sulfone)
High-density polyethylene (HDPE)	Thermoplastic elastomers
Ultrahigh-molecular-weight polyethylene	Polyolefin
(UHMWPE)	Polyester
Polypropylene (PP)	Block copolymers
Polybutylene (PB)	Styrene-butadiene block copolymer
Polyallomers	Styrene-isoprene block copolymer
Poly(phenylene oxide)	Styrene-ethylene block copolymer
Poly(phenylene sulfide) (PPS)	Styrene-butylene block copolymer
Polyurethanes	Urea formaldehyde
Silicones	Vinyls
Styrenics	Poly(vinyl chloride) (PVC)
Polystyrene (PS)	Poly(vinyl acetate) (PVAC)
Acrylonitrile-butadiene-styrene (ABS) copolymer	Poly(vinylidene chloride)
Styrene-acrylonitrile (SAN) copolymer	Poly(vinyl butyrate) (PVB)
Styrene-butadiene copolymer	Poly(vinyl formal)
Sulfones	Poly(vinyl alcohol) (PVAL)
Polysulfone (PSF)	

10.2.9 Plasticizers

Plasticizers are relatively nonvolatile liquids which are blended with polymers to alter their properties by intrusion between polymer chains. Diisooctyl phthalate is a common plasticizer. A plasticizer must be compatible with the polymer to avoid bleeding out over long periods of time. Products containing plasticizers tend to be more flexible and workable.

10.2.10 Ultraviolet Stabilizers

2-Hydroxybenzophenones represent the largest and most versatile class of ultraviolet stabilizers that are used to protect materials from the degradative effects of ultraviolet radiation. They function by absorbing ultraviolet radiation and by quenching electronically excited states.

    Hindered amines, such as 4-(2,2,6,6-tetramethylpiperidinyl) decanedioate, serve as radical scavengers and will protect thin films under conditions in which ultraviolet absorbers are ineffective. Metal salts of nickel, such as dibutyldithiocarbamate, are used in polyolefins to quench singlet oxygen or electronically excited states of other species in the polymer. Zinc salts function as peroxide decomposers.

10.2.11 Vulcanization and Curing

Originally, vulcanization implied heating natural rubber with sulfur, but the term is now also employed for curing polymers. When sulfur is employed, sulfide and disulfide cross-links form between polymer chains. This provides sufficient rigidity to prevent *plastic flow*. Plastic flow is a process in which coiled polymers slip past each other under an external deforming force; when the force is released, the polymer chains do not completely return to their original positions.

    Organic peroxides are used extensively for the curing of unsaturated polyester resins and the polymerization of monomers having vinyl unsaturation. The —O—O— bond is split into free radicals which can initiate polymerization or cross-linking of various monomers or polymers.

10.3 FORMULAS AND KEY PROPERTIES OF PLASTIC MATERIALS

10.3.1 Acetals

10.3.1.1 Homopolymer.   Acetal homopolymers are prepared from formaldehyde and consist of high-molecular-weight linear polymers of formaldehyde.

$$H-\overset{\overset{\displaystyle H}{|}}{C}=O \rightarrow \left[-\overset{\overset{\displaystyle H}{|}}{\underset{\underset{\displaystyle H}{|}}{C}}-O- \right]_n$$
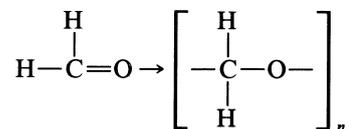
The good mechanical properties of this homopolymer result from the ability of the oxymethylene chains to pack together into a highly ordered crystalline configuration as the polymers change from the molten to the solid state.

Key properties include high melt point, strength and rigidity, good frictional properties, and resistance to fatigue. Higher molecular weight increases toughness but reduces melt flow.

10.3.1.2 Copolymer.   Acetal copolymers are prepared by copolymerization of 1,3,5-trioxane with small amounts of a comonomer. Carbon-carbon bonds are distributed randomly in the polymer chain. These carbon-carbon bonds help to stabilize the polymer against thermal, oxidative, and acidic attack.

10.3.2 Acrylics

10.3.2.1 Poly(methyl Methacrylate).   The monomer used for poly(methyl methacrylate), 2-hydroxy-2-methylpropanenitrile, is prepared by the following reaction:

$$CH_3-\overset{\overset{\displaystyle }{\underset{\underset{\displaystyle O}{\parallel}}{C}}}{}-CH_3 + HCN \rightarrow CH_3-\overset{\overset{\displaystyle OH}{|}}{\underset{\underset{\displaystyle CN}{|}}{C}}-CH_3$$
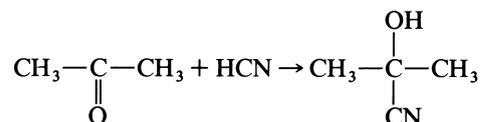
2-Hydroxy-2-methylpropanenitrile is then reacted with methanol (or other alcohol) to yield methacrylate ester. Free-radical polymerization is initiated by peroxide or azo catalysts and produce poly(methyl methacrylate) resins having the following formula:

$$\left[-CH_2-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle COOCH_3}{|}}{C}}- \right]_n$$
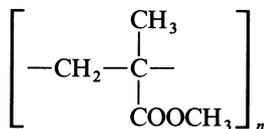
Key properties are improved resistance to heat, light, and weathering. This polymer is unaffected by most detergents, cleaning agents, and solutions of inorganic acids, alkalies, and aliphatic hydrocarbons. Poly(methyl methacrylate) has light transmittance of 92% with a haze of 1 to 3% and its clarity is equal to glass.

10.3.2.2   Poly(methyl Acrylate).   The monomer used for preparing poly(methyl acrylate) is produced by the oxidation of propylene. The resin is made by free-radical polymerization initiated by peroxide or azo catalysts and has the following formula:

$$\left[-CH_2-CH- \atop \qquad\qquad COOCH_3 \right]_n$$
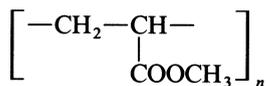
Resins vary from soft, elastic, film-forming materials to hard plastics.

10.3.2.3   Poly(acrylic Acid) and Poly(methacrylic Acid).   Glacial acrylic acid and glacial methacrylic acid can be polymerized to produce water-soluble polymers having the following structures:

$$\left[-CH_2-CH- \atop \qquad\qquad COOH \right]_n \qquad \left[{CH_3 \atop -CH_2-C- \atop \qquad\quad COOH} \right]_n$$
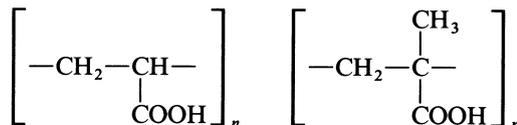
These monomers provide a means for introducing carboxyl groups into copolymers. In copolymers these acids can improve adhesion properties, improve freeze-thaw and mechanical stability of polymer dispersions, provide stability in alkalies (including ammonia), increase resistance to attack by oils, and provide reactive centers for cross-linking by divalent metal ions, diamines, or epoxides.

10.3.2.4   Functional Group Methacrylate Monomers.   Hydroxyethyl methacrylate and dimethylaminoethyl methacrylate produce polymers having the following formulas:

$$\left[{CH_3 \atop -CH_2-C- \atop \qquad\quad COOCH_2CH_2OH} \right]_n \qquad \left[{CH_3 \atop -CH_2-C- \atop \qquad\quad COOCH_2CH_2N(CH_3)_2} \right]_n$$
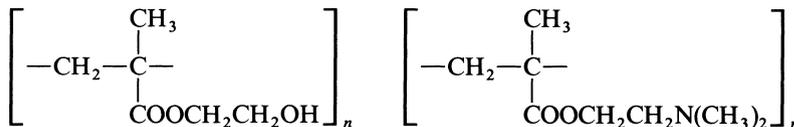
The use of hydroxyethyl (also hydroxypropyl) methacrylate as a monomer permits the introduction of reactive hydroxyl groups into the copolymers. This offers the possibility for subsequent cross-linking with an HO-reactive difunctional agent (diisocyanate, diepoxide, or melamine-formaldehyde resin). Hydroxyl groups promote adhesion to polar substrates.

Use of dimethylaminoethyl (also *tert*-butylaminoethyl) methacrylate as a monomer permits the introduction of pendent amino groups which can serve as sites for secondary cross-linking, provide a way to make the copolymer acid-soluble, and provide anchoring sites for dyes and pigments.

10.3.2.5   Poly(acrylonitrile).   Poly(acrylonitrile) polymers have the following formula:

$$\left[-CH_2-CH- \atop \qquad\quad CN \right]_n$$
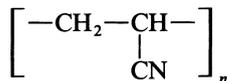
10.3.3   Alkyds

Alkyds are formulated from polyester resins, cross-linking monomers, and fillers of mineral or glass. The unsaturated polyester resins used for thermosetting alkyds are the reaction products of polyfunctional organic alcohols (glycols) and dibasic organic acids.

Key properties of alkyds are dimensional stability, colorability, and arc track resistance. Chemical resistance is generally poor.

10.3.4 Alloys

Polymer alloys are physical mixtures of structurally different homopolymers or copolymers. The mixture is held together by secondary intermolecular forces such as dipole interaction, hydrogen bonding, or van der Waals' forces.

Homogeneous alloys have a single glass transition temperature which is determined by the ratio of the components. The physical properties of these alloys are averages based on the composition of the alloy.

Heterogeneous alloys can be formed when graft or block copolymers are combined with a compatible polymer. Alloys of incompatible polymers can be formed if an interfacial agent can be found.

10.3.5 Allyls

10.3.5.1 Diallyl Phthalate (and Diallyl 1,3-Phthalate).   These allyl polymers are prepared from

$$CH_2-CH=CH_2$$
$$CH_2-CH=CH_2$$
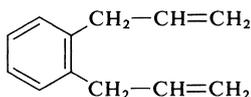
These resulting polymers are solid, linear, internally cyclized, thermoplastic structures containing unreacted allylic groups spaced at regular intervals along the polymer chain.

Molding compounds with mineral, glass, or synthetic fiber filling exhibit good electrical properties under high humidity and high temperature conditions, stable low-loss factors, high surface and volume resistivity, and high arc and track resistance.

10.3.6 Cellulosics

10.3.6.1 Cellulose Triacetate.   Cellulose triacetate is prepared according to the following reaction:

$$C_6H_{10}O_5 + \begin{matrix} CH_3-C \overset{O}{\diagup} \\ O \\ CH_3-C \underset{O}{\diagdown} \end{matrix} \longrightarrow \text{cellulose triester}$$
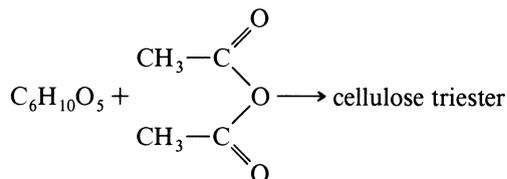
Because cellulose triacetate has a high softening temperature, it must be processed in solution. A mixture of dichloromethane and methanol is a common solvent.

Cellulose triacetate sheeting and film have good gauge uniformity and good optical clarity. Cellulose triacetate products have good dimensional stability and resistance to water and have good folding endurance and burst strength. It is highly resistant to solvents such as acetone. Cellulose triacetate products have good heat resistance and a high dielectric constant.

10.3.6.2 Cellulose Acetate, Propionate, and Butyrate.   Cellulose acetate is prepared by hydrolyzing the triester to remove some of the acetyl groups; the plastic-grade resin contains 38 to 40%

acetyl. The propionate and butyrate esters are made by substituting propionic acid and its anhydride (or butyric acid and its anhydride) for some of the acetic acid and acetic anhydride. Plastic grades of cellulose-acetate-propionate resin contain 39 to 47% propionyl and 2 to 9% acetyl; cellulose-acetate-butyrate resins contain 26 to 39% butyryl and 12 to 15% acetyl.

These cellulose esters form tough, strong, stiff, hard plastics with almost unlimited color possibilities. Articles made from these plastics have a high gloss and are suitable for use in contact with food.

10.3.6.3 Cellulose Nitrate. Cellulose nitrate is prepared according to the following reaction:

$$C_6H_{10}O_5 + HNO_3 \rightarrow [-C_6H_7O_2(OH)(ONO_2)_2-]_n$$
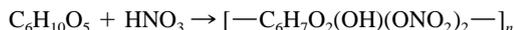
The nitrogen content for plastics is usually about 11%, for lacquers and cement base it is 12%, and for explosives it is 13%. The standard plasticizer added is camphor.

Key properties of cellulose nitrate are good dimensional stability, low water absorption, and toughness. Its disadvantages are its flammability and lack of stability to heat and sunlight.

10.3.6.4 Ethyl Cellulose. Ethyl cellulose is prepared by reacting cellulose with caustic to form caustic cellulose, which is then reacted with chloroethane to form ethyl cellulose. Plastic-grade material contains 44 to 48% ethoxyl.

Although not as resistant as cellulose esters to acids, it is much more resistant to bases. An outstanding feature is its toughness at low temperatures.

10.3.6.5 Rayon. Viscose rayon is obtained by reacting the hydroxy groups of cellulose with carbon disulfide in the presence of alkali to give xanthates. When this solution is poured (spun) into an acid medium, the reaction is reversed and the cellulose is regenerated (coagulated).

10.3.7 Epoxy

Epoxy resin is prepared by the following condensation reaction:
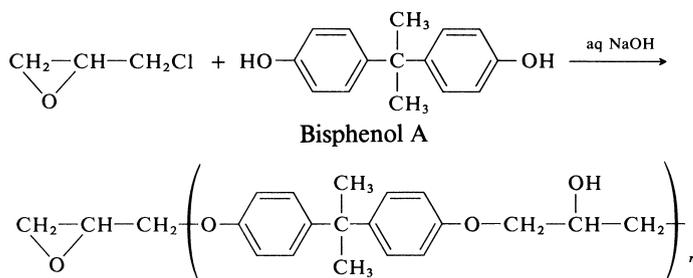
The condensation leaves epoxy end groups that are then reacted in a separate step with nucleophilic compounds (alcohols, acids, or amines). For use as an adhesive, the epoxy resin and the curing resin (usually an aliphatic polyamine) are packaged separately and mixed together immediately before use.

Epoxy novolac resins are produced by glycidation of the low-molecular-weight reaction products of phenol (or cresol) with formaldehyde. Highly cross-linked systems are formed that have superior performance at elevated temperatures.

10.3.8 Fluorocarbon

10.3.8.1 Poly(tetrafluoroethylene). Poly(tetrafluoroethylene) is prepared from tetrafluoroethylene and consists of repeating units in a predominantly linear chain:

$$F_2C{=}CF_2 \rightarrow [-CF_2-CF_2-]_n$$
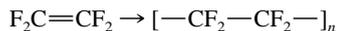
Tetrafluoroethylene polymer has the lowest coefficient of friction of any solid. It has remarkable chemical resistance and a very low brittleness temperature ($-100°C$). Its dielectric constant and loss factor are low and stable across a broad temperature and frequency range. Its impact strength is high.

10.3.8.2 Fluorinated Ethylene-Propylene Resin. Polymer molecules of fluorinated ethylene-propylene consist of predominantly linear chains with this structure:

$$\left[-CF_2-CF_2-CF_2-\underset{\underset{CF_3}{|}}{CF}- \right]_n$$
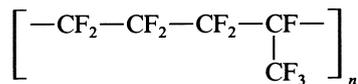
Key properties are its flexibility, translucency, and resistance to all known chemicals except molten alkali metals, elemental fluorine and fluorine precursors at elevated temperatures, and concentrated perchloric acid. It withstands temperatures from $-270°$ to $250°C$ and may be sterilized repeatedly by all known chemical and thermal methods.

10.3.8.3 Perfluoroalkoxy Resin. Perfluoroalkoxy resin has the following formula:

$$\left[-CF_2-CF_2-\underset{\underset{R}{\underset{|}{\underset{O}{|}}}}{CF}-CF_2-CF_2- \right]_n \qquad \text{where R is} -C_nF_{2n+1}$$
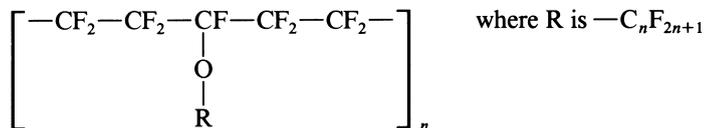
It resembles polytetrafluoroethylene and fluorinated ethylene propylene in its chemical resistance, electrical properties, and coefficient of friction. Its strength, hardness, and wear resistance are about equal to the former plastic and superior to that of the latter at temperatures above $150°C$.

10.3.8.4 Poly(vinylidene Fluoride). Poly(vinylidene fluoride) consists of linear chains in which the predominant repeating unit is

$$[-CH_2-CF_2-]_n$$

It has good weathering resistance and does not support combustion. It is resistant to most chemicals and solvents and has greater strength, wear resistance, and creep resistance than the preceding three fluorocarbon resins.

10.3.8.5 Poly(1-Chloro-1,2,2-Trifluoroethylene). Poly(1-chloro-1,2,2-trifluoroethylene) consists of linear chains in which the predominant repeating unit is

$$\left[-CF_2-\underset{\underset{Cl}{|}}{CF}- \right]_n$$

It possesses outstanding barrier properties to gases, especially water vapor. It is surpassed only by the fully fluorinated polymers in chemical resistance. A few solvents dissolve it at temperatures

above 100°C, and it is swollen by a number of solvents, especially chlorinated solvents. It is harder and stronger than perfluorinated polymers, and its impact strength is lower.

10.3.8.6 Ethylene-Chlorotrifluoroethylene Copolymer. Ethylene-chlorotrifluoroethylene copolymer consists of linear chains in which the predominant 1:1 alternating copolymer is

$$\left[-CH_2-CH_2-CF_2-\underset{\underset{Cl}{|}}{CF}- \right]_n$$

This copolymer has useful properties from cryogenic temperatures to 180°C. Its dielectric constant is low and stable over a broad temperature and frequency range.

10.3.8.7 Ethylene-Tetrafluoroethylene Copolymer. Ethylene-tetrafluoroethylene copolymer consists of linear chains in which the repeating unit is

$$[-CH_2-CH_2-CF_2-CF_2-]_n$$

Its properties resemble those of ethylene-chlorotrifluoroethylene copolymer.

10.3.8.8 Poly(vinyl Fluoride). Poly(vinyl fluoride) consists of linear chains in which the repeating unit is

$$[-CH_2-CHF-]_n$$

It is used only as a film, and it has good resistance to abrasion and resists staining. It also has outstanding weathering resistance and maintains useful properties from −100 to 150°C.

10.3.9 Nitrile Resins

The principal monomer of nitrile resins is acrylonitrile (see "Polyacrylonitrile"), which constitutes about 70% by weight of the polymer and provides the polymer with good gas barrier and chemical resistance properties. The remainder of the polymer is 20 to 30% methylacrylate (or styrene), with 0 to 10% butadiene to serve as an impact-modifying termonomer.

10.3.10 Melamine Formaldehyde

The monomer used for preparing melamine formaldehyde is formed as follows:

Hexamethylolmelamine

Hexamethylolmelamine can further condense in the presence of an acid catalyst; ether linkages can also form (see "Urea Formaldehyde"). A wide variety of resins can be obtained by careful selection of pH, reaction temperature, reactant ratio, amino monomer, and extent of condensation. Liquid coating resins are prepared by reacting methanol or butanol with the initial methylolated products. These can be used to produce hard, solvent-resistant coatings by heating with a variety of hydroxy, carboxyl, and amide functional polymers to produce a cross-linked film.

10.3.11 Phenolics

10.3.11.1 *Phenol-Formaldehyde Resin.*   Phenol-formaldehyde resin is prepared as follows:

$$C_6H_5OH + H_2C{=}O \rightarrow [{-}C_6H_2(OH)CH_2{-}]_n$$

 One-Stage Resins.   The ratio of formaldehyde to phenol is high enough to allow the thermosetting process to take place without the addition of other sources of cross-links.
 Two-Stage Resins.   The ratio of formaldehyde to phenol is low enough to prevent the thermosetting reaction from occurring during manufacture of the resin. At this point the resin is termed *novolac* resin. Subsequently, hexamethylenetetramine is incorporated into the material to act as a source of chemical cross-links during the molding operation (and conversion to the thermoset or cured state).

10.3.12 Polyamides

10.3.12.1 *Nylon 6, 11, and 12.*   This class of polymers is polymerized by addition reactions of ring compounds that contain both acid and amine groups on the monomer.
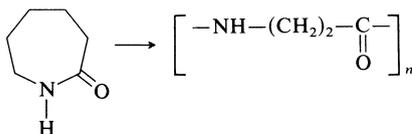
Nylon 6 is polymerized from 2-oxohexamethyleneimine (6 carbons); nylon 11 and 12 are made this way from 11- and 12-carbon rings, respectively.

10.3.12.2 *Nylon 6/6, 6/9, and 6/12.*   As illustrated below, nylon 6/6 is polymerized from 1,6-hexanedioic acid (six carbons) and 1,6-hexanediamine (six carbons).

$$HOOC{-}(CH_2)_4{-}COOH + H_2N{-}CH_2{-}(CH_2)_4{-}CH_2{-}NH_2 \rightarrow$$
1,6-Hexanedioic acid   1,6-Hexanediamine
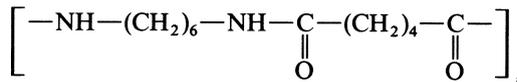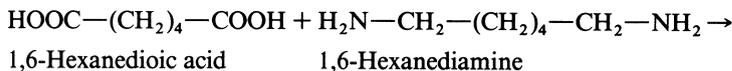
Poly(hexamethylene 1,6-hexanediamide)

Other nylons are made this way from direct combinations of monomers to produce types 6/9, 6/10, and 6/12.
 Nylon 6 and 6/6 possess the maximum stiffness, strength, and heat resistance of all the types of nylon. Type 6/6 has a higher melt temperature, whereas type 6 has a higher impact resistance and better processibility. At a sacrifice in stiffness and heat resistance, the higher analogs of nylon are useful primarily for improved chemical resistance in certain environments (acids, bases, and zinc chloride solutions) and for lower moisture absorption.
 Aromatic nylons, $[{-}NH{-}C_6H_4{-}CO{-}]_n$ (also called aramids), have specialty uses because of their improved clarity.

10.3.13 Poly(amide-imide)

Poly(amide-imide) is the condensation polymer of 1,2,4-benzenetricarboxylic anhydride and various aromatic diamines and has the general structure:
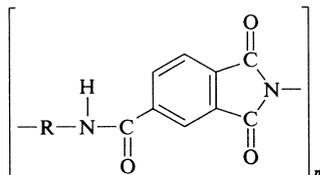
It is characterized by high strength and good impact resistance, and retains its physical properties at temperatures up to 260°C. Its radiation (gamma) resistance is good.

10.3.14 Polycarbonate

Polycarbonate is a polyester in which dihydric (or polyhydric) phenols are joined through carbonate linkages. The general-purpose type of polycarbonate is based on 2,2-bis(4′-hydroxybenzene)propane (bisphenol A) and has the general structure:
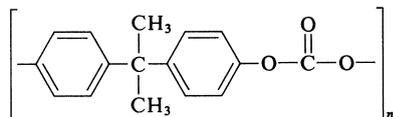
Polycarbonates are the toughest of all thermoplastics. They are window-clear, amazingly strong and rigid, autoclavable, and nontoxic. They have a brittleness temperature of −135°C.

10.3.15 Polyester

10.3.15.1 *Poly(butylene Terephthalate).* Poly(butylene terephthalate) is prepared in a condensation reaction between dimethyl terephthalate and 1,4-butanediol and its repeating unit has the general structure
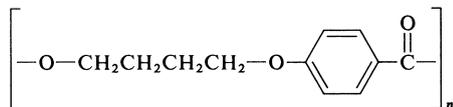
This thermoplastic shows good tensile strength, toughness, low water absorption, and good frictional properties, plus good chemical resistance and electrical properties.

10.3.15.2 *Poly(ethylene Terephthalate).* Poly(ethylene terephthalate) is prepared by the reaction of either terephthalic acid or dimethyl terephthalate with ethylene glycol, and its repeating unit has the general structure.

$$\left[-O-CH_2CH_2-O-\overset{\displaystyle O}{\underset{\displaystyle \|}{C}}- \right]_n$$
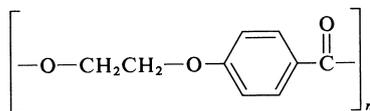
The resin has the ability to be oriented by a drawing process and crystallized to yield a high-strength product.

10.3.15.3   Unsaturated Polyesters.   Unsaturated polyesters are produced by reaction between two types of dibasic acids, one of which is unsaturated, and an alcohol to produce an ester. Double bonds in the body of the unsaturated dibasic acid are obtained by using maleic anhydride or fumaric acid.

10.3.15.4   PCTA Copolyester.   Poly(1,4-cyclohexanedimethylene terephthalic acid) (PCTA) co-polyester is a polymer of cyclohexanedimethanol and terephthalic acid, with another acid substituted for a portion of the terephthalic acid otherwise required. It has the following formula:

$$\left[-O-CH_2 \cdots CH_2-O-\overset{\displaystyle O}{\underset{\displaystyle \|}{C}}-\cdots-\overset{\displaystyle O}{\underset{\displaystyle \|}{C}}- \right]_n$$
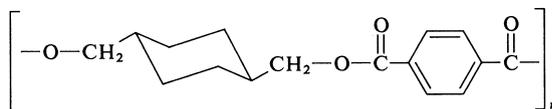
10.3.15.5   Polyimides.   Polyimides have the following formula:

$$\left[\cdots \right]_n$$
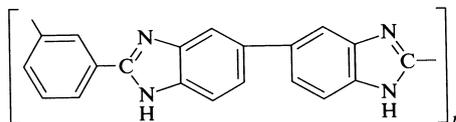
They are used as high-temperature structural adhesives since they become rubbery rather than melt at about 300°C.

10.3.16   Poly(methylpentene)

Poly(methylpentene) is obtained by a Ziegler-type catalytic polymerization of 4-methyl-1-pentene.

Its key properties are its excellent transparency, rigidity, and chemical resistance, plus its resistance to impact and to high temperatures. It withstands repeated autoclaving, even at 150°C.

10.3.17   Polyolefins

10.3.17.1   Polyethylene.   Polymerization of ethylene results in an essentially straight-chain high-molecular-weight hydrocarbon.

$$CH_2{=}CH_2 \rightarrow [-CH_2-CH_2-]_n$$
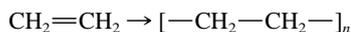
Branching occurs to some extent and can be controlled. Minimum branching results in a "high-density" polyethylene because of its closely packed molecular chains. More branching gives a less compact solid known as "low-density" polyethylene.

A key property is its chemical inertness. Strong oxidizing agents eventually cause some oxidation, and some solvents cause softening or swelling, but there is no known solvent for polyethylene at room temperature. The brittleness temperature is $-100°C$ for both types. Polyethylene has good low-temperature toughness, low water absorption, and good flexibility at subzero temperatures.

10.3.17.2 Polypropylene.   The polymerization of propylene results in a polymer with the following structure:

$$CH_2{=}CH{-}CH_3 \rightarrow \left[\begin{array}{c} {-}CH_2{-}CH{-} \\ | \\ CH_3 \end{array} \right]_n$$
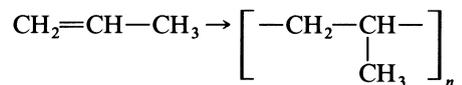
The desired form in homopolymers is the isotactic arrangement (at least 93% is required to give the desired properties). Copolymers have a random arrangement. In block copolymers a secondary reactor is used where active polymer chains can further polymerize to produce segments that use ethylene monomer.

Polypropylene is translucent and autoclavable and has no known solvent at room temperature. It is slightly more susceptible to strong oxidizing agents than polyethylene.

10.3.17.3 Polybutylene.   Polybutylene is composed of linear chains having an isotactic arrangement of ethyl side groups along the chain backbone.

$$CH_2{=}CH{-}CH_2{-}CH_3 \rightarrow \left[\begin{array}{c} {-}CH_2{-}CH{-} \\ | \\ CH_2 \\ | \\ CH_3 \end{array} \right]_n$$
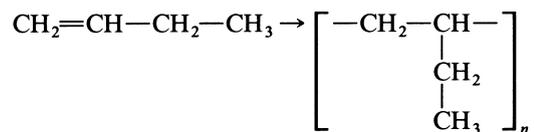
It has a helical conformation in the stable crystalline form.

Polybutylene exhibits high tear, impact, and puncture resistance. It also has low creep, excellent chemical resistance, and abrasion resistance with coilability.

10.3.17.4 Ionomer.   Ionomer is the generic name for polymers based on sodium or zinc salts of ethylene-methacrylic acid copolymers in which interchain ionic bonding, occurring randomly between the long-chain polymer molecules, produces solid-state properties.

The abrasion resistance of ionomers is outstanding, and ionomer films exhibit optical clarity. In composite structures ionomers serve as a heat-seal layer.

10.3.18 Poly(phenylene Sulfide)

Poly(phenylene sulfide) has the following formula:

$$\left[{-}\langle\bigcirc\rangle{-}S{-} \right]_n$$
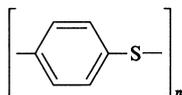
The recurring *para*-substituted benzene rings and sulfur atoms form a symmetrical rigid backbone.

The high degree of crystallization and the thermal stability of the bond between the benzene ring and sulfur are the two properties responsible for the polymer's high melting point, thermal stability, inherent flame retardance, and good chemical resistance. There are no known solvents of poly(phenylene sulfide) that can function below 205°C.

10.3.19   Polyurethane

10.3.19.1   Foams.   Polyurethane foams are prepared by the polymerization of polyols with isocyanates.

$$H\text{-}[O\text{--}CH_2\text{--}CH_2\text{-}]_nOH + \text{excess}$$
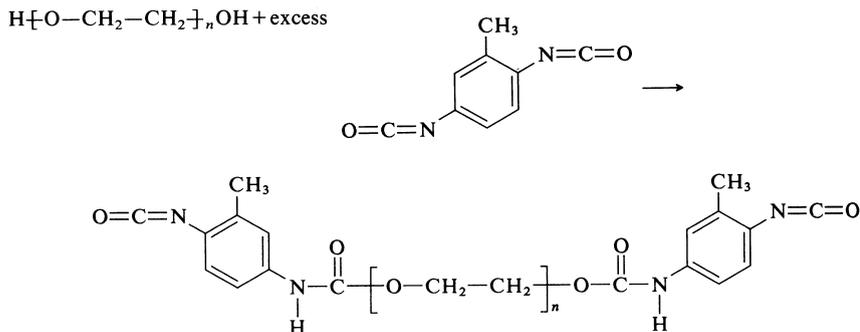
Commonly used isocyanates are toluene diisocyanate, methylene diphenyl isocyanate, and polymeric isocyanates. Polyols used are macroglycols based on either polyester or polyether. The former [poly(ethylene phthalate) or poly(ethylene 1,6-hexanedioate)] have hydroxyl groups that are free to react with the isocyanate. Most flexible foam is made from 80/20 toluene diisocyanate (which refers to the ratio of 2,4-toluene diisocyanate to 2,6-toluene diisocyanate). High-resilience foam contains about 80% 80/20 toluene diisocyanate and 20% poly(methylene diphenyl isocyanate), while semi-flexible foam is almost always 100% poly(methylene diphenyl isocyanate). Much of the latter reacts by trimerization to form isocyanurate rings.

Flexible foams are used in mattresses, cushions, and safety applications. Rigid and semiflexible foams are used in structural applications and to encapsulate sensitive components to protect them against shock, vibration, and moisture. Foam coatings are tough, hard, flexible, and chemically resistant.

10.3.19.2   Elastomeric Fiber.   Elastomeric fibers are prepared by the polymerization of polymeric polyols with diisocyanates.

$$
\begin{aligned}
&CH_2\text{--}(\text{--}OCH_2CH_2\text{--}O\text{--})_xH\\
&CH\text{--}(\text{--}O\text{--}CH_2CH_2\text{--}O\text{--})_yH \quad + \\
&CH_2\text{--}(\text{--}OCH_2CH_2\text{--}O\text{--}_zH
\end{aligned}
$$

Polymeric polyols

Diisocyanate

→ essentially linear polymers
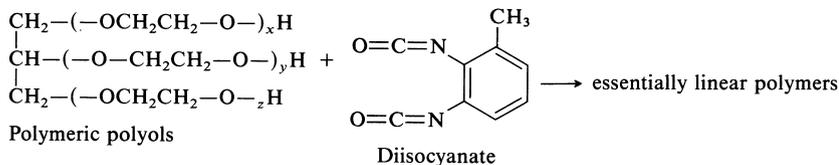
The structure of elastomeric fibers is similar to that illustrated for polyurethane foams.

10.3.20   Silicones

Silicones are formed in the following multistage reaction:

$$R_2SiCl_2 + 2H_2O \rightarrow R_2Si(OH)_2 + 2HCl$$
$$\downarrow$$
$$[\text{--}Si(R)_2\text{--}O\text{--}]_n$$
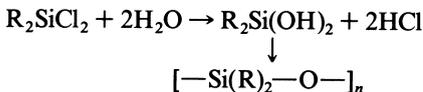
The silanols formed above are unstable and under dehydration. On polycondensation, they give polysiloxanes (or silicones) which are characterized by their three-dimensional branched-chain structure. Various organic groups introduced within the polysiloxane chain impart certain characteristics and properties to these resins.

Methyl groups impart water repellency, surface hardness, and noncombustibility.

Phenyl groups impart resistance to temperature variations, flexibility under heat, resistance to abrasion, and compatibility with organic products.

Vinyl groups strengthen the rigidity of the molecular structure by creating easier cross-linkage of molecules.

Methoxy and alkoxy groups facilitate cross-linking at low temperatures.

Oils and gums are nonhighly branched- or straight-chain polymers whose viscosity increases with the degree of polycondensation.

10.3.21   Styrenics

10.3.21.1   Polystyrene.   Polystyrene has the following formula:

$$\left[-CH_2-CH-\right]_n$$
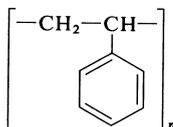
Polystyrene is rigid with excellent dimensional stability, has good chemical resistance to aqueous solutions, and is an extremely clear material.

Impact polystyrene contains polybutadiene added to reduce brittleness. The polybutadiene is usually dispersed as a discrete phase in a continuous polystyrene matrix. Polystyrene can be grafted onto rubber particles, which assures good adhesion between the phases.

10.3.21.2   Acrylonitrile-Butadiene-Styrene (ABS) Copolymers.   This basic three-monomer system can be tailored to yield resins with a variety of properties. Acrylonitrile contributes heat resistance, high strength, and chemical resistance. Butadiene contributes impact strength, toughness, and retention of low-temperature properties. Styrene contributes gloss, processibility, and rigidity. ABS polymers are composed of discrete polybutadiene particles grafted with the styrene-acrylonitrile copolymer; these are dispersed in the continuous matrix of the copolymer.

10.3.21.3   Styrene-Acrylonitrile (SAN) Copolymers.   SAN resins are random, amorphous copolymers whose properties vary with molecular weight and copolymer composition. An increase in molecular weight or in acrylonitrile content generally enhances the physical properties of the copolymer but at some loss in ease of processing and with a slight increase in polymer color.

SAN resins are rigid, hard, transparent thermoplastics which process easily and have good dimensional stability—a combination of properties unique in transparent polymers.

10.3.22   Sulfones

Below are the fomulas for three polysulfones.
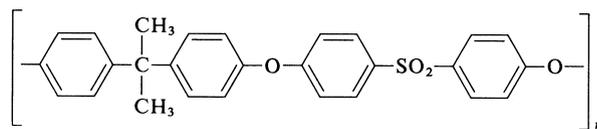
Polysulfone
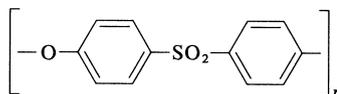
Poly(ester sulfone)
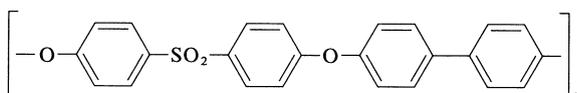
Poly(phenyl sulfone)

The isopropylidene linkage imparts chemical resistance, the ether linkage imparts temperature resistance, and the sulfone linkage imparts impact strength. The brittleness temperature of polysulfones is $-100°C$. Polysulfones are clear, strong, nontoxic, and virtually unbreakable. They do not hydrolyze during autoclaving and are resistant to acids, bases, aqueous solutions, aliphatic hydrocarbons, and alcohols.

10.3.23   Thermoplastic Elastomers

10.3.23.1   Polyolefins.   In these thermoplastic elastomers the hard component is a crystalline polyolefin, such as polyethylene or polypropylene, and the soft portion is composed of ethylene-propylene rubber. Attractive forces between the rubber and resin phases serve as labile cross-links. Some contain a chemically cross-linked rubber phase that imparts a higher degree of elasticity.

10.3.23.2   Styrene-Butadiene-Styrene Block Copolymers.   Styrene blocks associate into domains that form hard regions. The midblock, which is normally butadiene, ethylene-butene, or isoprene blocks, forms the soft domains. Polystyrene domains serve as cross-links.

10.3.23.3   Polyurethanes.   The hard portion of polyurethane consists of a chain extender and polyisocyanate. The soft component is composed of polyol segments.

10.3.23.4   Polyesters.   The hard portion consists of copolyester, and the soft portion is composed of polyol segments.

10.3.24   Vinyl

10.3.24.1   Poly(vinyl Chloride) (PVC).   Polymerization of vinyl chloride results in the formation of a polymer with the following formula:

$$CH_2=CHCl \rightarrow \left[-CH_2-\underset{\underset{Cl}{|}}{CH}- \right]_n$$
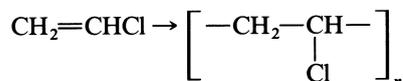
When blended with phthalate ester plasticizers, PVC becomes soft and pliable.
  Its key properties are good resistance to oils and a very low permeability to most gases.

10.3.24.2 Poly(vinyl Acetate). Poly(vinyl acetate) has the following formula:

$$\left[\begin{array}{c} -CH_2-CH- \\ | \\ O-CO-CH_3 \end{array} \right]_n$$
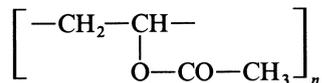
Poly(vinyl acetate) is used in latex water paints because of its weathering, quick-drying, recoatability, and self-priming properties. It is also used in hot-melt and solution adhesives.

10.3.24.3 Poly(vinyl Alcohol). Poly(vinyl alcohol) has the following formula:

$$\left[\begin{array}{c} -CH_2-CH- \\ | \\ OH \end{array} \right]_n$$
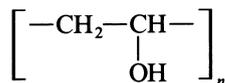
It is used in adhesives, paper coating and sizing, and textile warp size and finishing applications.

10.3.24.4 Poly(vinyl Butyral). Poly(vinyl butyral) is prepared according to the following reaction:

$$\left[\begin{array}{c} -CH_2-CH- \\ | \\ OH \end{array} \right]_n + CH_3CH_2CH_2CHO \rightarrow \left[\begin{array}{c} -CH_2-CH-CH_2-CH- \\ | \quad\quad | \\ O-CH\quad\quad O \\ | \\ CH_2-CH_2-CH_3 \end{array} \right]_n$$
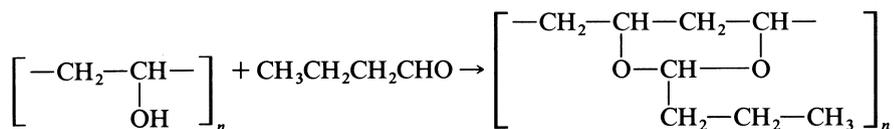
Its key characteristics are its excellent optical and adhesive properties. It is used as the interlayer film for safety glass.

10.3.24.5 Poly(vinylidene Chloride). Poly(vinylidene chloride) is prepared according to the following reaction:

$$CH_2{=}CCl_2 + CH_2{=}CHCl \rightarrow [-CH_2-CCl_2-CH_2-CHCl-]_n$$
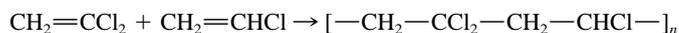
Random copolymer

10.3.25 Urea Formaldehyde

The reaction of urea with formaldehyde yields the following products, which are used as monomers in the preparation of urea formaldehyde resin.

$$H_2N-CO-NH_2 + H_2CO \rightarrow H_2N-CO-NH-CH_2OH$$

$$+ HOCH_2-NH-CO-NH-CH_2OH$$
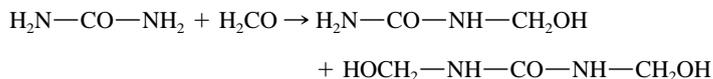
The reaction conditions can be varied so that only one of those monomers is formed. 1-Hydroxymethylurea and 1,3-bis(hydroxymethyl)urea condense in the presence of an acid catalyst to produce urea formaldehyde resins. A wide variety of resins can be obtained by careful selection of the pH, reaction temperature, reactant ratio, amino monomer, and degree of polymerization. If the reaction is carried far enough, an infusible polymer network is produced.

Liquid coating resins are prepared by reacting methanol or butanol with the initial hydroxymethylureas. Ether exchange reactions between the amino resin and the reactive sites on the polymer produce a cross-linked film.

TABLE 10.2 Properties of Commercial Plastics

Properties	Acetal				
	Homopolymer	Copolymer	20% glass-reinforced homopolymer	25% glass-reinforced copolymer	21% poly(tetrafluoroethylene)-filled homopolymer
Physical					
Melting temperature, °C					
Crystalline	175	175	181	175	181
Amorphous					
Specific gravity	1.42	1.41	1.56	1.61	1.54
Water absorption (24 h), %	0.25–0.40	0.22	0.25	0.29	0.20
Dielectric strength, KV · mm^{-1}	19.7	19.7	19.3	22.8	15.7
Electrical					
Volume (dc) resistivity, ohm-cm	10^{15}	10^{15}	5×10^{14}		3×10^{16}
Dielectric constant (60 Hz)	3.7	3.7	3.9		3.1
Dielectric constant (10^6 Hz)	3.7	3.7	3.9		3.1
Dissipation (power) factor (60 Hz)					
Dissipation factor (10^6 Hz)	0.005	0.005	0.005		0.005
Mechanical					
Compressive modulus, 10^3 lb · in^{-2}	670	450			

Property					
Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}	5.29	16 (10% yield)	18 (10% yield)	17 (10% yield)	13 (10% yield)
Elongation at break, %	25–75	40–75	7	3	15–22
Flexural modulus at 23°C, 10^3 lb · in^2	380–430	375	730	1100	340–350
Flexural strength, rupture or yield, 10^3 lb · in^{-2}	14	13	15	28	
Hardness, Rockwell (or Shore)	M94	M78	M90	M79	M78
Impact strength (Izod) at 23°C, J · m^{-1}	69–123	53–80	43	96	37–64
Tensile modulus, 10^3 lb · in^{-2}	520	410	1000	1250	
Tensile strength at break, 10^3 lb · in^{-2}	10	10	8.5	18.5	7.6
Tensile yield strength, 10^3 lb · in^{-2}	9.5–12	8.5			6.9–7.6
Thermal					
Burning rate, mm · min^{-1}	27.9				
Coefficient of linear thermal expansion, 10^{-6}°C	100	85	36–81		75
Deflection temperature under flexural load (264 lb · in^{-2}), °C	124	110	157	163	100
Maximum recommended service temperature, °C	84				
Specific heat, cal · g^{-1}	0.35				
Thermal conductivity, W · m^{-1} · K^{-1}	0.23	0.23			

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

			Acrylic				Alloy	
Properties	Poly(methyl methacrylate)	Cast sheet	Impact-modified	Heat-resistant	Alkyd, molded	Acrylic poly(vinyl chloride) alloy	Acrylonitrile-butadiene-styrene-poly(vinyl chloride) alloy
Physical							
Melting temperature, °C							
Crystalline	90–105	90–105	80–100	100–125		105	
Amorphous							
Specific gravity	1.17–1.20	1.18–1.20	1.11–1.18	1.16–1.19	2.22–2.24		
Water absorption (24 h), %	0.1–0.4	0.2–0.4	0.2–0.8	0.2–0.3		0.06	
Dielectric strength, KV · mm^{-1}	15.7–19.9	17.7–21.7	15.0–19.9	15.7–19.9		>15.7	19.7
Electrical							
Volume (dc) resistivity, ohm-cm	>10^{14}	>10^{14}					
Dielectric constant (60 Hz)	3.3–4.5	3.5–4.5			3.8–5.0		
Dielectric constant (10^6 Hz)		3.0–3.5			3.6–4.7		
Dissipation (power) factor (60 Hz)		0.04–0.06			0.012–0.026		
Dissipation factor (10^6 Hz)		0.02–0.03			0.01–0.016		
Mechanical							
Compressive modulus, 10^4 lb · in^{-2}	370–460	390–475	240–370	350–460		330–400	

Compressive strength, rupture or 1% yield, 10^3 lb $\cdot$ in^{-2}	12–18	11–19	4–14	17	16–20	8.4	
Elongation at break, %	2–10	2–7	20–70	3–5		100	
Flexural modulus at 23°C, 10^3 lb $\cdot$ in^{-2}	420–460	390–475	200–380	460–500		330–400	340
Flexural strength, rupture or yield, 10^3 lb $\cdot$ in^{-2}	13–19	12–17	7–13	12–16		10.7	9.6
Hardness, Rockwell (or Shore)	M85–M105	M80–M100	R105–R120	M95–M105	E76	R99–R105	R100
Impact strength (Izod) at 23°C, J $\cdot$ m^{-1}	16–27	16–21	43–133	16–21	27–240	800	560
Tensile modulus, 10^3 lb $\cdot$ in^{-2}	380–450	350–450	200–400	350–460		330–335	330
Tensile strength at break, 10^3 lb $\cdot$ in^{-2}	7–11	8–11	5–9	10	4.5–6.5	6.5	5.8
Tensile yield strength, 10^3 lb $\cdot$ in^{-2}					10–13		
Thermal							
Burning rate, mm $\cdot$ min^{-1}		0.5–2.2			Self-extinguishing		
Coefficient of linear thermal expansion, 10^{-6}°C	50–90	50–90	50–80	50–60	40–55		46
Deflection temperature under flexural load (264 lb $\cdot$ in^{-2}), °C	74–99	71–102	74–95	88–104	177–204	71	
Maximum recommended service temperature, °C		60–71			220		
Specific heat, cal $\cdot$ g^{-1}	0.36	0.35					
Thermal conductivity, W $\cdot$ m^{-1}, K^{-1}	0.17–0.25	0.17–0.25	0.17–0.21	0.19			

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

Properties	Alloy	Allyl			Cellulosic		
	Polycarbonate acrylonitrile-butadiene-styrene alloy	Allyl-diglycol-carbonate polymer	Diallyl phthalate molding		Cellulose acetate		Cellulose-acetate-butyrate resin
			Glass-filled	Mineral-filled	Sheet	Molding	Sheet
Physical							
Melting temperature, °C							
Crystalline		Thermoset	Thermoset	Thermoset	230	230	140
Amorphous	150						
Specific gravity	1.12–1.20	1.3–1.4	1.7–2.0	1.65–1.85	1.27–1.34	1.29–1.34	1.15–1.22
Water absorption (24 h), %	0.21–0.24	0.2	0.12–0.35	0.2–0.5	2–7	1.7–6.5	0.9–2.2
Dielectric strength, kV · mm^{-1}	17.7	15.0	15.7–17.7	15.7–17.7	11–24	9–24	9–18
Electrical							
Volume (dc) resistivity, ohm-cm					10^{10}–10^{13}	10^{10}–10^{13}	10^{10}–10^{12}
Dielectric constant (60 Hz)					3.4–7.4	3.5–7.5	3.7–4.3
Dielectric constant (10^6 Hz)					3.2–7.0	3.2–7.0	3.3–3.8
Dissipation (power) factor (60 Hz)					0.01–0.06	0.01–0.06	0.01–0.04
Dissipation factor (10^6 Hz)					0.01–0.06	0.01–0.10	0.01–0.04
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}		300					

Property							
Compressive strength, rupture or 1% yield, 10^3 lb·in^{-2}	11	21–23	25–35	20–32	22–33	25–36	
Elongation at break, %	10–15		3–5	3–5	17–40	6–40	50–100
Flexural modulus at 23°C, 10^3 lb·in^{-2}	300–400	250–330	1200–1500	1000–1400			740–1300
Flexural strength, rupture or yield, 10^3 lb·in^{-2}	13.0–13.7	6–13	9–20	8.5–11	6–10	2–16	4–9
Hardness, Rockwell (or Shore)	R117	M95–M100	E80–E87	E61	R85–R120	R100–R123	R50–R95
Impact strength (Izod) at 23°C, J·m^{-1}	560	11–21	21–800	16–43	107–454	53–214	133–288
Tensile modulus, 10^3 lb·in^{-2}	370–380	300	1400–2200	1200–2200			200–250
Tensile strength at break, 10^3 lb·in^{-2}	7.0–7.3	5–6	6–11	5–8	4.5–8.0	1.9–9.0	2.6–6.9
Tensile yield strength, 10^3 lb·in^{-2}	8.5				2.2–7.4	4.1–7.6	
Thermal							
Burning rate, mm·min^{-1}						1.3–3.8	1.3–3.8
Coefficient of linear thermal expansion, 10^{-6}°C	63–67	5.4–9.6	0.68–2.4	2.8	100–150	80–180	110–170
Deflection temperature under flexural load (264 lb·in^{-2}), °C	104–116	60–88	165–288+	160–288	44–91	51–98	49–58
Maximum recommended service temperature, °C							
Specific heat, cal·g^{-1}					0.3–0.4	0.3–0.42	0.3–0.4
Thermal conductivity, W·m^{-1}·K^{-1}	0.25–0.38	0.20–0.21	0.21–0.63	0.30–1.04	0.17–0.34	0.17–0.34	0.17–0.34

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

| | Cellulosic | | | | | Epoxy | |
| | | | | | | Bisphenol | |
Properties	Cellulose-acetate butyrate resin, molding	Cellulose-acetate propionate resin, molding	Ethyl cellulose	Cellulose nitrate	Chlorinated polyether	Glass-fiber-reinforced	Mineral-filled
Physical							
Melting temperature, °C							
Crystalline	140	190	135		125	Thermoset	Thermoset
Amorphous							
Specific gravity	1.15–1.22	1.17–1.24	1.09–1.17	1.35–1.40	1.4	1.6–2.0	1.6–2.1
Water absorption (24 h), %	0.9–2.2	1.2–2.8	0.8–1.8			0.04–0.20	0.03–0.20
Dielectric strength, kV · mm^{-1}	9–13	12–17.7	13.8–19.7			9.8–15.7	9.8–15.7
Electrical							
Volume (dc) resistivity, ohm-cm	10^{10}–10^{12}			10^{10}			
Dielectric constant (60 Hz)	3.5–6.4			7.0–7.5			
Dielectric constant (10^6 Hz)	3.2–6.2		3.01	6.6			
Dissipation (power) factor (60 Hz)	0.01–0.04						
Dissipation factor (10^6 Hz)	0.01–0.04						
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}						3000	

Property							
Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}	2.1–7.5	2.4–7.0		2.1–8.0		18,000–40,000	18,000–40,000
Elongation at break, %	40–88	29–100	5–40	40–45	600–800	4	
Flexural modulus at 23°C, 10^3 lb · in^{-2}	90–300	120–350				2–4.5	
Flexural strength, rupture or yield, 10^3 lb · in^{-2}	1.8–9.3	2.9–11.4	4–12	9–11	5	8–30	6–18
Hardness, Rockwell (or Shore)	R31–R116	R10–R122	R50–R115	R95–R115	R100	M100–M112	M100–M112
Impact strength (Izod) at 23°C, J · m^{-1}	53–582	27 to no break	21	267–374	21	16–533	16–22
Tensile modulus, 10^3 lb · in^{-2}	50–200	60–215		190–220		3	
Tensile strength at break, 10^3 lb · in^{-2}	2.6–6.9	2.0–7.8	2–8	7–8	1.5–1.8	5–20	4–10
Tensile yield strength, 10^3 lb · in^{-2}							
Thermal							
Burning rate, mm · min^{-1}	1.3–3.8				Self-extinguishing		
Coefficient of linear thermal expansion, 10^{-6}°C	110–170	110–170	100–200	80–120	6.6	11–50	20–60
Deflection temperature under flexural load (264 lb · in^{-2}), °C	44–94	44–109	45–88	60–71	185	107–260	107–260
Maximum recommended service temperature, °C					255		
Specific heat, cal · g^{-1}	0.3–0.4			0.31–0.41			
Thermal conductivity, W · m^{-1} · K^{-1}	0.17–0.30	0.17–0.30	0.16–0.30	0.23		0.17–0.42	0.17–1.48

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

| | Epoxy | | | Fluorocarbon | | | |
| | Casting resin | | Novolac resin | Poly(tetrafluoroethylene) | | Poly(chloro-trifluoro-ethylene) | |
Properties	Unfilled	Flexible	Mineral-filled	Granular	Glass-fiber-reinforced		Perfluoroalkoxy
Physical							
Melting temperature, °C							
Crystalline	Thermoset	Thermoset	Thermoset	327	327	220	310
Amorphous							
Specific gravity	1.11–1.40	1.05–1.35	1.7–2.1	2.14–2.20	2.2–2.3	2.1–2.2	2.12–2.17
Water absorption (24 h), %	0.08–0.15	0.27–0.50	0.05–0.2	0.01		0.03	
Dielectric strength,	11.8–19.7	9.3–15.8	11.8–13.8	18.9	12.6	19.7–23	19.7
kV · mm^{-1}							
Electrical							
Volume (dc) resistivity,							
ohm-cm	10^{12}–10^{17}			10^{18}		10^{18}	
Dielectric constant (60 Hz)	3.5–5.0			2.1		2.3–2.7	
Dielectric constant (10^6 Hz)	3.5–5.0			2.1		2.3–2.5	
Dissipation (power) factor (60 Hz)				0.0002		0.001	
Dissipation factor (10^6 Hz)				0.0002		0.005	
Mechanical							
Compressive modulus,							
10^3 lb · in^{-2}				60			

Compressive strength, rupture or 1% yield, 10^3 lb·in^{-2}	15–25	1–14	30	1.7		4.6–7.4	
Elongation at break, %	3–6	20–70	2–4	200–400	200–300	80–250	300
Flexural modulus at 23°C, 10^3 lb·in^{-2}			2000	80	235	120	
Flexural strength, rupture or yield, 10^{-3} lb·in^{-2}	13–21	1–13	16–20		2	7.4–9.3	
Hardness, Rockwell (or Shore)	M80–M110			(D50–D55)	(D60–D70)	R75–R95	(D64)
Impact strength (Izod) at 23°C, J·m^{-1}	10.7–53	187–267	21	160	144	133–160	No break
Tensile modulus, 10^3 lb·in^{-2}	350	1–350		58–80		150–300	
Tensile strength at break, 10^3 lb·in^{-2}	4–13	2–10	6–12	2–5	2–2.7	4.5–6	4–4.3
Tensile yield strength, 10^3 lb·in^{-2}			30				
Thermal							
Burning rate, mm·min^{-1}				Self-extinguishing	Self-extinguishing	Self-extinguishing	
Coefficient of linear thermal expansion, 10^{-6}°C	45–65	20–100	22–30	100	77–100	70	
Deflection temperature under flexural load (264 lb·in^{-2}), °C	46–288	23–121	149–260	121 (66 lb·in^{-2})		126 (66 lb·in^{-2})	74 (66 lb·in^{-2})
Maximum recommended service temperature, °C				260		200	
Specific heat, cal·g^{-1}				0.25		0.22	
Thermal conductivity, W·m^{-1}·K^{-1}	0.17–0.21			0.25	0.34–0.40	0.19–0.22	0.25

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

Properties	Fluorocarbon					Melamine formaldehyde	
			Ethylene-tetrafluoroethylene copolymer		Ethylene-chlorotrifluoro-ethylene copolymer		
	Fluorinated ethylene-propylene resin	Poly(vinylidene fluoride)	Unfilled	Glass-fiber-reinforced		Cellulose-filled	Glass-fiber-reinforced
Physical							
Melting temperature, °C							
Crystalline	275	156	270	270	245	Thermoset	Thermoset
Amorphous							
Specific gravity	2.14–2.17	1.75–1.78	1.7	1.8	1.68	1.47–1.52	1.5–2.0
Water absorption (24 h), %	<0.01	0.04–0.06	0.03	0.02	0.01	0.1–0.8	0.09–1.3
Dielectric strength, kV · mm^{-1}	20–24	10	16	17	19	11–16	5–15
Electrical							
Volume (dc) resistivity, ohm-cm							
Dielectric constant (60 Hz)	2.1	8–9	2.6		2.6		
Dielectric constant (10^6 Hz)	2.1	8–9	2.6		2.6		
Dissipation (power) factor (60 Hz)		High					
Dissipation factor (10^6 Hz)		High					
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}		120	120	1200	240		

Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}	2.2	8.7–10	7.1	10		33–45	20–35
Elongation at break, %	250–330	25–500	100–400	8	200–300	0.6–1.0	0.6
Flexural modulus at 23°C, 10^3 lb · in^{-2}	80–95	200	200	950	240	1100	
Flexural strength, rupture or yield, 10^3 lb · in^{-2}		8.6–11	5.5	10.7	7	9–16	14–23
Hardness, Rockwell (or Shore)	(D60–D65)	(D80)	R50 (D75)	R74	R95	M115–M125	M115
Impact strength (Izod) at 23°C, J · m^{-1}	No break	192–214	No break	480	No break	11–21	32–961
Tensile modulus, 10^3 lb · in^{-2}	50	120	120	1200	240	1.1–1.4	1.6–2.4
Tensile strength at break, 10^3 lb · in^{-2}	2.7–3.1	5.5–7.4	6.5	12	7	5–13	5–10.5
Tensile yield strength, 10^3 lb · in^{-2}							
Thermal							
Burning rate, mm · min^{-1}	Not combustible	Not combustible	Not combustible	Not combustible	Not combustible	Self-extinguishing	Self-extinguishing
Coefficient of linear thermal expansion, 10^{-6}°C	83–105	85	59	10–32	80	40–45	15–28
Deflection temperature under flexural load (264 lb · in^{-2}), °C	70 (66 lb · in^{-2})	80–90	71	210	77	177–199	190–204
Maximum recommended service temperature, °C	205	150				210	
Specific heat, cal · g^{-1}	0.28						
Thermal conductivity, W · m^{-1} · K^{-1}	0.25	0.19–0.24	0.24		0.16	0.27–0.41	0.41–0.49

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

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Properties	Melamine phenolic, woodflour- and cellulose- filled	Nitrile	Phenolic				
			Unfilled	Woodflour- filled	Glass-fiber- reinforced	Cellulose- filled	Mineral- filled
Physical							
Melting temperature, °C							
Crystalline	Thermoset		Thermoset	Thermoset	Thermoset	Thermoset	Thermoset
Amorphous		95					
Specific gravity	1.5–1.7	1.15	1.24–1.32	1.37–1.46	1.69–2.0	1.38–1.42	1.42–1.84
Water absorption (24 h), %	0.3–0.65	0.28	0.1–0.36	0.3–1.2	0.03–1.2	0.5–0.9	0.1–0.3
Dielectric strength, kV · mm^{-1}	8.7–12.8	8.7–9.5	9.8–15.8	10.2–15.8	5.5–15.8	11.8–15	7.9–13.8
Electrical							
Volume (dc) resistivity,							
ohm-cm		1.9×10^{15}	1×10^{12} to 7×10^{12}				
Dielectric constant (60 Hz)			6.5–7.5				
Dielectric constant (10^6 Hz)			4.0–5.5				
Dissipation (power) factor (60 Hz)			0.10–0.15				
Dissipation factor (10^6 Hz)			0.04–0.05				
Mechanical							
Compressive modulus,							
10^3 lb · in^{-2}							

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Compressive strength, rupture or 1% yield, 10^3 lb·in⁻²	26–30	12	18–32	25–31	26–70	22–31	22.5–34.6
Elongation at break, %	0.4–0.8	3–4	1.5–2.0	0.4–0.8	0.2	1–2	0.1–0.5
Flexural modulus at 23°C, 10^3 lb·in⁻²	1000–2000	500–590	700–1500	1000–1200	2000–33,000	900–1300	1000–2000
Flexural strength, rupture or yield, 10^3 lb·in⁻²	8–10	14	11–17	7–14	15–60	5.5–11	11–14
Hardness, Rockwell (or Shore)	E95–E100	M72–M76	M93–M120	M100–M115	E54–E101	M95–115	E88
Impact strength (Izod) at 23°C, J·m⁻¹	11–21	80–256	13–21	11–32	27–960	21–59	14–19
Tensile modulus, 10^3 lb·in⁻²	800–1700	510–580	700–1500	800–1700	1900–3300		2400
Tensile strength at break, 10^3 lb·in⁻²	6–8	9	6–9	5–9	7–18	3.5–6.5	6–9.7
Tensile yield strength, 10^3 lb·in⁻²			12–15				
Thermal							
Burning rate, mm·min⁻¹			Self-extinguishing				
Coefficient of linear thermal expansion, 10^{-6}°C	10–40	66	68	30–45	8–21	20–31	19–26
Deflection temperature under flexural load (264 lb·in⁻²), °C	140–154	73	74–80	149–188	177–316	149–177	320–246
Maximum recommended service temperature, °C							
Specific heat, cal·g⁻¹							
Thermal conductivity, W·m⁻¹·K⁻¹	0.17–0.30	0.26	0.15	0.17–0.34	0.34–0.59	0.25–0.38	0.42–0.57

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

	Polyamide						
	Nylon 6				Nylon 6/6		
Properties	Molding and extrusion	30–35% glass-fiber-reinforced	High-impact copolymer	Molding	33% glass-fiber-reinforced	Molybdenum disulfide-filled	Nylon 6/6-nylon 6 copolymer
Physical							
Melting temperature, °C							
Crystalline	216	216	216	265	265	265	240
Amorphous							
Specific gravity	1.12–1.14	1.35–1.42	1.08–1.17	1.13–1.15	1.38	1.15–1.17	1.08–1.14
Water absorption (24 h), %	2.9	1.2	1.3–1.5	1.0–1.3	1.0	0.8–1.1	1.5–2.0
Dielectric strength, kV · mm^{-1}	15.8	15.8	22	24		14	15.8
Electrical							
Volume (dc) resistivity, ohm-cm	10^{12}			10^{12}–10^{15}			10^{10}
Dielectric constant (60 Hz)	9.8			4.0			16
Dielectric constant (10^6 Hz)	3.7			3.6			4
Dissipation (power) factor (60 Hz)	0.14			0.01–0.02			0.4
Dissipation factor (10^6 Hz)	0.12			0.02–0.03			0.1
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}	250						

Compressive strength, rupture or 1% yield, 10^3 lb $\cdot$ in^{-2}	13–16	19		15 (yield)	24.9	12.5	
Elongation at break, %	30–100	3–6	150–270	60	3	15	40
Flexural modulus at 23°C, 10^3 lb $\cdot$ in^{-2}	390	1500	110–320	420	1300	450	150–410
Flexural strength, rupture or yield, 10^3 lb $\cdot$ in^{-2}	14	33	5–12	17	41	17	
Hardness, Rockwell (or Shore)	R119	M101	R81–R110	R120	M100	R119	R119
Impact strength (Izod) at 23°C, J $\cdot$ m^{-1}	32–53	160	96 to no break	43–53	117	240	37
Tensile modulus, 10^3 lb $\cdot$ in^{-2}	380	1450				550	150–410
Tensile strength at break, 10^3 lb $\cdot$ in^{-2}	11.8	25	7.5–11	12	28	13.7	7.4–12.4
Tensile yield strength, 10^3 lb $\cdot$ in^{-2}	8			8			
Thermal							
Burning rate, mm $\cdot$ min^{-1}	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing
Coefficient of linear thermal expansion, 10^{-6}°C	80–90	20–30	30–40	80	15–20	54	
Deflection temperature under flexural load (264 lb $\cdot$ in^{-2}), °C	68–85	210	45–54	75	249	127	77
Maximum recommended service temperature, °C	107			135			
Specific heat, cal $\cdot$ g^{-1}	0.4			0.4			
Thermal conductivity, W $\cdot$ m^{-1} $\cdot$ K^{-1}	0.24	0.24		0.24	0.22		

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

	Polyamide						Poly(amide-imide), unfilled
		Nylon 6/12					
Properties	Nylon 6/9, molding and extrusion	Molding	30–35% glass-fiber-reinforced	Nylon 11, molding and extrusion	Nylon 12, molding and extrusion	Aromatic nylon (aramid), molded and unfilled	
Physical							
Melting temperature, °C							
Crystalline	205	217	217	194	179	275	
Amorphous							275
Specific gravity	1.08–1.10	1.06–1.08	1.31–1.38	1.03–1.05	1.01–1.02	1.30	1.40
Water absorption (24 h), %	0.5	0.4	0.2	0.3	0.25	0.6	0.28
Dielectric strength, kV · mm^{-1}	24	16	21	17	18	31	24
Electrical							
Volume (dc) resistivity, ohm-cm		10^{15}			10^{14}		
Dielectric constant (60 Hz)		4.0			3.8		
Dielectric constant (10^6 Hz)		3.5			3.0		
Dissipation (power) factor (60 Hz)		0.02			0.07		
Dissipation factor (10^6 Hz)		0.02			0.04		
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}				180		290	413

Property							
Compressive strength, rupture or 1% yield, 10^3 lb $\cdot$ in^{-2}		2.4			7.5	30	40
Elongation at break, %	1125	150	4	300	300	5	12–18
Flexural modulus at 23°C, 10^3 lb $\cdot$ in^{-2}	290	290	1120	150	165	640	664
Flexural strength, rupture or yield, 10^3 lb $\cdot$ in^{-2}					1.5	25.8	30
Hardness, Rockwell (or Shore)	R111	R114	E40–E50	R108	R106–R109	E90	E78
Impact strength (Izod) at 23°C, J $\cdot$ m^{-1}	59	53	139	96	107–300	75	133
Tensile modulus, 10^3 lb $\cdot$ in^{-2}	275	290	1200	185	180		730
Tensile strength at break, 10^3 lb $\cdot$ in^{-2}	8.5	8.8	24	8	8–9	17.5	26.9
Tensile yield strength, 10^3 lb $\cdot$ in^{-2}		8.8					
Thermal							
Burning rate, mm $\cdot$ min^{-1}				Self-extinguishing			
Coefficient of linear thermal expansion, 10^{-6}°C		90		55–100	67–100	40	36
Deflection temperature under flexural load (264 lb $\cdot$ in^{-2}), °C	57–60	82	93–218	54	54	260	274
Maximum recommended service temperature, °C				100–120			260
Specific heat, cal $\cdot$ g^{-1}		0.4		0.58			
Thermal conductivity, W $\cdot$ m^{-1} $\cdot$ K^{-1}		0.22		0.34	0.22	0.22	0.25

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

		Polycarbonate		Thermoplastic polyester			
				Poly(butylene terephthalate)		Poly(ethylene terephthalate)	
Properties	Poly(aryl ether), unfilled	Low viscosity	30% glass-fiber reinforced	Unfilled	30% glass-fiber-reinforced	Unfilled	30% glass-fiber-reinforced
Physical							
Melting temperature, °C							
Crystalline				232–267	232–267	245	245
Amorphous	160	140	150				
Specific gravity	1.14	1.2	1.4	1.31–1.38	1.52	1.34–1.39	1.27
Water absorption (24 h), %	0.25	0.15	0.14	0.08–0.09	0.06–0.08	0.1–0.2	0.05
Dielectric strength, $kV \cdot mm^{-1}$	17	15	19	16–22	18–22		22
Electrical							
Volume (dc) resistivity, ohm-cm		2×10^{16}	$>10^{16}$		10^{16}	10^{16}	
Dielectric constant (60 Hz)		3.17	3.35				
Dielectric constant (10^6 Hz)		2.96	3.31			3.25	
Dissipation (power) factor (60 Hz)		0.0009	0.011				
Dissipation factor (10^6 Hz)		0.010	0.007				
Mechanical							
Compressive modulus, $10^3 \, lb \cdot in^{-2}$		350	1300				

Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}		12.5	18	8.6–14.5	18–23.5	11–15	25
Elongation at break, %	80	110	3–5	50–300	2–4	50–300	3
Flexural modulus at 23°C, 10^3 lb · in^{-2}	300	340	1100	330–400	1100–1200	35–450	1440
Flexural strength, rupture or yield, 10^3 lb · in^{-2}	11	13.5	23	12–16.7	26–29	14–18	33.5
Hardness, Rockwell (or Shore)	R117	M70	M92	M68–M78	M90	M94–M101	M100
Impact strength (Izod) at 23°C, J · m^{-1}	427	14	107	43–53	69–85	13–32	101
Tensile modulus, 10^3 lb · in^{-2}	320	345	1250	280	1300	400–600	1440
Tensile strength at break, 10^3 lb · in^{-2}	7.5	9.5	19	8.2	17–19	8.5–10.5	23
Tensile yield strength, 10^3 lb · in^{-2}		9.0					
Thermal							
Burning rate, mm · min^{-1}		Self-extinguishing	Self-extinguishing				
Coefficient of linear thermal expansion, 10^{-6}°C	65	68	22	60–95	25	65	29
Deflection temperature under flexural load (264 lb · in^{-2}), °C	149	138–145	146	50–85	220	38–41	224
Maximum recommended service temperature, °C		143					
Specific heat, cal · g^{-1}		0.3				0.27	
Thermal conductivity, W · m^{-1} · K^{-1}	0.30	0.20	0.22	0.18–0.30	0.30	0.15	

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

| | Thermoplastic polyester | | Thermosetting and alkyd polyester | | | | |
| | Aromatic polyester | | Unsaturated polyester | | Alkyd molding compounds | | |
Properties	Extrusion-transparent	Injection molding	Styrene-maleic acid copolymer, low-shrink	Butadiene-maleic acid copolymer	Putty, mineral-filled	Glass-fiber-reinforced	Polyimide, unfilled
Physical							
Melting temperature, °C							
Crystalline			Thermoset	Thermoset	Thermoset	Thermoset	
Amorphous	81						310–365
Specific gravity		1.39					1.36–1.43
Water absorption (24 h), %		0.01					0.24
Dielectric strength, $kV \cdot mm^{-1}$		14					22
Electrical							
Volume (dc) resistivity,							
ohm-cm							$>10^{16}$
Dielectric constant (60 Hz)							
Dielectric constant (10^6 Hz)							3–4
Dissipation (power) factor							
(60 Hz)							
Dissipation factor (10^6 Hz)							
Mechanical							
Compressive modulus,							
$10^3 \, lb \cdot in^{-2}$					2000–3000		

Property	1	2	3	4	5	6	7
Compressive strength, rupture or 1% yield, 10^3 lb·in^{-2}		10	15–30	14–30	12–38	15–36	30–40
Elongation at break, %	225	7–10	3–5				8–10
Flexural modulus at 23°C, 10^3 lb·in^{-2}	290	700	1000–2500		2000	2000	450–500
Flexural strength, rupture or yield, 10^3 lb·in^{-2}	10.6	12	9–35	16–24	6–17	8.5–26	19–28.8
Hardness, Rockwell (or Shore)	R105		40–70 (Barcol)	50–60 (Barcol)	E98	E95	E52–E99
Impact strength (Izod) at 23°C, J·m^{-1}	101		133–800	214–694	16–27	27–854	80
Tensile modulus, 10^3 lb·in^{-2}		300	1000–2500	1500–2500	500–3000		300
Tensile strength at break, 10^3 lb·in^{-2}	6	11	4.5–20	5–10	3–9	4–9.5	10.5–17.1
Tensile yield strength, 10^3 lb·in^{-2}	7						12.5
Thermal							
Burning rate, mm·min^{-1}							
Coefficient of linear thermal expansion, 10^{-6}°C		29	6–30		20–50	15–33	45–56
Deflection temperature under flexural load (264 lb·in^{-2}), °C	63	282	190–260	160–177	177–260	204–260	277–360
Maximum recommended service temperature, °C							
Specific heat, cal·g^{-1}							0.27
Thermal conductivity, W·m^{-1}·K^{-1}		0.29		0.76–0.93	0.51–0.89	0.6–0.89	0.10–0.11

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

| Properties | Poly(methyl pentene), unfilled | Polyolefin | | | | | |
| | | Polyethylene | | | | | |
		Low-density	Medium-density	High-density	Ultra high-molecular-weight	Glass-fiber-reinforced, high-density	Ethylene-vinyl acetate copolymer
Physical							
Melting temperature, °C							
Crystalline	230–240						65–90
Amorphous		95–130	120–140	120–140	125–135	120–140	
Specific gravity	0.84	0.910–0.925	0.926–0.94	0.941–0.965	0.94	1.28	0.92–0.95
Water absorption (24 h), %	0.01	$<$0.01	$<$0.01	$<$0.01	$<$0.01	0.02	0.05–0.13
Dielectric strength, kV · mm^{-1}		18–39	18–39	18–39	28	20	24–30
Electrical							
Volume (dc) resistivity, ohm-cm		$>10^{15}$	$>10^{15}$	$<10^{15}$			
Dielectric constant (60 Hz)		2.3	2.3	2.3			
Dielectric constant (10^6 Hz)		2.3	2.3	2.3			
Dissipation (power) factor							
(60 Hz)		$<$0.0005	$<$0.0005	$<$0.0005			
Dissipation factor (10^6 Hz)		$<$0.0005	$<$0.0005	$<$0.0005			
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}	114–171						

Property							
Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}	5–6.6			2.7–3.6		7	
Elongation at break, %	10–50	90–800	50–600	20–130	450–525	1.5	550–900
Flexural modulus at 23°C, 10^3 lb · in^{-2}	110–260	8–60	60–115	100–260	130–140	800	1–20
Flexural strength, rupture or yield, 10^3 lb · in^{-2}	4–6.5					11	
Hardness, Rockwell (or Shore)	L67–L74	(D40–D51)	(D50–D60)	R30–R50	R50	R75	
Impact strength (Izod) at 23°C, J · m^{-1}	16–64	No break	27–854	27–1068	No break	59	No break
Tensile modulus, 10^3 lb · in^{-2}	160–280	14–38	25–55	60–180			20–120
Tensile strength at break, 10^3 lb · in^{-2}	3.5–4	0.6–2.3	1.2–3.5	3.1–5.5	5.6	9	1.4–2.8
Tensile yield, strength, 10^3 lb · in^{-2}		0.8–1.2	1.0–2.2	3–4	3.1–4.0		
Thermal							
Burning rate, mm · min^{-1}		1.0	1.0	1.0			
Coefficient of linear thermal expansion, 10^{-6}°C	117	100–200	140–160	110–130	130	48	160–200
Deflection temperature under flexural load (264 lb · in^{-2}), °C	41	32–41	41–49	43–54	43–49	121	34
Maximum recommended service temperature, °C	175	70	93	200			
Specific heat, cal · g^{-1}		0.55	0.55	0.46–0.55			
Thermal conductivity, W · m^{-1} · K^{-1}	0.17	0.34	0.34–0.42	0.46–0.51		0.46	

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

		Polyolefin				Poly(phenylene sulfide)	
			Polypropylene				
Properties	Polybutylene extrusion	Homopolymer	Copolymer	Impact copolymer	Polyallomer	Injection molding	40% glass-fiber-reinforced
Physical							
Melting temperature, °C							
Crystalline	126	168	160–168		120–135	290	290
Amorphous							
Specific gravity	0.91–0.925	0.90–0.91	0.89–0.905	0.90	0.90	1.3	1.6
Water absorption (24 h),%	0.01–0.02	0.01–0.03	0.03	<0.03	<0.01	<0.02	0.05
Dielectric strength, kV · mm^{-1}	18	24	24	24	31	15	18
Electrical							
Volume (dc) resistivity,							
ohm-cm		10^{17}	10^{17}	10^{17}			
Dielectric constant (60 Hz)		2.2–2.6	2.3				
Dielectric constant (10^6 Hz)		2.2–2.6	2.3	2.3			
Dissipation (power) factor							
(60 Hz)		<0.0005	0.0001–0.0005				
Dissipation factor (10^6 Hz)		0.0005–0.002	0.0001–0.0002	0.0003			
Mechanical							
Compressive modulus,							
10^3 lb · in^{-2}	31	150–300					

Property							
Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}		5.5–8.0	3.5–8.0			16	21
Elongation at break, %	300–380	100–600	200–700	8–20	400–500	1–2	1
Flexural modulus at 23°C, 10^3 lb · in^{-2}	45–50	170–250	130–200	130–190	70–110	550	1700
Flexural strength, rupture or yield, 10^3 lb · in^{-2}	2–2.3	6–8	5–7			14	29
Hardness, Rockwell (or Shore)		R80–R102	R50–R96	R40–R90	R50–R85	R123	R123
Impact strength (Izod) at 23°C, J · m^{-1}	No break	21–53	53–1068	80–900	91–203	<27	75
Tensile modulus, 10^3 lb · in^{-2}	30–40	165–225	100–170			480	1100
Tensile strength at break, 10^3 lb · in^{-2}	3.8–4.4	4.5–6	4–5.5		3–3.8	9.5	19.5
Tensile yield strength, 10^3 lb · in^{-2}	1.7–2.5	4.5–5.4	3.5–4.3	2.5–3.1	3–3.4		
Thermal							
Burning rate, mm · min^{-1}							
Coefficient of linear thermal expansion, 10^{-6}°C	128–150	81–100	68–95	60–90	83–100	49	22
Deflection temperature under flexural load (264 lb · in^{-2}), °C	54–60	48–57	45–57	90–105 (66 lb · in^{-2})	51–56	135	249
Maximum recommended service temperature, °C		160	240	140–160			
Specific heat, cal · g^{-1}		0.44–0.46	0.45–0.50	0.45–0.50			
Thermal conductivity, W · m^{-1} · K^{-1}	0.22	0.12	0.15–0.17	0.12–0.17	0.09–0.17	0.29	0.29

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

	Polyurethane			Silicone			Styrenic
	Casting resin		Thermoplastic elastomer	Cast resin, flexible	Mineral- and/or glass-filled	Epoxy molding and encapsulating compound	Polystyrene
Properties	Liquid	Unsaturated					Crystal
Physical							
Melting temperature, °C							
Crystalline	Thermoset	Thermoset		Thermoset	Thermoset	Thermoset	
Amorphous			120–160				85–105
Specific gravity	1.1–1.5	1.05	1.05–1.25	0.99–1.5	1.8–1.94	1.84	1.04–1.05
Water absorption (24 h), %	0.02–1.5	0.1–0.2	0.7–0.9				0.03–0.10
Dielectric strength, kV $\cdot$ mm^{-1}	12–20		13–25	22	8–15	10	24
Electrical							
Volume (dc) resistivity,							$>10^{16}$
ohm-cm	10^{11}–10^{15}		10^{11}–10^{13}	10^{14}–10^{15}			
Dielectric constant (60 Hz)	4.0–7.5		5.4–7.6	2.7–4.2			
Dielectric constant (10^6 Hz)							2.5
Dissipation (power) factor							
(60 Hz)							
Dissipation factor (10^6 Hz)							
Mechanical							
Compressive modulus,							
10^3 lb $\cdot$ in^{-2}	10–100		4–9				

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Property							
Compressive strength, rupture or 1% yield, 10^3 lb·in^{-2}	20		20		10–16	28	11.5–16
Elongation at break, %	100–1000	3–6	100–1100	100–700			1–2
Flexural modulus at 23°C, 10^3 lb·in^{-2}	10–100	610	10–350		1000–2500		380–450
Flexural strength, rupture or yield, 10^3 lb·in^{-2}	0.7–4.5	19	0.7–9		9–14	17	8–14
Hardness, Rockwell (or Shore)			(A65–D80)	(A15–A65)	M80–M90		M60–M75
Impact strength (Izod) at 23°C, J·m^{-1}	1334 to flexible	21	No break		13–427	16	13–21
Tensile modulus, 10^3 lb·in^{-2}	10–100		10–350				350–485
Tensile strength at break, 10^3 lb·in^{-2}	0.175–10	10–11	1.5–8.4	0.35–1.0	4–6.5	6–8	5.3–7.9
Tensile yield strength, 10^3 lb·in^{-2}							
Thermal							
Burning rate, mm·min^{-1}					0–78		
Coefficient of linear thermal expansion, 10^{-6}°C	100–200		100–200	300–800	20–50	30	70–80
Deflection temperature under flexural load (264 lb·in^{-2}), °C	Varies over wide range	87–93	Varies over wide range		260	74–100	
Maximum recommended service temperature, °C					371		93
Specific heat, cal·g^{-1}	0.43		0.43				0.3
Thermal conductivity, W·m^{-1}·K^{-1}	0.21		0.07–0.31	0.15–0.31	0.30	0.68	0.09–0.13

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

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		Styrenic					
	Polystyrene	Acrylonitrile-butadiene-styrene copolymer					
				Molding			
Properties	Heat-resistant	Extrusion	Heat-resistant	High-impact	Flame-retarded	Platable	20% glass-reinforced
Physical							
Melting temperature, °C							
Crystalline							
Amorphous	110–125	88–120	110–125	100–110	110–125	100–110	
Specific gravity	1.05–1.09	1.02–1.06	1.05–1.08	1.01–1.04	1.16–1.21	1.06–1.07	1.22
Water absorption (24 h), %	0.03–0.12	0.20–0.45	0.20–0.45	0.20–0.45	0.2–0.6		
Dielectric strength, kV · mm^{-1}	20	14–20	14–20	14–20	14–20	16–22	18
Electrical							
Volume (dc) resistivity,							
ohm-cm							
Dielectric constant (60 Hz)				2.4–5.0			
Dielectric constant (10^6 Hz)				2.4–3.8			
Dissipation (power) factor							
(60 Hz)				0.003–0.008			
Dissipation factor (10^6 Hz)				0.007–0.015			
Mechanical							
Compressive modulus,							
10^3 lb · in^{-2}		150–390	190–440	140–300	130–310		

Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}	11.5–16	5.2–10	7.2–10	4.5–8	6.5–7.5		14
Elongation at break, %	2–60	20–100	3–20	5–70	5–25		
Flexural modulus at 23°C, 10^3 lb · in^{-2}	340–470	130–420	300–400	250–350	300–400	340–390	710
Flexural strength, rupture or yield, 10^3 lb · in^{-2}	8.9–14	4–14	10–13	8–11	9–14	10.5–11.5	15.5
Hardness, Rockwell (or Shore)	L80–L108	R75–R115	R100–R115	R85–R105	R100–R120	R103–R109	M85
Impact strength (Izod) at 23°C, J · m^{-1}	21–181	133–640	107–347	347–400	160–640	267–283	64
Tensile modulus, 10^3 lb · in^{-2}	320–460	130–380	300–350	230–330	320–400	330–380	740
Tensile strength at break, 10^3 lb · in^{-2}	5–7.8	2.5–8.0	6–7.5	4.8–6.3	5–8	6–6.4	11
Tensile yield strength, 10^3 lb · in^{-2}			5.5–7	4–5.5	4–6		
Thermal							
Burning rate, mm · min^{-1}		1.3		1.3			
Coefficient of linear thermal expansion, 10^{-6}°C	60–70	60–130	60–93	95–110	65–95	47–53	21
Deflection temperature under flexural load (264 lb · in^{-2}), °C	93–120	77–104 annealed	104–116 annealed	96–102 annealed	90–107 annealed	96–102 annealed	99
Maximum recommended service temperature, °C				110			
Specific heat, cal g^{-1}				0.3–0.4			
Thermal conductivity, W · m^{-1} · K^{-1}			0.19–0.34				

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

| | Styrenic | | | Sulfone | | | |
| | Styrene-acrylonitrile copolymer | | | Polysulfone | | | |
Properties	Unfilled	20% glass-fiber-reinforced	Styrene-butadiene copolymer, high-impact	Unfilled	20% glass-fiber-reinforced	Poly(ether sulfone)	Poly(phenyl sulfone)
Physical							
Melting temperature, °C							
Crystalline							
Amorphous	115–125	115–125	90–110	200	200	230	220
Specific gravity	1.07–1.08	1.22	1.03–1.06	1.24	1.46	1.37	1.29
Water absorption (24 h), %	0.2–0.3	0.15–0.20	0.05–0.10	0.22	0.23	0.43	1.1–1.3 (saturated)
Dielectric strength, $kV \cdot mm^{-1}$	16–20	20	18	17	17	17	16
Electrical							
Volume (dc) resistivity, ohm-cm				10^{15}			
Dielectric constant (60 Hz)				3.14	3.7		
Dielectric constant (10^6 Hz)				3.26	3.7		
Dissipation (power) factor (60 Hz)				0.004	0.002		
Dissipation factor (10^6 Hz)				0.008	0.009		
Mechanical							
Compressive modulus, $10^3 \, lb \cdot in^{-2}$	530			370			

Compressive strength, rupture of 1% yield, 10^3 lb $\cdot$ in^{-2}	14–17	19	4–9	13.9	22		
Elongation at break, %	1–4	1–2	13–50	50–100	2	30–80	60
Flexural modulus at 23°C, 10^3 lb $\cdot$ in^{-2}	550	100–1100	280–450	390	1000	375	330
Flexural strength, rupture or yield, 10^3 lb $\cdot$ in^{-2}	14–17	20	5.3–9.4	15.4	23	18.7	12.4
Hardness, Rockwell (or Shore)	M80–M90	R122	M10–M68	M69, R120	M123	M88	
Impact strength (Izod) at 23°C, J $\cdot$ m^{-1}	19–27	53	32–192	64	59	85	640
Tensile modulus, 10^3 lb $\cdot$ in^{-2}	400–560	1150–1200	280–465	360	1200	350	310
Tensile strength at break, 10^3 lb $\cdot$ in^{-2}	9–12	15.8–18	3.2–4.9		17		
Tensile yield strength, 10^3 lb $\cdot$ in^{-2}			2.9–4.9	10.2		12.2	10.4

Thermal

Burning rate, mm $\cdot$ min^{-1}							
Coefficient of linear thermal expansion, 10^{-6}°C	36–38	38–40	70–101	52–56	25	55	31
Deflection temperature under flexural load (264 lb $\cdot$ in^{-2}), °C	88–104	99	74–93	174	182	203	204
Maximum recommended service temperature, °C				149			
Specific heat, cal $\cdot$ g^{-1}							
Thermal conductivity, W $\cdot$ m^{-1} $\cdot$ K^{-1}	0.12	0.26–0.28	0.12–0.21	0.12	0.38	0.14–0.19	

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

| | | | Thermoplastic elastomers | | | Vinyl | |
| | | | | | | Poly(vinyl chloride) and poly(vinyl acetate) | |
Properties	Polyolefin	Polyester	Block copolymers of styrene and butadiene or styrene and isoprene	Block copolymers of styrene and ethylene or styrene and butylene	Urea formaldehyde, alpha-cellulose filled	Rigid	Flexible and unfilled
Physical							
Melting temperature, °C							
Crystalline		168–206			Thermoset		
Amorphous						75–105	75–105
Specific gravity	0.88–0.90	1.17–1.25	0.9–1.2	0.9–1.2	1.47–1.52	1.30–1.58	1.16–1.35
Water absorption (24 h), %	0.01		0.19–0.39		0.4–0.8	0.04–0.4	0.15–0.75
Dielectric strength, kV · mm^{-1}	24–26		16–21		12–16	14–20	12–16
Electrical							
Volume (dc) resistivity, ohm-cm					0.5–5.0	10^{12}–10^{15}	10^{11}–10^{14}
Dielectric constant (60 Hz)					7.7–9.5	3.2–4.0	5.0–9.0
Dielectric constant (10^6 Hz)					6.7–8.0	3.0–4.0	3.0–4.0
Dissipation (power) factor (60 Hz)					0.036–0.043	0.01–0.02	0.03–0.05
Dissipation factor (10^6 Hz)					0.025–0.035	0.006–0.02	0.06–0.1
Mechanical							
Compressive modulus, 10^3 lb · in^{-2}			3.6–120				

Property							
Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}					25–45	8–13	0.9–1.7
Elongation at break, %	150–300	350–450	500–1350	600–800	<1	40–80	200–450
Flexural modulus at 23°C, 10^3 lb · in^{-2}	1.5–2.0	7–75	4–150	4–100	1300–1600	300–500	
Flexural strength, rupture or yield, 10^3 lb · in^{-2}					10–18	10–16	
Hardness, Rockwell (or Shore)	(A65–A92)	(D40–D72)	(A40–A90)	(A50–A90)	M110–M120	(D65–D95)	(A50–A100)
Impact strength (Izod) at 23°C, J · m^{-1}	No break	208 to no break	No break	No break	13–21	21–1068	Varies over wide range
Tensile modulus, 10^3 lb · in^{-2}		1.1–2.5	0.8–50		1000–1500	350–600	
Tensile strength at break, 10^3 lb · in^{-2}	0.65–2.0	3.7–5.7	0.6–3.0	1–3	5.5–13	6–75	1.5–3.5
Tensile yield strength, 10^3 lb · in^{-2}							
Thermal							
Burning rate, mm · min^{-1}					Self-extinguishing	Self-extinguishing	Slow to self-extinguishing
Coefficient of linear thermal expansion, 10^{-6}°C	130–170		130–137		22–36	50–100	70–250
Deflection temperature under flexural load (264 lb · in^{-2}), °C			<0–49		127–143	60–77	
Maximum recommended service temperature, °C					77	70–74	80–105
Specific heat, cal · g^{-1}					0.6	0.2–0.28	0.36–0.5
Thermal conductivity, W · m^{-1} · K^{-1}	0.19–0.21		0.15		0.30–0.42	0.15–0.21	0.13–0.17

TABLE 10.2 Properties of Commercial Plastics (*Continued*)

Properties	Vinyl						
	Poly(vinyl chloride) and poly(vinyl acetate)	Poly(vinyl chloride), 15% glass-fiber-reinforced	Poly(vinylidene chloride)	Poly(vinyl formal)	Chlorinated poly(vinyl chloride)	Poly(vinyl butyral), flexible	
	Flexible and filled						
Physical							
Melting temperature, °C							
Crystalline			210				
Amorphous	75–105	75–105		105	110	49	
Specific gravity	1.3–1.7	1.54	1.65–1.72	1.2–1.4	1.49–1.56	1.05	
Water absorption (24 h),%	0.5–1.0	0.01	0.1	0.5–3.0	0.02–0.15	1.0–2.0	
Dielectric strength, $kV \cdot mm^{-1}$	9.8–12	24–31	16–24	19		14	
Electrical							
Volume (dc) resistivity, ohm-cm			$10^{14}–10^{16}$				
Dielectric constant (60 Hz)			4.5–6.0				
Dielectric constant (10^6 Hz)							
Dissipation (power) factor (60 Hz)							
Dissipation factor (10^6 Hz)							
Mechanical							
Compressive modulus, $10^3 lb \cdot in^{-2}$					335–600		

Compressive strength, rupture or 1% yield, 10^3 lb · in^{-2}	1.0–1.8	9	2–2.7		9–22	
Elongation at break, %	200–400	2–3	50–250	5–20	4–65	150–450
Flexural modulus at 23°C, 10^3 lb · in^{-2}		750			380–450	
Flexural strength, rupture or yield, 10^3 lb · in^{-2}		13.5	4.2–6.2	17–18	14.5–17	
Hardness, Rockwell (or Shore)	(A50–A100)	R118	M50–M65	M85	R117–R122	A10–A100
Impact strength (Izod) at 23°C, J · m^{-1}	Varies over wide range	53	16–53	43–75	53–299	Varies over wide range
Tensile modulus, 10^3 lb · in^{-2}		870	50–80	350–600	360–475	
Tensile strength at break, 10^3 lb · in^{-2}	1–3.5	9.5	3–5	10–12	7.5–9	0.5–3.0
Tensile yield strength, 10^3 lb · in^{-2}						
Thermal						
Burning rate, mm · min^{-1}			Self-extinguishing			Slow
Coefficient of linear thermal expansion, 10^{-6}°C			190	64	68–78	
Deflection temperature under flexural load (264 lb · in^{-2}), °C		68	54–71	71–77	94–112	
Maximum recommended service temperature, °C			100			
Specific heat, cal · g^{-1}			0.32			
Thermal conductivity, W · m^{-1} · K^{-1}	0.13–0.17		0.13	0.16	0.14	

10.4   FORMULAS AND ADVANTAGES OF RUBBERS

10.4.1   Gutta Percha

Gutta percha is a natural polymer of isoprene (3-methyl-1,3-butadiene) in which the configuration around each double bond is *trans*. It is hard and horny and has the following formula:

$$\left[\begin{array}{c} CH_3 \\ | \\ C \\ \diagup \quad \diagdown \\ CH_2 \qquad CH \end{array} \begin{array}{c} \\ CH_2 \\ \end{array} \right]_n$$
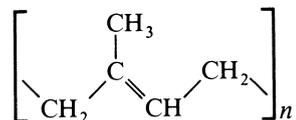
10.4.2   Natural Rubber

Natural rubber is a polymer of isoprene in which the configuration around each double bond is *cis* (or *Z*):

$$\left[\begin{array}{c} H_3C \\ \diagdown \\ C=CH \\ \diagup \qquad \diagdown \\ -CH_2 \qquad CH_2- \end{array} \right]_n$$
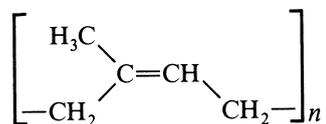
Its principal advantages are high resilience and good abrasion resistance.

10.4.3   Chlorosulfonated Polyethylene

Chlorosulfonated polyethylene is prepared as follows:

$$[-CH_2-CH_2-]_n + HSO_3Cl \rightarrow \left[\begin{array}{c} -CH_2-CH- \\ | \\ SO_3H \end{array} \right]_n + HCl$$
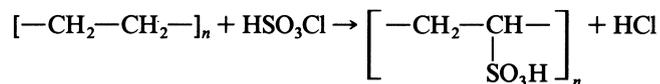
Cross-linking, which can occur as a result of side reactions, causes an appreciable gel content in the final product.

The polymer can be vulcanized to give a rubber with very good chemical (solvent) resistance, excellent resistance to aging and weathering, and good color retention in sunlight.

10.4.4   Epichlorohydrin

Epichlorohydrin is a product of covulcanization of epichlorohydrin (epoxy) polymers with rubbers, especially *cis*-polybutadiene.

Its advantages include impermeability to air, excellent adhesion to metal, and good resistance to oils, weathering, and low temperature.

10.4.5   Nitrile Rubber (NBR, GRN, Buna N)

Nitrile rubber can be prepared as follows:

$$CH_2\!\!=\!\!CH\!-\!CH\!\!=\!\!CH_2 + CH_2\!\!=\!\!CH\!-\!CN \rightarrow$$

    2 parts   1 part

$$\left[-CH_2-CH\!\!=\!\!CH-CH_2-CH_2-\underset{\underset{CN}{|}}{CH}-CH_2-CH\!\!=\!\!CH-CH_2- \right]_n$$
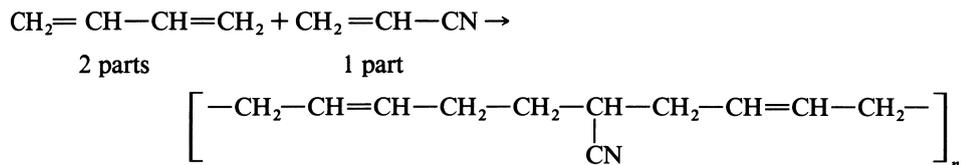
Nitrile rubber is also known as nitrile-butadiene rubber (NBR), government rubber nitrile (GRN), and Buna N.

It possesses resistance to oils up to 120°C and excellent abrasion resistance and adhesion to metal.

10.4.6   Polyacrylate

Polyacrylate has the following formula:

$$\left[-CH_2-\underset{\underset{CN}{|}}{CH}- \right]_n$$
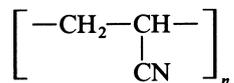
It possesses oil and heat resistance to 175°C and excellent resistance to ozone.

10.4.7   *cis*-Polybutadiene Rubber (BR)

cis-Polybutadiene is prepared by polymerization of butadiene by mostly 1,4-addition.

$$CH_2\!\!=\!\!CH\!-\!CH\!\!=\!\!CH_2 \rightarrow [-CH_2-CH\!\!=\!\!CH-CH_2-]_n$$
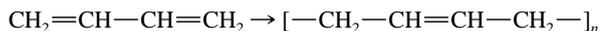
The polybutadiene produced is in the Z (or *cis*) configuration.

cis-Polybutadiene has good abrasion resistance, is useful at low temperature, and has excellent adhesion to metal.

10.4.8 Polychloroprene (Neoprene)

Polychloroprene is prepared as follows:

$$CH_2\!=\!CH\!-\!\underset{\underset{Cl}{|}}{C}\!=\!CH_2 \rightarrow [-CH_2\!-\!CH\!=\!C(Cl)\!-\!CH_2\!-]_n$$
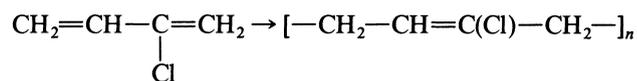
It has very good weathering characteristics, is resistant to ozne and to oil, and is heat-resistant to 100°C.

10.4.9 Ethylene-Propylene-Diene Rubber (EPDM)

Ethylene-propylene-diene rubber is polymerized from 60 parts ethylene, 40 parts propylene, and a small amount of nonconjugated diene. The nonconjugated diene permits sulfur vulcanization of the polymer instead of using peroxide.

It is a very lightweight rubber and has very good weathering and electrical properties, excellent adhesion, and excellent ozone resistance.

10.4.10 Polyisobutylene (Butyl Rubber)

Polyisobutylene is prepared as follows:

$$H_3C\!-\!\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}\!=\!CH_2 + CH_2\!=\!\underset{}{\overset{\overset{CH_3}{|}}{C}}\!-\!CH\!=\!CH_2 \rightarrow$$

98 parts   2 parts

$$\left[\left(-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}\!-\!CH_2\!- \right)_n -CH_2\!-\!\overset{\overset{CH_3}{|}}{C}\!=\!CH\!-\!CH_2\!- \right]$$
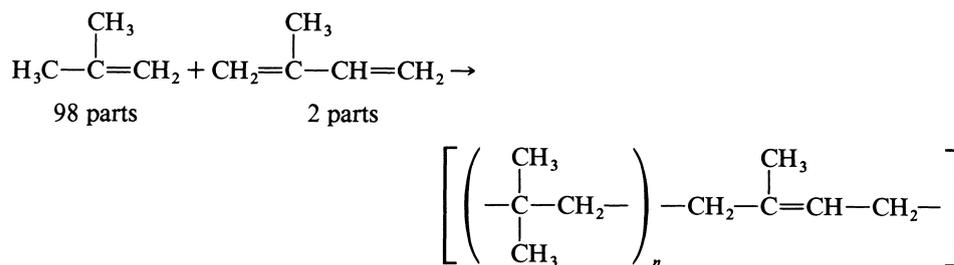
It possesses excellent ozone resistance, very good weathering and electrical properties, and good heat resistance.

10.4.11 (*Z*)-Polyisoprene (Synthetic Natural Rubber)

Polymerization of isoprene by 1,4-addition produces polyisoprene that has a *cis* (or *Z*) configuration.

$$\left[\begin{array}{c} H_3C \\ -CH_2 \end{array} \!\!\! C\!=\!C \!\!\! \begin{array}{c} H \\ CH_2- \end{array} \right]_n$$
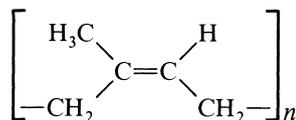
10.4.12 Polysulfide Rubbers

Polysulfide rubbers are prepared as follows:

$$Cl-R-Cl + Na-S-S-S-S-Na \rightarrow HS[-R-S-S-S-S-]_n R-SH$$

where R can be

$$-CH_2CH_2-, \quad -CH_2CH_2-O-CH_2CH_2-,$$

or
$$-CH_2CH_2-O-CH_2-O-CH_2CH_2-.$$
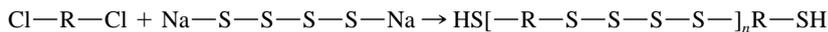
Polysulfide rubbers possess excellent resistance to weathering and oils and have very good electrical properties.

10.4.13 Poly(vinyl Chloride) (PVC)

Poly(vinyl chloride) as previously discussed in Sec. 10.3, Formulas and Key Properties of Plastic Materials, has the following structures:

$$\left[\begin{array}{c} -CH_2-CH- \\ | \\ Cl \end{array} \right]_n$$
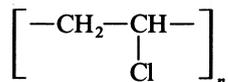
PVC polymer plus special plasticizers are used to produce flexible tubing which has good chemical resistance.

10.4.14 Silicone Rubbers

Silicone rubbers are prepared as follows:

$$Cl-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{Si}}-Cl \xrightarrow{H_2O} HO-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{Si}}-OH \xrightarrow{polymerize} \left[-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{Si}}-O- \right]_n$$
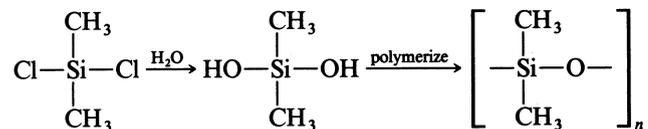
Other groups may replace the methyl groups.

Silicone rubbers have excellent ozone and weathering resistance, good electrical properties, and good adhesion to metal.

10.4.15 Styrene-Butadiene Rubber (GRS, SBR, Buna S)

Styrene-butadiene rubber is prepared from the free-radical copolymerization of one part by weight of styrene and three parts by weight of 1,3-butadiene. The butadiene is incorporated by both 1,4-addition (80%) and 1,2-addition (20%). The configuration around the double bond of the 1,4-adduct is about 80% *trans.* The product is a random copolymer with these general features:
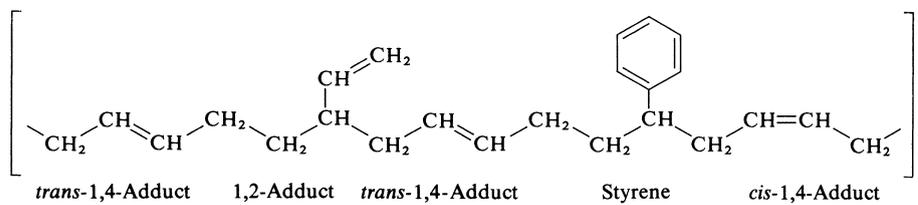
Styrene-butadiene rubber (SBR) is also known as government rubber styrene (GRS) and Buna S.

10.4.16 Urethane

See Table 10.3.

TABLE 10.3 Properties of Natural and Synthetic Rubbers

Rubber	Specific gravity	Durometer hardness (or Shore)	Ultimate elongation % (23°C)	Tensile strength, lb · in^{-2} (23°C)	Service temperature, °C	
					Minimum	Maximum
Gutta percha (hard rubber)	1.2–1.95	(65–95)	3–8	4000–10,000		104
Natural rubber (NR)	0.93	20–100	750–850	3000–4500	−56	82
Chlorosulfonated polyethylene	1.10	50–95	100–500	500–3000	−54	121
Epichlorohydrin	1.27	60–90	100–400	1000–2500	−46	121
Fluoroelastomers	1.4–1.95	60–90	100–350	2000–3000	−40	232
Isobutene-isoprene rubber (IIR) [also known as government rubber I(GR-I)]	0.91	(40–70)	750–950	2300–3000		121
Nitrile rubber (butadiene-acrylonitrile rubber) (also known as Buna N and NBR)	1.00	30–100	100–600	500–4000	−54	121
Polyacrylate	1.10	40–100	100–400	1000–2200	−18	149
Polybutadiene rubber (BR)	0.93	30–100	100–700	2500–3000	−62	79–100
Polychloroprene (neoprene)	1.23	20–90	800–1000	2000–3500	−54	121
Poly(ethylene-propylene-diene) (EPDM)	0.85	30–100	100–300	1000–3000	−40	149
Polyisobutylene (butyl rubber)	0.92	30–100	100–700	1000–3000	−54	100
Polyisoprene	0.94	20–100	100–750	2000–3000	−54	79–82
Polysulfide (Thiokol ST)	1.34	20–80	100–400	700–1250	−54	82–100
Poly(vinyl chloride) (Koroseal)	1.32	(80–90)		2400–3000		71
Silicone, high-temperature				700–800		316
Silicone	0.98	20–95	50–800	500–1500	−84	232
Styrene-butadiene rubber (SBR) (also known as Buna S)	0.94	40–100	400–600	1600–3700	−60	107
Urethane	0.85	62–95	100–700	1000–8000	−54	100

10.5 CHEMICAL RESISTANCE

TABLE 10.4 Resistance of Selected Polymers and Rubbers to Various Chemicals at 20°C

The information in this table is intended to be used only as a general guide. The chemical resistance classifications are E = excellent (30 days of exposure causes no damage), G = good (some damage after 30 days), F = fair (exposure may cause crazing, softening, swelling, or loss of strength), N = not recommended (immediate damage may occur).

	Chemical												
Polymers	Acids, dilute or weak	Acids, strong and concentrated	Alcohols, aliphatic	Aldehydes	Alkalies, concentrated	Esters	Ethers	Glycols	Hydrocarbons, aliphatic	Hydrocarbons, aromatic	Hydrocarbons, halogenated	Ketones	Oxidizing agents, strong
Acetals	F	N	F	N	N	N	N	G	N	N	N	N	N
Acrylics: poly(methyl methacrylate)	G	N	E	—	N	N	E	E	G	N	N	N	N
Allyls: diallyl phthalate	G	—	—	—	N	—	—	—	E	G	G	N	—
Cellulosics: cellulose-acetate-butyrate and cellulose-acetate-propionate polymers	F	N	N	N	N	N	N	G	F	N	N	N	—
Fluorocarbons	E	E	E	E	E	E	E	E	E	E	E	E	E
Polyamides	N	N	G	E	E	G	—	G	G	F	F	G	N
Polycarbonates	G	N	G	F	N	N	N	G	N	N	N	N	N
Polyesters	G	G	N	—	N	N	F	G	G	F	F	N	F
Poly(methyl pentene)	E	E	G	G	E	G	N	E	F	G	N	F	F
Low-density polyethylene	E	E	E	G	E	G	N	E	F	F	N	G	F
High-density polyethylene	E	E	E	E	E	G	N	E	G	G	N	G	F
Polybutadiene	G	F	E	—	—	—	—	—	—	E	E	E	—

Material													
Polypropylene and polyallomer	E	E	E	E	E	G	N	E	G	F	N	G	F
Polystyrene	N	N	E	—	N	N	—	E	N	F	N	N	N
Styrene-acrylonitrile copolymers	—	—	E	—	N	—	—	F	N	—	—	—	—
Styrene-acrylonitrile-butadiene copolymers	—	N	G	—	G	N	—	—	F	N	N	N	—
Sulfones: polysulfone	G	N	F	F	E	N	F	G	F	N	N	N	G
Vinyls: poly(vinyl chloride)	E	G	E	G	G	N	F	F	G	N	N	N	G

Rubbers

Material													
Natural rubber	—	—	E	—	—	N	N	E	N	N	N	N	—
Nitrile rubber	—	—	E	—	—	N	G	E	E	N	N	N	—
Polychloroprene	—	—	E	—	—	N	F	E	F	N	N	N	—
Polyisobutylene	—	—	E	—	—	F	F	E	N	N	N	N	—
Polysulfide rubbers: Thiokol	—	—	E	—	—	E	E	E	E	F	N	N	—
Styrene-butadiene rubber	—	—	E	—	—	N	N	E	N	N	N	N	—

10.6 GAS PERMEABILITY

TABLE 10.5 Gas Permeability Constants ($10^{10}\,P$) at 25°C for Polymers and Rubbers

The gas permeability constant P is defined as

$$P = \frac{\text{amount of permeant}}{(\text{area}) \times (\text{time}) \times (\text{driving forced across the film})}$$

The gas permeability constant is the amount of gas expressed in cubic centimeters passed in 1 s through a 1-cm^2 area of film when the pressure across a film thickness of 1 cm is 1 cmHg and the temperature is 25°C. All tabulated values are multiplied by 10^{10} and are in units of seconds^{-1} (centimeters of Hg)$^{-1}$. Other temperatures are indicated by exponents and are expressed in degrees Celsius.

Polymer or rubber	Gas						
	He	N_2	H_2	O_2	CO_2	H_2O	Other
Cellulose (cellophane)	0.005[20]	0.003 2	0.006 5	0.002 1	0.004 7	1 900	0.006[45] (H_2S); 0.001 7 (SO_2)
Cellulose acetate	13.6[20]	0.28[30]	3.5[20]	0.78[30]	22.7[30]	5 500	3.5[30] (H_2S); 17[0] (ethylene oxide); 6.8[60] (bromomethane)
Cellulose nitrate	6.9	0.12	2.0[20]	1.95	2.12	6 290	57.1 (NH_3); 1.76 (SO_2)
Ethyl cellulose	400[30]	8.4[30]	87[20]	26.5[30]	41.0[30]	12 000[20]	705 (NH_3); 204 (SO_2); 420[0] (ethylene oxide)
Gutta percha		2.17	14.4	6.16	35.4	510	
Natural rubber		9.43	52.0	23.3	15.3	2 290	15.7 (CO); 30.1 (CH_4); 1.68 (C_3H_8); 98.9 (C_2H_2); 550 ($CH_3C{\equiv}CH$); 3.59 (SF_6)
Nylon 6	0.53[20]	0.009 5[30]		0.038[30]	0.10[30]	177	0.33[30] (H_2S); 1.2[20] (NH_3); 0.84[60] (CH_3Br)
Nylon 11	1.95[30]		1.78[30]		1.00[40]		0.344[30] (Ne); 0.189[40] (Ar); 13.6[50] (propyne)
Poly(acrylonitrile)				0.000 2	0.000 8	300	

Acrylonitrile-styrene copolymer (66:34)				0.048	0.21	2 000	
Poly(1,3-butadiene)		6.42	41.9	19.0	138.0	5 070	
Poly (cis-1,4-butadiene)	32.6	19.2					19.2 (Ne); 41.0 (Ar)
Butadiene-acrylonitrile copolymer (80:20)	12.2	1.06	15.9	3.85	30.8		24.8 (C_2H_2); 7.7 (propyne)
Butadiene-styrene copolymer (80:20)	13.4	1.71					5.01 (Ne); 4.49 (Ar)
Butadiene-styrene copolymer (92:8)	22.9	5.11					9.70 (Ne); 12.7 (Ar)
Polychloroprene		1.2	13.6	4.0	25.8		3.79 (Ar); 3.27 (CH_4)
Polyethylene, low-density	4.9	0.969	12.0^{30}	2.88	12.6	90	2.88 (CH_4); 6.81 (C_2H_6); 9.43 (C_3H_8); 1.48 CO; 49^0 (ethylene oxide); 14.4 (propene); 42.2 (propyne); 0.170 (SF_6); 472^{60} (CH_3Br)
Polyethylene, high-density	1.14	0.143	3.0^{20}	0.403	0.36	12.0	0.388 (CH_4); 0.590 (C_2H_6); 0.537 (C_3H_8); 0.008 3 (SF_6); 1.69 (Ar); 4.01 (propene)
Poly(ethylene terephthalate)							
Crystalline	1.32	0.006 5	3.70^{20}	0.035	0.17	130	0.003 2 (CH_4); 0.08^{60} (CH_3Br)
Amorphous	3.28	0.013		0.059	0.30		0.009 (CH_4)
Poly(ethyl methacrylate)	6.82	0.220		1.15	5.00	3 200	2.98 (Ne); 0.565 (Ar); 0.370 (Kr); 3.83 (H_2S); 0.000 001 65 (SF_6)
Isobutene-isoprene copolymer (98:2)	8.38	0.324	7.20	1.30	5.16	110^{38}	13.6^{50} (C_3H_8)
Isoprene-acrylonitrile copolymer (76:24)	7.77	0.181	7.41	0.852	4.32		

TABLE 10.5 Gas Permeability Constants (10^{10} P) at 25°C for Polymers and Rubbers (*Continued*)

Polymer or rubber	Gas						
	He	N_2	H_2	O_2	CO_2	H_2O	Other
Isoprene-methacrylonitrile copolymer (76:24)		0.596	13.6	2.34	14.1		
Methacrylonitrile-styrene-butadiene copolymer (88:7:5)				0.004 8	0.014	600	
Poly(methylpentene)	101	7.83	136	32.0	92.6		
Polypropylene	38[20]	0.44[30]	41[20]	2.3[30]	9.2[30]	51	0.33[20] (H_2S); 9.2[20] (NH_3)
Silicone rubber, 10% filler	233[0]	227[0]	464[0]	489[0]	3 240	43 000[35]	191[0] (Ne); 550[0] (Ar); 1 020[0] (Kr); 2 550[0] (Xe); 19 000[0] (butane)
Polystyrene	18.7	0.788	23.3	2.63	10.5	1 200	
Poly(tetrafluoroethylene)		1.4	9.8	4.2	11.7		15.7 (NO_2); 37.5 (N_2O_4)
Poly(trifluoroethylene)	6.8[20]	0.003	0.94[20]	0.025[40]	0.048[40]	0.29	1.2[0] (ethylene oxide); 4.6[60] (CH_3Br)
Poly(vinyl acetate)	12.6[30]		89[30]	0.50[30]			2.64[30] (Ne); 0.19[30] (Ar); 0.078[30] (Kr); 0.050[30] (CH_4)
Poly(vinyl alcohol)	0.001[30]	<0.001[14]	0.009	0.008 9	0.001[23]		0.007 (H_2S); 0.002[0] (ethylene oxide)
Poly(vinyl chloride)	2.05	0.011 8	1.70	0.045 3	0.157	275	3.92 (Ne); 0.011 5 (Ar); 0.028 6 (CH_4)
Poly(vinylidene chloride)	0.31[34]	0.000 94[30]		0.005 3[30]	0.03[30]	0.5	0.03[30] (H_2S); 0.008[60] (CH_3Br)

TABLE 10.6 Vapor Permeability Constants ($10^{10} P$) at 35°C for Polymers

All tabulated values are multiplied by 10^{10} and are in units of seconds^{-1} (centimeters of Hg)$^{-1}$.

Polymer	Vapor				
	Benzene	Hexane	Carbon tetrachloride	Ethanol	Ethyl acetate
Cellulose	1.4	0.912	0.836	85.8	13.4
Cellulose acetate	512	2.80	3.74	2 980	3 595
Poly(acrylonitrile)	2.61	1.59	1.47	0	1.34
Polyethylene, low-density	5 300	2 910	3 810	55.9	513
Polystyrene	10 600		6 820	0	soluble
Poly(vinyl alcohol)	3.58	2.34	1.61	32.7	2.53

10.7 FATS, OILS, AND WAXES

TABLE 10.7 Constants of Fats and Oils

Fat or oil	Solidification point, °C	Specific gravity (15°C/15°C)	Refractive index	Acid value	Saponification value	Iodine value
			Animal origin			
Butterfat	20–23	$0.91^{40°C}_{15°C}$	$1.45^{40°C}$	0.5–35	210–230	26–38
Chicken fat	21–27	0.924		1.2	193–205	66–72
Cod-liver oil	−3	0.92–0.93	$1.481^{25°C}$	5.6	171–189	137–166
Deer fat		0.96–0.97		0.8–5.3	195–200	26–36

TABLE 10.7 Constants of Fats and Oils (*Continued*)

Fat or oil	Solidification point, °C	Specific gravity (15°C/15°C)	Refractive index	Acid value	Saponification value	Iodine value
			Animal origin (*continued*)			
Dolphin	−3 to +5	0.91–0.93		2–12	203 (body); 290 (jaw)	127 (body); 33 (jaw)
Goat butter		0.91–0.94$_{38°C}^{38°C}$			233–236	25–37
Goose fat	22–24	0.92–0.93		0.6	191–193	58–67
Herring oil		0.92–0.94	1.4610$^{60°C}$	1.8–44	170–194	102–149
Horse fat	20–45	0.92–0.93		0–2.4	195–200	75–86
Human fat	15	0.903	1.460		193–200	57–73
Lard oil	−2 to +4	0.913–0.915	1.462	0.1–2.5	193–198	63–79
Lard oil, fatty tissue	27–30	0.93–0.94	1.462	0.5–0.8	195–203	47–67
Menhaden oil	−5	0.92–0.93	1.465$^{60°C}$	3–12	189–193	148–185
Neat's-foot oil	−2 to +10	0.91–0.92	1.464$^{25°C}$	0.1–0.6	193–199	58–75
Porpoise, body oil	−16	0.926		1.2	203	127
Rabbit fat	17–23	0.93–0.94		1.4–7.2	199–203	70–100
Sardine oil	20–22	0.92–0.93	1.466$^{60°C}$	4–25	188–196	130–152
Seal	3	0.915–0.926		1.9–40	188–196	130–152
Shark		0.916–0.919			157–164	115–139
Sperm oil	15.5	0.878–0.884		13	120–137	80–84
Tallow, beef	31–38	0.895		0.25	196–200	35–42
Tallow, mutton	32–41	0.937–0.953	1.457$^{40°C}$	2–14	195–196	48–61
Whale oil	−2 to 0	0.917–0.924	1.460$^{60°C}$	1.9	160–202	90–146
			Plant origin			
Acorn	−10	0.916			199	100
Almond	−20 to −15	0.914–0.921		0.5–3.5	183–208	93–103
Babassu oil	22–26	0.893$^{60°C}$	1.443$^{60°C}$		247	16
Beechnut oil	−17	0.922			191–196	97–111

Castor oil	-18 to -17	0.960–0.967	1.477	0.1–0.8	175–183	84
Chaulmoogra oil, USP	<-25	0.950$^{25°C}$			196–213	98–110
Chinese vegetable tallow	24–34	0.918–0.922		2.4	179–206	23–41
Cocoa butter	21.5–23	0.964–0.974	1.457$^{40°C}$	1.1–1.9	193–195	33–42
Coconut oil	14–22	0.926	1.449$^{40°C}$	2.5–10	153–262	6–10
Corn (maize) oil	-20 to -10	0.921–0.928	1.473$^{40°C}$	1.4–2.0	187–193	111–128
Cottonseed oil	-13 to $+12$	0.918$^{25°C}_{25°C}$	1.474$^{40°C}$	0.6–0.9	194–196	103–111
Hazelnut oil	-18 to -17	0.917			191–197	87
Hemp-seed oil	-28 to -15	0.928–0.934		0.45	190–195	145–162
Linseed oil	-27 to -19	0.930–0.938	1.478$^{25°C}$	1–3.5	188–195	175–202
Mustard, black, oil	16	0.918–0.921	1.475$^{40°C}$	5.7–7.3	173–175	99–110
Neem oil	-3	0.917	1.462$^{40°C}$		195	71
Niger-seed oil		0.925	1.471$^{40°C}$		190	129
Oiticica oil		0.974$^{25°C}$				140–180
Olive oil	-6	0.914–0.918	1.468$^{40°C}$	0.3–1.0	185–196	79–88
Palm oil	35–42	0.915	1.458$^{40°C}$	10	200–205	49–59
Palm kernel oil	24	0.918–0.925	1.457$^{40°C}$	0.3–0.6	220–231	26–32
Peanut oil	3	0.917–0.926	1.469$^{40°C}$	0.8	186–194	88–98
Perilla oil		0.930–0.937	1.481$^{25°C}$		188–194	185–206
Pistachio-nut oil	-10 to -5	0.913–0.919			191	83–87
Poppy-seed oil	-18 to -16	0.924–0.926	1.469$^{40°C}$	2.5	193–195	128–141
Pumpkin-seed oil	-15	0.923–0.925			188–193	121–130
Rapeseed oil	-10	0.913–0.917	1.471$^{40°C}$	0.36–1.0	168–179	94–105
Safflower oil	-18 to -13	0.925–0.928	1.462$^{60°C}$	0.6	188–203	122–141
Sesame oil	-6 to -4	0.919$^{25°C}_{25°C}$	1.465$^{40°C}$	9.8	188–193	103–117
Soybean oil	-16 to -10	0.924–0.927	1.473$^{40°C}$	0.3–1.8	189–194	122–134
Sunflower-seed oil	-17	0.924–0.926	1.469$^{40°C}$	11.2	188–193	129–136
Tung oil	-2.5	0.94–0.95	1.517$^{25°C}$	2	190–197	163–171
White-mustard-seed oil	-16 to -8	0.912–0.916		5.4	171–174	94–98
Wheat-germ oil						125

TABLE 10.8 Constants of Waxes

Wax	Melting point, °C	Specific gravity (15°C/15°C)	Refractive index	Acid value	Saponification value	Iodine value
Bamboo leaf	79–80	$0.961^{25°C}$		14–15	43–44	7.8
Bayberry (myrtle)	47–49	0.99	$1.436^{80°C}$	3–4	205–212	4–9.5
Beeswax, ordinary	62–66	0.95–0.97	$1.44–1.48^{40°C}$	17–21	88–100	8–11
Beeswax, East Indian	61–67	0.95–0.97	$1.44^{40°C}$	5–10.5	87–117	4–10.5
Beeswax, white, USP	61–69	0.95–0.98	$1.45–1.47^{65°C}$	17–24	90–96	7–11
Candelilla	73–77	0.98–0.99	$1.45–1.46^{85°C}$	19–24	55–64	14–20
Cape berry	40–45	1.01	$1.45^{45°C}$	2.5–4.0	211–215	0.5–2.5
Caranda	80–85	0.99–1.00		5.0–9.5	64–79	8–9
Carnauba, No. 1 yellow	86–88	0.99–1.00		1.5–2.5	75–86	
Carnauba, No. 3, crude	86–90	0.99–1.01		3.0–8.5	75–89	
Carnauba, No. 3, refined	86–89	0.96–0.97	$1.47^{40°C}$	3.0–5.0	76–85	7–13.5
Castor oil, hydrogenated	83–88	$0.98–0.99^{20°C}$		1.0–5.0	177–181	2.5–8.5
Chinese insect	80–85	0.95–0.97	$1.46^{40°C}$	2–9	78–93	1.0–2.5
Cotton	68–71	0.96		32	71	25
Cranberry	207–218	0.97–0.98		42–59	131–134	44–53
Esparto	75–79	0.985–0.995		22–27	58–73	7–15
Flax	61–70	0.91–0–0.99		17–48	37–102	22–29
Japan	49–56	0.97–1.00		4–15	210–235	4–15
Jojoba	11–12	$0.86–0.90^{25°C}$	$1.465^{25°C}$	0.2–0.6	92–95	82–88

Microcrystalline, amber	64–91	0.91–0.94	1.42–1.45$^{80°C}$	0	0	0
Microcrystalline, white	71–89	0.93–0.94	1.441$^{80°C}$	0	0	0
Montan, crude	76–86	1.01–1.02$^{25°C}$		22–31	59–92	14–18
Montan, refined	77–84	1.02–1.04		23–45	72–115	10–14
Ouricury	86–89	0.99–1.01		12–19	88–96	6.9–7.8
Ozokerite	56–82	0.90–1.00		0	0	4–8
Palm	74–86	0.99–1.05		5–11	64–104	9–17
Paraffin, American	49–63	0.896–0.925	1.44–1.48$^{80°C}$	0	0	0
Shellac	79–82	0.97–0.98		12–24	64–83	6–9
Sisal hemp	74–81	1.007–1.010		16–19	56–58	28–29
Spermaceti	41–49	0.905–0.960		0.5–3.0	121–135	2.5–8.5
Sugarcane, refined	76–82	0.96–0.98	1.51$^{25°C}$	8–23	55–70	13–29
Wool	38–40	0.97	1.48$^{40°C}$	6–22	82–130	15–47