

# **Polypropylene**

**The Definitive User's Guide and Databook**

**Clive Maier  
Teresa Calafut**

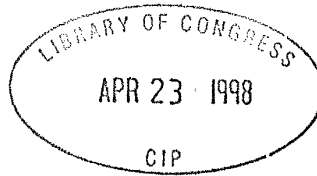


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bilization in experimental studies and had lower volatility and extractibility. It was not absorbed by fibers present in the formulation and did not interact with pigments during fiber spinning. [885]

### 3.4.5 Screeners

Pigments added to a formulation to provide opacity or translucence, such as carbon black, titanium dioxide, and zinc oxide, act as UV screeners by absorbing or reflecting ultraviolet light. Carbon black absorbs ultraviolet and visible light throughout the entire spectrum and may also act as a free radical scavenger. It can be used at concentrations as low as 1 – 2%. The stabilization of resins containing carbon black can be enhanced by addition of antioxidants or HALS. Titanium dioxide (rutile) reflects light and is effective at high loadings. Some pigments can act as synergists with compounds such as phosphites and nickel-organic salts to improve embrittlement time for polypropylene by over 60%. [822, 878]

### 3.4.6 Evaluation of UV stability

The most accurate test of UV stability is use of the material in its intended end-use environment over a period of time. Due to the long-term nature of outdoor weathering tests, accelerated testing using artificial light sources (xenon arc lamp, sunshine carbon arc lamp, mercury arc lamp, fluorescent sun lamp) is common. Filtered xenon most accurately reproduces the spectral energy distribution of sunlight, while light sources with significant emission below 290 nm can produce different results than those obtained with long-term, outdoor weathering. Accelerated exposure tests may underestimate the effectiveness of HALS due to the very high levels of UV radiation produced. [819, 821, 843, 885]

### 3.4.7 Use of light stabilizers

Use levels of light stabilizers range from 0.05–2.0%, depending on the type of stabilizer, part thickness, presence of other additives, type of resin, and application requirements. Benzophenones and hindered amines are widely used in polypropylene. A combination of stabilizers is used to obtain the desired stabilization; highly stabilized polypropylene contains an ultraviolet absorber, a phosphite stabilizer, and a nickel quencher or hindered amine. [821, 878, 822]

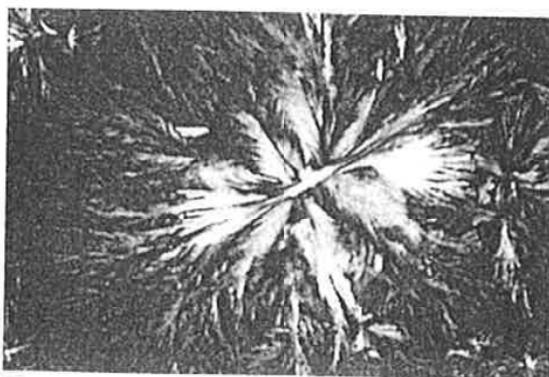
Compatibility with the resin is more important in light stabilizers than in antioxidants, since they are used at higher concentrations. Higher concen-

trations of stabilizers can be dissolved at high temperatures than at low temperatures, so that stabilizers dissolved during resin processing may exhibit blooming, migration of the stabilizer to the part surface, when the resin is cooled. Blooming and turbidity can occur if the stabilizer is incompatible with the resin; compatibility of the generally polar light stabilizers is more difficult to achieve with nonpolar resins such as polypropylene. Diffusion of additives through the resin decreases in resins with increased crystallinity, crosslinking, or orientation. Low molecular weight stabilizers can migrate in incompatible resins; migration is considerably reduced with high molecular weight stabilizers. [858]

## 3.5 Nucleating agents

Nucleating agents are added to polypropylene to improve processing characteristics and clarity and alter its mechanical properties. The addition of nucleating agents provides a large number of sites for the initiation of crystallization, so that spherulites formed are smaller and more numerous than in un-nucleated polypropylene (See Figure 2.2 in Chapter 2: Morphology for a comparison of spherulite sizes in nucleated and un-nucleated polypropylene). Spherulite crystallization around a nucleating agent is shown in Figure 3.11. [886, 693]

Nucleation increases the crystallization temperature and the rate of crystallization; as a result, parts can be removed from the mold at higher temperatures, and molding cycle times are reduced. Crystallization is more complete in nucleated resins than in un-nucleated resins, producing high levels of



**Figure 3.11** Micrograph of a spherulite of polypropylene formed in the presence of a nucleating agent. The nucleating agent is at the center of the spherulite, suggesting that the nucleating agent initiated crystal formation. The nucleating agent was sodium 2,2'-methylenebis(4,6-di-tert-butylphenyl) phosphate. [886]



crystallinity. Nucleated materials have higher tensile strength, stiffness, flexural moduli and heat deflection temperatures than unnucleated materials, but impact strength is lower. The high levels of crystallinity can result in reduced tolerance to radiation sterilization compared to unnucleated polypropylene, and the effectiveness of hindered amine light stabilizers and other stabilizing additives can be reduced. Because nucleated polypropylene shrinks more rapidly in the mold, shrinkage of the resin onto mold cores can occur if parts are not ejected fast enough. [696, 693, 67]

Clarity is enhanced due to the increased cooling rate and the decreased spherulite size, which reduces the scattering of light as it passes through the material (See 2.3.4 *haze* for an explanation of haze in unnucleated polypropylene). Smaller spherulites can reduce warpage in some applications and can provide a harder, more stain-resistant surface. [696, 693]

Nucleating agents used in polypropylene include carboxylic acid salts, benzyl sorbitols, and salts of organic phosphates. Carboxylic acid salts provide limited clarity enhancement but do enhance the mechanical properties by an increase in the crystallization rate. Dibenzylidene sorbitols reduce crystal size dramatically, resulting in greatly improved clarity. Benzyl sorbitols can result in odor generation during processing which produces odor in the finished part. Pigments, such as phthaloxyanine blue and green and phthalyl blue, and mineral fillers such as talc can also act as nucleating agents, although talc is not as effective. [693, 886, 779, 696]

Applications of nucleated polypropylene include food bottles and packaging, automobile parts, medical syringes, and houseware containers. [855]

### 3.6 Flame retardants

Many plastics are inherently flammable due to their origins in petroleum manufacturing. Polypropylene ignites when in contact with a flame and burns with a faintly luminous flame even after the ignition source is removed. Melting occurs due to the high heat of the flame, producing burning drips. For applications in the construction, automotive, appliances, and electronics industries, polypropylene must be stabilized by the use of flame retardants. [825, 820, 326]

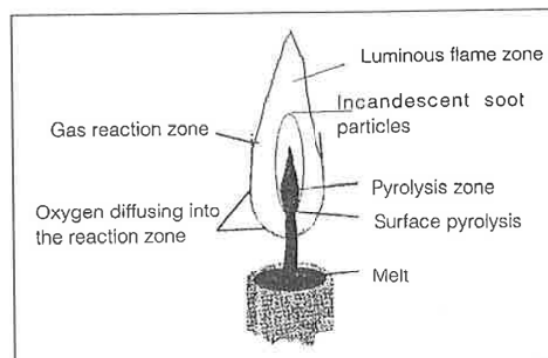
Polypropylene is one of the most difficult plastics to make flame retardant. High levels of flame retardants are required in the polypropylene

formulation to meet standards for applications such as in the electronics industry; 25% flame retardant is required in polypropylene compared to 10–20% for styrenics or engineering thermoplastics. These high levels of flame retardant increase brittleness and impair the mechanical performance of the material. Flame retardants can also reduce processability and can interfere with the action of other additives, such as hindered amine light stabilizers. [834, 836, 837]

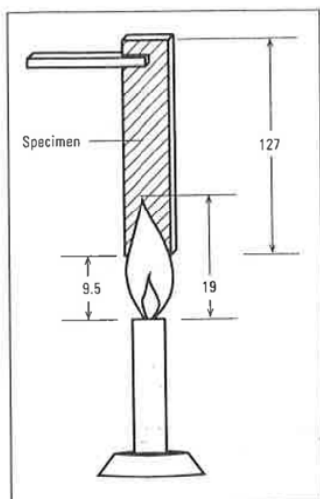
#### 3.6.1 Fire

Combustion is a highly exothermic reaction, in which hydrocarbons are oxidized to carbon dioxide and water. Combustion is a gas-phase reaction — polypropylene or its decomposition products must become gaseous for a fire to begin. Fire in a candle occurs when melting wax (composed of hydrocarbons) migrates up the wick through capillary action and is pyrolyzed at 600–800°C (1100–1500°F) to gaseous hydrocarbon decomposition products (Figure 3.12). Pyrolysis is the decomposition of a material by heat alone (in the absence of oxygen). Some of the gaseous hydrocarbons are converted to soot; smoke consists of suspended soot particles. Reaction with carbon dioxide and water in the luminous region produces carbon monoxide. Most of the gaseous hydrocarbons react with oxygen at the exterior of the flame to produce heat, which melts more wax and begins the cycle again. [768, 828, 662, 896]

A fully developed, damaging fire results when



**Figure 3.12 A candle flame.** Melting wax migrates up the wick and pyrolyzes at the surface of the wick to form gaseous hydrocarbon decomposition products. Some of the gaseous hydrocarbons form soot in the incandescent region of the flame; gases can also react with water and carbon dioxide in air, forming carbon monoxide in the luminous flame zone. Most gases react with oxygen at the exterior of the flame to produce heat. [896]



**Figure 3.15 The UL 94 vertical burn test.** A specimen suspended vertically over absorbent cotton is ignited by a bunsen burner. Duration of the flame and afterglow is measured, and any generation of flaming drips that ignite the cotton is noted. Each of five samples are ignited for 10 seconds; rating criteria include V-0, V-1, V-2, V-5, and HB levels. [888]

rial under specified conditions, in order to predict its performance in an actual fire. Many applications require specific performance levels in particular tests. The most common test is the UL 94 in electrical devices, in which burning times resulting from various ignition orientations are measured. The purpose of the test is to ensure that a spark or electrical short will not result in a fire. In the UL 94 V test (Figure 3.15), a specimen is suspended vertically over a bunsen burner and surgical cotton. The results rate the specimen at different levels based on thicknesses; a V-0 rating, the highest, corresponds to a flame duration of 0–5 seconds, an afterglow of 0–25 seconds, and no flaming drips that ignite the absorbent cotton. [828, 662]

In the limiting oxygen index (LOI) test, the minimum concentration of oxygen necessary for candle-like burning of  $\geq 3$  minutes is measured. It is primarily used for product development. Numerical data are obtained, and the LOI is generally directly proportional to the concentration of flame retardants. A higher LOI indicates that more oxygen is needed to support combustion. Air contains  $\sim 21\%$  oxygen, so a rating lower than this will usually support combustion under normal atmospheric conditions. [662, 828]

Combinations of flame retardants are generally used to achieve the required level of fire inhibition. A V-0 or V-1 ( $\leq 30$  s flame duration,  $\leq 60$  s afterglow, no cotton ignition) rating can be

achieved in polypropylene with  $\geq 30\%$  of a cycloaliphatic chlorine and  $\geq 13\%$  antimony oxide. A V-2 rating ( $\leq 30$  s flame duration,  $\leq 60$  s afterglow, cotton ignition) can be achieved with 5–10% brominated cycloaliphatic imides, ammonium fluoroborates, or chlorinated polyolefins, with an antimony oxide synergist. [822]

### 3.7 Colorants

Color is used in almost all plastic applications. Color can improve the aesthetic appeal of a product — qualities such as “warm”, “soft”, “bright”, or “pleasant” are determined primarily by color. Product color influences consumer perception and can determine how well the product sells, and color changes may be necessary over time as consumer preferences change. A variety of colors are available for use in plastics, in addition to special effect colorants that produce metallic effects, pearlescence, fluorescence, and phosphorescence. [871, 821, 824]

Colorants used in plastics are pigments or dyes. Dyes are organic compounds that are soluble in the plastic, forming a molecular solution. They produce bright, intense colors and are transparent and easy to disperse and process. They can have poor thermal and UV stability, however, and are mainly used in applications with low processing temperatures and low UV stability requirements, such as toys. Dyes are not compatible with polyolefins, having a tendency to bleed and plate out, but they have been used in oriented or crosslinked polypropylene. [826, 871]

Pigments are generally insoluble in the plastic; color results from the dispersion of fine particles ( $\sim 0.01$ – $1 \mu\text{m}$ ) throughout the resin. They produce opacity or translucence in the final product. Pigments can be organic or inorganic compounds, and they are available in a variety of forms — dry powders, color concentrates, liquids, and precolored resins. [821, 826]

#### 3.7.1 Optical effects of pigments

Pigments and dyes produce color in a resin from selective absorption of visible light (wavelength range from  $\sim 380$  nm (violet) to 760 (red)). The perceived color is the color of the light transmitted through the colorant and not the light that was absorbed. Complementary colors are seen by the eye; light absorption at 490–560 nm (green) will be perceived as a red color. (Complementary colors

are red-green, blue-orange, violet-yellow). The human eye can detect color differences of about 1 nm in wavelength. Absorption at all wavelengths of visible light will produce a black color, while no absorption will appear colorless. [766, 590]

Because dyes are in solution, color is produced only from light absorption, and the material is transparent. A dispersion of pigment particles in a resin can also reflect or scatter light. If the refractive index of the pigment particle is different from that of the spherulites in the plastic microstructure, light will be reflected, and the particle dispersion will scatter light in all directions. Light reflection and scattering produces opacity in an originally transparent resin. Resins can be colored and opaque if light was absorbed only at particular wavelengths, or white and opaque if all light was reflected (no absorption). The color shade is affected by particle size of the pigment. Ultramarine blue pigments are nonreflective due to a refractive index similar to that of the plastic. [859]

### 3.7.2 Pigment characteristics

Pigments must be adequately dispersed in the resin for optimum light scattering; specks and uneven coloration can result from incomplete dispersion. Primary pigment particles tend to agglomerate; these must be broken up and distributed homogeneously throughout the polymer during processing, usually by viscous forces or milling. The presence of agglomerated pigment particles in the final part can result in brittleness and part breakage, and large particle sizes can dramatically decrease Gardner impact strength — the large pigment particles act as stress concentrators that reduce the energy required for crack initiation. Higher shear forces can produce pigments with smaller particle sizes. [871, 825, 840, 820]

Pigments should be compatible with the polymer; poor compatibility can be a cause of part failure. Some pigments are partially soluble in the resin and can migrate through the polymer to the surface, where they rub off. Pigments must also be compatible with any other additives present in the formulation. Slip or antistatic agents can cause migration of some colorants. [819]

Most pigments exhibit good light stability, but fading, color changes, or degradation can occur, especially in the presence of both sunlight and humidity. Some colorants, such as FD&C lakes (FDA-approved), can fade even under fluorescent

lights. Surface treatments can improve weathering resistance. [819]

High temperatures during processing can damage or destroy the pigment, causing changes in shade or loss of color. Thermal sensitivity is related to both temperature and duration of exposure — long cycles in injection molding or rotational molding can have a more adverse effect than high-speed extrusion. [871]

Some pigments can act as nucleating agents, altering the mechanical properties and improving the clarity of the resin. In studies with colored filaments, phthalyl blue was found to be an effective nucleator; titanium dioxide (rutile) and carbon black (furnace black) were less effective. [779]

### 3.7.3 Inorganic pigments

The most common inorganic pigments include oxides, sulfides, chromates and other complexes based on heavy metals such as cadmium, zinc, titanium, lead, and molybdenum. They are generally more thermally stable than organic pigments and are more opaque and resistant to migration, chemicals, and fading. They can cause wear on processing equipment such as extrusion machine screws and barrels. The use of heavy metals has been restricted due to OSHA regulations; alternative formulations have been developed, but cost can be up to eight times that of heavy metal pigments, especially for bright colors. [825, 820, 871]

Sulfides — cadmium sulfoselenides (red and orange), cadmium sulfide (orange), cadmium/zinc sulfides (green to yellow), zinc sulfide (white), and ultramarines (blue and violet) — are generally thermally and light stable and migration and alkali resistant but are sensitive to acids. Cadmium compounds have a moderately high cost, and toxicity may be a problem due to the heavy metal content. Compounds with low or no selenium content are less resistant to weathering, since they can easily oxidize to sulfates. [826, 825]

Ultramarines are sulfide-silicate complexes containing sodium and aluminum. They are transparent pigments with weak tinting strength (a measure of brightness) and are widely used in polypropylene and high density polyethylene. Ultramarine blue pigments are highly acid-sensitive and can fade in the presence of acidic catalyst residues. They exhibit poor UV stability; calcium carbonate (CaCO<sub>3</sub>)-filled grades have shown greater UV stability than talc-filled grades, due to the higher absorption capacity of talc and to the

greater amount of heavy metal residues (Fe, Cu, Mn), which catalyze oxidation. Addition of UV stabilizers increases the UV resistance of ultramarine blue; however, it is not usually recommended for outdoor applications of filled polypropylene. [826, 825, 838]

Oxides of iron, barium, titanium, antimony, nickel, chromium, lead, and combinations of two or more metals are used in pigments. They have high thermal stability if the metal is present in its highest oxidation state (i.e.  $\text{Fe}^{+3}$  in  $\text{Fe}_2\text{O}_3$ ; iron oxide red), but oxidation can occur if the metal is present in a lower oxidation state (i.e.  $\text{Fe}^{+2}$  in  $(\text{FeO})_x \cdot (\text{Fe}_2\text{O}_3)_y$ ; iron oxide brown — oxidation from  $\text{Fe}^{+2}$  to  $\text{Fe}^{+3}$ ). Iron oxide colors used in plastics are mainly red and brown; colors produced are relatively dull. They have excellent hiding power (a measure of opacity produced in the resin) and good alkali and light resistance. They are easy to disperse but require careful processing at high temperatures. Chromium oxides produce dull green colors with moderate opacity and low tinting strength. They are light and chemically resistant and have high thermal stability if not hydrated. [859, 826]

Titanium dioxide ( $\text{TiO}_2$ ) is a widely used white pigment that exhibits excellent brightness and opacity and good thermal stability. It represents >90% of the inorganic pigments used in plastics coloration and over 65% of all colorants used in the plastics industry. Titanium dioxides can accelerate surface photooxidation of the plastic if not surface-treated; the anatase form of  $\text{TiO}_2$  has a greater effect. Anatase is not as widely used as the rutile form, which also has better hiding power. Anatase is used when a bluer white, lower abrasiveness, or controlled chaulking is required. [825, 859]

Lead chromates are yellow, bright pigments with very good migration resistance, moderate tint strength, and temperature stability to  $180^\circ\text{C}$  ( $354^\circ\text{F}$ ). They are alkali-sensitive and, if not treated, darken when exposed to light. Molybdate orange, a combination of lead chromate, lead sulfite, and lead molybdate, is an orange pigment with good light stability and acid resistance but poor alkali resistance. It can be combined with other pigments to make a red shade. [826]

Iron blues, based on ferric ammonium ferrocyanide, and chrome greens, a combination of iron blues, lead chromate, and lead sulfate, are not generally used in polypropylene. Chrome greens are

primarily used in low density polyethylene garbage bags and iron blues in low cost applications. [826]

### 3.7.4 Organic pigments

Organic pigments are usually brighter, stronger, and more transparent than inorganic pigments but are not as light-resistant. They can be partially soluble in plastic, with a greater tendency to migrate. Azo pigments are the largest group of organic pigments; they contain one or more azo ( $-\text{N}=\text{N}-$ ) chromophoric groups and form yellow, orange, and red pigments. Monoazo pigments, with only one chromophore, exhibit low thermal and light stability and have a tendency to bleed; they are not usually used in plastics. Polyazos, with more than one chromophore, do not tend to bleed and have better thermal stability and excellent chemical resistance. Polypazos include disazo pigments; higher molecular weight disazo condensation products, with brighter colors and thermal and light stability; di-anisidine orange, with a brilliant color but poor light stability; and pyrazolone pigments, with good thermal stability and migration resistance and good light stability in red pigments. Metallized azos are prepared by precipitating from a metal salt or laking onto an absorptive surface. These red-maroon pigments have poor to good thermal stability, fair to good light stability, and good migration resistance. They include Lake Red C, Permanent Red 2B, Nickel azo yellow, Lithol Red, and Pigment Scarlet. [871, 820, 826]

Nonazo pigments have varied structures, usually polycyclic and sometimes complexed with metals. Phthalocyanine blues and greens, most of which form complexes with copper, are highly stable to light, heat, and chemicals; they form highly transparent, intense colors with high tinting strength. Quinacridones (red, violet, orange) exhibit good light stability and excellent bleed and chemical resistance, but they are expensive and are best suited for plastics such as polystyrene and acrylic due to low thermal stability. Dioxazines (violet) are strong, high cost pigments with excellent light stability and limited heat stability. They are used in tinting other pigments and in low temperature applications in acrylic sheet, polyethylene and polyvinyl chloride. Isoindolinones (yellow, orange, red) are applicable to all plastics but are primarily used in automotive applications due to their high cost. Other nonazo pigments include perylenes, flavanthrones, and anthraquinones. [859, 826]

Carbon blacks are the most widely used black pigment. They are formed from incomplete combustion of natural gas (channel blacks) or by reduction of liquid hydrocarbons in refractory chambers (furnace blacks). They are composed of different functional groups (carboxyl, phenol, lactone, etc.) which increase dispersibility, and different particle sizes; finer particle sizes result in deeper shades. Carbon blacks have some of the smallest particle sizes and highest surface areas of all pigments; furnace black particles are larger than those of channel blacks. Carbon blacks have high strength, but loose forms can cause severe dusting. [826, 859]

### 3.7.5 Special effect pigments.

Some colorants produce special effects in the plastic, such as pearlescence or phosphorescence. The pigment must be well dispersed in the resin and must be carefully handled during processing. These pigments are most effective on transparent plastics; mechanical abuse and the presence of opaque fillers or pigments can reduce the effect desired. [826]

A "granite" appearance is produced by adding a foreground color, such as colored mica flakes (500–2000  $\mu\text{m}$ ) or large glitter flakes ( $\geq 6.4$  mm;  $\geq 0.25$  in.) to a background color. Pearlescent pigments produce pearly lusters and iridescence — the resin has a soft, silky and/or multicolor appearance. Luster is produced by reflection of light by thin ( $< 1$   $\mu\text{m}$ ) platelets oriented in parallel layers. Length of the platelets is 10–40  $\mu\text{m}$ . Any scattering of light by the plastic or other pigments will reduce the platelet reflection and the pearlescence. Pearlescent pigments must be inert. Due to the orientation of the platelets, the appearance of the material can change with the angle of viewing. Pearlescent pigments include titanium dioxide-coated mica (muscovite), ferric oxide-coated mica, and bismuth oxychloride. The coatings vary in concentration from 10–60%; mica also provides mechanical support. Coated mica can resist several years of outdoor exposure. [872, 826]

Metallic flakes are used to produce silvery lusters or gold bronze effects. Aluminum, copper and alloys of copper and zinc (bronze) are commonly used. Flake particles are  $< 1$   $\mu\text{m}$  in thickness and  $< 50$   $\mu\text{m}$  in length; smaller particles produce greater opacity and a metallic sheen, while larger particles result in more brilliance and glitter. Aluminum can be processed up to 310–340°C

(600–650°F), with loadings from 0.5–4%. It is usually treated to resist oxidation. Copper is susceptible to oxidation beginning at  $\sim 120^\circ\text{C}$  (250°F) and can tarnish, depending on the temperature and duration of exposure. Slow discoloration occurs in outdoor applications. [826, 872]

Fluorescent pigments appear to glow in daylight; they absorb visible and ultraviolet light, then emit the light at longer wavelengths. A glow appears when this light combines with the reflected color of the plastic. Phosphorescent pigments also emit light at longer wavelengths than it was absorbed, but the yellow-green glow appears only in darkness. Phosphorescence is produced by the addition of doped zinc sulfide. [826, 872]

### 3.7.6 Colorant forms

Colorant forms include dry color, color or pellet concentrates, liquid color, and precolored resin. A precolored resin contains the color already dispersed in the resin; all other forms require dispersion by the resin processor. The colorant form selected is dependent on factors such as volume requirements, handling provisions, regulatory concerns, labor and inventory costs, and equipment, in addition to performance requirements such as color strength development, color-matching tolerances, and color consistency in long runs. [826]

Dry colorants are powders composed of one or more pigments or dyes. They are supplied in preweighed packets and must be compounded and dispersed into the resin. Dry pigments are usually dispersed in polypropylene by batch blending; addition of wetting agents helps the pigment adhere to the resin surface. Careful attention is required for consistent color from batch to batch, and accurate weighing and blending are necessary for long-term, uniform color. Dry colorants are most often used for short runs, emergency situations, and the rotational molding of polyethylene. Dry colorants can be dusty and dirty during handling. Anti-dusting agents are available from suppliers, as well as closed packaging systems that hook up to pneumatic conveying equipment. [871, 821, 642]

Dry colorants are the most economical colorants. They provide the largest selection of colors and use a minimum of warehouse space. They are difficult to disperse, however, and dusting and cross-contamination problems discourage their use. Higher costs may result from problems with clean-up, color changes, scrap generation, and OSHA regulations concerning dust. [871, 826]



Color concentrates are colorants dispersed in a resin carrier that is formulated for use with a particular polymer family. In order to obtain a melt flow similar to that of the polymer, the carrier resin frequently has a lower melt flow than the polymer in order to compensate for the effects of pigments on melt flow. Low density polyethylene is frequently used as a carrier; however, for demanding applications, polypropylene should be used to insure optimum processing and compatibility. The form of the color concentrate can be matched to that of the polymer to be colored and includes pellets, beads, cubes, wafers, microbeads, and chips. [821, 826, 642]

Color concentrates can contain 10–80% colorant, depending on the application requirements, the pigment used, and the compounding equipment, and are added to the polymer at a level of 1–10%. Concentrates can be blended either by batch blending or by automatic metering at the processing equipment. Letdown ratios of 100:1 to 10:1 (polymer matrix:color concentrate) can be accurately metered with modern equipment, and other additives can be incorporated during pigment compounding. [821, 826]

Color concentrates are the most popular form of colorant for in-house coloring. They are dust-free, easy flowing, and easy to meter. They require little warehouse space, and color changes are relatively easy. Newer concentrates include those designed for specific applications, such as injection-molded polypropylene battery cases, and concentrates that can be used in a wide variety of polymers, simplifying inventory for plastics processors. [826, 821]

Liquid color is composed of a pigment in a non-volatile liquid carrier. Liquid carriers include mineral oils and complex fatty acid derivatives and can contain surfactants for easier dispersibility and clean-up. A range of viscosities are available, from maple syrup to gel-like consistencies, and good

dispersion can frequently be obtained with high pigment loadings (10–80%); higher loadings are possible with liquid color than with color concentrates. High pigment loadings can result in letdown ratios of greater than 100:1. Usually the highest loading possible is used, both for economy and to minimize the amount of carrier added to the matrix polymer. The carrier can affect polymer properties and can lubricate the polymer, affecting process cycling and back pressure in injection molding. [821, 826]

Liquid colorants are compatible with many plastics; however, they require special metering equipment and are most cost-effective for long runs. They are used in injection molding and extrusion and are usually pumped in below the hopper at the throat. Consistent color levels can be obtained by electronically matching the metering speed of the pump with that of the extruder. Extreme hot or cold temperatures can cause adverse effects on the liquid colorant, and spills and disposal of used containers may be costly. Other additives can be added to the liquid concentrate to tailor it for a specific application. [826, 821, 642]

In precolored resins, the colorant is already compounded into the polymer, and no additional compounding is necessary before processing. Precolored resin can be in the form of pellets, beads, or fine powder. The best dispersion is usually obtained with precolored resins; as little as 0.25–2 weight % pigment is necessary for non-filled polymers. Precolored resins are more expensive, however, and require more warehouse space than other forms of colorant. They are useful for hard-to-color materials such as highly-filled plastics, engineering plastics, and polymers with a high inherent color. [871, 821, 825]

Advantages and disadvantages of the various forms of colorant are compared in Table 3.1. [642]

**Table 3.1** Comparison of Coloring Techniques

LEGEND: 1-Highest 2-Medium 3-Lowest

Factor	Color Concentrate	Liquid Colorant	Dry Pigment	Precolored Resin
Cost	1	2	3	1
Dispersion Characteristics	1–2	1–2	3	1
Ease of Handling	2	1	3	1
Inventory Required	1	2	3	1
Difficulty of Matching Color	2	3	1	3
Ease of Color Change	2	1	3	1–2

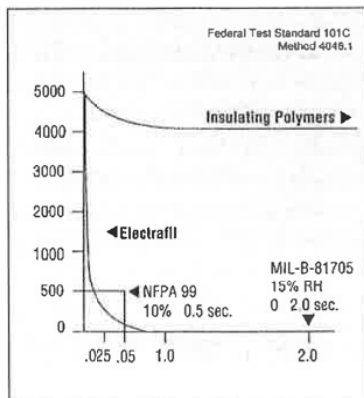
### 3.8 Antistatic agents

Polypropylene is an insulator; because it does not conduct electricity, a static charge can build up on the surface of a part, leading to problems with dust accumulation, static cling in films and fabrics, electric discharges that can produce shocks or fires, and damage to electronic components. Polypropylene and other polymers used in computer rooms (furnishing, fixtures, flooring) and in the handling and packaging of microelectronic chips require protection against electrostatic discharges. [870]

#### 3.8.1 Electrostatic charges

Static electricity or an electrostatic charge is a deficiency or excess of electrons which occurs on ungrounded or insulating surfaces. It is produced by triboelectric charges, charges that are generated by friction between two surfaces, such as the movement of paper through a copier or printer. The ability of a material to discharge static electricity is classified according to its surface resistivity, the ratio of DC voltage to current passing across a square unit of area, in ohms/sq. (Table 3.2) Surface resistivity is independent of the size of the square or its units.

A material with useful antistatic properties has a surface resistivity between  $10^9$  and  $10^{12}$  ohms/square. Static decay testing measures the ability of a grounded material to dissipate a charge induced on its surface. The decay rate of insulating polymers is much slower than those treated with electrically dissipative materials (Figure 3.16). [870, 698]



**Figure 3.16** The static decay rate of an insulating polymer and a polymer containing a conductive filler (Electrafil; DSM Engineering Plastics). Static decay testing is performed according to methods such as the Federal Test Standard 101C; antistatic formulations must meet military or industrial standards such as MIL-B-81705 (decay to 0% of initial charge in  $\leq 2$  s) or NFWA 99 (decay to 10% of initial charge in 0.5 s). [698]

#### 3.8.2 Types of antistatic agents

Antistatic agents, commonly called antistats, can be ionic or nonionic. Ionic antistats include cationic compounds, such as quaternary ammonium, phosphonium, or sulfonium salts, and anionic compounds, usually sodium salts of sulfonates, phosphates, and carboxylic acids. Nonionic antistatic agents include esters, such as glycerol esters of fatty acids, and ethoxylated tertiary amines. Many are FDA-approved. Nonionic antistats are commonly used in polyolefins; glyceryl monostearate is used in many polypropylene injection molding applications, at levels ranging from 0.5 to  $>1\%$ . Loading levels depend on resin processing temperatures, the presence of other additives, and application requirements such as clarity, printability, and FDA compliance. [862, 861, 822, 824]

Antistat molecules are generally both hydrophilic and a hydrophobic; the hydrophobic portion is compatible with the polymer, while the hydrophilic portion extends onto the surface and attracts water molecules from the air. A thin film of moisture forms along the surface, which increases the surface conductivity. Electrons are transferred out into the air, and the potential difference producing the static electricity is eliminated. Ionic antistats also function by conducting electrons through ions present at the plastic surface. [824, 822].

Antistatic agents can be internal or external. Internal antistats are compounded into the polymer. They have limited compatibility with the polymer and continually migrate to the polymer surface, forming a thin film that does not alter the surface appearance. The antistat must exhibit the proper level of compatibility with the particular polymer for a controlled migration to the surface. [820, 822, 862, 870]

External antistats are applied directly to the plastic surface after processing, usually from an aqueous and/or alcoholic solution (1–2%) as a spray or dip. External antistats can be easily removed by contact with solvents or by rubbing or wiping. They are used primarily in textile fibers, cosmetic packaging, medicine bottles, and household cleaner bottles to eliminate dust pickup dur-

**Table 3.2** Classifications of Surface Resistivity

Surface Resistivity (ohms / sq)	Classification
$\leq 10^5$	Conductive
$> 10^5$ to $\leq 10^9$	Static Dissipative
$> 10^9$ to $\leq 10^{14}$	Antistatic
$> 10^{14}$	Insulative

ing shipping and handling. Internal and external antistatic agents can also function as lubricants and mold release agents; lubricants can reduce surface friction and the resultant triboelectric charging. [820, 822, 862, 870]

### 3.8.3 Electrically conductive materials

Static electricity can also be dissipated by addition of a conductive filler, such as carbon black. Electrons are then conducted through the polymer. High conductivities are possible — surface resistivities of  $10^2$  —  $10^3$  ohms/sq can be obtained with high loadings. Applications include printer brackets, trays, and bushings. [698]

## 3.9 Slip agents

Slip agents are used in polypropylene films and sheets to provide surface lubrication during and immediately after processing. They have limited compatibility with the polymer and exude to the surface, providing a coating that reduces the coefficient of friction. Slip agents reduce sticking of the plastic to itself by minimizing tack and facilitate processing on high-speed packaging equipment. They also can improve antistatic properties, lower plasticity, and act as mold release agents. [877, 870]

Slip agents are usually modified fatty acid esters, used in concentrations of 1–3 parts per hundred (phr) or fatty amides, especially erucamide and oleamide. Erucamide is commonly used in polypropylene. Erucamide exhibits slower blooming than oleamide and is more resistant to high processing temperatures. Both have FDA acceptance for a wide variety of applications [822, 825, 877]

Slip agents can also provide antifog properties in food packaging. Fogging occurs when water droplets, formed from exposure of the moisture in foods to low storage temperatures, condense on the inside surfaces of packaging films. Fatty acid esters form a continuous film on the interior film surface, maintaining the clarity of the packaging. [877]

## 3.10 Antiblocking agents

Antiblocking agents prevent plastic films from sticking together due to cold flow or a buildup of static electricity. They can be applied externally or internally. When incorporated internally, they must be partially incompatible with the polymer so that they can exude to the surface. Antiblocking agents include natural and manufactured waxes, metallic

salts of fatty acids, silica compounds, or polymers such as polyvinyl alcohol, polyamides, polyethylene, polysiloxanes, and fluoroplastics. [822, 877]

## 3.11 Lubricants.

Lubricants are used in plastics processing to lower melt viscosity or to prevent the polymer from sticking to metal surfaces. Internal lubricants act intermolecularly, making it easier for polymer chains to slip past one another. They reduce melt viscosity and provide better polymer flow. External lubricants act at the molten polymer surface, between the polymer and the processing equipment. Materials used for lubricants include metal soaps, hydrocarbon waxes, polyethylenes, amide waxes, fatty acids, fatty alcohols, and esters. [825, 876, 822]

Polyolefins are more easily processed than other polymers and generally require little, if any, lubricants. Calcium stearates are used for internal lubrication in polyolefins, to alter melt viscosity, promote fusion, and increase internal shear. They also can function as external lubricants, depending on the formulation and processing temperatures. Zinc stearates are also used as processing lubricants. Polyethylene waxes provide improved melt flow in some polyolefins and are also used as mold release agents. Low molecular weight waxes function primarily as internal lubricants; molecules with branching and higher molecular weights provide external lubrication. The optimum molecular weight for a particular application depends on the lubrication desired, processing conditions, and formulation. [876, 88, 822]

## 3.12 Blowing or foaming agents

Blowing agents, or foaming agents, are liquids or solids that form a gas during polymer processing. The gas forms minute cells or bubbles within the polymer, resulting in a foamed or porous structure. The foaming process is affected by the type of blowing agent used, the gas and its solubility in the polymer, the compounding method, processing temperatures and pressures, and the melt viscosity and crystallinity of the polymer. [822, 901, 819, 821]

Foaming agents are used to decrease the density of a polymer — density reductions of about 50–60% can be achieved with loading levels of about 0.5–2.5% by weight — and to reduce material costs. Finishing costs are higher in foamed polymers, however, due to the necessity of paint-

ing or covering the foamed material. Foamed plastics have improved electrical and thermal insulative properties and higher strength-to-weight ratios; however, mechanical properties such as stiffness, tensile strength, and compressive strength are decreased due to a lower amount of plastic material in the foam compared to the solid. [819, 821]

The amount of blowing agent used affects the properties of the foamed plastic, and different amounts are used for particular applications: 0.1% for elimination of sink marks in injection molded parts, 0.2–0.8% for production of injection molded structural forms, 0.3% for extruded foamed profiles, 1–15% for formation of vinyl foams, and 5–15% for compression-molded foam products. Nucleating and cell-sizing agents can be added to produce cells of a more uniform size and to enhance the symmetrical expansion of cells during the foaming process. [822, 819, 821]

Blowing agents can be classified as physical or chemical, depending on how the gas is generated. Physical blowing agents undergo a change of state during processing, while chemical blowing agents, usually solids, undergo a decomposition reaction during polymer processing that results in formation of a gas. [819]

### 3.12.1 Physical blowing agents

Physical blowing agents are compressed gases or volatile liquids. Compressed gases, usually nitrogen, are injected under high pressure into the polymer melt; as the pressure is relieved, the gas becomes less soluble in the polymer melt and expands to form cells. Nitrogen is inert, nonflammable, and can be used at any processing temperature. No residue is left in the foamed plastic, so that recycling of the plastic part is easier. The use of compressed nitrogen, however, generally produces foams with a coarser cell structure and poorer surface appearance than nitrogen produced with chemical blowing agents, although nucleating agents can be added for a finer cell structure. [819, 822, 901]

Liquid physical blowing agents are volatile and change from a liquid to a gaseous state when heated to polymer processing temperatures. They are short-chain chlorinated and fluorinated aliphatic hydrocarbons (CFCs). Although they can be used over a wide temperature range and at low (atmospheric) pressures, they have been discontinued in most formulations due to their role in the reduction of stratospheric ozone. [822, 819]

### 3.12.2 Chemical blowing agents

Chemical blowing agents decompose at processing temperatures to form a gas. The most important criterion for selection of a chemical blowing agent is that the decomposition temperature match the processing temperature of the polymer; little or no foaming will occur at processing temperatures below the decomposition temperature, while processing temperatures that are too high can result in overblown or ruptured cells and poor surface quality. Activators (“kickers”), including alcohols, glycols, antioxidants, and metal salts, can be added to lower the decomposition temperature. Other selection considerations include the type and amount of gas liberated and its effect on the final product. [822, 819]

Chemical blowing agents (CBAs) can be classified as inorganic or organic, and the decomposition can be endothermic or exothermic. Endothermic blowing agents, usually inorganic, require the input of energy for the decomposition reaction to take place, while exothermic blowing agents, usually organic, release energy during decomposition. Exothermic chemical blowing agents commonly have a higher gas yield than endothermic CBAs, while the lower gas yield and pressure associated with endothermic CBAs produce foams with a smaller cell structure, resulting in improved appearance and physical property performance. Endothermic and exothermic CBAs have recently been combined in a single product, in which the exothermic CBA provides the gas volume and pressure necessary for lower densities, and the endothermic CBA produces a fine, uniform cell structure. [824, 821]

#### 3.12.2.1 Inorganic chemical blowing agents

Typical inorganic blowing agents are sodium bicarbonate, sodium borohydride, polycarbonic acid, and citric acid, which evolve primarily carbon dioxide gas upon decomposition. Sodium bicarbonate is the most common inorganic blowing agent. It is inexpensive, and it decomposes endothermically at a low temperature, over a broad temperature range (100–140°C; 212–284°F). At temperatures  $\geq 142^\circ\text{C}$  (287°F), decomposition becomes more rapid, facilitating its use in polyolefins. Its decomposition is less controllable than organic blowing agents, however, and it can form an open-celled foam structure. Its gas yield is 267 cc/g. Polycarbonic acid decomposes at about 160°C (287°F), with a gas yield of about 100 cc/g. It is



also used as a nucleating agent in physical blowing agents. [822, 819]

### 3.12.2.2 Organic chemical blowing agents

Organic blowing agents evolve gas over a specific, narrow temperature range and are selected according to the processing temperature of the polymer. The most common low temperature blowing agent is 4,4'-oxybis(benzenesulfonyl hydrazide) (OBSh), with a decomposition temperature of 157–160°C (315–320°F) and gas yield of 125 cc/g. High temperature blowing agents, with decomposition temperatures of greater than about 230°C (450°F), include 5-phenyltetrazole, with a decomposition temperature of 240–250°C (460–480°F) and trihydrazine triazine (THT). [822, 824, 819]

Azodicarbonamide (ABFA), with a decomposition temperature of 204–213°C (400–415°F) is commonly used in polypropylene (melting temperature ~168°C; 334°F). The use of activators can reduce the decomposition temperature to 150°C (300°F). ABFA is a yellow powder that decomposes exothermically, with a gas yield of about 220 cc/g, to produce a gas mixture containing 65% nitrogen. ABFA produces a fine, uniform cell structure but can produce discoloration in the foamed part. It is nontoxic and is FDA-approved for a wide variety of applications, including those involving food contact. The high gas yield, good performance, and low cost (\$1.80–\$2.00/lb in US dollars) of ABFA make it the most widely used foaming agent. [822, 819, 821]

The average particle size of ABFA ranges from 2–20 µm; fine particle sizes decompose at lower temperatures than coarser particles. Particle size has a large effect on the final cell structure in low pressure applications; however in high pressure processing such as injection molding or extrusion, the effect of particle size is less critical. The effect of activators is also dependent on ABFA particle size; fine particles are more easily activated than coarse particles. [819]

p-Toluenesulfonyl semicarbazide (TSSC) is also used in polypropylene, although it decomposes at an intermediate-to-high temperature (228–236°C; 442–456°F). Activators can be used to decrease the decomposition temperature. It has a gas yield of about 140 cc/g; the gas mixture consists of nitrogen, carbon monoxide, carbon dioxide, and trace amounts of ammonia. Its white color and nonstaining residue are important in applications requiring color quality. It is flammable and burns rapidly when ignited, producing a large amount of residue. [822, 819, 824]

### 3.12.3 Available forms of blowing agents

Chemical foaming agents are available as dry powders, liquid dispersions, and pellet concentrates. They can be incorporated by dry-blending with the resin powder, tumble-blended with resin pellets, blended using a hopper blender, metered in at the feed throat, or pumped into the barrel. [822, 821]



### 8.1 General characteristics of polymeric foams.

Polymer foams are composed of a cellular core structure that is created by expansion of a blowing agent (See *Blowing Agents* in Chapter 3.12). Foam structures consist of at least two phases, a polymer matrix and gaseous voids or bubbles. An open-cell or closed-cell structure is formed, with cellular walls enclosing the gaseous voids. In closed cell foams, the gas cells are completely enclosed by cell walls, while in open-cell foams, the dispersed gas cells are unconfined and are connected by open passages. The presence of voids or discontinuities due to the cellular structure reduces material consumption. A blend of polymers can be present in the matrix, in addition to polymeric or inorganic fillers, and the polymer can be stabilized against cell rupture by crosslinking. Foams can be flexible or rigid; closed-cell foams are generally rigid, while open-cell foams are more flexible. [936, 937, 904, 903, 905, 772]

Plastic foam densities range from about 1.6–960 kg/m<sup>3</sup> (0.1–60 lb/ft<sup>3</sup>); mechanical properties are usually proportional to foam density. Low density (~30 kg/m<sup>3</sup>), flexible polymer foams are used in applications such as furniture and automotive seating; high density foams are required for structural, load-bearing applications. Mechanical properties of conventional polymer foams are lower than in solid parts due to a lower material content; however microcellular foams — foams with a pore or cell size of 1–10 μm — provide good mechanical properties in addition to weight reduction. The microstructure of a microcellular foam is shown in Figure 8.1. [936, 848, 847, 849]

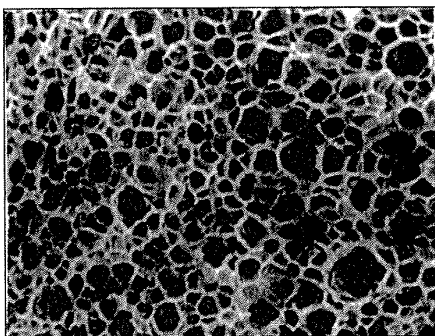


Figure 8.1 Microstructure of a typical microcellular foamed polymer. [905]

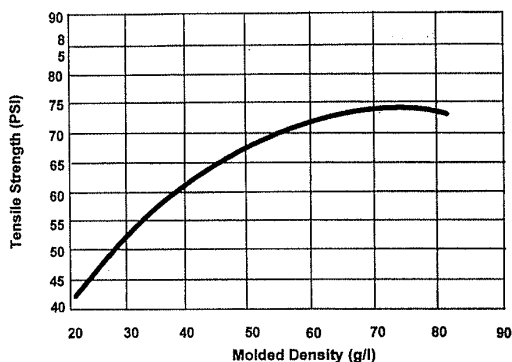
### 8.2 Comparison with other foamed polymers

Polyethylene, polyurethane, and polystyrene are the most common polymeric foams; however, polypropylene foams can provide favorable properties at a lower material cost. Polypropylene is stiffer than polyethylene and performs better in load bearing or structural applications. The low glass transition temperature of polypropylene compared to polystyrene provides increased flexibility and impact strength. [848, 847, 905]

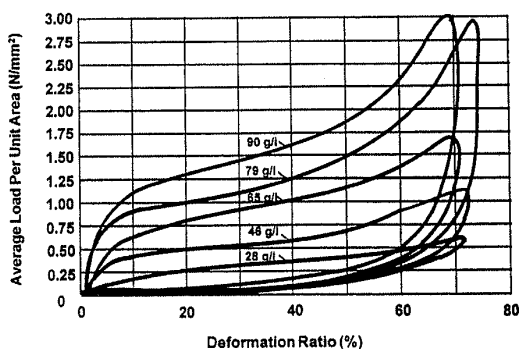
### 8.3 Polypropylene foam processing properties

Polypropylene is difficult to foam due to a weak melt strength and low melt elasticity. Melt strength is the resistance of the melt to extension, while melt elasticity is a measure of elastic recovery. Melt strength and melt elasticity are directly related; the higher the melt elasticity, the higher the melt strength. With weak melt properties, cell walls separating gas bubbles in the foaming polymer are not strong enough to bear the extensional force as the gas expands, and they rupture. As a result, polypropylene foam has a high open cell foam content, which is unsatisfactory for many applications. Melt strength is commonly increased by polymer modification, such as crosslinking; other methods include the use of high injection pressures (>3.5 MPa), two blowing agents, or two polypropylene resins with different viscosities. [772, 903, 904]

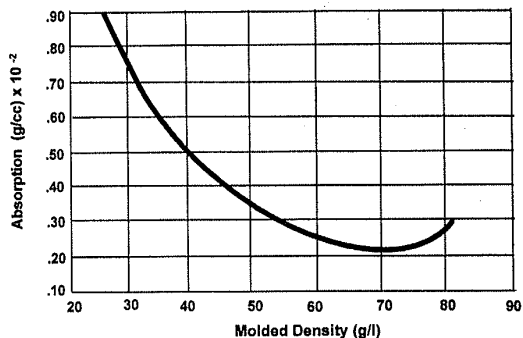
Semicrystalline polymers are generally more difficult to foam than amorphous polymers. The morphology and degree of crystallinity of semicrystalline polymers influence the solubility and diffusivity of the blowing agent and the cellular structure of the foam. The gas resulting from use of the blowing agent does not dissolve in the crystalline regions, so that absorption and diffusion occurs mostly in the amorphous polymer regions. As a result, bubble nucleation is nonhomogeneous, and the cell structure is nonuniform. In experiments with microcellular polypropylene foams, resins with 46% crystallinity produced a nonuniform cell structure, while a crystallinity of 41% resulted in a uniform cell structure. [906, 905, 901]



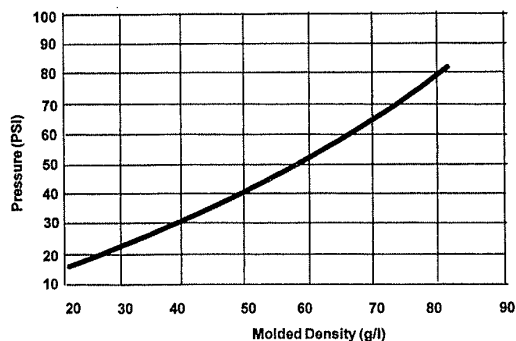
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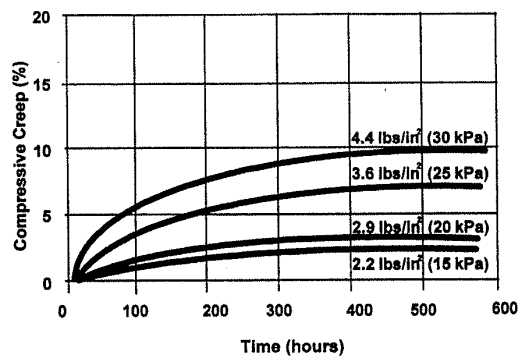
c



e



b



d

**Figure 8.2 Properties of expanded polypropylene** (Neopolen P, BASF; a closed-cell foam formed from polypropylene and polyethylene beads) a) Dependence of tensile strength on molded density, ASTM method D3575 b) Dependence of compressive strength @ 25% on molded density, ASTM method D3575 c) Dynamic stress/strain curve at densities of 28 g/l, 46 g/l, 65 g/l, 79 g/l, 90 g/l; velocity = 5 mph; temperature = 24°C (75°F) d) Long term creep performance; density = 30 g/l (1.9 pcf) e) Water absorption, ASTM method D3575 [899]

### 8.4 Properties of polypropylene foams

Properties of polypropylene foams include good heat resistance, high chemical resistance, and good insulation. Polypropylene's high melting point makes it useful in heat-sensitive applications such as hot metal or glass processing; some foams can withstand temperatures as high as 120°C (250°F) without warpage. Polypropylene does not absorb water but is permeable to water vapor and other gases, and it is mold- and mildew-resistant. Several properties of commercial polypropylene or polypropylene blend foams are given in Tables 8.1 and 8.2 and Figure 8.2. [843, 937, 907]

**Table 8.1 Properties of Microfoam Extruded Foam Sheet<sup>1</sup>**

Property	Unit	Microfoam
Density	kg/m <sup>3</sup>	10
Cell Size	mm	0.5–1.0
Tensile Strength	kPa	240 <sup>2</sup>
Tensile Elongation	%	190 <sup>2</sup>
Thermal Conductivity	W/(mK)	0.042
R-Factor		3.7 <sup>3</sup>

<sup>1</sup> Microfoam from Astro-Valcour, Inc.

<sup>2</sup> Average of two directions

<sup>3</sup> Rated at 1 in. thickness

**Table 8.2** Permeability of Microfoam<sup>1</sup> to Gases and Moisture

	Permeability
Water Vapor (g/100 in <sup>2</sup> /24 hr)	7.3 <sup>2</sup>
Oxygen (cc/100 in <sup>2</sup> /24 hr)	1475
Carbon Dioxide (cc/100 in <sup>2</sup> /24 hr)	5000
Water Absorption (lbs/ft <sup>2</sup> )	0.04

<sup>1</sup> Microfoam is a closed-cell, low density polypropylene foam from Astro-Valcour, Inc.  
<sup>2</sup> Higher numbers indicate that vapors are transmitted more readily

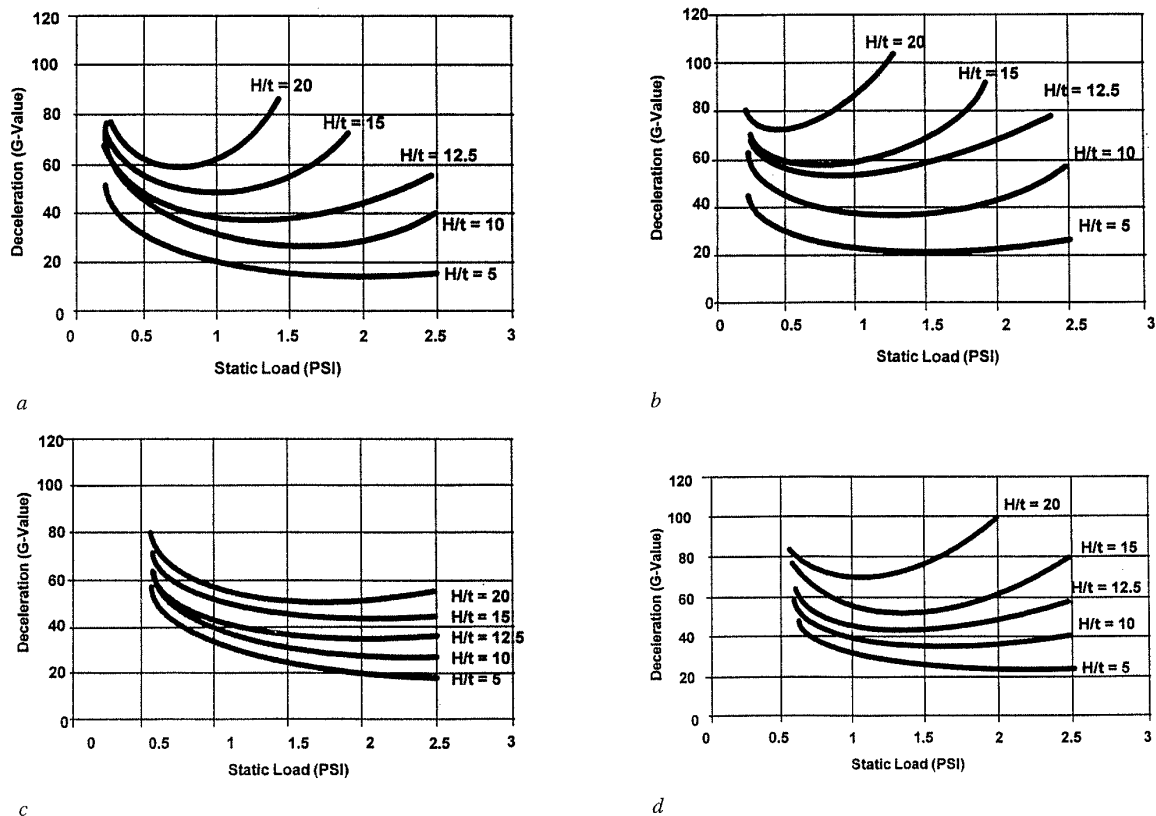
### 8.5 Applications of polypropylene foams

Polypropylene foams are used in packaging, automotive, insulation, and structural applications. They are used in concrete insulating blankets and as overwinter protection for plants, flotation booms for oil and chemical spills, and protection for buried pipelines. Polypropylene foams are used to provide cushioning and surface protection in the packaging of electronics, furniture, appliances, and

agricultural and construction products. Low density foams (>90% voids) are generally used for sound or heat insulation; medium density foams (50–90% voids) are commonly used in packaging. High density foams (<50% voids) are used in structural applications. [901, 907, 899]

Properties useful in packaging and automotive applications include shape retention and the ability to withstand repeated impacts without breakage or a decrease in properties. Impact cushioning is especially important in the packaging of heavier products, such as appliances, electronic components, and computers. The dynamic cushioning performance of expanded polypropylene (BASF) is shown in Figure 8.3. [901, 907, 899]

The interior chassis of a Hewlett Packard workstation (HP 700) used expanded polypropylene (EPP) foam to provide cushioning and structural support. EPP replaced conventional metal and plastic chassis structures that required assembly, resulting in a 50% reduction in assembly time and a 30% reduction in weight, and the foam protected the



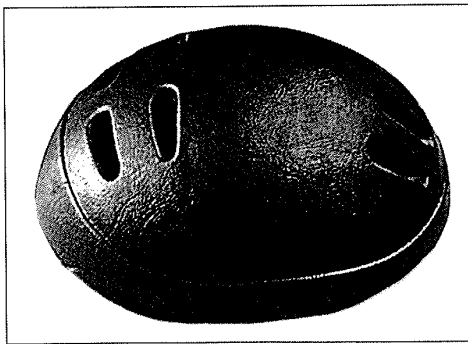
**Figure 8.3** The dynamic cushioning performance of expanded polypropylene (Neopolen P; BASF). H/t = drop height/cushion thickness ratio a) initial impact, foam density = 20g/l (1.3 pcf) b) 2 to 5 impacts, foam density = 20g/l (1.3 pcf) c) initial impact, foam density = 30 g/l (1.9 pcf) d) 2 to 5 impacts, foam density = 30 g/l (1.9 pcf) [899]

computer components from impact damage during shipping. [899]

Polypropylene foams find greater use in automotive applications than LDPE due to the ability to withstand higher service temperatures; LDPE foams can only be used at service temperatures of up to 80°C (176°F). The use of polypropylene foams in automotive applications is expected to increase with the development of new applications, such as the use of molded foam beads (expanded polypropylene) as energy absorbers in bumpers. [937, 899]

Automobile applications include head and side impact energy absorbers, instrument panels, tool caddies, door liners, sun visors, sound barriers, firewalls, and heat shields. Bumper cores, door panels, and glove compartments can be made from dual density foams, in which low and high density foams are molded together in one operation, replacing monodensity foams that require thermoplastic inserts at high stress areas. European glove boxes use a talc-reinforced polypropylene carrier, EPP foam, and a thermoplastic olefin skin to provide impact protection. Dual density foams simplify processing and reduce weight by replacing metal backing, polyurethane foam, and vinyl skins. [899, 937]

Automotive interior trim and other parts such as bicycle helmets (Figure 8.4) can be produced with a solid, integral skin on one surface that does not need a separate covering. The bicycle helmet has a leather-grain texture on the outer skin surface, while the usual bead-foam appearance shows on the inside and around the edges of the helmet. [899]



**Figure 8.4** A bicycle helmet with an integral skin, molded from expanded polypropylene (BASF). The usual bead-foam appearance shows on the inside of the helmet and around the sides, with a leather-grain texture on the outer skin surface. To form an integral skin, the bead-molding process is modified by a high pressure (10–12 bar) steam chamber on the side of the mold where the skin is desired. High pressure steam does not penetrate the mold cavity but only heats the tool enough to melt the beads and form a skin. [899]

Other applications of foamed polypropylene include hairbrush backs, shoe heels, toothbrush backs, and steering wheels. Hairbrush backs molded from 60% general purpose polypropylene (GPP) and 40% foamed polypropylene (Tenite P2635–08AA; Eastman Plastics) required a cycle time of 67 seconds, compared to 97 seconds for ABS. Shoe heels, molded with a blend of 90% GPP and 10% foamed polypropylene, were molded ten seconds faster than with ABS. Blends of GPP and foamed polypropylene produce small, uniform cells that increase in number as the concentration of foamable polypropylene increases, and large voids and sink marks in the part are eliminated with the optimum blend (10%, 20%, 30%, and 40% of foamed polypropylene for shoe heels, toothbrush backs, steering wheels, and hairbrush backs, respectively). An unreinforced steering wheel molded with a 60% GPP–40% foamable polypropylene blend is shown in Figure 8.5. [727]

Typical mechanical properties of two different parts (Moldings A and B) made with 100% foamable polypropylene (Tenite P2635–08AA) are shown in Table 8.3. Mold shrinkage values for typical parts made with general purpose polypropylene, foamable polypropylene, and blends are given in Table 8.4. [727]



**Figure 8.5** A steering wheel molded from a blend of 60% general purpose polypropylene and 40% foamable polypropylene (Tenite, Eastman Plastics). Molding conditions were: cycle time 35 seconds; melt temperature 193°C (380°F); mold temperature 4.4°C (40°F). [727]

**self-reinforcing plastics** Plastics with densely packed, fibrous polymer chains. Liquid crystal polymers are called self-reinforcing plastics.

**self-tapping screw** A method of mechanically fastening two plastic parts together in which screws inserted into a pilot hole form mating threads in the plastic part. Self-tapping screws can be either thread-forming or thread-cutting. See also thread forming screw, thread cutting screw.

**semicrystalline plastic** A plastic material characterized by localized regions of crystallinity. Also called crystalline plastic. See also amorphous plastic.

**shear** Displacement of a plane of a solid body parallel to itself, relative to other parallel planes within the body; deformation resulting from this displacement.

**shear joint** A joint design used in welding in which the thermoplastic parts melt in a telescoping action due to a small interference in one of the mating parts.

**shear strain** The tangent of the angular change, due to force, between two lines originally perpendicular to each other through a point in a body. See also strain, tensile strain, flexural strain, compressive strain.

**shelf life** Time during which a physical system such as material retains its storage stability under specified conditions. Also called storage life.

**Shore A** See *Shore hardness*.

**Shore D** See *Shore hardness*.

**Shore hardness** Indentation hardness of a material as determined by the depth of an indentation made with an indenter of the Shore-type durometer. The scale reading on this durometer is from 0, corresponding to 0.100" depth, to 100 for zero depth. The Shore A indenter has a sharp point, is spring-loaded to 822 gf, and is used for softer plastics. The Shore B indenter has a blunt point, is spring-loaded to 10 lbf, and is used for harder plastics. Also called Shore D, Shore A.

**short glass fiber** See *chopped glass fiber*.

**shrinkage** Contraction of a material upon cooling as in molding of metals or plastics or upon drying as in wet processing of textiles. See also mold shrinkage.

**SI** See *silicone*.

**silicone** Silicones are polymers, the backbone of which consists of alternating silicon and oxygen atoms. Pendant organic groups are attached to silicon atoms. They are usually made by hydrolyzing chlorosilanes, followed by polycondensation and crosslinking. Depending on the degree of crosslinking and the nature of pendant groups, silicones can be liquid, elastomeric, or rigid. Liquid silicones or silicone fluids such as dimethylsiloxane have very good antiadhesive properties, lubricity, resistance to heat and chemicals and are used as release agents, surfactants, and lubricants in plastics. As lubricants they improve wear resistance of plastics. Silicone elastomers, or rubbers, have high adhesion, resistance to compression set, flexibility, good dielectric properties, weatherability, low flammability, good moisture barrier properties, and thermal stability, but somewhat low strength. Optically clear grades are available. Processed by coating and injection molding. Used as optical fiber coatings, electronic

connector encapsulants, printed circuit board coatings, seals, diaphragms, fabric coatings, medical products, adhesives, sealants, and glazing compounds. Rigid silicone resins offer good flexibility, weatherability, dirt release properties, dimensional stability, and are stronger and harder than silicone rubbers. The resins are attacked by halogenated solvents. Processed by coating, casting, injection molding, compression molding, and transfer molding. Used as coatings, adhesives, sealants, bonding agents, and molded parts. Also called siloxane, silicone rubber, silicone plastic, silicone fluid, SI, polysiloxane.

**silicone fluid** See *silicone*.

**silicone plastic** See *silicone*.

**silicone rubber** See *silicone*.

**siloxane** See *silicone*.

**sink mark** A shallow depression on the surface of an injection molded part. Usually caused by collapse of the part surface following local internal shrinkage after the gate seals. Frequently occurs on the part face opposite to a face in which the section thickness increases, as in a rib. Also called shrink mark, heat mark.

**sliding velocity** The relative speed of movement of one body against the surface of another body (counterbody) without the loss of contact as in a sliding motion during wear and friction testing of materials. In the sliding motion, the velocity vectors of the body and the counterbody remain parallel and should be unequal if they have the same direction.

**slip agent** A material such as erucamide or oleamide (modified fatty acid esters) that provides surface lubrication to films and sheets during and immediately after processing. Slip agents reduce sticking of the plastic to itself and facilitate processing on high speed processing equipment.

**snap fit** A method of mechanical fastening in which two plastic parts are joined by an interlocking configuration that is molded directly into the parts. A protrusion molded into one part, such as a hook or bead, is briefly deflected during assembly and engages a depression or undercut molded into the other part. The joint is usually stress-free after joining. Snap-fit design is important in proper functioning of the snap-fit. Cantilever snap-fits are the most common; other types of snap-fits include annular and torsional.

**snap-on connection** A type of snap-fit connection in which one part is snapped onto another part, such as a lid on a container. Usually used with rounded parts.

**softening point** Temperature at which the material changes from rigid to soft or exhibits a sudden and substantial decrease in hardness.

**solubility** The solubility of a substance is the maximum concentration of a compound in a binary mixture at a given temperature forming a homogeneous solution. Also called dissolving capacity.

**solubility parameter** Solubility parameter characterizes the capacity of a substance to be dissolved in another substance, e.g., of a polymer in a solvent. It represents the cohesive energy of molecules in a substance and determines the magnitude and the sign of the heat of mixing