

Manufacturers of wood–plastic composites in North America have used about 600 million pounds of thermoplastics in 2005, of which polyethylene accounts for about 90% of the volume and polypropylene and PVC for the remaining 10%. Of these, reclaimed resin is about 35–40% of the total resin demand, virgin plastics is 60–65% [1].

Table 1.1 lists 26 commercially available brands of wood–plastic composite deck boards. Twenty of them are made of filled polyethylene, three of filled polypropylene, and three of filled PVC. In fact, only one brand of each of the two latter categories has established itself in the market (CorrectDeck and Boardwalk). Of ten the most sellable brands of composite deck boards (Trex, TimberTech, Fiberon, ChoiceDeck, WeatherBest, Evergrain, Monarch, GeoDeck, EverX/Latitudes, RhinoDeck) all ten are polyethylene-based products.

Why so?

This is a subject of this chapter, among some other things related to thermoplastics.

This chapter is not a comprehensive description of thermoplastics because those readings are abundant in the literature. This chapter aims at a brief description of plastic properties directly related to behavior of wood–plastic composites and at a comparison of these properties for thermoplastics currently used in making WPC. Besides, this comparison is extended to Nylon and ABS as prospective—apparently—plastics for future brands of WPC possessing superior properties.

POLYETHYLENE

Polyethylene (PE) is the largest volume plastic produced in the world. It has a relatively low-melting temperature (typically between 106 and 130°C, depending on density/branching of PE) and can be produced in a very wide range of viscosity of its melts. The melts mix well with fillers, and the low melting point allows the use of cellulose fiber as a filler without much risk of significant thermal degradation.

Polyethylene is a semicrystalline polymer. It means that at ambient temperatures the polymer consists of two rather distinct fractions, or phases—crystalline and amorphous. The amorphous part of polyethylene, which is a sort of rubbery at ambient temperatures, becomes a glass-like at a certain transition temperature, the so-called glass transition point. For polyethylene the glass transition point varies from very low to low (from –130 to –20°C), thus making the plastic ductile at common temperatures. The lower glass transition point (γ -transition) is always present in the range of –130 to –100°C, the higher one (β -transition, at –20°C) is manifested not in all PE materials. To complicate the picture even more, we can notice that there is one more transition in polyethylenes, called α -transition, commonly found between 10 and 70°C, and it is associated with crystallinity of PE. For WPC the last two transitions (α - and β -) are of little importance.

Polyethylene is rather soft, making PE-based composite deck boards easier to nail, screw, cut, and saw. Polyethylene, as well as polypropylene, shows near-zero moisture absorption (typically below 0.02% after 24 h underwater immersion) and

very high resistance to chemicals, including strong acids, such as sulfuric, hydrochloric, and nitric. Only fuming acids can produce some staining of polyethylene, but those acids are not common in households.

Polyethylene shows a relatively high resistance to oxidation compared to other polyolefins (polypropylene among them, see below), hence, requires lesser amount of antioxidants for processing and for the following service outdoors.

On the contrary, polyethylene is rather flexible and not very strong. Its high flexibility forces PE-based deck boards to be installed at a maximum clear span of 16"–24" on center (o.c.), with installations typically at 16" o.c., and also as low as 12" o.c. Its high flexibility does not allow it to be used for composite handrails without special reinforcements, such as metal inserts. Its relatively low strength is generally acceptable for composite deck boards with a standard code requirement to withstand a uniformly distributed load of 100 lb/sq.ft. (with the additional safety factor of 2.5), but it is generally not enough to make safe railing system posts and handrails without reinforcements.

Compared to wood, polyethylene shows a higher coefficient of thermal expansion–contraction. A 20-ft. long unrestrained HDPE-based composite deck board expands or contracts (lengthwise) by 3/8" to one inch in the temperature range between 50 and 130°F, depending on the amount and type of fillers. Fasteners on a real deck often restrict that movement, though it is still typically larger than that of wood.

Polyethylene is manufactured in various polymeric forms, differing by their molecular weight and "linearity," or presence of irregularities, or branches, unsaturations, and so on. This in turn determines the density, or specific gravity of the polymer, which is used as the principal classification feature of polyethylenes. The main forms of polyethylenes are as follows:

- High-density PE (HDPE)
- High-molecular weight HDPE (HMW-HDPE)
- Ultra high-molecular-weight HDPE (UHMW-HDPE)
- Low-density PE (LDPE)
- Linear low-density PE (LLDPE)
- Very low-density PE (VLDPE).

Naturally, there are all possible combinations of intermediate forms. Weight average molecular weight of UHMW-HDPE is typically higher than three million, whereas HMW-HDPE is in the range of 200,000–500,000. A pattern of molecular weight of polyethylenes (and of most polymers) is rather complicated, as a result of their various molecular weight distributions. In a real estate market, for example, it does not have much sense to talk about "average" cost of houses, if there are, say, ten \$100,000 houses and one \$10,000,000 house. Formally speaking, the average price of these houses is 1.1 million dollars each. It surely does not give much information to a potential buyer of any one of the houses.

Such an approach to polymers gives a "weight-average" molecular weight and does not provide much of information either, particularly when the polymer has a

wide distribution of molecular weights of its individual chains. “Number-average” molecular weight is a median, which is equal to the molecular weight at which half of polymeric chains are smaller in size (molecular weight), and half is larger than the “number-average” figure. It shows which is the molecular weight of majority of polymers in the polymeric mix. For the above real estate example, the number-average is \$100,000.

Finally, “viscosity-average” molecular weight is that of the highest molecular weight fraction. For example, if one studies the polymeric mix using viscometry, he would not “see” small molecules, as they do not add to viscosity of the system compared with long polymers. He would “see” practically only long molecules. For the above real estate example, the “viscosity-average” is \$10,000,000 house.

Hence, for a better and more adequate picture, polymers are characterized by all three “average” figures—weight-average, number-average, and viscosity-average. Some particular examples will be given below in this book.

Table 2.1 shows the density and melt flow index values for low-, medium-, and high-density polyethylenes. By definition, these polymers are characterized by a certain range of density. Each of them can have practically any melt flow index, hence, MFI is independent of the respective density category. Table 2.1 shows only the most applicable range of MFI, though it varies between 0.01 and 100 and wider.

Many users do not consider medium density PE as a separate category and divide polyethylenes into low- and high- density materials by the benchmark density of 0.94 g/cm³. Generally, none of these subdivisions of PE were scientifically defined, though they are largely (but not specifically) determined by methods of their synthesis. The classification is commonly accepted just for convenience.

Generally, the density of a 100% amorphous PE sample is considered to be 0.85 g/cm³, whereas that of a 100% crystalline PE sample is 1.0 g/cm³. The degree of crystallinity in HDPE is typically in the range of 60–80%, and 40–50% for LDPE. 50% crystallinity (in LDPE) corresponds to about two branches per hundred carbon atoms in the chain, and 60–90% crystallinity (in HDPE) corresponds to about 0.5 to practically zero branches per hundred carbon atoms. However, in polyethylenes usually the density rather than the crystallinity is referred to because both are connected by a certain linear relationship [4], and density can be faster and more precisely determined experimentally.

Polyethylene resins, employed in wood–plastic composite materials, typically belong to HDPE, and only in one case (Trex deck boards) it was LDPE (or LDPE/HDPE), originated from grocery sacks and stretch film, used as reclaimed plastic source.

TABLE 2.1 Polyethylene, molded or extruded [2, 3]

Polyethylene	Density (g/cm ³)	Melt flow index (g/10 min)
High-density	0.941–0.965	0.2–30
Medium-density	0.926–0.940	1–20
Low-density	0.915–0.925	0.3–26
Linear low-density	0.915–0.925	0.1–100
Very low-density	0.870–0.914	0.02–10

There are many grades of polyethylene available (see Chapter 7 for flexural modulus values for LDPE, LLDPE, and HDPE, supplied by Chevron Phillips Chemical Company). Flexural modulus values vary from 30,000 to 50,000 psi for LDPE, equal to 60,000 psi for one particular LLDPE material (in fact, they can vary from about 40,000 psi to 130,000 psi), and from 125,000 to 240,000 psi for HDPE. Hence, HDPE is much stiffer compared with LDPE and LLDPE.

Similar in kind, comparisons of flex strength are difficult because most of PE samples do not break when bent at conditions of ASTM D 790. Some data indicate that HDPE shows flex strength around 1400 psi. Filling polyethylene with wood fiber, rice hulls, and other plant fiber material increases flexural strength of resulting composites—to about 1600–2200 psi (for Trex composites) and higher, for HDPE-based composite materials up to about 3000 psi. Further increase of flex strength of wood-HDPE composites, to about 3800 psi and higher, is typically achieved by using coupling and cross-linking agents (see Chapter 5).

Low-Density Polyethylene (LDPE)

As the number of branch points in PE chains increases, PE density decreases. The amount of unsaturations in PE also increases with the decrease in density. For example, an average number of methyl branches per 1000 carbons in LDPE increased from 21 at 0.922 g/cm³ to 43 at 0.916 g/cm³. An average number of vinylidene unsaturations/branches per 1000-Da (molecular weight) segments of LDPE increased from 16 at 0.922 g/cm³ to 35 at 0.912 g/cm³ [5]. Hence, sensitivity of PE to oxidation increases as its density decreases. LDPE is more vulnerable to oxidation compared to HDPE. On the contrary, LDPE is oxidized rather uniformly compared to HDPE, in which amorphous areas are oxidized faster than crystalline ones.

LDPE typically has long side-chain branching off the main molecular chain and therefore is a more amorphous polymer. As a result, it shows lower shrinkage compared to a more crystalline HDPE, in which many of the polymer molecules are packed closely together.

Linear low-density PE (LLDPE) has a density similar to LDPE, but the linearity of HDPE. Branches of LLDPE are comparatively short. None of WPC manufacturers has reported that they make composite deck boards based on LLDPE, as well as on VLDPE (very low-density PE) and ULDPE (ultra low-density PE). The two latter polyethylenes have extremely high flexibility, which would make them inappropriate for composite deck boards or railing systems.

LDPE can be easily scratched by a thumbnail, HDPE can be scratched with difficulty, and polypropylene can hardly be scratched at all. This is also related to the respective WPC. Apparently, this is why unbrushed polypropylene-based WPC feels more like a plastic. This property is directly related to hardness, which is the resistance of a material to deformation, indentation, scratching, and to abrasion resistance. The latter is lower for LDPE compared to that of HDPE (10–15 mg/100 cycles and 2–5 mg/100 cycles, respectively) [6].

Maximum operating temperature of LDPE is considered to be 71°C (160°F), compared to 82°C (180°F) for HDPE.

Medium-Density Polyethylene (MDPE)

MDPE is typically a mixture of LDPE and HDPE and will not be considered here as a separate type of PE. None of WPC manufacturers have reported that they use “medium-density polyethylene” to make their products. Trex, apparently, can get into this category, but they report that they use “polyethylene” for the manufacturing of WPC (ICC-ES Report ESR-1190, June 1, 2005).

High-Density Polyethylene (HDPE)

Due to its higher crystallinity compared to LDPE, HDPE is stronger and stiffer than LDPE, but is more prone to warpage. It shows a higher shrinkage, due to formation of crystalline, packed areas upon transition from melted state to solid one. Its tensile strength is two to three times that of LDPE and it has a reasonably good compressive strength (4600 psi), whereas LDPE typically does not break on compression. Both of them generally have a very good impact resistance, though some HDPE-made materials with a high degree of crystallinity could be rather brittle.

Some polyethylenes are supplied as so-called bimodal grades: a mix of high- and low-molecular weight components in similar concentrations. They often show quite different processing characteristics compared to “normal,” monomodal (unmodified) polyethylenes. Bimodal grades PE often have higher die swell.

Ultra high molecular weight PE (UHMWPE) is a linear homopolymer, structurally similar to HDPE, but having average molecular weight of 10–100 times higher than that of standard grades of HDPE. None of WPC manufacturers have reported that they use “ultra high molecular weight” PE.

As crystallinity of HDPE is generally higher than that of LDPE, the following HDPE properties, depending on crystallinity, are higher than that of LDPE: strength, modulus, density, shrinkage, creep resistance, wear resistance, and hardness. On the contrary, lower crystallinity often offers better processability and impact resistance. Degree of crystallinity and a character of crystal areas often depend on how rapidly the profile is cooled; this in turn can effect postmanufactured shrinkage and brittleness of the product, as well as stresses and—as a result of it—a sensitivity of the product to oxidation and to a thermal expansion–contraction.

Permeability by gases is significantly lower for HDPE compared to that for LDPE. As the permeability (P) for gases is determined as $P = D \times S$, where D = diffusion constant and S = solubility coefficient, the units of permeability are expressed in the amount of gases (cm^3) through a film of a unit thickness (mm) per unit area (cm^2) per time (s) per pressure difference (cm Hg), that is $(\text{cm}^3 \cdot \text{mm})/(\text{cm}^2 \cdot \text{s} \cdot \text{cm Hg})$. In these units, the permeability of HDPE and LDPE (at 25°C) for nitrogen is 1.4 and 9.7, for helium 11 and 49, for oxygen 4 and 29, for CO₂ 3.6 and 126, respectively. At 30°C these values are as follows: for nitrogen 2.7 and 19, for oxygen 11 and 55, for CO₂ 35 and 352 [7]. Obviously, a higher rate of penetration for oxygen would lead to a faster oxidative degradation of LDPE compared to HDPE.

Linear PE (more crystalline) is more stable to oxidation than branched (more amorphous) PE. When the polymer is melted (140°C, or 284°F), oxidation rates are

similar for both crystalline and amorphous PE. The amorphous regions are oxidized faster compared to crystalline regions of polyethylene because of two reasons: higher reactivity of PE at branched points and a higher oxygen diffusion into amorphous domains compared with that of crystalline ones. However, the oxidation of amorphous areas (such as at outdoor exposure) in partially crystalline PE leads to a noticeable increase of its brittleness due to an increased fraction of the crystalline regions.

Generally, the increase of density and the respective transition from LDPE to HDPE leads to increase in abrasion resistance, chemical resistance, hardness, strength, stiffness, decrease in gas and water permeability, thermal expansion, and impact strength.

In terms of creep—the gradual deformation of a sample under prolonged loading—LDPE is inferior compared with HDPE. In creep, once a sample has yielded, the deformation is practically irreversible. Creep is less pronounced in samples with a higher crystallinity, hence, it is less pronounced in HDPE than in LDPE. Generally, the higher the density of PE, the lower the creep. Overall, polyethylenes are poor plastics compared to polypropylene and PVC, and even more so compared to engineering plastics, such as Nylon. Creep of polyethylenes is a major obstacle to make them structural plastics, and, therefore, to make WPC based on PE structural composite materials.

Oriented plastic samples are less prone to creep compared to isotropic samples. Apparently, on the same reason extruded WPC composites, such as deck boards, which show clear signs of anisotropy, might produce less creep compared to the base plastic, even considering a contribution of the fillers.

An important parameter for deck boards is coefficient of friction at their surface. This subject is described in detail in Chapter 11, “Slip resistance and coefficient of friction of composite deck boards.” To a certain extent friction determines safety of the deck and a liability of the manufacturer. A slippery deck could literally bankrupt the manufacturer. Regarding friction, polyethylenes vary in a wide range, by about 500%, with the lowest friction of HDPE of the highest density (coefficient of friction of 0.1), and the highest friction of LDPE of the lowest density (coefficient of friction of 0.5) [8]. These are values for PE sliding against itself. Values of the coefficient of friction of WPC against a leather sole are given in Chapter 11.

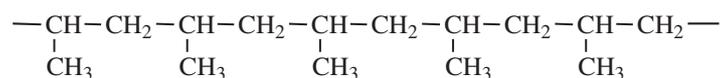
POLYPROPYLENE

The share of polypropylene-based WPC decking in the market is relatively small. There are only two recognized brands—CorrectDeck and Cross Timbers—that totally account for about 10% sales of WPC materials. For example, reported sales of PE-based Trex composite deck boards in 2005 were \$294 million out of about \$956 million total for WPC, whereas sales of PP-based Cross Timbers (Elk Composite Building Products) in 2005 were \$27 million.

In a number of properties polypropylene is superior compared to polyethylene. It is lighter, stronger, stiffer; it shows improved creep resistance, less wear, and less slippery. However, it is more brittle than polyethylene, particularly at low

temperatures, and so stiff that it is difficult to fasten using nails or screws. That is why PP-based WPC are installed using special fastening systems, recommended by the manufacturers. For a comparison, using common nails and screws makes polyethylene-based WPC boards so easy to install. Also, PP-based boards are much harder to cut and saw at a job site, compared to PE-based boards.

Unlike polyethylene, which exists—in an ideal case—in a form of a monotonous ($-\text{CH}_2-\text{CH}_2-\text{CH}_2-$) chain, polypropylene has a “microbranched” chemical structure



This structure largely determines chemical and other properties of polypropylene, for example, faster oxidation compared to polyethylene.

Description of polypropylene in the literature is often accompanied by terms “atactic,” “isotactic,” or “syndiotactic.” The origin of the terms is as follows. Side methyl groups in polypropylene chains can be all on the same side of plane (as it is shown above in a very simplified manner, as in reality carbon atoms in the chain are in *zig-zag* stereoconfiguration), on alternate sides, or in a random arrangement with respect to plane of carbon atom chain. These forms of PP are called isotactic (fiber-forming), syndiotactic, and atactic, respectively. All these forms are related to homopolymers of polypropylene. PP used for common applications, including WPC, is atactic and will be referred to here as polypropylene.

Polypropylenes are subdivided to homopolymers and copolymers. Homopolymers are more crystalline, have a rather well-defined melting temperature at 161–165°C (322–329°F), softens at about 155°C (311°F), and have a rather narrow molecular weight distribution. Copolymers typically contain some amount of ethylene comonomer and in turn are subdivided to random and block copolymers. Their melting points are in the range of 140–155°C (284–311°F). Polypropylenes have a specific gravity (density) of 0.90–0.91 g/cm³, which is approximately equal to that of very low-density polyethylene and lower than that of majority of polyethylenes, particularly HDPE (0.941–0.965 g/cm³). PP homopolymers are stiffer than copolymers, with their flexural modulus of 165,000–290,000 psi and 130,000–175,000 psi, respectively. PP homopolymers, in turn, are generally stiffer compared to HDPE, which has flex modulus in the range of 125,000–240,000 psi.

For polypropylene homopolymer, the glass transition temperature varies from –20 to –18°C (–4 to 0°F). However, in a number of cases it was recorded at –4°C (25°F), or between –1 and 5°C, that is, between 30 and 41°F [9]. What it all means in practical terms is that between –4 and 40°F polypropylene becomes brittle.

Flexural strength for polypropylene (6000–7000 psi) is much higher than that for polyethylene (around 1400 psi, if can be measured because of its high flexibility). Compressive strength for PP is also higher than that for HDPE, and for some specific examples they equal to 6720 and 4570 psi, respectively.

As it was mentioned above, polypropylenes are more prone to oxidation, hence, requiring significantly higher amounts of antioxidants and UV stabilizers compared to PE. It was shown that oxygen intake is much faster in polypropylene compared to that in PE [10]. The primary reason is in the “microbranched” chemical structure of PP (see above), containing tertiary hydrogens that makes formation of hydroperoxides in PP much easier compared to that in polyethylenes. Overall, the mechanisms of oxidation (both photo- and thermooxidation) in PP and PE are quite different. For example, the termination reaction rates for oxidation in PE are 100–1000 times faster compared to PP [11].

Typical polypropylenes used for extrusion of WPC have melt flow index (MFI) of 2–5 g/10 min. However, standard MFI for PP cannot be directly compared to standard MFI for PE, as these are measured at different temperatures (190 and 230°C, respectively), however under the same constant load (commonly 2.16 kg).

Polypropylene, as well as polyethylene, shows negligible water absorption (less than 0.01% after 24 h underwater submersion; some data show 0.008% for PP, and 0.03% for HDPE).

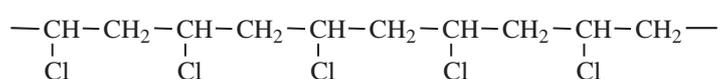
Thermal expansion–contraction of plastics will be considered in detail in Chapter 10, “Temperature-driven expansion–contraction of wood–plastic composites. Linear coefficient of thermal expansion–contraction.” Here it can be briefly mentioned that this property is about the same with HDPE, polypropylene, PVC, ABS, and Nylons 6 and 6/6, and the respective coefficients of thermal expansion are all overlapping in the range of $2\text{--}7 \times 10^{-5} \text{ 1/}^\circ\text{F}$ ($4\text{--}13 \times 10^{-5} \text{ 1/}^\circ\text{C}$). Only with LDPE the coefficient is noticeably higher and equal to $6\text{--}12 \times 10^{-5} \text{ 1/}^\circ\text{F}$ ($10\text{--}22 \text{ 1/}^\circ\text{C}$) [12].

According to some other data the coefficient of expansion–contraction for HDPE is $8\text{--}11 \times 10^{-5} \text{ 1/}^\circ\text{F}$, for LDPE $13.1 \times 10^{-5} \text{ 1/}^\circ\text{F}$, and for homopolymer PP $3.8\text{--}5.8 \times 10^{-5} \text{ 1/}^\circ\text{F}$. That is, PP-based profiles can thermally move more compared with PE-based ones.

POLYVINYL CHLORIDE

In the WPC decking market, the total share of PVC-based materials is even smaller than those based on PP. There are only three commercially available brands—Boardwalk, Millenium, and Procell, the last two are only entering the market. According to a Saint Gobain’s data, CertainTeed reported sales of their WPC boards Boardwalk for 1,361,000 euros in Q1 2005, which approximately corresponds (if sales are at the same level through the year) to less than \$8 million in 2005. According to Principia Partners, sales of Boardwalk boards in 2005 reached \$12 million. For a comparison, as it was indicated above, sales of PE-based Trex composite deck boards in 2005 was \$294 million out of about \$956 million total for WPC, and sales of PP-based Cross Timbers in 2005 was \$27 million.

PVC is a thermoplastic polymer of a chemical structure



As with polypropylene (see above), PVC can be syndiotactic (chlorine atoms in the polymer chains on the same side of plane, as it is shown above in a very simplified manner because in reality chlorine atoms in the chain are in *zig-zag* stereoconfiguration), isotactic (on alternate sides), and atactic (in a random arrangement with respect to plane of carbon atom chain). PVC is mostly atactic, but some portions of the polymer can be syndiotactic, making PVC crystalline at some regions (often as low as 5% crystallinity). Average molecular weight of PVC is often in the range of 100,000–200,000, with its number-average molecular weight of 45,000–64,000.

There are two principal forms of PVC, rigid and plasticized, or flexible. Rigid, unmodified PVC is stronger and stiffer than polyethylene and polypropylene. Credit cards are made of rigid PVC. Flexible, modified, plasticized PVC has a rubbery behavior more suited for tubing and shower curtains and is not employed in composite deck boards manufacturing. In order to reduce the cost of PVC-based WPC and to avoid difficulties with installation (sawing, nailing, and screwing) of tough PVC-based composite deck boards, most of PVC-based WPC are currently foamed.

PVC is the heaviest material compared to polyethylenes and polypropylenes. Specific gravity (density) for PVC is 1.32–1.44 g/cm³, compared to HDPE (0.94–0.96 g/cm³) and polypropylene (0.90–0.91 g/cm³).

Compared to polyethylene and polypropylene, PVC has some inherent disadvantages, among them low thermal stability and high brittleness (for example, compared to HDPE). The high brittleness of PVC at ambient temperatures is caused by a relatively high glass transition temperature of PVC, which is typically in the range of 70–90°C (approx. 160–190°F). For crystalline regions of polymers at temperatures between the glass transition temperature and melting temperature, chain mobility is constrained by the crystalline regions of the polymer. The crystalline structures are not fully mobile until the temperature exceeds the crystalline melting point. Practically, below the glass transition temperature the polymer is more brittle.

One of principal beneficial properties of PVC is that it is inherently flame resistant. PVC contains about 57% chlorine. Flame spread index for a PVC-based WPC (Boardwalk) is 25, whereas HDPE-based WPC is in the range of 50–170, depending mainly on a shape of the board (solid or hollow) and content of mineral fillers. However, the self-ignition point for PVC-based composites is slightly lower than that for HDPE-based WPC (e.g., 345°C for Boardwalk, 395°C for Trex, and 436°C for EverX). Flash ignition points are about the same for all three said materials: 361°C for Boardwalk, 370°C for Trex, and 355°C for EverX (see Chapter 14, “Flammability and fire rating of wood–plastic composites,” Table 14.3).

When it burns, PVC releases toxic hydrogen chloride, HCl, hence, it is commonly considered as the most environmentally damaging among thermoplastics. Even at temperatures above 70°C (158°F), PVC, if not stabilized, can start to degrade and release HCl. As this temperature can be reached in the south (the average July high temperature in Phoenix, AZ is 109°F, so the composite deck surface reaches a temperature of 150–160°C), the use of PVC-based composite boards in the south might be of a certain concern.

That is why PVC-based building materials, including WPC, are often considered as “not environmentally preferable” materials. Environmentally oriented studies place in that category such PVC-based products (containing wood or neat PVC) as Boardwalk (CertainTeed), Millenium (Wood Composite Technologies), AmeriDeck (American Composite Building Products), Procell (Procell Decking Systems), Country Estate (Nebraska Plastics), Deck Lok (Royal Crown), Deck/Dock (Westech Fencing), Dream Deck (Thermal Industries), EverNew, Bufftech (CertainTeed), Forever-Wood (Forever Wood), Oasis PVC Deck (Alcoa Home Exteriors), Sheerline (L.B. Plastics), Synboard (Synboard America), VEKAdeck (VEKA), and vinyl decking (Poly Vinyl Creations). However, as Principia has noticed [13], there is no discernible recognition among distributors or end users of any pushback against PVC. As Principia has estimated, PVC-based WPC make 4% of decking (that has not changed much between 2002 and 2005) and 22% of railing products [13].

There is another aspect of the thermally induced toxic and corrosive fumes of HCl relating to the processing PVC-based materials. PVC decomposes at 148°C (298°F). This causes corrosion in processing equipment and requires corrosion-resistant metals and coatings. Besides, PVC has a very narrow processing window and undergoes fast degradation at even a slight overheating. This thermal degradation results in a color change and malodor in the extrudate. The result of this color shift and thermal instability along with environmental concerns is that PVC recycling is often unrealistic.

Photodegradation of PVC outdoors takes place, naturally, in the upper layer of the product, with a thickness of the degraded layer in the range of 0.2–0.3 mm [14].

Flexural strength for PVC (6000 to 10,000–16,000 psi) is higher than that for polypropylene (6000–7000 psi) and HDPE (which is too flexible to break, or sometimes breaks around 1400 psi). It is interesting, though, that a PVC-based solid composite board “Boardwalk” (CertainTeed) has flex strength of only about 2700 psi—apparently, because of foaming of the material. For a comparison, commercial wood-PP composites have flex strength in the range of 5300–6200 psi. There might be some inherent problem in making Boardwalk, particularly in the light of a recent announcement on a voluntary recall of Boardwalk HFS™ Planks (on July 27, 2005) due to some incidents of planks breaking on decks [15]. However, the relatively low-flex strength of Boardwalk can be explained by just its foaming.

Flexural modulus for PVC (350,000–600,000 psi) is also higher compared to polypropylene (165,000–250,000 psi) and HDPE (125,000–240,000 psi).

Compressive strength for PVC (close to 11,000 psi) is higher compared to that of polypropylene (6700 psi) and HDPE (4600 psi).

PVC exhibits very low water absorption—about 0.1% after underwater submersion for 24 h. This places it close to polypropylene and polyethylene, which both show negligible water absorption (less than 0.01% after 24 h underwater submersion, see above).

In terms of thermal expansion-contraction, PVC is practically overlapping with other thermoplastics (HDPE, PP, ABS, Nylons) in the range of $2-7 \times 10^{-5}$ 1/° F ($4-13 \times 10^{-5}$ 1/°C). This will be discussed in more detail in Chapter 10,

“Temperature-driven expansion–contraction of wood–plastic composites. Linear coefficient of thermal expansion–contraction.”

ACRYLONITRILE–BUTADIENE–STYRENE COPOLYMER (ABS)

This is a group of tough, rigid thermoplastics, in which all three monomers can vary in a fractional amount to tailor properties of the final copolymer. The acrylonitrile component contributes strength, heat resistance, and chemical resistance. The butadiene component contributes impact resistance, toughness, and flexibility. The styrene component contributes rigidity and processability. Disadvantages of ABS include poor durability/weatherability, low fire resistance, high density/weight, and a relatively high cost compared to polyolefines.

An attractive property of ABS as a plastic for WPC is its relatively low melt point of 100–110°C (212–230°F). This keeps wood fiber from burning during processing. However, a recommended processing temperature for neat ABS is typically in the range of 177–260°C (351–500°F), which makes WPC manufacturing rather difficult.

There is apparently only one commercial ABS-based WPC product, containing two-thirds ABS and one-third wood flour. The product is a railing system. Compared to HDPE, the ABS material behaved quite favorably with respect to temperature. Flex strength for ABS-based bottom rails at 70°F and 130°F were 5200 ± 200 psi and 4400 ± 200 psi, respectively. That is, “high temperature loss” was 800 ± 400 psi (15% only). For the balusters the figures were 6000 ± 100 psi and 4800 ± 80 psi, respectively, and “high temperature loss” was 1200 psi (20% only). For HDPE-based WPC this “high temperature loss” often reaches 50% (see below).

Flex modulus values for ABS-based bottom rails were 560,000 ± 40,000 psi and 500,000 ± 70,000 psi at 70 and 130°F, respectively, hence, the “high temperature loss” was 11%, and for balusters the respective figures were 460,000 ± 20,000 and 390,000 ± 30,000 psi, hence, the “high temperature loss” was 15%. The highest figure, 20%, was taken for the temperature adjustment, unlike 50% for HDPE-based railing system (see Chapter 7). This allowed to reduce the code requirement: (a) for in-fill from 187.5 lb for HDPE-based material to 150 lb for ABS-based one, (b) for uniform load on the top rail from 1125 lb for HDPE-based rail to 900 lb for ABS-based rail, and (c) for concentrated load test (at top of the rail) from 750 to 600 lb. As a result, the ABS-based railing system has met all the code requirements, unlike the corresponding HDPE-based railing system.

The above data also show how superior ABS-based WPC is when compared to HDPE-based WPC in terms of flexural strength and flexural modulus. Under the same conditions (ambient temperature), flex strength for HDPE-based WPC was 2200 psi, whereas that for ABS-based WPC it was 5200–6000 psi. Flexural modulus was 360,330 ± 33,600 psi (for HDPE-based railing) and 560,000 ± 40,000 psi (for ABS-based railing).

Overall, flex strength for neat ABS is 4300–6400 psi compared to about 1400 psi for HDPE, 6000–7000 psi for polypropylene, and 6000 to 10,000–16,000 psi for PVC. Flex modulus is 130,000–420,000 psi for ABS, 125,000–240,000 for HDPE, 165,000–250,000 psi for polypropylene, and 350,000–600,000 psi for PVC.

Tensile strength for ABS is around 6800 psi compared to 3500–5300 psi for polypropylene, 3000–5000 psi for PVC, and 10,150–10,875 for Nylon 6 and Nylon 66.

Compressive strength for ABS is 6750 psi compared to 4600 psi for HDPE, 6700 psi for polypropylene, and about 11,000 psi for PVC.

ABS shows higher water absorption (0.3% after 24 h underwater, 0.7% at saturation) compared to HDPE, PP, and PVC (less than 0.01, 0.01, and 0.1%, respectively). However, an ABS-based WPC, containing 50% w/w of 80-mesh maple wood flour, showed a very reasonable water absorption performance, namely 5.5% after 10 days, 8% after 20 days, and 9.5% after a month [16]. These values are similar with those for many HDPE-based WPC products.

In terms of thermal expansion–contraction, ABS is practically overlapping with other thermoplastics (HDPE, PP, PVC, Nylons) in the range of $2\text{--}7 \times 10^{-5} 1/^\circ\text{F}$ ($4\text{--}13 \times 10^{-5} 1/^\circ\text{C}$). This will be discussed in more detail in Chapter 10.

An increased interest in manufacturing WPC deck boards from ABS might be observed soon as a result of a project aiming by using recycled ABS from discarded computers [17].

It was mentioned above that disadvantages of ABS include poor durability/weatherability, low fire resistance, high density/weight, and a higher material cost. Besides, it was observed that processing of ABS-based WPC is a rather difficult task, primarily due to high viscosity of hot melt and, hence, very high torque (it is very easy to get torque values near 80% of maximum torque); die pressure fluctuations (die surging); severe melt fracture, particularly at a high wood fiber content, such as 50% w/w; difficulties with pelletizing extruded strands (extrusion instability) [16].

NYLON 6 AND OTHER POLYAMIDES

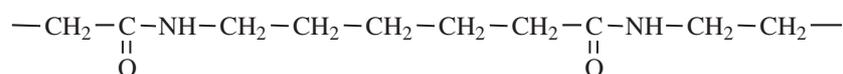
Currently there are no commercial wood–nylon deck boards or other wood-filled composite materials. Melting temperatures of Nylon 6, 216–223°C (421–433°F) and Nylon 6/6, 255–265°C (491–509°F) are seemingly too high to avoid burning wood. It is generally considered that only those thermoplastics are applicable in WPCs that can be processed at temperatures below 200°C (about 400°F). However, using delignified cellulosics, either as it is or blended with thermo insulating minerals, and/or decreasing a residence time for cellulosic materials in compounders and extruders by increasing processing speed and by other means to shorten contact time of cellulosics with hot melt, can make cellulose–Nylon composites possible. These composites could possess superior properties, such as high strength and high modulus, as Nylons are structural plastics.

Nylon is a family of polyamide polymers characterized by the presence of amide group–CONH. Nylon 66 comprises approximately 75% of the U.S. consumption of

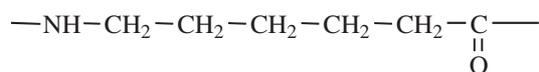
polyamide polymers, with Nylon 6 comprising most of the remainder. Except the difference in melting point (see above), their properties are almost identical. Density (specific gravity) of both the Nylons is 1.13–1.14 g/cm³. Other types of Nylons are 4, 9, 11, and 12. As Nylon 6 has a lower melting point compared to Nylon 66, it is more suitable for making—potentially—WPC materials.

Each nylon has a very sharp melting point. The rather wide range of melting points (see above) reflects different polyamide materials. Nylons also have low melt viscosity, convenient for injection molding, but difficult to handle in extrusion. That is why in extrusion processing a wide molecular weight distribution of nylon is often preferred, along with using a screw with a short compression zone and an ability to reduce temperature at the exit to increase melt viscosity. Nylon is often processed at 232–271°C (450–520°F).

Nylon is a crystalline polymer with high strength, modulus, and impact resistance. The general chemical structure of Nylon is as follows:



The type of nylon, such as Nylon 6, is identified by a number of carbon atoms in the repeating block. The repeating block in Nylon 6 is



This is defined by the number of carbon atoms in the monomers used in the polymerization. When two different monomers are used in the preparation of the polymer, the nylon is identified using two numbers, such as Nylon 6/6 or Nylon 66.

Nylon properties are greatly affected by the amount of crystallinity, which in turn is controlled, to a great extent, by the cooling of the polymer. A slowly cooled nylon will have greater crystallinity, in the range of 50–60%. A rapidly cooled nylon will have crystallinity as low as 10%. In addition, slowly cooled nylon contains larger crystals than when rapidly cooled.

Due to the presence of the polar groups (CO-NH), nylon attracts water. Hence, water absorption by nylon is relatively high, and higher than by any other thermoplastics, considered in this book. Compared to water absorption (24 h) of HDPE and PP (less than 0.01%), PVC (0.1%) and ABS (0.3%), Nylon 6 absorbs 1.2% water in 24 h (underwater), and 9% water when reached saturation. The lower the degree of crystallinity of nylon, the higher the water absorption. Due to this hygroscopicity, nylons must be dried before melt processing.

Because of its hygroscopicity, the moisture content of nylon affects the glass transition temperature of the polymer. Dried nylon has the glass transition temperature near 50°C (122°F), though other data place it between 45 and 57°C (113 and 135°F), whereas wet nylon can have it from 20°C (68°F) to 0°C (32°F). The last figure apparently refers to water freezing temperature in wet nylon. At any rate, dry nylon is more brittle at ambient temperature compared to that of wet nylon.

Flexural strength of Nylon 6 is from 9700 to 14,000–16,500 psi, that is higher than for all other thermoplastics considered in this book, except PVC, which generally has a similar flex strength (6000 to 10,000–16,000 psi). For a comparison, flex strength of HDPE is around 1400 psi (when can be measured), PP 6000–7000 psi, ABS 4300–6400 psi, sometimes to 12,000 psi [18].

Flexural modulus of Nylon 6 is 100,000–464,000 psi, which is in the same range with that of PVC and ABS, and generally higher than that of HDPE and polypropylene.

Compressive strength of Nylon 6 is 12,000 psi, higher than that of PVC (10,830 psi), ABS (6750 psi), polypropylene (6720 psi), and HDPE (4570 psi).

Coefficient of friction of Nylon 6 against itself (0.36) is generally between that of HDPE (0.10–0.23) and those of LDPE and PVC (0.50) and polypropylene (0.67) [19].

Nylon is commonly considered as an engineering thermoplastic. In terms of wear, it is one of the most superior among other thermoplastics. The most wear-sensitive among common thermoplastics is polyethylene, following by polypropylene and PVC [20].

Nylon 6 has a high flame-resistance and is a self-extinguishing material. Generally, nylon is not considered as a weather-stable material.

As examples of commercial product line, Ultramid[®] polyamides, supplied by BASF, can be considered. They are molding compounds based on Nylon 66 (Ultramid A) and Nylon 6 (Ultramid B), and also on their copolymer (Ultramid C). There are many brands available—more than 10 variants of Ultramid B of “general purpose,” plus flame retarded PA6 (Ultramid[®] 8232 G HS FR BK-102), impact modified PA6 (16 versions), mineral reinforced PA6 (30- and 40%-mineral reinforced, three versions), glass reinforced (26 versions, from 14- to 63%-glass fiber-filled material), and so on. There are eight variants of Ultramid A available for “general purpose,” besides those of flame retarded, impact modified, and reinforced brands. These materials are employed in almost all fields of engineering and for many special applications, due to their high strength, high rigidity, and thermal stability. Many of them afford good impact resistance even at low temperatures.

Two of the most common concerns associated with nylon polymers are brittleness at low temperatures and moisture absorption. For example, a nylon material dried to a moisture content of 0.20% may flow 30–40% faster than the same material dried 10 times better, to 0.02% [21]. In some cases it could be taken as a sign of the polymer degradation.

However, it is moisture absorption that gives nylon its toughness. Upon initial injection molding manufactured nylon profiles are typically very hard and brittle. After they left to cure, they absorb moisture from the air and become very impact resistant. The curing (or “softening”) period for nylon profiles takes 2–3 weeks. Clearly, at outdoors conditions it usually takes much less time.

CONCLUSION

Table 2.2 compares some important properties of thermoplastics used in making WPC materials on a commercial scale, or, as in case of Nylon 6, can be used in a near future.

TABLE 2.2 Some important properties of thermoplastics [12, 21–23]

Material	Specific gravity (density) (g/cm ³)	Flexural properties		Compressive strength (psi)	Water absorption after 24 h (%)	Coefficient of thermal expansion–contraction, × 10 ⁻⁵ (1/°F)	Weather stability
		Strength, psi	Modulus, psi				
LDPE	0.910–0.925	No break	30,000–50,000	No break	< 0.01	6–12 (13.1)	Medium
HDPE	0.941–0.965	~1400 or no break	125,000–240,000	4570	< 0.01	3–6 (8–11)	Medium
PP (homopolymer)	0.90–0.91	6000–7000	165,000–290,000	6720	0.008	3.8–5.8	Medium w/UV stabilizers
PVC (rigid)	1.32–1.44	6000 to 10,000–16,000	350,000–600,000	10,830	0.1	2.8–3.3	Good for light colors
ABS	1.01–1.08	4300–6400	130,000–420,000	6750	0.3	5.3	Poor
Nylon 6	1.12–1.14	9700 to 14,000–16,500	100,000–464,000	12,000	1.2	4.8	Poor

Despite unfavorable mechanical properties of polyethylene compared to polypropylene, PVC, ABS, and Nylon, HDPE is the most popular plastic in WPCs. Polypropylene is too tough and makes difficult to use nails and screws as fasteners at a deck installation. Polypropylene-based composites require special fastening systems. PVC is typically considered as not environmentally friendly. Other polymers are not weather stable, brittle, or expensive.

Globally, manufacturing and sales of HDPE, LLDPE, polypropylene, and some engineering resins, such as nylon, are likely to grow above average growth rates of plastics (5% or better) annually from 2007 to 2009, whereas PVC and LDPE will likely show below-average growth (4% or less annually) [24]. It is expected that PVC will be gradually replaced by polyolefins and other resins, spurred by environmental concern. This concern might not be always justified scientifically, but public perception is a powerful thing, which should not be underestimated.

Obviously, the resin price is a very serious factor in choosing plastics for WPC. However, in a long run a situation with prices is largely unpredictable. As of November 27, 2006, for example, resin-pricing chart looked as follows (Table 2.3)

TABLE 2.3 *Plastic News resin pricing chart, November 27, 2006. Prices are given for annual volumes greater than 20 million pounds, in U.S. cents per pound for prime resin or as indicated, unfilled, natural color, FOB supplier*

Resin/grade	Price for prime resin	Lowest price in the plastic grades	Price for recycled plastics, pellets
HDPE, HMW, extrusion	83–85 37–39 ^a	69–70	55–58 31–36 ^a
LDPE, fractional melt, extrusion	76–78	76–78	51–55
Polypropylene, profiles, extrusion	81–84 35–38 ^a	77–79	40–44 20–25 ^a
ABS, general purpose, extrusion	92–94	80–81	50–60 (mixed colors)
PVC, general purpose, homopolymer	63–67 27–29 ^a	63–65	28–34 13–21 ^a
Engineering plastics, annual volume greater than 1 million pounds			
ABS, extra high impact	106–116	106–116	—
PVC/ABS (alloy)	119–124	119–124	—
Nylon 6	165–175	165–175	—
Nylon 66	172–180	172–180	—
Nylon/ABS (alloy)	164–174	164–174	—

^aPlastic News, May 7, 1998 (as a reference).

ADDENDUM: ASTM TESTS COVERING DEFINITIONS OF TECHNICAL TERMS AND THEIR CONTRACTIONS USED IN PLASTIC INDUSTRY AND SPECIFICATIONS OF PLASTICS

The following ASTM standards explain terminology used in this chapter.

ASTM D 883 “Standard Terminology Relating to Plastics”

Block copolymer: an essentially linear copolymer in which there are repeated sequences of polymeric segments of different chemical structure.

Branched polyethylene plastics: those containing significant amount of both short-chain and long-chain branching and having densities in the 0.910–0.940 g/cm³ range.

Crosslinking: the formation of a three-dimensional polymer by means of inter-chain reactions resulting in changes in physical properties.

Ethylene plastics: plastics based on polymers of ethylene or copolymers of ethylene with other monomers, the ethylene being in the greatest amount by mass.

Glass transition: the reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one.

Glass transition temperature (T_g): the approximate midpoint of the temperature range over which the glass transition takes place.

High-density polyethylene plastics (HDPE): those linear polyethylene plastics, having a standard density of 0.941 g/cm³ or greater.

Homopolymer: a polymer resulting from polymerization involving a single monomer.

Isotactic: pertaining to a type of polymeric molecular structure containing a sequence of regularly spaced asymmetric atoms arranged in like configuration in a polymer chain.

Linear low-density polyethylene plastics (LLDPE): those linear polyethylene plastics, having a standard density of 0.919–0.925 g/cm³.

Linear medium-density polyethylene plastics (LMDPE): those linear polyethylene plastics, having a standard density of 0.926–0.940 g/cm³.

Linear polyethylene plastics: those containing insignificant amounts of long-chain branching but which may contain significant amounts, by design, of short-chain branching.

Low-density polyethylene plastics (LDPE): those branched polyethylene plastics, having a standard density of 0.910–0.925 g/cm³.

Medium-density polyethylene plastics (MDPE): those branched polyethylene plastics, having a standard density of 0.926–0.940 g/cm³.

Melt temperature: the temperature of the molten plastic.

Nylon plastics: plastics based on resins composed principally of a long-chain synthetic polymeric amide that has recurring amide groups as an integral part of the main polymer chain.

Polyethylene: a polymer prepared by the polymerization of ethylene as the sole monomer.

Polypropylene: a polymer prepared by the polymerization of propylene as the sole monomer.

Poly(vinyl chloride): a polymer prepared by the polymerization of vinyl chloride as the sole monomer (vinyl chloride content in monomer not less than 99%).

Propylene plastics: plastics based on polymers of propylene or copolymers of propylene with other monomers, the propylene being in the greatest amount by mass.

Rigid plastic: for purpose of general classification, a plastic that has a modulus of elasticity, either in flexure or in tension, greater than 700 MPa (100,000 psi) at 23°C and 50% relative humidity when tested in accordance with Test Methods D 747, D 790, D 638, or D 882.

Note: ASTM methods D 790 is described in Chapter 7, D 638 in Chapter 8.

Thermoplastic: a plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and that in the softened state can be shaped by flow into articles by molding or extrusion.

ASTM D 1600 “Standard Terminology for Abbreviated Terms Relating to Plastics”

Acrylonitrile–butadiene–styrene plastics	ABS
High-density polyethylene plastics	HDPE
Linear low-density polyethylene plastics	LLDPE
Linear medium-density polyethylene plastics	LLDPE
Low-density polyethylene plastics	LDPE
Medium-density polyethylene plastics	MDPE
Nylon (see also polyamide)	PA
Poly(vinyl chloride)	PVC
Polyamide (Nylon)	PA
Polyamide 6	PA6
Polyamide 66	PA66
Polyethylene	PE
Polypropylene	PP
Ultra-high molecular weight polyethylene	UHMWPE

ASTM D 1784 “Standard Specifications for Rigid Poly(Vinyl Chloride) PVC Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds”

Of properties, related to the subject of this book, the following specifications can be quoted with respect to PVC homopolymer (all—the minimum property values):

- Impact resistance, ASTM D 256, <34.7 J/m of notch, or <0.65 ft. lb/in. of notch
- Tensile strength, ASTM D 638, <5000 psi
- Modulus of elasticity in tension, ASTM D 638, <280,000 psi
- Flammability, ASTM D 635, <25 mm; average time of burning, <10 s.

ASTM D 1972 “Standard Practice for Generic Marking of Plastic Products”

The following are examples of plastic products marking:

- For example, for products made from acrylonitrile–butadiene–styrene polymer:

>ABS<

- For a polypropylene containing 30 mass percentage of mineral powder:

>PP–MD30<

Note: abbreviations for mineral powder (MD), flame retardants (FR), glass fiber (GF). Presence of a flame retardant is indicated by “FR.” The “FR” should be followed by the code number to identify the flame retardant.

- For a polyamide 66 containing a mixture of 15 mass percentage of mineral powder (MD) and 25 mass percentage of glass fiber (GF):

>PA66–(GF25 + MD15)<

or:

>PA66–(GF + MD)40<

ASTM D 4066 “Standard Classification System for Nylon Injection and Extrusion Materials (PA)”

General-purpose Nylon plastics (minimum requirements)

Nylon 6

- Density 1.12–1.15 g/cm³
- Tensile strength 10,150–10,875 psi
- Flexural modulus 319,000–348,000 psi
- Impact resistance 3–4 kJ/m².

Nylon 66

- Density 1.13–1.15 g/cm³
- Tensile strength 10,150 psi

- Flexural modulus 333,500 psi
- Impact resistance 3.3 kJ/m².

ASTM D 4101 “Standard Specification for Polypropylene Injection and Extrusion Materials”

General-purpose polypropylene homopolymer (minimum requirements)

- Density 0.910 g/cm³
- Tensile strength 3480–3988 psi
- Flexural modulus 116,000–152,250 psi
- Izod impact resistance 12–32 J/m.

ASTM D 4216 “Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) and Related PVC and Chlorinated Poly(Vinyl Chloride) (CPVC) Building Products Compounds”

Of properties, related to the subject of this book, the following specifications can be quoted with respect to rigid PVC (all—the minimum property values):

- Impact resistance, ASTM D 256, >34.7 J/m of notch, or >0.65 ft. lb/in. of notch
- Impact resistance, drop dart. ASTM D 4226, >4450 J/m, or >1.0 ft. lb/in.
- Tensile strength, ASTM D 638, >5000 psi
- Modulus of elasticity in tension, ASTM D 638, >290,000 psi
- Coefficient of linear expansion, $<4 \times 10^{-5}$ 1/C, or $<2.2 \times 10^{-5}$ 1/F.

ASTM D 4396 “Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds for Plastic Pipe and Fittings Used in Nonpressure Applications”

Of properties, related to the subject of this book, the following specifications can be quoted with respect to rigid PVC (all—the minimum property values):

- Impact resistance, ASTM D 256, 40.0 J/m of notch, or 0.65 ft. lb/in. of notch
- Tensile strength, ASTM D 638, 3000 psi
- Modulus of elasticity in tension, ASTM D 638, 280,000 psi.

ASTM D 4673 “Standard Classification System for Acrylonitrile–Butadiene–Styrene (ABS) Plastics and Alloys Molding and Extrusion Materials”

Of properties, related to the subject of this book, the following specifications can be quoted with respect to ABS materials suitable for extrusion and injection molding (all—the minimum property requirements).

ABS—medium impact

- Impact resistance, ASTM D 256, 80–150 J/m (Izod), 3–8 kJ/m² (Charpy)
- Tensile strength, ASTM D 638, 5075–7250 psi
- Flexural modulus of elasticity, ASTM D 790, 290,000–377,000 psi.

ABS—high impact

- Impact resistance, ASTM D 256, 200–440 J/m (Izod), 13–34 kJ/m² (Charpy)
- Tensile strength, ASTM D 638, 3625–5075 psi
- Flexural modulus of elasticity, ASTM D 790, 261,000–348,000 psi.

ASTM D 4976 “Standard Specification for Polyethylene Plastics Molding and Extrusion Materials”

All PE plastics—fractional melt (melt index 0.4–1.0 g/10 min at 190°C/2.16 kg). The figures below are minimum requirements.

Branched LDPE, density 0.910–0.925 g/cm³

- Tensile strength at yield, ASTM D 638, 1378 psi
- Elongation at break, ASTM D 638, 300%
- Secant modulus at 2% strain, 18,125 psi.

Branched MDPE, density >0.925–0.940 g/cm³

- Tensile strength at yield, ASTM D 638, 1595 psi
- Elongation at break, ASTM D 638, 200%
- Secant modulus at 2% strain, 36,250 psi.

Linear LDPE, density 0.910–0.925 g/cm³

- Tensile strength at yield, ASTM D 638, 1450 psi
- Elongation at break, ASTM D 638, 400%
- Secant modulus at 2% strain, 50,750 psi.

Linear MDPE, density >0.925–0.940 g/cm³

- Tensile strength at yield, ASTM D 638, 2175 psi
- Elongation at break, ASTM D 638, 200%
- Secant modulus at 2% strain, 87,000 psi.

Linear HDPE, density >0.940–0.960 g/cm³

- Tensile strength at yield, ASTM D 638, 2755 psi
- Elongation at break, ASTM D 638, 400%
- Secant modulus at 2% strain, 72,500 psi.

Linear HDPE, density .0.960 g/cm³

- Tensile strength at yield, ASTM D 638, 4060 psi
- Elongation at break, ASTM D 638, 300%
- Secant modulus at 2% strain, 130,500 psi.

ASTM D 5203 “Standard Specification for Polyethylene Plastics Molding and Extrusion Materials from Recycled Postconsumer (HDPE) Sources”

Fractional melt indexes below are measured as g/10 min at 190°C/2.16 kg. The figures below (Table 2.4) are minimum specification requirements.

ASTM D 6263 “Standard Specification for Extruded Rods and Bars Made from Rigid Poly(Vinyl Chloride) (PVC) and Chlorinated Poly(Vinyl Chloride) (CPVC)”

Of properties, related to the subject of this book, the following specifications can be quoted with respect to PVC materials suitable for extrusion (all—the minimum property requirements).

- Impact resistance, ASTM D 256, 35J/m of notch (Izod), or <0.65 ft. lb/in. of notch
- Tensile strength, ASTM D 638, 7000 psi
- Tensile modulus, ASTM D 638, 400,000 psi
- Flexural modulus of elasticity, ASTM D 790, 375,000 psi.

TABLE 2.4 Specification values

Source of HDPE	Melt index (g/10 min)	Density (g/cm ³)	Tensile strength (psi)	Secant modulus (psi)
Blow molded or thermoformed containers for chemicals, food, personal care	0.2–0.6	<0.959	2030	90,000
Containers from milk, juice, water	0.4–1.0	>0.958	2900	97,000
Spunbonded materials	0.4–0.9	>0.955	2900	97,000
Injection molded articles from food and beverage base cups	>20	0.956–0.962	2500	90,000
Injection molded articles from housewares	4–20	0.956–0.962	2500	80,000

ASTM D 6779 “Standard Classification System for Polyamide Molding and Extrusion Materials (PA)”

General-purpose Nylon plastics (minimum requirements)

Nylon 6

- Density 1.12–1.15 g/cm³
- Tensile strength 10,150–10,875 psi
- Tensile modulus 319,000–348,000 psi
- Charpy impact resistance 3–4 kJ/m².

Nylon 66

- Density 1.13–1.15 g/cm³
- Tensile strength 10,150 psi
- Tensile modulus 333,500 psi
- Charpy impact resistance 3.3 kJ/m².

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