

1.1 Introduction

To understand wood–plastic composites (WPCs) adequately, we must first understand the two main constituents. Though both are polymer based, they are very different in origin, structure, and performance. Polymers are high molecular weight materials whose performance is largely determined by its molecular architecture. In WPCs, a polymer matrix forms the continuous phase surrounding the wood component. These matrix polymers are typically low-cost commodity polymers that flow easily when heated, allowing for considerable processing flexibility when wood is combined with them. These polymers tend to shrink and swell with temperature but absorb little moisture and can be effective barriers to moisture intrusion in a well-designed composite.

Wood itself contains polymers such as lignin, cellulose, and various hemicelluloses but has very different properties from the synthetic polymers with which it is most often combined. Wood is less expensive, stiffer, and stronger than these synthetic polymers, making it a useful filler or reinforcement. Though wood does not shrink and swell much with temperature, it readily absorbs moisture, which alters its properties and dimensions and can lead to biodegradation if not protected.

In this chapter, we explore the basic structure and properties of polymers and wood individually to lay a foundation for a greater understanding of the composites made from them. Basic concepts and properties are briefly summarized with emphasis on materials common to current commercial technology. Sources of further information are listed at the end of the chapter.

1.2 Polymers: structure and properties

Polymers are high molecular weight substances consisting of molecules that are, at least approximately, multiples of simple units (Carley, 1993). The word polymer comes from the Greek *poli*, which means many, and *meros*, which means parts (Osswald and Menges, 1996). Polymers can be natural (e.g. cellulose, collagen, keratin) or synthetic (e.g. polypropylene, polyethylene) in origin. A polymer is called a plastic when it has other materials such as stabilizers, plasticizers, or other additives in it.

Owing to the low thermal stability of wood flour, plastics that can be processed at temperatures lower than about 200 °C are usually used in WPCs. In North America, the great majority of WPCs use polyethylene as the matrix, though polypropylene, polyvinyl chloride, and others are also used (Morton *et al.*, 2003). The large use of polyethylene is, due, in part, to that fact that much of the early WPCs were developed as an outlet for recycled film as well as the low cost and availability of recycled source of polyethylene. Polypropylene is widely used in Europe.

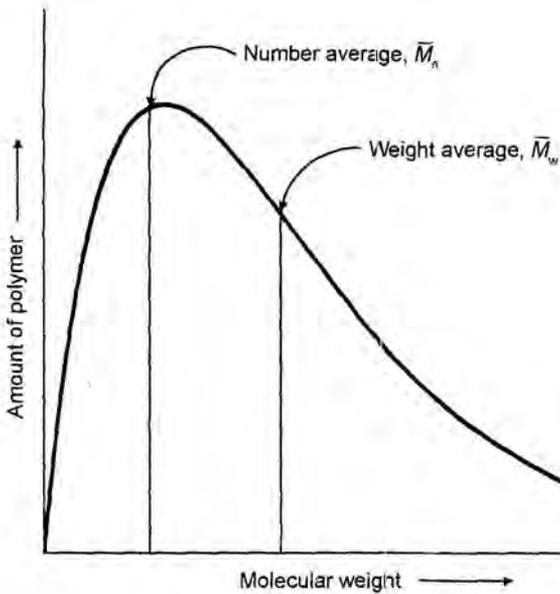
1.2.1 Structure and organization

Molecular structure

Much of how a polymer performs is determined by its molecular structure. This structure is developed during the polymerization process where low molecular weight monomers are reacted to form long polymer chains. Table 1.1 shows the basic chemical structural units of several common polymers as well as their common abbreviations.

Table 1.1 Structural units for selected polymers with approximate glass transition (T_g) and melting (T_m) temperatures. Condensed from Osswald and Menges (1996)

Structural unit	Polymer	T_g (°C)	T_m (°C)
$-\text{CH}_2-\text{CH}_2-$	Polyethylene (PE)	-125	135
$-\text{CH}_2-\underset{\text{CH}_3}{\text{CH}}-$	Polypropylene (PP)	-20	170
$-\text{CH}_2-\underset{\text{C}_6\text{H}_5}{\text{CH}}-$	Polystyrene (PS)	100	-
$-\text{CH}_2-\underset{\text{Cl}}{\text{CH}}-$	Polyvinyl chloride (PVC)	80	-
$-\text{C}(=\text{O})-\text{C}_6\text{H}_4-\text{C}(=\text{O})-\text{O}-\text{CH}_2-\text{CH}_2-\text{O}-$	Polyethylene-terephthalate (PET)	75	280



1.1 Typical molecular weight distribution of a polymer.

The number of repeat units in the polymer is the degree of polymerization. The molecular weight of the polymer is then the molecular weight of the repeat unit times the degree of polymerization. However, not all polymer chains have the same molecular weight and a distribution such as that shown in Fig. 1.1 is typical. The two most common measures of molecular weight are the number-average molecular weight (M_n) and the weight-average molecular weight (M_w), given by the following equations (Osswald and Menges, 1996):

$$M_n = \frac{\sum m_i}{\sum n_i} = \frac{\sum n_i M_i}{\sum n_i} \quad 1.1$$

$$M_w = \frac{\sum m_i M_i}{\sum m_i} = \frac{\sum n_i M_i^2}{\sum n_i M_i} \quad 1.2$$

where m_i is the weight, M_i is the molecular weight, and n_i is the number of molecules with i repeat units. The number-average molecular weights of many commercial polymers are typically about 10 000–100 000 (Billmeyer, 1984). A useful measure of the breadth of the molecular weight distribution curve is the polydispersity index, defined as the ratio of weight-average to number-average molecular weight ratio (M_w/M_n) (Osswald and Menges, 1996).

Polymers can contain one type of monomer (as with the homopolymers in Table 1.1) or multiple monomers (copolymers, terpolymers, etc.). In the latter, the arrangement of the repeat units can be controlled during polymerization to influence the performance of the polymer (see Fig. 1.2). One commercial

4 Wood–polymercomposites

Random Copolymer	AABABBAABABBBABAAB
Alternating copolymer:	ABABABABABABABAB
Block copolymer.	AAABBBAAABBBAAABBB
Graft copolymer:	AAAAAAAAAAAAAAAAAAAA
	B B B B
	B B

1.2 Copolymer types. A, B represent different repeat units.

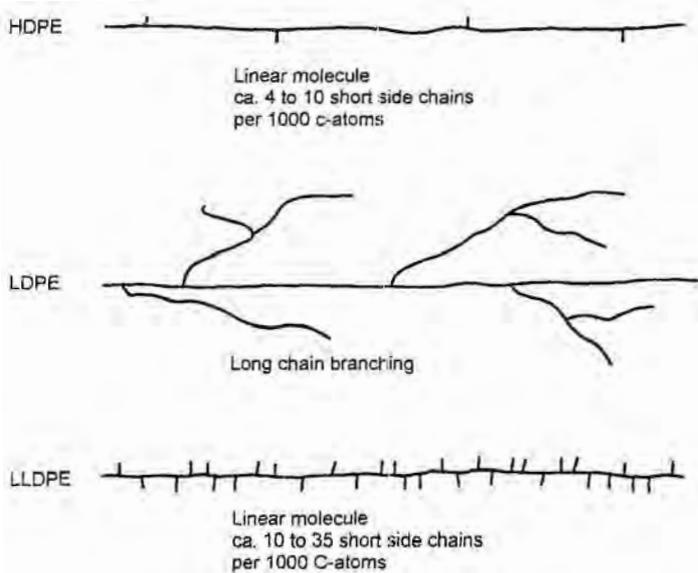
example is random polypropylene copolymer where 1–8 wt% of ethylene is added during polymerization of the polypropylene to form a copolymer with improved clarity, slightly better impact properties, and enhanced flexibility (Kissel *et al.*, 2003). Another example is maleated polypropylene, a graft copolymer that is commonly used as a coupling agent to improve the adhesion between wood and polypropylene (see Chapter 3).

Tacticity is important in the arrangement of repeat units in polymers with asymmetrical repeat units. For example, polypropylene contains a methyl group (CH₃) attached to a carbon chain (see Table 1.1). The methyl groups can be attached to one side of the chain (isotactic), alternating sides of the chain (syndiotactic), or lack a consistent arrangement (atactic). Whereas atactic polypropylene is a soft material that is mainly used in applications such as sealants and caulks, highly isotactic polypropylene has more desirable properties in the solid state and is a large-volume, commercial polymer used in a wide variety of applications (Kissel *et al.*, 2003).

Some polymers have considerable branching of molecular chains, often as a result of side reactions during polymerization. The type and amount of branching can influence the structure and properties of the polymer. For example, Fig. 1.3 shows the branching in different polyethylenes. Branching can inhibit the ability of the molecules to pack together to form highly ordered (i.e. crystalline) regions. As a result, polyethylenes that have long branches (LDPE) or many branches (LLDPE) have lower density than those that do not (HDPE). In contrast to branching, where a molecule is still considered discrete, some polymers can form chemical links (called crosslinks) between molecular chains that can increase rigidity but also can restrict or prevent flow.

Molecular organization

Polymers are often categorized by their behavior, which is influenced by their molecular organization. *Thermosets* are polymers that crosslink extensively and, as a result, are substantially infusible and insoluble in their final state (Carley, 1993). Once cured, increasing temperature eventually leads to degradation rather than melting. Thermosets include epoxies, phenols, and isocyanates. Thermosets have been used with wood and other natural fibers since the early 1900s. One of the earliest wood–thermoset composites was in a phenol-formaldehyde and wood

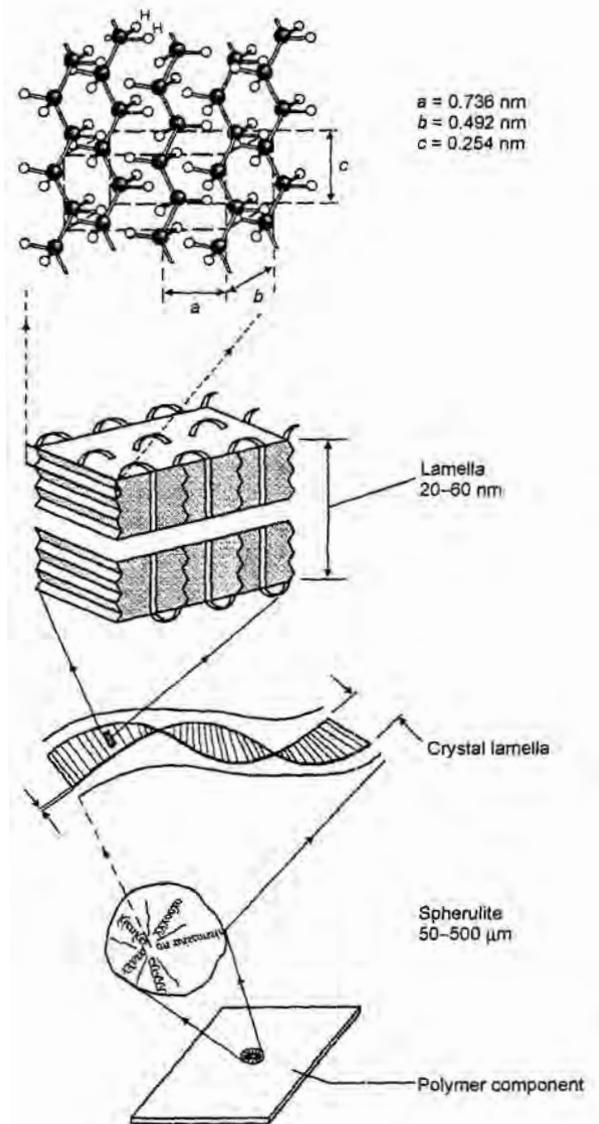


1.3 Branching in high-density polyethylene (HDPE), low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE). Reprinted with permission from Osswald and Menges (1996).

flour composite called Bakelite. Its first commercial product was reportedly a gearshift knob for Rolls-Royce in 1916 (Gordon, 1988). However, in recent years, the growth of thermosets as matrices in WPCs has not matched that of thermoplastics.

In contrast to its use in thermosets, large-scale use of wood flour in thermoplastics did not occur until the past several decades but recent growth has been great. Most of this is due to the rapid growth of exterior building products such as railings, window and door profiles, and especially decking. Unlike thermosets, thermoplastic polymers can be repeatedly softened by heating. When cooled, they harden as motion of the long molecules is restricted. If the polymer molecules remain disordered as they are cooled from the melt, they are considered amorphous thermoplastics and the temperature at which they solidify is known as the glass transition temperature (T_g). Polystyrene is an amorphous thermoplastic, for example.

Some thermoplastics form regions of highly ordered and repetitive molecular arrangements on cooling. These are called Semicrystalline polymers since much, though not all, of the molecular structure is in an ordered state. A crystallinity of 40–80% is typical for common semicrystalline polymers such as polypropylene and polyethylene and depends on molecular architecture as well as processing history. In addition to a glass transition (T_g) semicrystalline polymers have crystalline melting points (T_m), above which temperature the crystal order disappears and flow is greatly enhanced.



1.4 General molecular structure and arrangement of typical semicrystalline materials. Reprinted with permission from Osswald and Menges (1996).

Though the molecular and crystalline arrangement of polymers is complex, Fig. 1.4 shows a general hierarchy of ordering in a typical semicrystalline polymer. The crystalline regions form lamellae which, in turn, form spherulites. Spherulites are the largest domain with a specific order and their size is typically much larger than the wavelength of light, making semicrystalline polymers translucent and not transparent (Osswald and Menges, 1996). Though molecular

architecture such as tacticity, polymer branching, and molecular weight are important parameters affecting crystalline structure, processing also plays a large role. For example, cooling rates can affect the types of crystals formed and the size and number of spherulites formed. Also, processing-induced molecular orientation can increase the final crystallinity of the solid polymer.

1.2.2 Properties

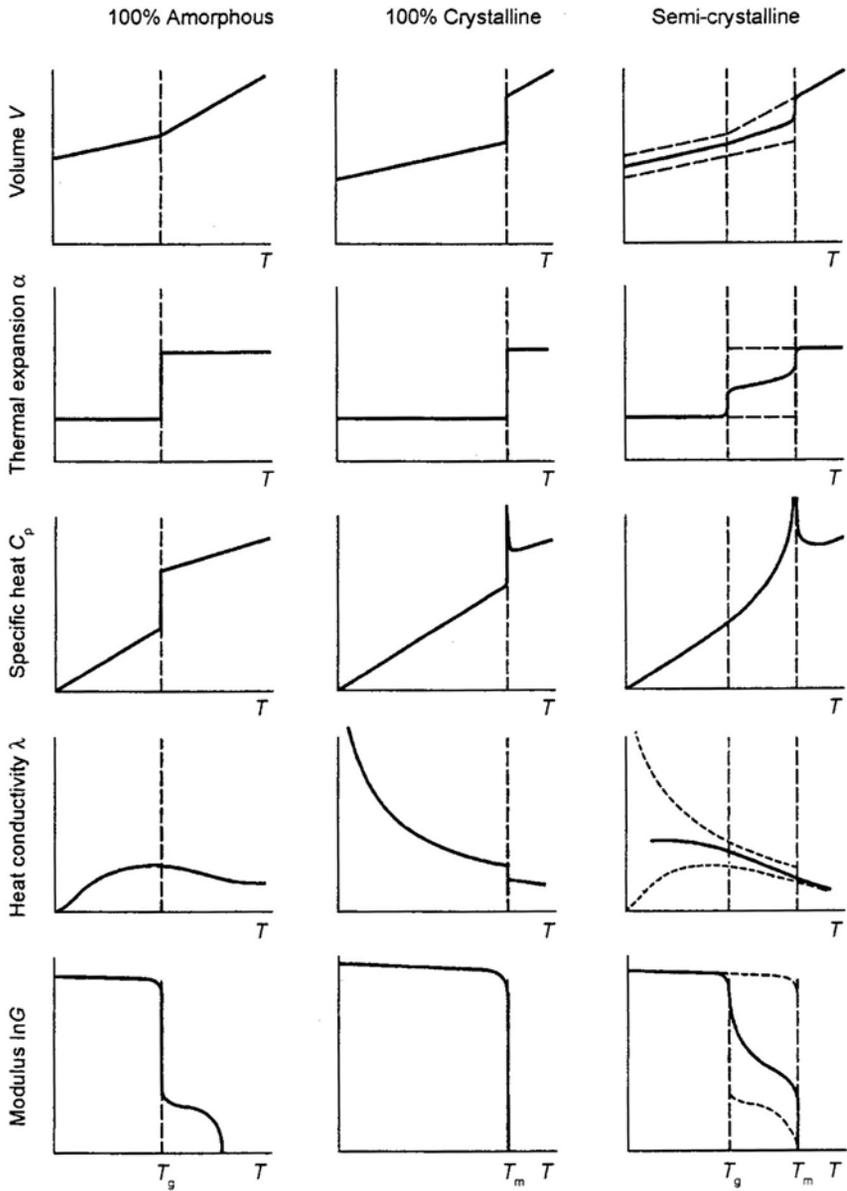
The properties of thermoplastic polymers are often highly dependent on the temperature at which they are measured and the speed at which they are tested. Generally speaking, when the temperature of a polymer melt is reduced below the melt temperature the material behaves as a leathery solid. If a polymer is semicrystalline, a crystal structure develops. As the temperature is further reduced below its glass transition, the amorphous portions solidify and form a glassy, stiff and, in some cases, brittle material (Osswald and Menges, 1996). Figure 1.5 shows how different polymer properties change with temperature.

While polymers have solid-like properties such as elasticity and dimensional stability, they also have liquid-like characteristics such as flow over time that depend on temperature, stress, and pressure. This tendency of a polymer to behave as it were a combination of a viscous liquid and an elastic solid is generally referred to as viscoelasticity (Carley, 1993). For example, most polymers have higher moduli when stress is rapidly applied versus when it is applied slowly. Also, some polymers tend to sag over time (i.e. creep) when bearing sustained loads, an important consideration in structural applications.

Typical room temperature properties of commonly used polymers in WPCs are summarized in Table 1.2. These values are provided to give a general indication of the polymer properties. However, the exact performance of these polymers is difficult to summarize since various grades of plastics are produced, whose performance has been tailored by controlling polymerization and additive content. Polyvinyl chloride in particular often contains a considerable amount of additives such as heat stabilizers and plasticizers, resulting in a wide range of processability and performance. However, some general comments can be made.

Generally speaking, though these polymers tend to have considerably lower mechanical performance than the so-called engineering plastics, the commodity plastics listed have reasonably good mechanical performance for many applications and low price. The polyethylenes are by far the most common polymers used in WPCs in North America. Polypropylene is common in other parts of the world. They absorb little moisture and act as effective moisture barriers. This is important since moisture sorption in WPCs can negatively affect the performance of the composite.

Though polyethylene and polypropylene are largely impervious to moisture, they are susceptible to degradation by UV radiation, and the use of light-stabilizing additives is common. The thermal expansion and contraction of



1.5 Trends in the polymer properties of thermoplastics as a function of temperature, T . Reprinted with permission from Osswald and Menges (1996).

polyethylene and polypropylene are significant and they tend to creep (or sag over time), especially under load or at high temperatures, limiting their structural performance. However thermal expansion and creep can be reduced with fillers and reinforcements.

Table 1.2 Typical room temperature properties of common polymers. Condensed from Osswald and Menges (1 996)

Polymer	Density (g/cm ³)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Water absorption in 24 h (%)	Coefficient of thermal expansion (K ⁻¹ x 10 ⁶)	Thermal conductivity (W/m K)
Low- density polyethylene (LDPE)	0.91-0.93	8-23	0.2-0.5	300-1000	<0.01	250	0.32-0.40
High-density polyethylene (HDPE)	0.94-0.96	18-35	0.7-1.4	100-1000	<0.01	200	0.38-0.51
Polypropylene (PP)	0.90-0.92	21-37	1.1-1.3	20-800	0.01-0.03	150	0.17-0.22
Rigid polyvinyl chloride (PVC)	1.4-1.6	50-75	1.0-3.5	10-50	3-18	70-80	0.14-0.17

Polyvinyl chloride is also used in WPCs, although not nearly as much as polyethylene and polypropylene. Despite its good mechanical performance, complexities in formulating and processing as well as patent issues have limited broader use in WPCs.

More detailed information on specific polymer grades can be obtained from manufacturers and distributors but are somewhat dependent on process history as well. Different grades of a particular polymer have been tailored for a specific application and processing method. For example, a bottle grade of high-density polyethylene (HDPE) has high molecular weight to provide the toughness needed for a bottle application and high melt strength necessary for the melt blowing process. An injection molding grade might have a lower molecular weight yielding lower melt viscosity and good flow properties.

1.3 Wood: structure and properties

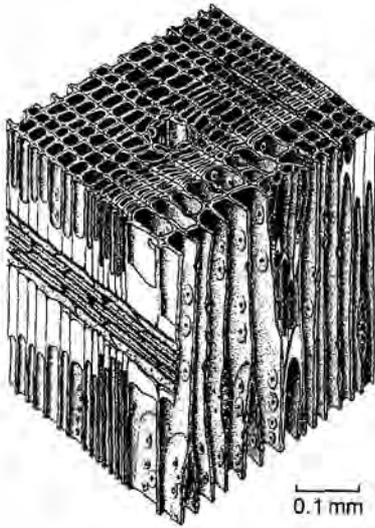
Wood contains natural polymers such as lignin, cellulose, and various hemicelluloses but has very different properties from the synthetic polymers with which it is most often combined. The efficient structure and anatomy make it a stiff, strong, tough, and lightweight material that can efficiently perform functions such as moisture transport that are critical for survival of the tree. Its excellent material performance and low cost have made it a useful structural material for millennia.

From a polymer composite standpoint, wood is less expensive, stiffer, and stronger than many commodity synthetic polymers, making it a candidate for filling or reinforcing them. However, some of the same material behavior such as moisture sorption that serves it well in nature can be problematic in a composite material. Therefore, to effectively use wood as a filler or reinforcement in polymers, an understanding of its material behavior is important. We will first discuss the structure and anatomy of wood and then describe its behavior and that of the fillers and reinforcements made from them.

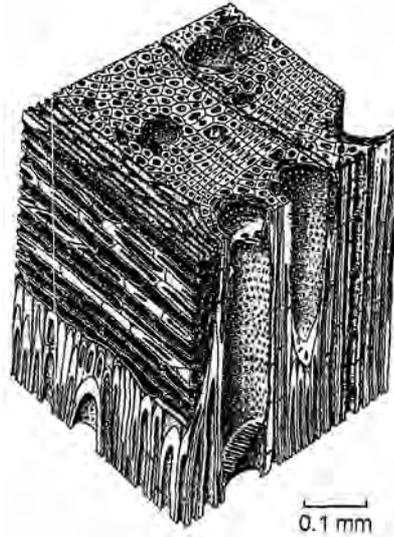
1.3.1 Structure and anatomy of wood

Wood anatomy

As with most natural materials, the anatomy of wood is complex. Wood is porous, fibrous, and anisotropic. Wood is often broken down into two broad classes: softwoods and hardwoods, which are actually classified by botanical and anatomical features rather than wood hardness. Figures 1.6 and 1.7 are schematics of a softwood and hardwood, respectively, showing the typical anatomies of each wood type. Softwoods (or gymnosperms) include such species as pines, firs, cedars, and spruces; hardwoods (or angiosperms) include species such as the oaks, maples, and ashes.



1.6 Schematic of a softwood.



1.7 Schematic of a hardwood.

Wood is primarily composed of hollow, elongated, spindle-shaped cells (called tracheids or fibers) that are arranged parallel to each other along the trunk of the tree (Miller, 1999). The lumen (hollow center of the fibers) can be completely or partially filled with deposits, such as resins or gums, or growths from neighboring cells called tyloses (Miller, 1999). These fibers are firmly cemented together and form the structural component of wood tissue. The length of wood fibers is highly variable but average about 1 mm (1/25 in.) for hardwoods and 3–8 mm (1/8 to 1/3 in.) for softwoods (Miller, 1999). Fiber diameters are typically 15–45 μm .

Chemical constituents

The wood substance itself is a complex, three-dimensional, polymer composite made up primarily of cellulose, hemicellulose, and lignin (Rowell, 1983). These three hydroxyl-containing polymers are distributed throughout the cell wall. The chemical compositions of selected woods are shown in Table 1.3.

Cellulose varies the least in chemical structure of the three major components. It is a highly crystalline, linear polymer of anhydroglucose units with a degree of polymerization (n) around 10 000 (Fig. 1.8). It is the main component providing the wood's strength and structural stability. Cellulose is typically 60–90% crystalline by weight and its crystal structure is a mixture of monoclinic and triclinic unit cells (Imai and Sugiyama, 1998; Wada *et al.*, 1994). Hemicelluloses are branched polymers composed of various 5- and 6-carbon sugars whose molecular weights are well below those of cellulose but which still contribute as a structural component of wood (Pettersen, 1984).

Table 1.3 Approximate chemical composition of selected woods from Petterson (1984)

Species	Cellulose ^a	Hemicellulose ^b	Lignin ^c	Extractives ^d	Ash
Ponderosa pine	41	27	26	5	0.5
Loblolly pine	45	23	27	4	0.2
Incense cedar	37	19	34	3	0.3
Red maple	47	30	21	2	0.4
White oak	47	20	27	3	0.4
Southern red oak	42	27	25	4	0.4

^aAlpha cellulose content as determined by ASTM D1103-60 (1977).

^bApproximate hemicellulose content determined by subtracting the alpha cellulose content from the holocellulose content values from Petterson (1984).

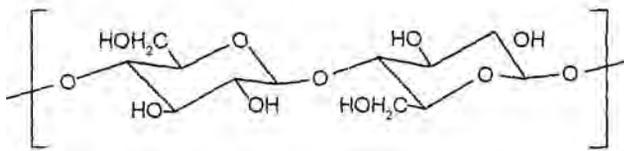
^cKlason lignin content as determined by ASTM D1106-96 (2001).

^dSolubility in 1:2 volume ratio of ethanol and benzene according to ASTM D1107-96 (2001).

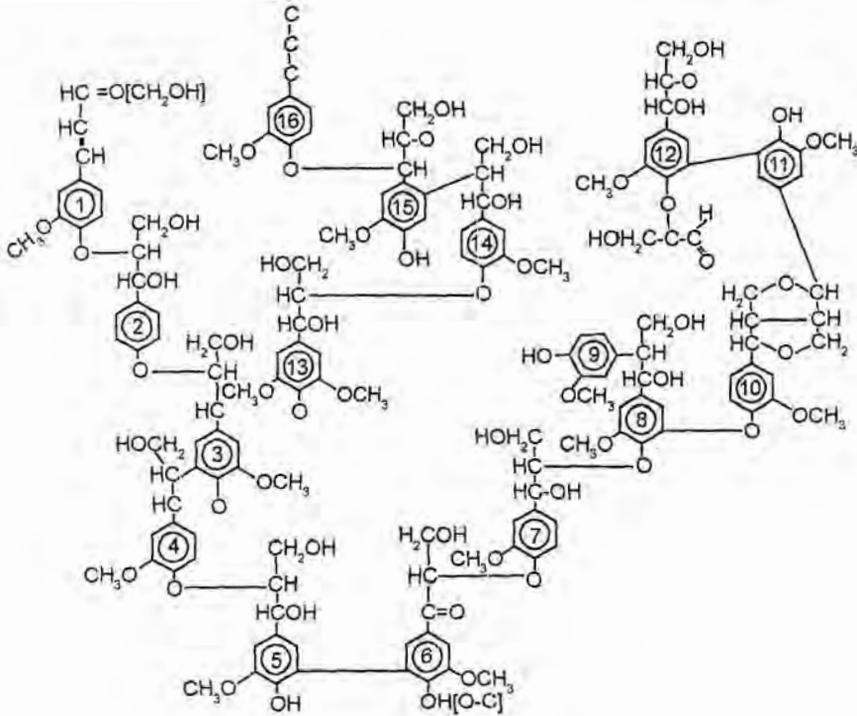
Lignin is an amorphous, crosslinked polymer network consisting of an irregular array of variously bonded hydroxy- and methoxy-substituted phenylpropane units (Pettersen, 1984). The chemical structure varies depending on its source. Figure 1.9 represents a partial softwood lignin structure illustrating a variety of possible structural components. Lignin is more non-polar than cellulose and acts as a chemical adhesive within and between the cellulose fibers.

Additional organic components, called extractives, make up about 3–10% of the dry wood grown in temperate climates, but significantly higher quantities are found in wood grown in tropical climates (Pettersen, 1984). Extractives include substances such as fats, waxes, resins, proteins, gums, turpenes, and simple sugars. Many of these extractives function in tree metabolism and act as energy reserves or defend against microbial attack. Though often small in quantity, extractives can have large influences on properties such as color, odor, and decay resistance (Pettersen, 1984). Small quantities (typically 1%) of inorganic matter, termed ash, are also present in wood grown in temperate regions.

Cellulose forms crystalline microfibrils held together by hydrogen bonds and then cemented to lignin into the wood fiber cell wall. The microfibrils are aligned in the fiber direction in most of the cell wall, winding in a helix along the fiber axis. The angle between the microfibril and fiber axes is called the microfibril helix angle. The microfibril helix angle is typically 5–20° for most of



1.8 Chemical structure of cellulose (Pettersen, 1984).



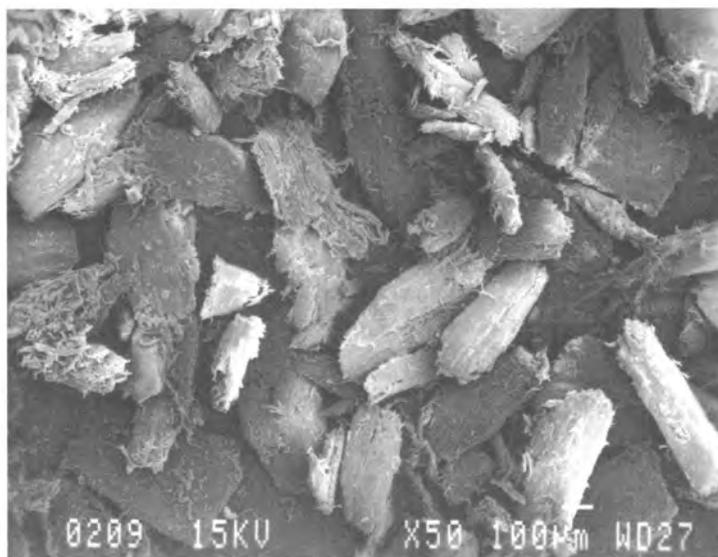
1.9 A partial softwood lignin structure (Pettersen, 1984).

the cell wall (Parham and Gray, 1984) and varies depending upon many factors, including species and stresses on the wood during growth.

1.3.2 Sources and production of fillers and reinforcements from wood

There are a number of methods of producing fillers and reinforcements from wood for use in polymer composites. However, most commercial methods result in either some type of fiber or particulate.

Though often used somewhat loosely, wood fibers more precisely refer to the spindle-shaped cells of wood and are the main structural element of wood on the macroscopic scale. Fibers can be separated from wood by various mechanical or chemical pulping methods, for example, which influence the final properties of the fibers themselves. These fibers offer good reinforcing potential because their high strength and reasonably high aspect ratio (i.e. length-to-diameter ratio) can allow efficient transfer of stresses to the fiber if fiber-matrix adhesion is promoted. However, the use of fibers in polymer composites still greatly lags that of wood flour owing to greater cost and increased processing difficulties when using conventional plastics processing methods.



1.10 Scanning electron micrograph of pine wood flour.

The term 'wood flour' is somewhat ambiguous, referring to wood reduced to finely divided particles approximating those of cereal flours in size, appearance, and texture (Reineke, 1966). Wood flour comprises fiber bundles, rather than individual wood fibers, with aspect ratios typically only about 1–5 (see Fig. 1.10). Though the low aspect ratio limits the reinforcing ability (Bigg *et al.*, 1988), mechanical performance of the composite is sufficient for many applications. Wood flour is also less expensive and is easier to feed and meter into conventional plastics processing equipment than fibers derived from wood. Wood flour particle size is often described by mesh of the wire cloth sieves used to classify them. Table 1.4 lists the US standard mesh sizes and their equivalent particle diameters. However, different standards may be used internationally

Table 1.4 Conversion between US standard mesh and particle diameter

Mesh US	Particle diameter (μm)	Mesh US	Particle diameter (μm)	Mesh US	Particle diameter (μm)
20	850	60	250	170	90
25	710	70	212	200	75
30	600	80	180	230	63
35	500	100	150	270	53
40	425	120	125	325	45
45	355	140	106	400	38
50	300				

(*International Sieve Chart*, 1997). Grades of commercially manufactured wood flours used as fillers in thermoplastics are supplied in different particle size ranges but these ranges typically fall within 180–840 μm (80–20US standard mesh).

Wood flour is derived from various scrap wood from wood processors. Though there is no standard method of producing wood flour, the main steps in wood flour production are: (i) size reduction using various mills and (ii) size classification by screening or air classification (Reineke, 1966). Many different species of wood flours are available and are often based on the regional availability of clean, raw materials from wood-processing industries. The most commonly used wood flours for plastic composites in the United States are made of pines, maples, and oaks. Many reasons are given for species selection including slight color differences, availability, and familiarity. Additionally, some species that contain significant amounts of extractives that can be leached from the wood by water are avoided. This water can migrate to the surface and evaporate, leaving behind stains from the extractives. Extractives can also volatilize or darken during processing if the temperature are too high.

1.3.3 Properties

Owing to its commercial importance, the properties of common wood species are readily available. However, the properties of fibers and particles derived from wood can be significantly different from the wood from which it is derived. Methods for producing wood-derived fillers and fibers as well as the high temperatures and pressures often found during composite processing influence attributes such as surface chemistry, density, and moisture content of the wood component in the final composite. For example, wood fibers produced by thermomechanical means lead to lignin-rich surfaces while those produced by chemical means lead to carbohydrate-rich surfaces (Stokke and Gardner, 2003). These changes in surface chemistry can affect adhesion with polymers, for example. Important properties of wood and fillers and fibers derived from them are discussed below.

Density

Though the density of the wood cell wall is about 1.44–1.50 g/cm^3 (Kellogg, 1981), the porous anatomy of solid wood results in overall densities of about 0.32–0.72 g/cm^3 (2045 lb/ft^3) when dry (Simpson and TenWolde, 1999). Not surprisingly, production of fillers and reinforcements from wood result in materials with bulk densities that are significantly lower than wood. For example, the bulk density of wood flour depends on factors such as moisture content, particle size, and species, but typically is about 0.19–0.22 g/m^3 (12–14 lb/ft^3).

The bulk density of reinforcing fibers derived from wood is considerably lower, especially with long fibers, and is quite variable. This low bulk density and entanglement of the fibers make metering and feeding into conventional polymer processing equipment such as extruders difficult. Though methods have been developed that overcome these hurdles, they typically add cost.

As a filler in polymers, wood flour is unusual in that it is compressible. The high pressures found during many plastics processing methods can collapse the hollow fibers that constitute the wood flour or fill them with low molecular weight additives and polymers. The degree of collapsing or filling will depend on such variables as particle size, processing method, and additive viscosity, but wood densities in composites approaching the wood cell wall density (i.e. 1.44–1.50 g/cm³) can be found in high-pressure processes such as injection molding. Consequently, adding wood to commodity plastics such as polypropylene, polyethylene, and polystyrene increases their density despite having densities higher than that of wood prior to compounding. However, even the density of compressed wood is considerably lower than those of common inorganic fillers and reinforcements, which are typically about 2.5–2.8 g/m³ (Xanthos, 2005). This density advantage is important in applications where weight is important, such as automotive components.

Moisture sorption

The major chemical constituents of the wood cell wall contain hydroxyl and other molecular groups that attract moisture. Absorbed moisture interferes with and reduces hydrogen bonding between cell wall polymers and alters its mechanical performance (Winandy and Rowell, 1984). However, the interior of the crystalline cellulose is not accessible to moisture, which is important in maintaining rigidity in the tree even at high moisture contents (Tarkow, 1981).

The equilibrium moisture content of wood is affected by temperature and humidity and can vary as much as 34% depending on if it is approached from a higher or lower humidity (i.e. wood exhibits a moisture sorption hysteresis). Table 1.5 shows approximate equilibrium moisture contents for wood at different temperatures and humidities at a midpoint between the hysteresis curves.

The moisture sorption of fillers and reinforcements derived from wood are affected by the methods used to produce them. However, wood flour is produced mechanically and its moisture sorption properties are similar to that of solid wood. Wood flour usually contains at least 4% moisture when delivered, which must be removed before or during processing with thermoplastics. Even if dried, wood flour can still absorb moisture quickly. Depending on ambient conditions, wood flour can absorb several percent of moisture within hours (Fig. 1.11).

Moisture of up to about 30% can be adsorbed by the cell wall with a corresponding reversible increase in apparent wood volume. Volume changes of the wood component due to moisture sorption, especially repeated moisture cycling,

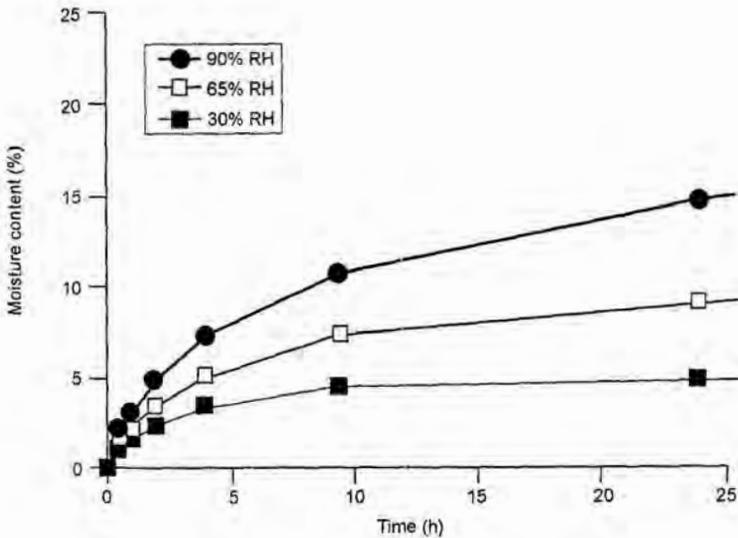
Table 1.5 Equilibrium moisture content for wood at different temperatures and humidities from Simpson and TenWolde (1999)

Temperature		Moisture content (%) at various relative humidities									
°C	°F	10%	20%	30%	40%	50%	60%	70%	80%	90%	
-1.1	30	2.6	4.6	6.3	7.9	9.5	11.3	13.5	16.5	21.0	
4.4	40	2.6	4.6	6.3	7.9	9.5	11.3	13.5	16.5	21.0	
10.0	50	2.6	4.6	6.3	7.9	9.5	11.2	13.4	16.4	20.9	
15.6	60	2.5	4.6	6.2	7.8	9.4	11.1	13.3	16.2	20.7	
21.1	70	2.5	4.5	6.2	7.7	9.2	11.0	13.1	16.0	20.5	
26.7	80	2.4	4.4	6.1	7.6	9.1	10.8	12.9	15.7	20.2	
32.2	90	2.3	4.3	5.9	7.4	8.9	10.5	12.6	15.4	19.8	
37.8	100	2.3	4.2	5.8	7.2	8.7	10.3	12.3	15.1	19.5	

can lead to interfacial damage and matrix cracking (Peyer and Wolcott, 2000). As a result, many manufacturers of WPCs used in exterior applications limit wood flour content to 50–65% by weight and rely on the partial encapsulation of the wood by the polymer matrix to prevent major moisture sorption and subsequent negative effects.

Durability properties

The surface of wood undergoes photochemical degradation when exposed to UV radiation. This degradation takes place primarily in the lignin component and

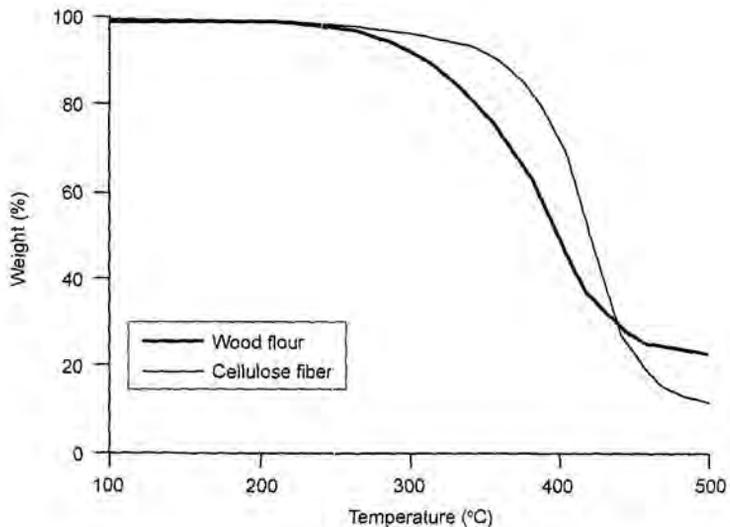


1.11 Moisture sorption of pine wood flour at several relative humidities (RH) and 26°C (80°F).

results in a characteristic color change (Rowell, 1984). Mold can form on moist surfaces of WPCs. Although mold does not reduce the structural performance, it can be an important aesthetic issue. In severe cases, where the moisture content of the wood flour in the composite exceeds about 25–30%, decay fungi can begin to attack the wood component leading to weight loss and significant reduction in mechanical performance. Wood is degraded biologically because organisms recognize the celluloses and hemicelluloses in the cell wall and can hydrolyze them into digestible units using specific enzyme systems (Rowell, 1984). Further information on the durability of wood and WPCs can be found in Chapter 7.

Thermal properties

The onset of degradation differs for the major components of wood with cellulose being the most thermally stable. Owing to its low thermal stability, wood flour is usually used as a filler only in plastics that are processed at temperatures lower than about 200 °C. Above these temperatures the cell wall polymers begin to decompose. High-purity cellulose pulps, where nearly all of the less thermally stable lignin and hemicelluloses have been removed, have recently been investigated for use in plastic matrices, such as nylon, that are processed at higher temperatures than most commodity thermoplastics (Sears *et al.*, 2001). Figure 1.12 shows thermogravimetric analysis curves showing weight loss of pine wood flour and high purity cellulose fiber as temperature is increased. Wood flour begins to degrade at significantly lower temperature than the cellulose fiber.



1.12 Thermogravimetric analysis of pine wood flour and cellulose fibers made from wood.

The thermal expansion of wood is less than that of the commodity plastics commonly used as matrices. Thermal expansion coefficients for wood are directional but are roughly (Kellogg, 1981):

$$\alpha = A p \times 10^{-6} \quad 1.3$$

where a is the coefficient of thermal expansion (in K^{-1}), p is the specific gravity (oven-dry basis), and A is roughly 50–80 perpendicular to the fiber direction and about 5–10 times less in the fiber direction. This roughly yields an average of about $10\text{--}15 \times 10^{-6}/K$ if we assume a density of 1.5. This is well below that of common matrix materials for WPCs for which a is about $150\text{--}250 \times 10^{-6}/K$ (Osswald and Menges, 1996).

Mechanical properties

Reported mechanical properties for reinforcing fibers, particularly natural fibers, vary greatly. Variability is due to differences in preparation methods as well as to differences in species, growing conditions, age, and location. Also, differences in methods of determining mechanical performance are common and make direct comparisons of literature values difficult (Mark, 1967). However, some general statements regarding mechanical performance can be made.

Table 1.6 lists typical tensile properties for solid wood as well as various fibers used in polymer composites. The mechanical properties of wood are quite anisotropic with the largest values are found parallel to the grain, which corresponds to the direction of alignment of the wood fibers. The strength properties of wood pulp fibers are larger than those of wood itself. This is not surprising since the fiber is the main macroscopic structural element of wood. Strengths of air-dried pulp fibers tend to increase with removal of lignin (Mark, 1967). The mechanical properties of some natural fibers such as flax are considerably higher than those of wood, which is one of the reasons that flax

Table 1.6 Typical mechanical properties of wood and various reinforcements

Material	Tensile modulus (GPa)	Tensile strength (MPa)	Reference
Southern pine wood*	12–27 () 0.7–1.4 (⊥)	100–200 () 3–5 (⊥)	Kretschmann and Green (1996)
Southern pine sulfate pulp fiber	5–10	350–700	Mark (1967)
Flax fiber	26–107	750–1100	Mark (1967)
E-glass fiber	76	1500	Xanthos (2005)
Carbon fiber	230–340	3200–2500	Xanthos (2005)

* Properties are for uncompressed wood at 4% moisture content and densities between 0.4 and 0.7 g/cm^3 . (||) and (⊥) refer to the properties parallel and perpendicular to the grain.

fibers are of considerable interest in polymer composites in applications in the automotive industry, for example (Sudell and Evans, 2004). Common synthetic reinforcing fibers such as glass and carbon fibers have greater mechanical performance than natural fibers. However, advantages such as low cost and low density of the natural fibers offer advantages in some applications.

The strength of wood flour would be expected to be less than that of wood fiber at the same conditions since it is easier to separate fibers than to break them. Also, the low aspect ratio of the flour and limited adhesion between the wood flour and plastic often lead to incomplete stress transfer that prevents optimal reinforcement of matrix. However, sufficiently useful property improvements (e.g. increased modulus, heat deflection temperature, and dimensional stability with changes in temperature), ease of processing, and low cost make wood flour desirable as a filler.

1.4 Sources of further information and advice

There are many introductory texts on polymer science including several used as references for this chapter (Billmeyer, 1984; Osswald and Menges, 1996). Additionally, practical information on various polymers can be obtained from polymer manufacturers and distributors as well as industry handbooks. The recent advent of electronic material databases offers further opportunity for comparisons of polymer properties.

Similarly, many introductory texts are available on wood science and technology (Wangaard, 1981; Fengel and Wegener, 1983). Another popular, readily available source of basic information on wood is the Wood Handbook: Wood as an Engineering Material (1999). As its use as a filler increases, handbooks are beginning to include information on wood-derived fillers and reinforcements alongside more traditional ones (Clemons and Caulfield, 2005). Suppliers are also a source of practical information on commercial grades.

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