

Wood Flour

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15.1

Introduction

The term “wood flour” is somewhat ambiguous. Reineke [1] states that the term wood flour “is applied somewhat loosely to wood reduced to finely divided particles approximating those of cereal flours in size, appearance, and texture”. Though its definition is imprecise, the term wood flour is in common use. Practically speaking, wood flour usually refers to wood particles that are small enough to pass through a screen with 850-micron openings (20 US standard mesh).

Wood flour has been produced commercially since 1906 [2] and has been used in many and varied products including soil amendments, extenders for glues, and absorbents for explosives. One of its earliest uses in plastics was in a phenol–formaldehyde and wood flour composite called Bakelite. Its first commercial product was reportedly a gearshift knob for Rolls Royce in 1916 [3]. Though once quite prevalent as a filler for thermosets, its use has diminished.

In contrast to its use in thermosets, large-scale use of wood flour in thermoplastics has only occurred within the last few decades. Recent growth has been great: use of wood–plastic composites has grown from less than 50,000 tonnes in 1995 to nearly 600,000 tonnes in 2002 (Figure 15-1) [4]. Most of this has been due to the rapid growth in the manufacture of exterior building products such as railings, window and door profiles, and especially decking (Figure 15-2).

Due 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. The great majority of wood–plastic composites use polyethylene as the matrix (Figure 15-3). This is due, in part, to the fact that many of the early wood–plastic composites were developed as an outlet for recycled film. Some manufacturers also use combinations of thermoplastics and thermosets as the matrix material.

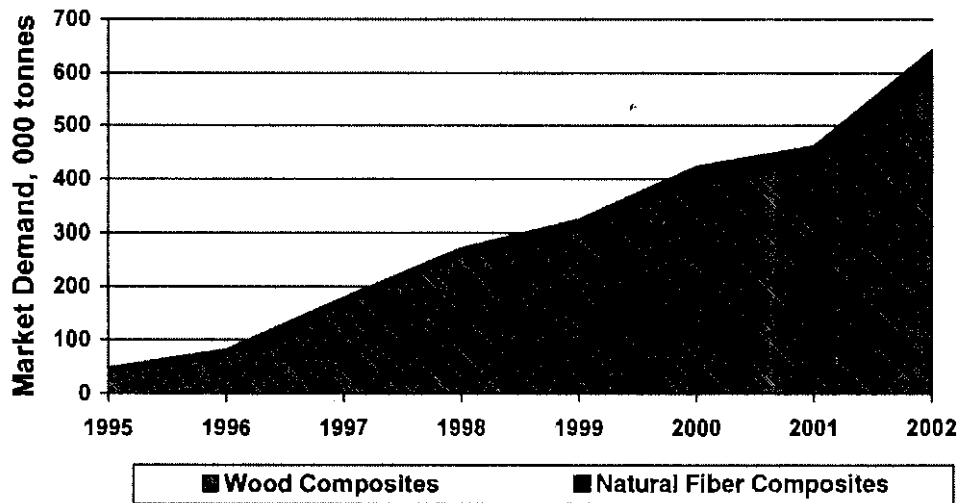


Fig. 15.1 Market demand for wood and natural fiber plastic composites in North America and Europe. (Reprinted with permission from ref. [4]).

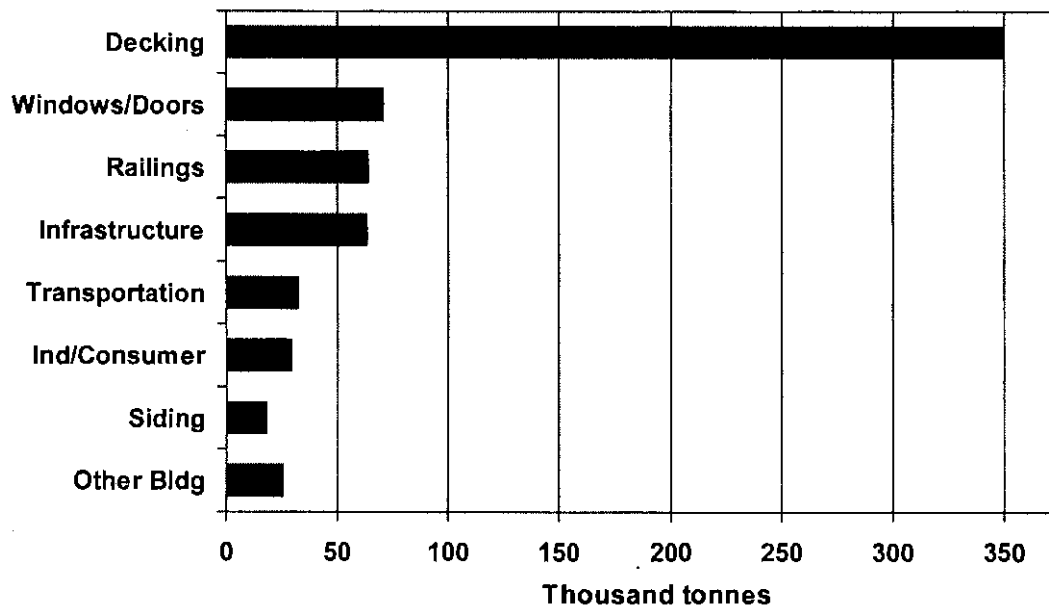


Fig. 15-2 Current applications and market size of plastics with wood flour or natural fibers. (Reprinted with permission from ref. [4]).

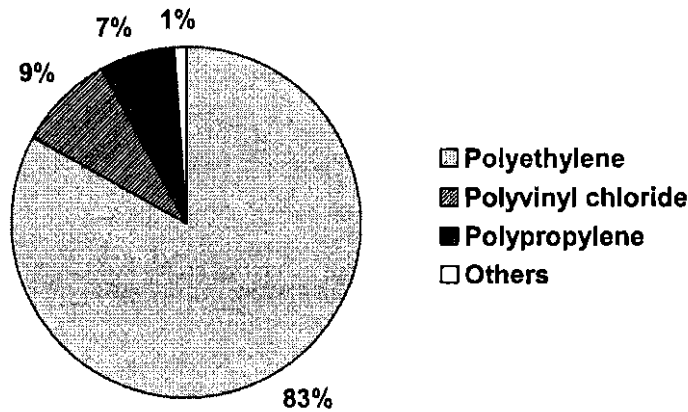


Fig. 15.3 Plastics used in wood-plastic composites. (Reprinted with permission from ref. [4].)

15.2

Production Methods

Wood flour is derived from various scrap wood from wood processors. High quality wood flour must be of a specific species or species group and must be free from bark, dirt, and other foreign matter. Many different species of tree are offered as wood flour 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 from pine, oak, and maple. Many reasons are given for species selection, including slight color differences, regional availability, and familiarity. Some species, such as red oak, can contain low MW phenolic compounds, which may cause stains if the composite is repeatedly wetted [5].

Though there is no standard method of producing wood flour, some generalities can be discussed. The main steps in wood flour production are size reduction and size classification. If larger raw materials are used, their initial size may be reduced using equipment such as a hammer mill, hog, or chipper [2]. Once coarsely ground, the wood is pulverized by grinding between disks as in attrition mills, beating with impactors or hammers as in hammer mills, or crushing between rollers as in roller mills [2]. Other mills can also be used but are less common.

Pulverizing results in a mixture of particles that contains fiber bundles and fiber fragments. These particles typically have aspect ratios (i.e., length-to-diameter ratios) of only 1–5 (Figure 15-4). These low aspect ratios allow wood flour to be more easily metered and fed than individual wood fibers, which tend to bridge. However, the low aspect ratio limits their reinforcing ability [6].

Once pulverized, the wood can be classified using vibrating, rotating, or oscillating screens. Air classifying is also used, especially with very finely ground wood flours [1]. Wood flour particle size is often described by the mesh of the wire cloth sieves used to classify the particles. Table 15-1 lists the US standard mesh sizes and their equivalent particle diameters. However, different standards may be used interna-



Fig. 15-4 Scanning electron micrograph of pine wood flour.

tionally [7]. Most commercially manufactured wood flours used as fillers in thermoplastics are less than 425 μm (40 US standard mesh). Very fine wood flours can cost more and increase melt viscosity more than coarser wood flours, but composites made with them typically have more uniform appearance and a smoother finish. If ground too finely, fiber bundles become wood dust, fragments that no longer resemble fibers or fiber bundles.

Tab. 15-1 Conversion between US standard mesh and particle diameter.

Mesh US. [41]	Particle Diameter (μm)
20	850
25	710
30	600
35	500
40	425
45	355
50	300
60	250
70	212
80	180
100	150
120	125
140	106
170	90
200	75
230	63
270	53
325	45
400	38

Wood flour is commonly packaged in: 1) multi-walled paper bags (approximately 23 kg or 50 lbs), 2) bulk bags (typically 1.5 cubic meter or 55 cubic feet), or 3) bulk trailers [8]. Wood flour is typically supplied to the customer with moisture contents in the range 4–8% and must be dried before use in thermoplastics. Some wood flour manufacturers offer standard grades, while others prefer to customize for individual buyers and applications. Specifications depend on the application, but include size distribution, moisture content, species, color, and cost.

15.3

Structure and Properties

15.3.1

Wood Anatomy

As with most natural materials, the anatomy of wood is complex. Wood is porous, fibrous, and anisotropic. Wood is often subdivided into two broad classes, namely softwoods and hardwoods, which are classified by botanical and anatomical features rather than actual wood hardness. Figures 15-5 and 15-6 are schematics of a softwood and a hardwood, respectively, showing the typical anatomies of each wood type. Softwoods (or *Gymnosperms*) include pines, firs, cedars, and spruces among others; hardwoods (or *Angiosperms*) include species such as the oaks, maples, and ashes.

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 [9]. 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 [9]. These fibers are firmly cemented together and form the structural component of

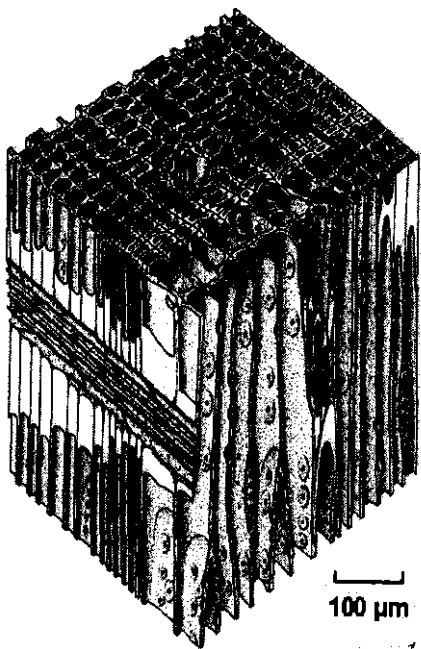


Fig. 15-5 Schematic of a softwood.

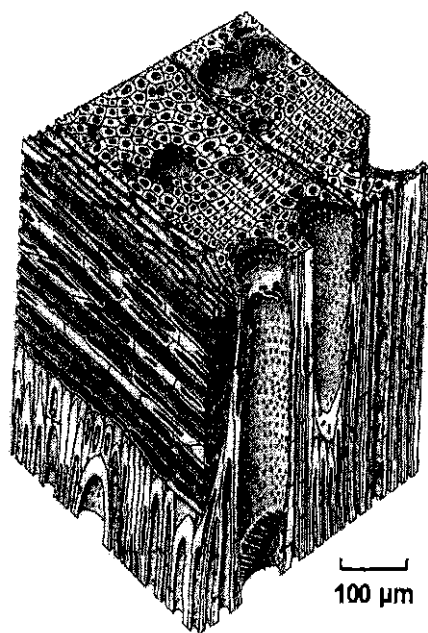


Fig. 15.6 Schematic of a hardwood

wood tissue. The length of wood fibers is highly variable, but averages about 1 mm (1/25 in.) for hardwoods and 3 to 8 mm (1/8 to 1/3 in.) for softwoods [9]. Fiber diameters are typically 15–45 μm. When wood is reduced to wood flour, the resulting particles are actually bundles of wood fibers rather than individual fibers and can contain lesser amounts of other features such as ray cells and vessel elements. Further information on wood anatomy can be found in refs. [10, 11].

15.3.2

Chemical Components

Wood itself is a complex, three-dimensional, polymer composite made up primarily of cellulose, hemicellulose, and lignin [12]. These three hydroxyl-containing polymers are distributed throughout the cell wall. The chemical compositions of selected woods are shown in Table 15-2.

Of the three major components, cellulose shows the least variation in chemical structure. It is a highly crystalline, linear polymer of anhydroglucose units with a degree of polymerization (n) of around 10,000 (Figure 15-7). 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 [13, 14]. Hemicelluloses are branched polymers composed of various five- and six-carbon sugars, the molecular weights of which are well below those of cellulose but which still contribute as a structural component of wood [15].

Lignin is an amorphous, cross-linked polymer network consisting of an irregular array of variously bonded hydroxy- and methoxy-substituted phenylpropane units [15]. The chemical structure varies depending on its source. Figure 15-8 depicts part of a softwood lignin structure, illustrating a variety of possible structural compo-

Tab. 15.2 Approximate chemical compositions (%) of selected woods [15].

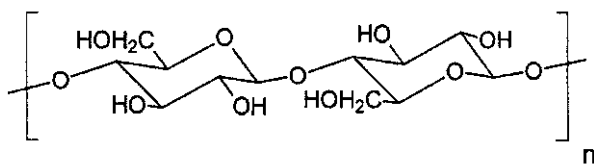
Species	Cellulose ^[a]	Hemicellulose ^[b]	Lignin ^[c]	Extractives ^[d]	Ash
Ponderosa Pine	41	27	26	5	0.5
Loblolly Pine	45	23	27	4	0.2
Incense Cedar	37	19	34	3	0.3
Red Maple	47	30	21	2	0.4
White Oak	47	20	27	3	0.4
Southern Red Oak	42	27	25	4	0.4

[a] Alpha cellulose content as determined by ASTM D 1103 [41].

[b] Approximate hemicellulose content determined by subtracting the alpha cellulose content from the holocellulose content values from ref. [15].

[c] Klason lignin content as determined by ASTM D 1106 [42].

[d] Solubility in 1:2 (v/v) ethanol/benzene according to ASTM D 1107 [43].

**Fig. 15-7** Chemical structure of cellulose [15].

nents. Lignin is less 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 [15]. Extractives include substances such as fats, waxes, resins, proteins, gums, terpenes, and simple sugars, among others. Many of these extractives function in tree metabolism and act as energy reserves or defend against microbial attack [15]. Though often small in quantity, extractives can have large influences on properties such as color, odor, and decay resistance [15]. 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, which are in turn cemented to lignin in 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 the cell wall [16] and varies depending upon many factors including species and stresses on the wood during growth.

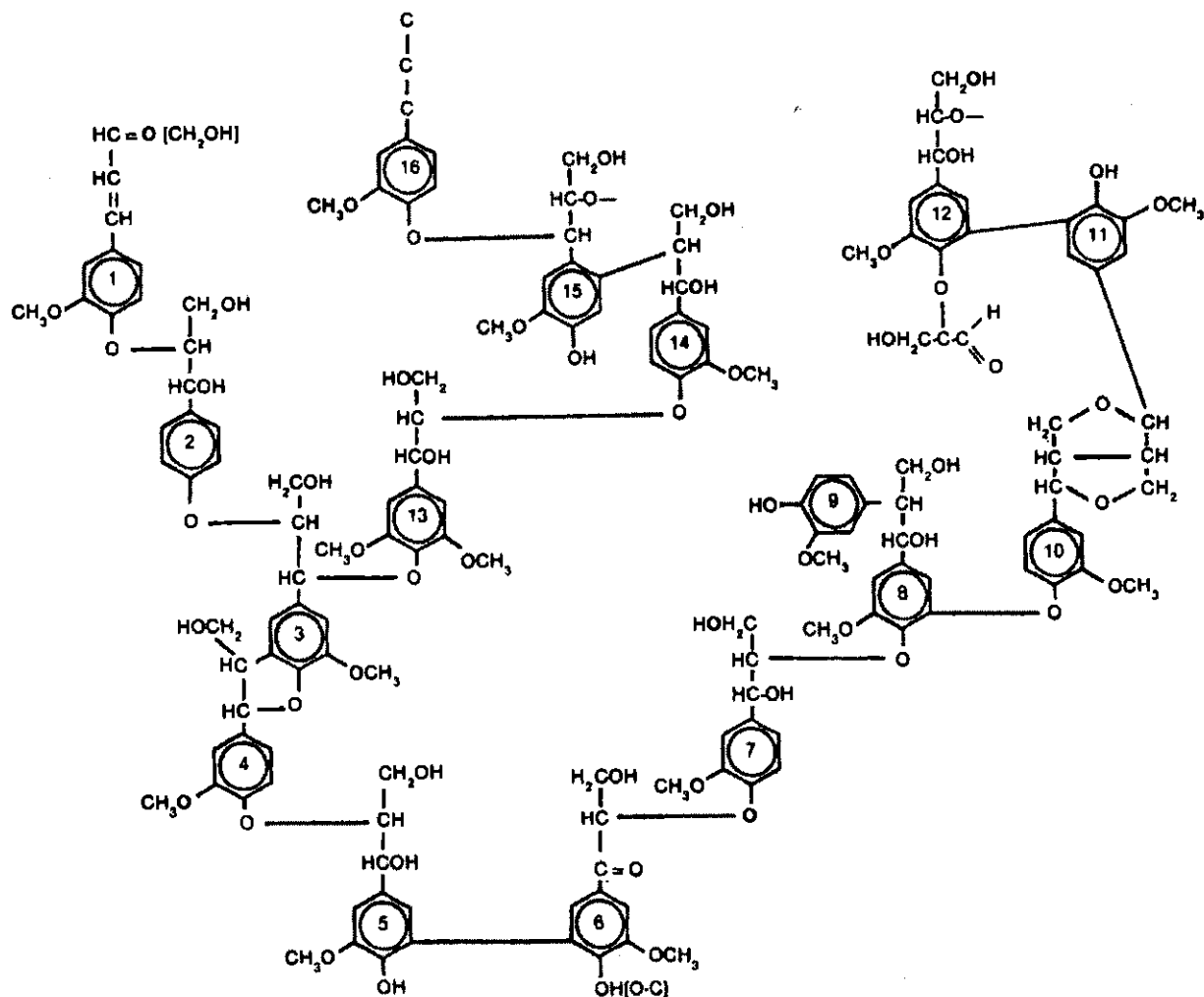


Fig. 15.8 A partial softwood lignin structure [15].

15.3.3

Density

The bulk density of wood flour depends on factors such as moisture content, particle size, and species, but typically is about 190–220 kg m⁻³ (12–14 lbs ft⁻³) [8]. Because of its low bulk density, special equipment, such as a crammer, is sometimes used to aid feeding of wood flour.

As a filler, wood flour is unusual in that it is compressible. Though the density of the wood cell wall is about 1.44 to 1.50 g cm⁻³ [17], the porous anatomy of solid wood results in overall densities of about 0.32 to 0.72 g cm⁻³ (20 to 45 lb ft⁻³) when dry [18]. However, the high pressures encountered during the processing of plastics can cause the hollow fibers of the wood flour to collapse or fill them with low molecular weight additives or polymers. The degree of collapse or filling will depend on such variables as particle size, the processing method, and additive viscosity, but wood densities in

composites approaching the wood cell wall density can be attained in high-pressure processes such as injection molding. Consequently, adding wood fibers to commodity plastics such as polypropylene, polyethylene, and polystyrene increases their densities.

Even these higher densities are considerably lower than those of inorganic fillers and reinforcements. This density advantage is important in applications where weight is important, such as in automotive components. Recently, chemical foaming agents and microcellular foaming technology have been investigated with a view to reducing the density of wood–plastic composites [19–21].

15.3.4

Moisture

The major chemical constituents of the cell wall bear hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding [26]. This hygroscopicity can cause problems both in composite fabrication and in the performance of the end product.

Moisture sorption in wood is complex and the final equilibrium moisture content is affected by temperature and humidity. The equilibrium moisture content can also vary by up to 3–4% (although usually less) depending on whether it is approached from a higher or lower humidity (i.e., wood exhibits a moisture sorption hysteresis). Table 15-3 shows approximate equilibrium moisture contents for wood at different temperatures and humidities at a midpoint between the hysteresis curves.

Tab. 15-3 Equilibrium moisture content for wood at different temperatures and humidities [18].

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	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

Wood flour usually contains at least 4% moisture when delivered, which must be removed before or during processing with thermoplastics. Though moisture could potentially be used as a foaming agent to reduce density, this approach is difficult to control and is not common industrial practice. Commercially, moisture is removed from the wood flour: 1) before processing using a dryer, 2) by using the first part of an extruder as a dryer in some in-line process, or 3) during a separate compounding step (or in the first extruder in a tandem process).

Once dried, wood flour can still absorb moisture quickly. Depending on the ambient conditions, wood flour can absorb several weight percent of moisture within hours (Figure 15-9). Even compounded material often needs to be dried prior to further processing, especially if high weight percentages of wood flour are used. Figure 15-10 shows moisture sorption curves for compounded pellets of polypropylene containing 40% wood flour at different humidities.

The hygroscopicity of wood flour can also affect the end composite. Absorbed moisture interferes with and reduces hydrogen bonding between cell wall polymers and alters the mechanical performance of the product [22]. A moisture content of up to about 30% can be adsorbed by the cell wall, with a corresponding reversible increase in apparent wood volume. The wood volume V_1 , at a moisture content M , has been roughly approximated by [16]:

$$V_1 = V_0 (1 + 0.84 M r) \quad (15-1)$$

where V_0 is the dry volume and p is the specific gravity of the wood when dry.

Volume changes due to moisture sorption, especially repeated moisture cycling, can lead to interfacial damage and matrix cracking [23]. This damage, and the resulting irreversible mechanical property reductions after the composites have been exposed to a humid environment or to liquid water, have been discussed in a number of papers [23–25]. Water uptake depends on many variables, including wood flour content, wood flour particle size, matrix type, processing method, and additives such as coupling agents. Many manufacturers of wood–plastic composites used in exterior applications limit wood flour content to 50–60% by weight and rely on the partial encapsulation of the wood by the polymer matrix to prevent significant moisture sorption and the consequent negative effects.

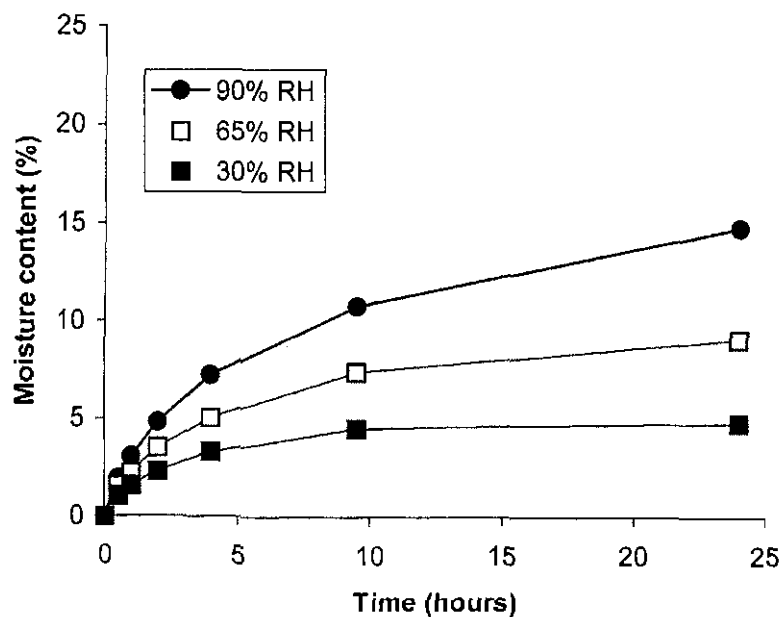


Fig. 15-9 Moisture sorption of wood flour at several relative humidities and 26 °C.

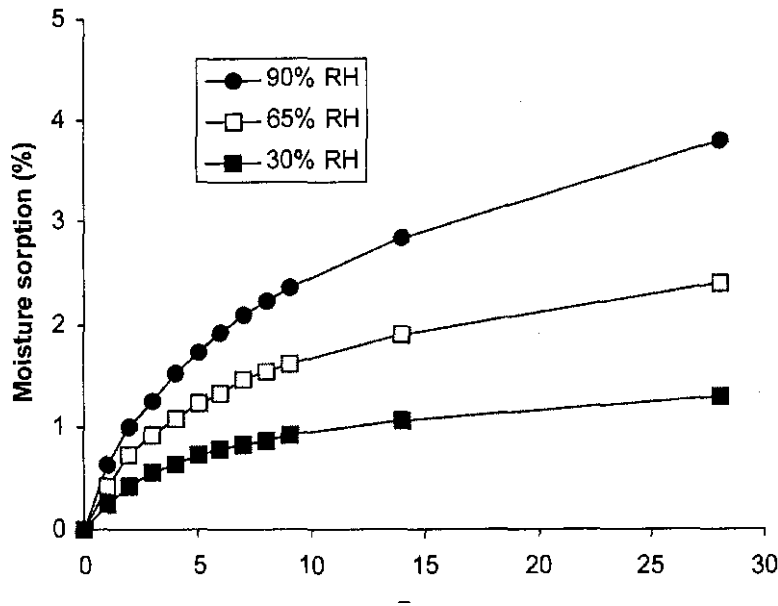


Fig.15-10 Moisture sorption of compounded pellets of polypropylene containing 40% wood flour at several relative humidities and 26 °C [49].

15.3.5

Durability

Wood will last for decades in exterior environments, especially if it is stained, painted or otherwise protected. However, wood–plastic composites are not commonly protected. In fact, a common selling point for wood–plastic composites is that they are low maintenance materials and do not require painting or staining for use in outdoor applications.

The surface of wood undergoes photochemical degradation when exposed to UV radiation. This degradation takes place primarily in the lignin component and results in a characteristic color change [26]. Hence, wood–plastic composites containing no pigments usually fade to a light gray when exposed to sunlight. Photostabilizers or pigments are commonly added to wood–plastic composites to help reduce this color fade when they are used in exterior environments.

Mold can form on surfaces of wood–plastic composites. Mold growth has been attributed to various effects, among them moisture sorption by the wood flour, build-up of organic matter on the composite surface, and the lubricants used in processing the composites. The relative contributions of these factors to mold growth are uncertain. Although mold does not reduce the structural performance of the composite, it is an aesthetic issue.

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 [26]. If the moisture content of the wood flour in the compos-

ite exceeds the fiber saturation point (approximately 30% moisture), decay fungi can begin to attack the wood component leading to weight loss and significant reduction in mechanical performance. Figure 15-11 shows the weight loss due to exposure of a wood–plastic composite to the decay fungi *Gleophyllum Trabeum* in a laboratory soil block test. Decay does not commence until a moisture threshold of about 15% is reached. Since HDPE does not absorb moisture, the average moisture content of the wood flour in the composite would be expected to be roughly twice that shown. This suggests that when the moisture content of the wood flour reaches about 30%, approximately the fiber saturation point, significant decay begins. Additives such as zinc borate are sometimes added to wood–plastic composites to improve fungal resistance.

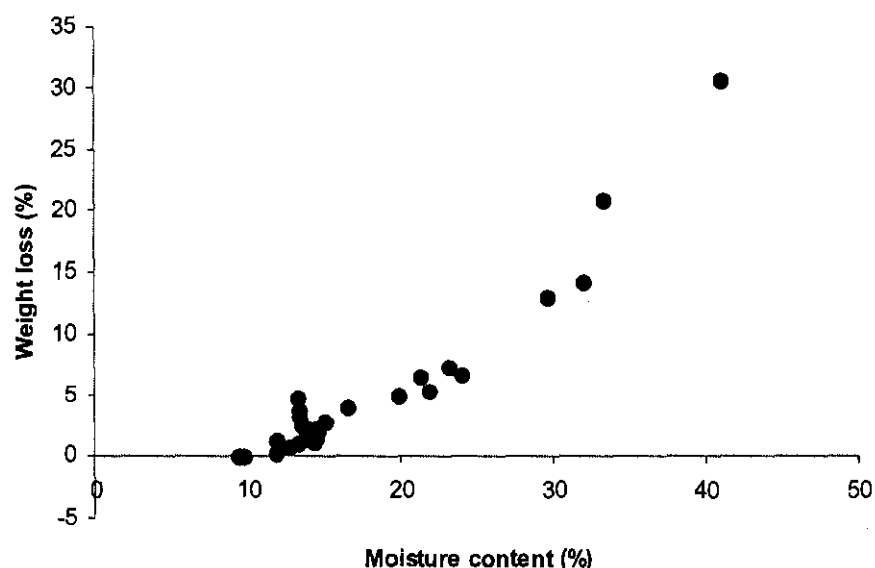


Fig. 15-11 Weight loss due to fungal attack (*Gleophyllum trabeum*) as a result of moisture sorption. Extruded composites of high density polyethylene containing 50% wood flour [SO]

15.3.6

Thermal Properties

Figure 15-12 shows a thermogravimetric analysis of wood flour and its constituents. The onset of degradation differs for the major components of wood, with cellulose being the most thermally stable. Due to its low thermal stability, wood flour is usually used as a filler only in plastics that are processed at low temperatures, lower than about 200 °C. Above these temperatures, the cell wall polymers begin to decompose. High purity cellulose pulps, from which 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 [27].

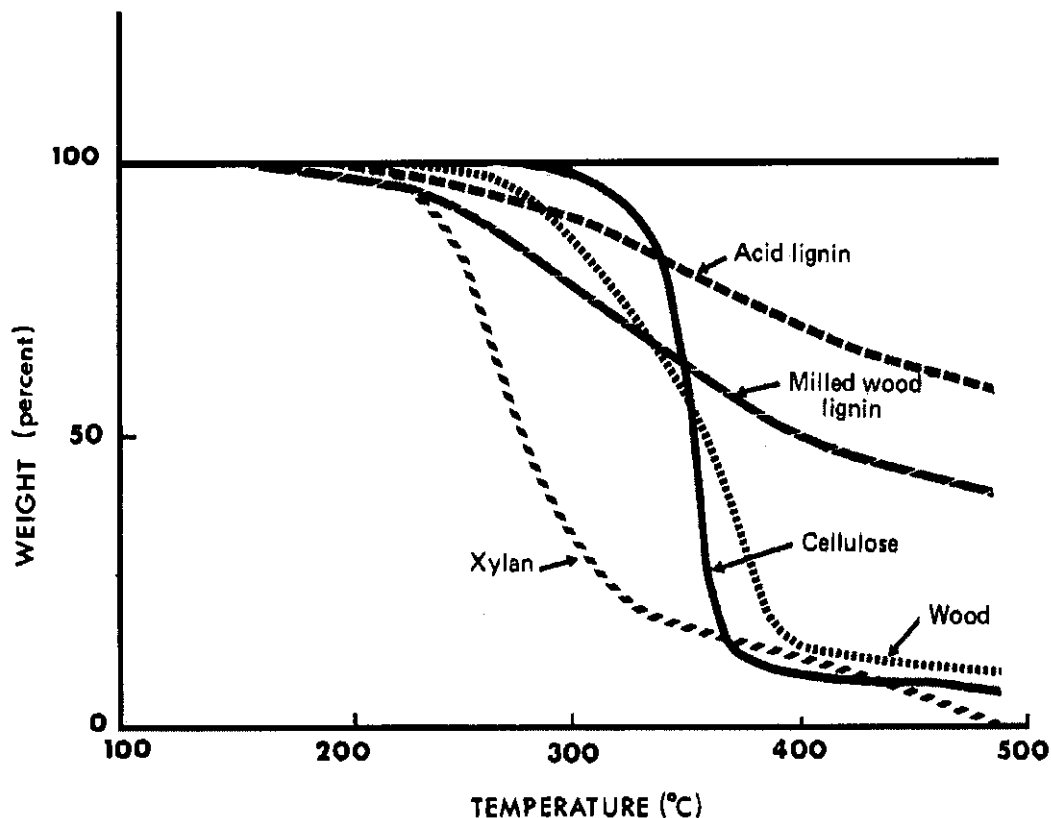


Fig. 15-12 Thermogravimetric analysis of wood and wood components. (Reprinted with permission from ref. [51]).

Because of its practical performance, the thermal properties of wood have been extensively investigated [17]. Understandably, this work has generally been performed on uncompressed wood at moisture contents typical of those found in service. Information on dry, compressed wood as might be found in a wood-thermoplastic composite is lacking. Additionally, thermal properties vary depending on the chemistry and structure of the wood. Factors such as extractive content, grain direction, and fibril angle are important. Though precise numbers are not known, some approximations may be made for a broad discussion on the topic.

The thermal expansion of wood is less than that of the commodity plastics commonly used as matrices. Thermal expansion coefficients for wood are directional and are roughly given by [17]:

$$\alpha = A \rho \times 10^{-6} \quad (15-2)$$

where a is the coefficient of thermal expansion (in K^{-1}), ρ is the specific gravity (oven-dried 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 $70 \times 10^{-6} K^{-1}$ if we assume a density of 1.5. This is about half that of polypropylene ($150 \times 10^{-6} K^{-1}$) and 3.5 times less than that of low density polyethylene

($250 \times 10^{-6} \text{ K}^{-1}$), both of which are commonly used as matrix materials for wood-plastic composites [28].

The specific heat of dry wood does not show a strong dependence on specific gravity and is roughly $0.324 \text{ cal g}^{-1} \text{ K}^{-1}$ or $1,360 \text{ J kg}^{-1} \text{ K}^{-1}$ [17]. This is about half the specific heat of common polyolefins such as polypropylene and polyethylene, for which the values are approximately $2\text{--}3,000 \text{ J kg}^{-1} \text{ K}^{-1}$.

The thermal conductivity, k , of dry wood has been reported to increase approximately linearly with specific gravity, ρ , according to [17]:

$$k = 0.200 \rho + 0.024 \quad (15-3)$$

where k is in units of $\text{W m}^{-1} \text{ K}^{-1}$. Assuming the specific gravity of compressed wood flour in a composite to be 1.5, the thermal conductivity is calculated as $0.32 \text{ W m}^{-1} \text{ K}^{-1}$. This is the same order of magnitude as the values reported for polypropylene and polyethylene ($0.17\text{--}0.51 \text{ W m}^{-1} \text{ K}^{-1}$).

Thermal diffusivity is a measure of the rate at which a material changes temperature when the temperature of its surroundings changes. The thermal diffusivity, h , is the ratio of thermal conductivity k to the product of specific heat, c , and density, D [17]:

$$h = k / c D \quad (15-4)$$

Calculations for wood flour yield a value of $0.16 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$, compared to $0.11\text{--}0.17 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ for polypropylene and polyethylene.

15.4 Suppliers

There is a wide range of wood flour suppliers and they cater to a number of different industries. These are both large companies that have broad distribution networks, as well as small, single source suppliers catering to single customers. Because of the varied and dispersed nature of these suppliers, there are currently few good resources that list wood flour manufacturers.

Wood-plastic composite manufacturers obtain wood flour either: 1) directly from forest products companies such as lumber mills and furniture, millwork, or window and door manufacturers that produce it as a by-product, or 2) commercially from companies that specialize in wood flour production.

With a growing number of wood flour suppliers targeting the wood-plastic composites industry, they are beginning to be listed in plastics industry resources. The following is a list of major suppliers of wood flour to the U.S. wood-plastic composite industry from one industry resource [29].

- American Wood Fibers (Schofield, Wisconsin)
- Composition Materials (Fairfield, Connecticut)

- Lang Fiber (Marshfield, Wisconsin)
- Marth Manufacturing (Marathon, Wisconsin)
- P. J. Murphy Forest Products (Montville, New Jersey)

15.5

Cost/Availability

As with most materials, wood flour costs are variable and depend on such factors as volume, availability, particle size, and shipping distance. However, wood flour is typically about \$0.11–0.22 kg⁻¹ (\$0.05–0.10 lb⁻¹) in the United States. Narrow particle size distributions and fine sizes tend to increase cost. Because there are many small manufacturers and the volume is small relative to other wood products (solid wood, wood composites, and paper), information on wood flour availability is scarce.

15.6

Environmental/Toxicity Considerations

The environmental benefits of wood and other natural fibers have been an important influence on their use, particularly in Europe. Wood flour is derived from a renewable resource, does not have a large energy requirement to process, and is biodegradable [30].

Wood is a commonly used material and most people are very comfortable with its use. Most of the risk in using wood flour lies in the facts that: 1) it has low thermal stability and can degrade and burn resulting in a fire and explosion hazard that is greater than that with solid wood, and 2) inhalation of finely ground wood flour can lead to respiratory difficulties. Some basic precautions include avoiding high processing temperatures, using well-ventilated equipment, eliminating ignition sources, and using good dust protection, prevention, and control measures. For detailed information on environmental and health risks, manufacturers should consult their suppliers and material safety data sheets. Regulatory bodies such as the Occupational Safety and Health Association (OSHA) also have good information on health and safety aspects of wood dust (see, e.g., www.osha.gov/SLTC/wooddust/index.html).

15.7

Applications (Primary and Secondary Functions)

15.7.1

Thermosets

In thermosetting adhesives, wood flour has been used for several functions. As an extender, it is added to reduce cost while retaining bulk for uniform spreading. Unfortunately, wood flour extenders generally also reduce the durability of a given resin.

As a filler, it is added to thermoset adhesives to control penetration when bonding wood and to improve the characteristics of the hardened film [31].

High weight percentages of wood flour have been used with thermosets such as phenolic or urea/formaldehyde resins to produce molded products. The wood flour is added to improve toughness and reduce shrinkage on curing. Wood filler may be added to the thermoset resin at elevated temperatures to form a moldable paste. This paste is then transferred to a mold and cured under heat and pressure [32]. Alternatively, a mixture of powdered thermoset resin and wood flour is poured directly into a mold and pressed under heat and pressure. Although this type of composite was very prevalent throughout much of the 20th century, often under trade names such as “Bakelite”, its use has diminished considerably. However, a variety of products, such as some salad bowls, trays and cutting boards, are still manufactured from wood thermoset composites.

15.7.2

Thermoplastics

15.7.2.1 Mechanical Property Modification (Primary Function)

Wood flour is often added to thermoplastics as a low cost filler to alter mechanical performance, especially the stiffness of low melt temperature, commodity thermoplastics such as polypropylene and polyethylene, without increasing their density excessively. Wood is much stiffer than the commodity thermoplastics usually used as matrices. Additionally, wood and pulp fibers can nucleate crystal growth in polyalkenes, resulting in a transcrystalline layer that can influence mechanical behavior [33, 34].

The wood flour stiffens these plastics but also embrittles them, reducing properties such as elongation and unnotched impact energy. Tensile and flexural strengths are at best maintained, but more often decreased in the absence of a coupling agent. Many different coupling agents have been investigated for use in wood–plastic composites and these are reviewed elsewhere [35, 36]. When a coupling agent is desired, maleated polyalkenes are most often used commercially. However, even when a coupling agent is used, improvements in strength are limited by the low aspect ratio of the wood flour (Figure 15-13). It is often unclear as to how much of the strength increase is due to better wetting and dispersion and how much is due to the increased bonding. Small amounts of thermosets have also been added to wood–plastic formulations to improve mechanical performance [37].

Table 15-4 summarizes some typical mechanical property changes when wood flour from various species of tree is added to an injection-molding grade of polypropylene [44]. Both tensile and flexural moduli increase with the addition of wood flour. Composites with hardwoods (maple and oak) yield the highest flexural moduli at 60% wood flour content; i.e., approximately four times that of unfilled polypropylene. The heat deflection temperature is also approximately doubled by adding 60% wood flour. The increase in modulus with the addition of wood flour comes at the expense of elongation, a drastic reduction in unnotched impact strength, and a general decrease in tensile strength.

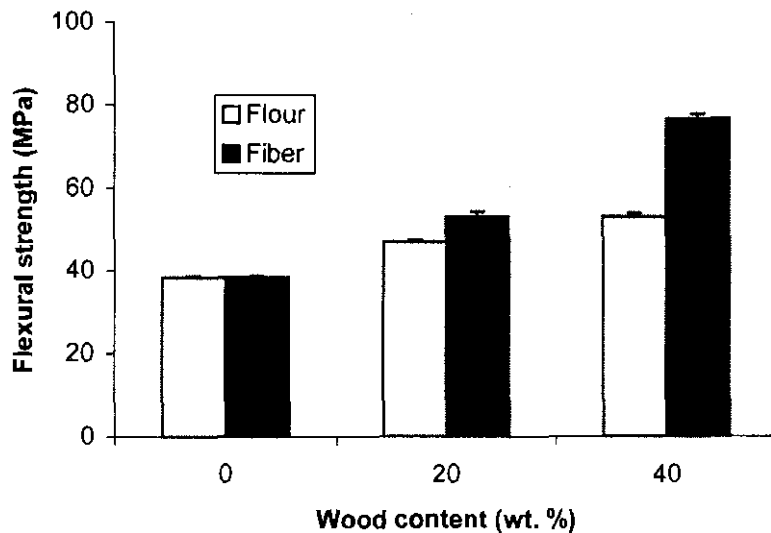


Fig. 15.13 Comparison between wood flour and wood fiber as a reinforcement in polypropylene. Injection-molded composites; 3% maleated polypropylene added as a coupling agent. (Derived from ref. [56]).

The effects of wood flour particle size on the mechanical performance of wood-filled polypropylene are summarized in Table 15-5. The largest particle size range (0.425–0.600 μm) yields the lowest performance, except in the case of notched impact strength. For the three smaller particle size ranges, properties generally decrease as particle size is reduced, except for the unnotched impact strength. Similar trends were found when broader particle size ranges more typical of commercially available blends were investigated [38].

15.7.2.2 To Impart Wood-Like Properties (Primary Function)

Wood flour is also often added to make plastics perform more like wood. Customers and builders have a certain familiarity with wood in applications such as decking and railings (the largest wood–plastic composite market) and often desire an alternative that may have similar attributes. As a result, many manufacturers add 50–60% wood flour to plastics to impart some wood-like qualities.

Adding wood flour to thermoplastics results in a composite with a wood color, although color-fade remains an issue in exterior applications. If desired, extruded wood–plastic composites can usually be painted or stained. Though not nearly as stiff as solid wood, these composites are stiffer than unfilled plastics. They do not usually require special fasteners or design changes such as shorter spans in applications such as deck boards. Adding wood flour also improves dimensional stability with respect to temperature changes. Although more expensive than wood, many consumers have been willing to pay for the lower maintenance required when wood–plastic composites are used.

However, wood–plastic composites are heavier than wood and do not have as good mechanical performance, often having only one-third to a half of the modulus of elasticity of wood [39]. The swelling of wood with moisture can create irreversible dam-

Tab.15-4 Effect of adding wood flour on the mechanical performance of injection-molded polypropylene^[a] [44].

Filler Content	Izod Impact strength ^[b] Notched	Unnotched	Flexural Max. flexural strength	properties ^[c] Modulus of elasticity	Tensile properties ^[d] Maximum tensile strength	Modulus of elasticity	Elongation at max. strength	Heat deflection temp. ^[e]
(wt.%)	(Jm ⁻¹)	(Jm ⁻¹)	(MPa)	(GPa)	(MPa)	(GPa)	(%)	(%)
No filler								
0	15.0	600	34.7	1.03	28.5	1.31	10.4	55
Ponderosa pine								
20	15.4	128	41.6	1.89	26.5	1.99	5.7	69
30	19.0	95	43.1	2.58	24.6	3.24	3.1	76
40	20.8	76	44.2	3.22	25.5	3.71	2.3	85
50	20.5	58	41.8	3.66	23.0	4.25	1.7	89
60	21.1	41	38.8	4.04	20.1	4.56	1.4	91
Loblolly pine								
20	12.4	120	40.6	1.71	24.9	2.14	4.8	64
30	12.7	75	41.2	2.28	23.7	2.53	3.5	72
40	13.7	49	39.3	2.84	21.4	3.28	1.8	78
50	13.8	42	37.1	3.40	19.7	3.97	1.3	79
GO	10.4	31	34.1	3.81	17.8	4.32	0.9	77
Maple								
20	12.8	113	46.2	2.16	27.9	2.87	4.1	69
30	15.0	87	46.5	2.47	27.1	3.33	3.3	88
40	16.5	63	45.4	3.23	25.6	4.72	2.0	104
50	17.7	49	42.1	4.16	24.0	5.20	1.4	111
60	17.9	44	38.0	4.35	19.9	4.77	1.1	110
Oak								
20	14.6	87	44.1	1.83	27.2	2.48	4.7	74
30	17.5	63	45.9	2.87	25.7	3.81	2.4	98
40	18.6	68	44.8	3.39	25.2	4.19	2.1	100
50	20.9	46	42.8	3.99	23.4	4.79	1.5	112
60	18.8	33	38.1	4.60	19.8	5.05	1.2	114
Avg. COV								
12	6	2	4	2	8	10	2	

[a] Fortilene 3907, polypropylene homopolymer, Solvay Polymers, Deer Park, TX, USA.

[b] ASTM D-256 [45].

[c] ASTM D-790 [46].

[d] ASTM D-638 [47].

[e] ASTM D-648 [48].

[f] Wood flour was commercial grade from American Wood Fibers, Schofield, WI, USA.

age, and the exact durability of wood–plastic composites in exterior applications is unknown. Most deck board manufacturers currently offer a ten-year warranty. As a result of these limitations, much research and development effort is underway to try to increase structural performance, improve durability, and decrease weight without too great an increase in cost.

Table 15.5 Mechanical properties of composites made from polypropylene^[a] filled with 40 wt. % wood flour [37].

Particle size range	Izod Impact strength ^[b]		Flexural properties ^[c]		Tensile properties ^[d]		
	Notched	Un-notched	Max. flexural strength	Modulus of elasticity	Maximum tensile strength	Modulus of elasticity	Elongation at max. strength
(μm)	(J m^{-1})	(J m^{-1})	(MPa)	(GPa)	(MPa)	(GPa)	(%)
No filler							
—	15.0	600	34.7	1.03	28.5	1.31	10.4
Composites with 40% wood flour ^[e]							
425–600	22	54	38.7	2.69	21.8	3.20	2.3
180–250	20	79	42.6	3.15	25.5	3.61	2.3
106–150	19	84	42.9	3.00	24.9	3.47	2.2
53–75	16	91	41.4	2.89	24.3	3.46	2.1
Avg. COV	5	10	1	2	1	7	6

[a] Fortilene 3907, polypropylene homopolymer, Solvay Polymers, Deer Park, TX, USA.

[b] ASTM D-256 [45].

[c] ASTM D-790 [46].

[d] ASTM D-638 [47].

[e] Specially screened wood flour from American Wood Fibers, Schofield, WI, USA.

15.7.2.3 Environmental Preference and Biodegradability (Secondary Function)

The environmental advantages of wood and other natural fibers have been an important influence, particularly in Europe. Wood flour is manufactured from industrial by-products, mitigating a disposal issue. Wood flour and other natural fibers are derived from a renewable resource, do not have a large energy requirement to process, and are biodegradable [40]. These features are advantageous in applications where environmental benefits and impact are important. Though not specifically added to plastics to impart biodegradability, wood flour can be used as a filler in biodegradable polymers where its biodegradability is an attribute rather than the detriment it is sometimes considered to be in more durable composites.

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References

- 1 Reineke, L. H., Wood Flour, U.S. Forest Service Research Note FPL-0113, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, **1966**, 13 pages.
- 2 Panshin, A. J., et al., Chapter 13: "Wood Flour", in *Forest Products: Their Sources, Production, and Utilization*, McGraw-Hill, New York, 1962, p. 265–271.
- 3 Gordon, J. E., *The New Science of Strong Materials (or why you don't fall through the floor)*, 2nd ed., Princeton University Press, Princeton, NJ, 1988, p. 179.
- 4 Morton, J., Rossi, L., "Current and Emerging Applications for Natural and Wood Fiber Composites", Proc. 7th International Conference on Woodfiber-Plastic Composites, Madison, WI, Forest Products Society, 2003.
- 5 Rowe, J. W., Conner, A. H., "Extractives in Eastern Hardwoods –A Review", General Technical Report FPL 18, USDA Forest Service, Forest Products Laboratory, Madison, WI, **1979**, p. 17.
- 6 Bigg, D. M., et al., *J. Thermoplastic Composite Materials* **1988**, 1, 146–161.
- 7 "International Sieve Chart", www.reade.com/Sieve/international_sieve.html ©1997 Reade Advanced Materials.
- 8 "Wood Flour: Discover the Possibilities", product literature, P. J. Murphy Forest Products Corp., Montville, NJ.
- 9 Miller, R. B., "Structure of Wood", Chapter 2 in the Wood Handbook: Wood as an Engineering Material, General Technical Report, FPL-GTR-113, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, 1999, 463 pages.
- 10 Panshin, A. J., de Zeeuw, C., *Textbook of Wood Technology*, 4th ed., McGraw-Hill, New York, 1980.
- 11 Hoadley, R. B., *Identifying Wood, Accurate Results with Simple Tools*, Taunton Press, Newtown, CT, 1990.
- 12 Rowell, R. M., "Chemical Modification of Wood", *Forest Products Abstracts* **1983**, 6(12), 363–382.
- 13 Imai, T., Sugiyama, J., *Macromolecules* **1998**, 31, 6278–6279.
- 14 Wada, M., et al., "The Monoclinic Phase is Dominant in Wood Cellulose", *Mokuzai Gakkaishi* **1994**, 40(1), 50–56.
- 15 Pettersen, R. C., "The Chemical Composition of Wood", Chapter 2 of *The Chemistry of Solid Wood* (Ed.: Rowell, R. M.), American Chemical Society, Washington DC, 1984, pp 76–81.
- 16 Parham, R. A., Gray, R. L., "Formation and Structure of Wood", in *The Chemistry of Solid Wood* (Ed.: Rowell, R. M.), American Chemical Society, Washington DC, 1984, pp. 1–56.
- 17 Kellogg, R. M., "Physical Properties of Wood", in *Wood: Its Structure and Properties* (Ed.: Wangaard, F. F.), Pennsylvania State University, College Park, PA, 1981, pp 191–223.
- 18 Simpson, W., TenWolde, A., "Physical Properties and Moisture Relations of Wood", Chapter 3 in *The Wood Handbook: Wood as an Engineering Material*, General Technical Report, FPL-GTR-113, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, 1999, p. 2-1 to 2-4.
- 19 Karayan, V., "The Effect of Chemical Foaming Agents on the Processing and Properties of Polypropylene-Wood Flour Composites", Proc. 6th International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, 2001, pp 249–282.
- 20 Turng, L.-S., et al., "Applications of Nano-Composites and Woodfiber Plastics for Microcellular Injection Molding", Proc. 7th International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, 2003.
- 21 Matuana-Malanda, L., et al. *J. Cellular Plastics* **1996**, 32(5), 449–469.
- 22 Winandy, J. E., Rowell, R. M., "The Chemistry of Wood Strength", Chapter 5 of *The Chemistry of Solid Wood* (Ed.: Rowell, R. M.), American Chemical Society, Washington, DC, 1984, p 218.
- 23 Peyer, S., Wolcott, M., "Engineered Wood Composites for Naval Waterfront Facilities", 2000 Yearly Report to Office of Naval Research, Wood Materials and Engineering Laboratory, Washington State University, Pullman, WA, 14 pages.
- 24 Stark, N. S., *J. Thermoplastic Composite Materials* **2001**, 14(5), 421–432.

- 25 Balatinez, J. J., Park, B.-D., *J. Thermoplastic Composite Materials* **1997**, 10, 476–487.
- 26 Rowell, R. M., “Penetration and Reactivity of Cell Wall Components”, Chapter 4 of *The Chemistry of Solid Wood* (Ed.: Rowell, R. M.), American Chemical Society, Washington, DC, 1984, p. 176.
- 27 Sears, K. D., et al., “Reinforcement of Engineering Thermoplastics with High Purity Cellulose Fibers”, *Proc. 6th International Conference on Woodfiber-Plastic Composites*, Forest Products Society, Madison, WI, 2001, pp. 27–34.
- 28 Osswald, T. A., Menges, G., *Materials Science of Polymers for Engineers*, Carl Hanser Verlag, New York City, NY, 1996, pp 458–459.
- 29 Anonymous, “Special Report: Who’s Who in WPC”, in *Natural and Wood Fiber Composites*, Principia Partners, 2003, 2(8), p. 4.
- 30 Suddell, B. C., Evans, W. J., “The Increasing Use and Application of Natural Fibre Composite Materials within the Automotive Industry”, *Proc. 7th International Conference on Woodfiber-Plastic Composites*, Madison, WI, 2003.
- 31 Marra, A. A., *Technology of Wood Bonding: Principles in Practice*, Van Nostrand Reinhold, New York, NY, 1992, p. 438.
- 32 Dahl, W. S., *Woodflour*, The Mercury Press, The Parade, Northampton, England, 1948, 119 pages.
- 33 Quillin, D. T., et al., *J. Applied Polymer Science* **1993**, 50, 1187–1194.
- 34 Lee, S. Y., et al., Influence of Surface Characteristics of TMP Fibers to the Growth of TCL on the Linear Fibers Surface (I): Aspect in the Surface Roughness”, *Proc. 6th International Conference on Woodfiber-Plastic Composites*, Forest Products Society, Madison, WI, 2001, pp 107–118.
- 35 Lu, J. Z., et al., “Chemical Coupling in Wood Fiber and Polymer Composites: A Review of Coupling Agents and Treatments”, *Wood and Fiber Science* 2000, 32(1), 88–104.
- 36 Bledski, A. K., et al., *Polymer and Plastics Technology and Engineering* **1998**, 37(4), 451–468.
- 37 Wolcott, M. P., Adcock, T., “New Advances in Wood Fiber-Polymer Formulations”, *Proc. Wood-Plastic Conference*, Baltimore, MD, *Plastics Technology Magazine and Polymer Process Communications*, 2000, pp. 107–114.
- 38 Stark, N. M., Berger, M. J. “Effect of Particle Size on Properties of Wood Flour Reinforced Polypropylene Composites”, *Proc. 4th International Conference on Woodfiber-Plastic Composites*, Forest Products Society, Madison, WI, 1997, pp 134–143.
- 39 English, B. W., Falk, R. H., “Factors that Affect the Application of Woodfiber-Plastic Composites”, *Proc. Woodfiber-Plastic Composites: Virgin and Recycled Wood Fiber and Polymers for Composites Conf.*, The Forest Products Society, Madison, WI, 1995, pp 189–194.
- 40 Test Method ASTM E11-01: “Standard Specification for Wire Cloth and Sieves for Testing Purposes”, *Annual Book of ASTM Standards*, Vol. 14.02, ASTM International, West Conshohocken, PA, 2001.
- 41 Test Method ASTM D1103-60 (1977): “Method of Test for Alpha-Cellulose in Wood”, *Annual Book of ASTM Standards*, Vol. 04.10, ASTM International, West Conshohocken, PA, 2001.
- 42 Test Method ASTM D1106-96 (2001): “Standard Test Method for Acid-Insoluble Lignin in Wood”, see ref. [41].
- 43 Test Method ASTM D1107-96: “Standard Test Method for Ethanol-Toluene Solubility of Wood”, see ref. [41].
- 44 Berger, M. J., Stark, N. M., “Investigations of Species Effects in an Injection-Molding Grade, Wood-Filled Polypropylene”, *Proc. 4th International Conference on Woodfiber-Plastic Composites*, Forest Products Society, Madison, WI, 1997, pp 19–25.
- 45 Test Method D256-02e1: “Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics”, *Annual Book of ASTM Standards*, Vol. 08.01, ASTM International, West Conshohocken, PA, 2002.
- 46 Test Method D790-03: “Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials”, see ref. [45].
- 47 Test Method D638-02a: “Standard Test Method for Tensile Properties of Plastics”, see ref. [45].
- 48 Test Method D648-01: “Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position”, see ref. [46].
- 49 English, B., et al., “Waste-Wood Derived Fillers for Plastics”, *General Technical Re-*

- port FPL-GTR-91, Madison, WI, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1996, pp 282–291.
- 50 Clemons, C. M., Ibach, R. E., “The Effects of Processing Method and Moisture History on the Laboratory Fungal Resistance of Wood-HDPE Composites”, *Forest Products Journal*, in press
- 51 Nakagawa, S., Shafizadeh, F., “Thermal Properties” in *Handbook of Physical and Mechanical Testing of paper and Paperboard* (Ed.: Mark, R. E.), Marcel Dekker, New York, 1984.
- 52 Stark, N. M., *Forest Products Journal* **1999**, 49(6), 39–45.

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