15
Wood Flour

Craig M. Clemons

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 μm 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 filler for thermosets, its use has diminished over the years.

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; composites made from plastics and wood or other natural fibers have grown from less than 50 000 tons in 1995 to nearly 900 000 tons in 2007 [4]. Most of this is due to the rapid growth of wood–plastic composites in exterior building products, especially decking and railing (Figure 15.1).

Due to its low thermal stability, wood flour is usually used as filler only in plastics that are processed at temperatures lower than about 200°C. The majority of wood–plastic composites use polyethylene as the matrix (Figure 15.2). This is, in part, due to that fact that much of the early wood–plastic composites were developed as an outlet for recycled film. Polypropylene is more commonly used in automotive applications, and polyethylene is more commonly used in exterior building applications.

Functional Fillers for Plastics: Secund, updated and enlarged edition. Edited by Marino Xanthos
Copyright © 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
ISBN: 978-3-527-32361-6

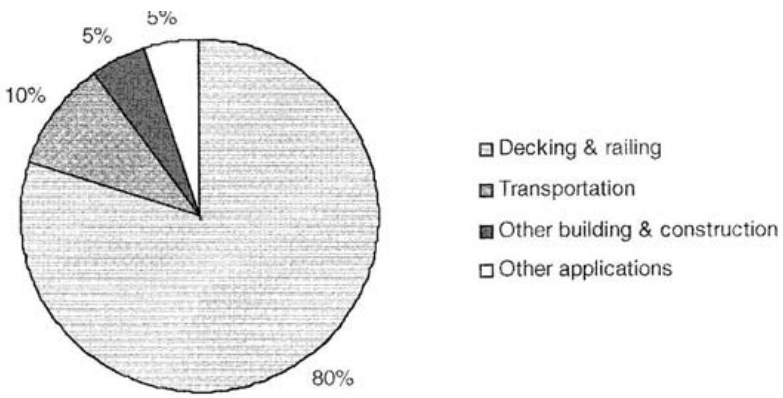

Figure 15.1 Current applications and the market size of plastics with wood flour or natural fibers [4]. "Other building and construction" include windows, doors, panels, roofing, fencing, siding, and flooring. "Other applications" include consumer products, furniture, and industrial/ infrastructure.

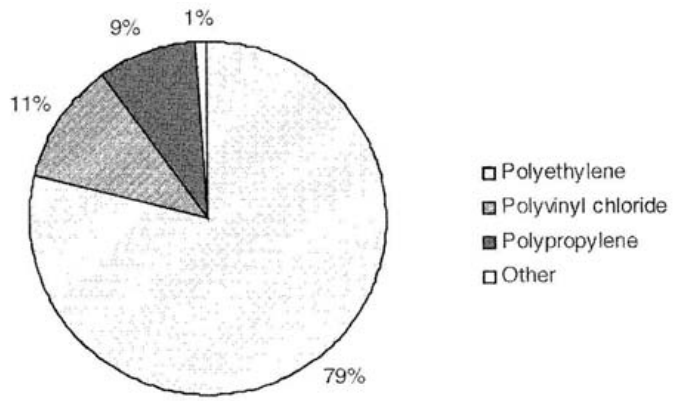

Figure 15.2 Plastics used in wood–plastic composites [4].

15.2 Production Methods

Wood flour is derived from various scrap wood from wood processors. The 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 wood 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 phenolic compounds that can be oxidized and cause stains when wet [5].

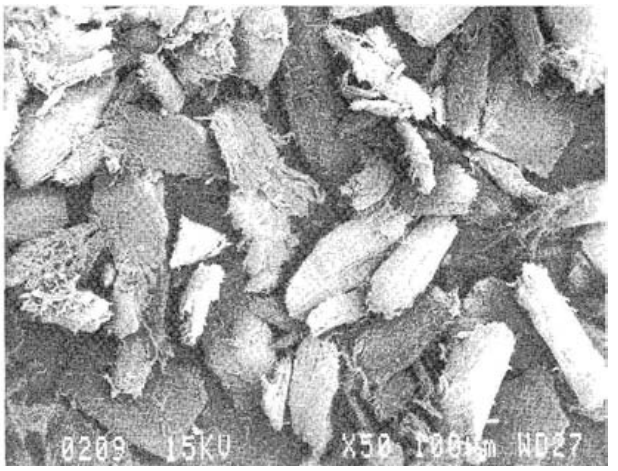

Figure 15.3 Scanning electron micrograph of pine wood flour

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, initial size may be reduced using equipments 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 particles that contain fibers and fiber fragments. These particles typically have aspect ratios (i.e., length to diameter ratios) of only 1–5 (Figure 15.3). 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 the 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 mesh of the wire cloth sieves used to classify them. Table 15.1 lists the US standard mesh sizes and their equivalent particle diameters. However, different standards may be used internationally [7]. Most commercially manufactured wood flours used as fillers in thermoplastics are in the size range of 180–425µm (80-40 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 fine, fiber bundles become wood dust, fragments that no longer resemble fiber or fiber bundles.

Wood flour is commonly packaged in (i) multiwalled paper bags (approximately 23 kg or 50 lb), (ii) bulk bags (1.5 m^3 or 55 ft^3 typical), or (iii) bulk trailers [8]. Wood flour is typically supplied to the customer at moisture contents between 4 and 8% and must be dried before use in thermoplastics. Some wood flour manufacturers offer standard grades, others prefer to customize for individual buyers and applications.

Table 15.1 Conversion between US standard mesh and particle diameter

US standard mesh [40]	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

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 broken down into two broad classes: softwoods and hardwoods that are actually classified by botanical and anatomical features rather than wood hardness. Figures 15.4 and 15.5 are schematics of a softwood and 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 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 [9].

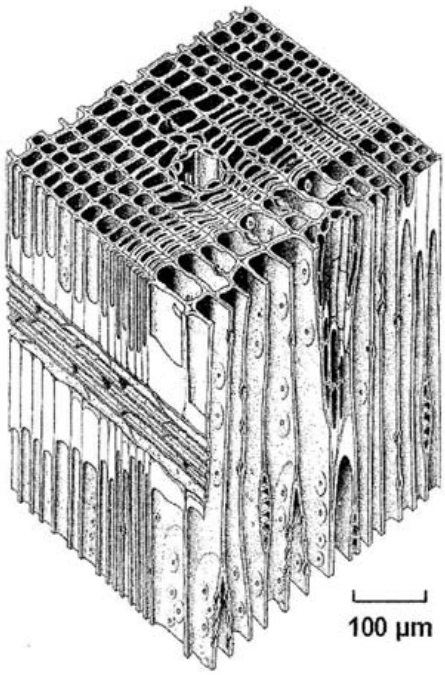

Figure 15.4 Schematic of a softwood.

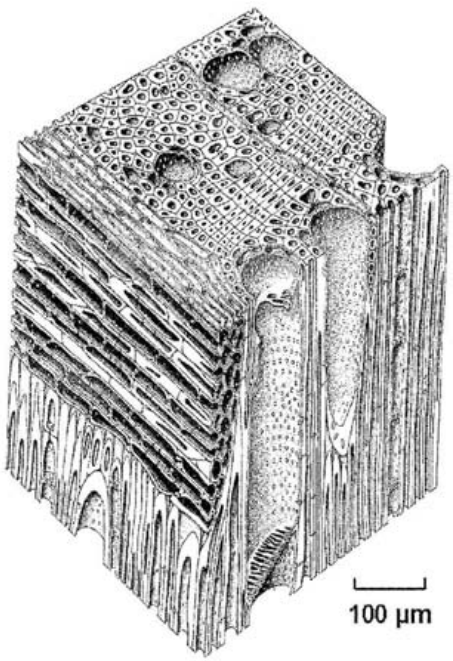

Figure 15.5 Schematic of a hardwood.

Table 15.2 Approximate chemical composition 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 volume ratio of ethanol and benzene according to ASTM D 1107 [43].

Fiber diameters are typically 15–45μm. 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.

Cellulose varies the least in the 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 (Figure 15.6). 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 5- and 6-carbon sugars whose molecular weights 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 15.7

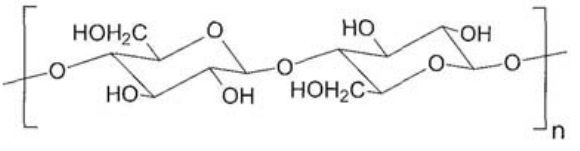

Figure 15.6 Chemical structure of cellulose [15]

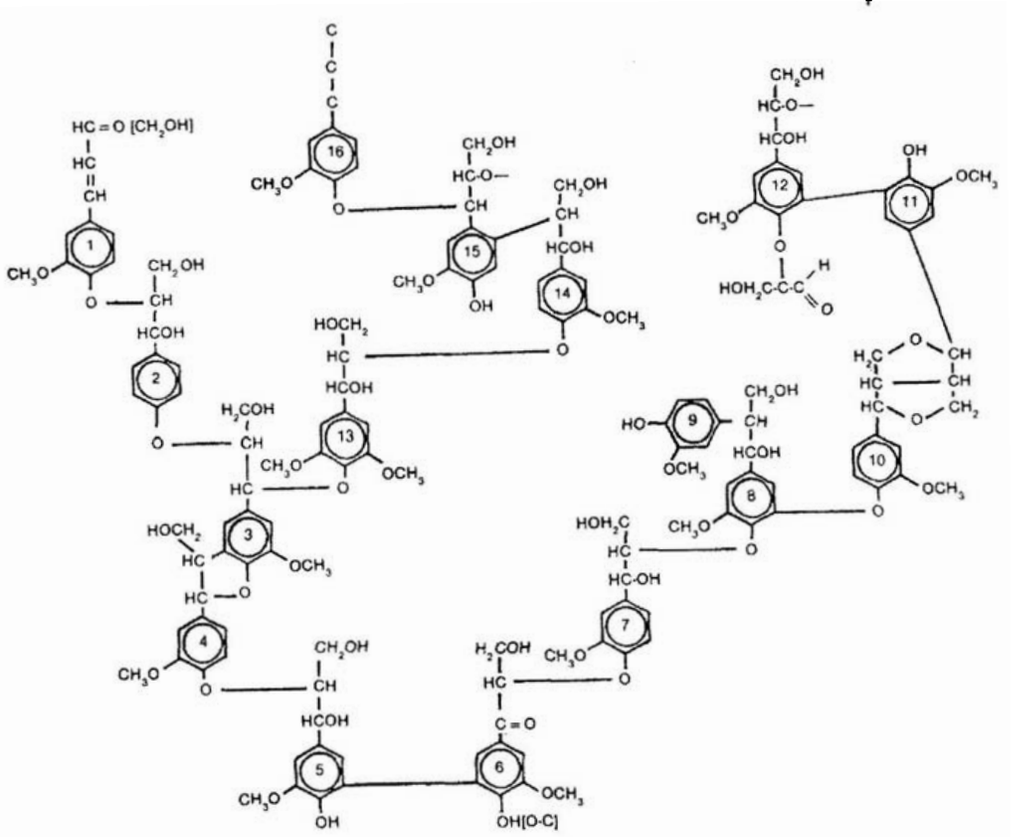

Figure 15.7 A partial softwood lignin structure [15].

represents a partial softwood lignin structure illustrating a variety of possible structural components. Lignin is more nonpolar 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 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 the cell wall [16] and varies

depending upon many factors including species and stresses on the wood during growth.

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 lb/ft^3) [8]. Because of its low bulk density, special equipment such as crammers is sometimes used to aid the feeding of wood flour.

As a filler, wood flour is unusual since it is compressible. Though the density of the wood cell wall is about 1.44–1.50 g/cm^3 [17], the porous anatomy of solid wood results in overall densities of about 0.32–0.72 g/cm^3 (20 and 45 lb/ft^3) when dry [18]. However, the high pressures found during plastics processing can collapse the hollow fibers that comprise the wood flour or fill them with low molecular weight additives and polymers. The degree of collapsing or filling will depend on variables such as particle size, processing method, and additive viscosity, but wood densities in composites approaching the wood cell wall density can be found in high-pressure processes such as injection molding. Consequently, adding wood fibers to commodity plastics such as polypropylene, polyethylene, and polystyrene increases their density.

Even these high 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 to reduce the density of wood–plastic composites [19–21].

15.3.4 Moisture

The major chemical constituents of the cell wall contain hydroxyl and other oxygen containing groups that attract moisture through hydrogen bonding [23]. 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.

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: (i) before processing using a dryer, (ii) by using the first part of an

Table 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

extruder as a dryer in some inline process, or (iii) 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 ambient conditions, wood flour can absorb several weight percents of moisture within hours (Figure 15.8). Even a compounded material often needs to be dried prior to further processing, especially if high-weight percentages of wood flour are used. Figure 15.9 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. The absorbed moisture interferes and reduces hydrogen bonding between the cell wall polymers and alters its mechanical performance [22]. Moisture of up to about 30% can be adsorbed by the cell wall with a corresponding reversible increase in apparent wood

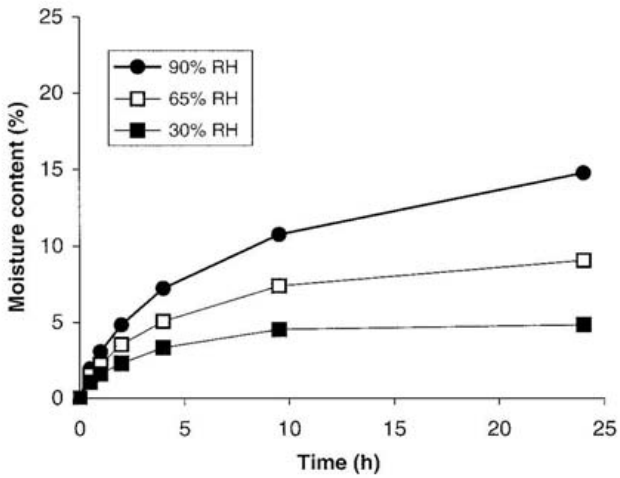

Figure 15.8 Moisture sorption of wood flour at several relative humidities and 26°C

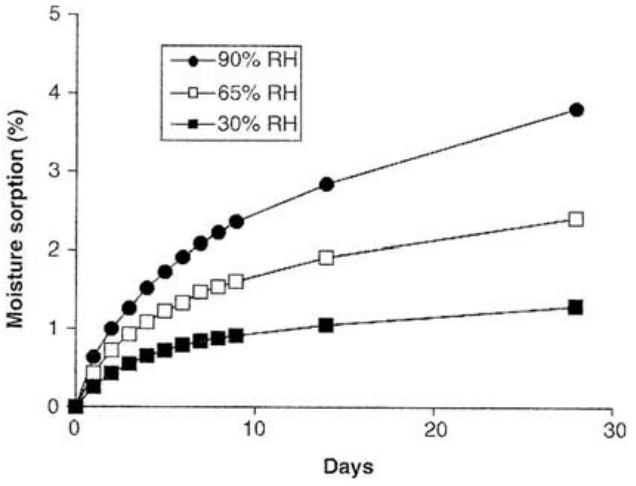

Figure 15.9 Moisture sorption of compounded pellets of polypropylene containing 40% wood flour at several relative humidities and 26°C [49].

volume. The wood volume V_1, at a moisture content M, has been roughly approximated by [16]

$$V_1 = V_0(1 + 0.84M\varrho),$$

where V_0 is the dry volume and ϱ is the density of the wood when dry.

Volume changes due to moisture sorption, especially repeated moisture cycling, can lead to interfacial damage and matrix cracking [23]. A number of papers have discussed damage and the resulting irreversible mechanical property reductions after the composites were exposed to a humid environment or liquid water [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 the wood–plastic composites used in exterior applications limit wood flour content to 50–60wt% and rely on the partial encapsulation of the wood by the polymer matrix to prevent major moisture sorption and subsequent negative effects.

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 material and do not require painting or staining 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 used in exterior environments.

Mold can form on surfaces of wood–plastic composites. Mold growth has been ascribed as arising from various effects, among them moisture sorption by the wood flour, buildup of organic matter on the composite surfaces, and the lubricants used in processing of the composites. The relative contribution of these factors to mold growth is 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 [22]. If the moisture content of the wood flour in the composite 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 15.10 shows the weight loss due to exposure of a wood–plastic composite to the decay fungi *Gleophylum trabeum* in a laboratory soil block test. Decay is not found until a moisture threshold of about 15% is reached. As 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.

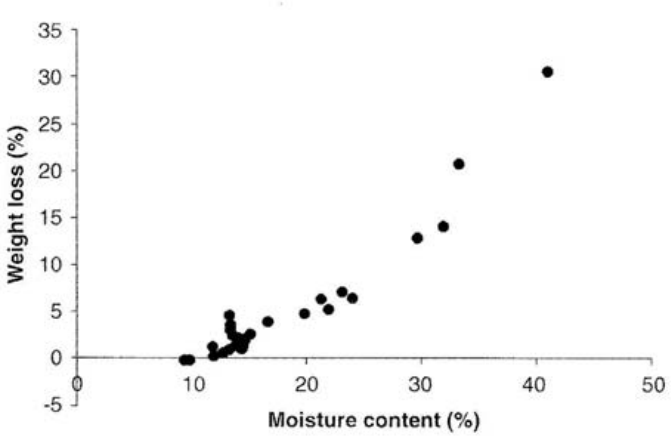

Figure 15.10 Weight loss due to fungal attack (*G. trabeum*) as a result of moisture sorption. Extruded composites of high density polyethylene containing 50% wood flour [50].

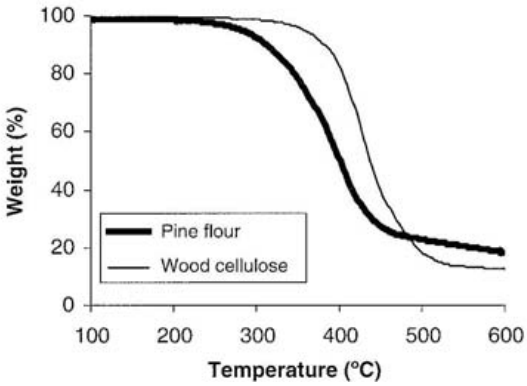

Figure 15.11 Thermogravimetric analysis of pine flour and wood cellulose.

15.3.6 Thermal Properties

Figure 15.11 shows a thermogravimetric analysis of pine flour and wood cellulose. Due to its low thermal stability, wood flour is usually used as 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, 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 [27].

Because of its practical performance, the thermal properties of wood have been extensively investigated [17]. Understandably, this work is generally performed on uncompressed wood with 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 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 [17]

$$\alpha = A\varrho \times 10^{-6},$$

where α is the coefficient of thermal expansion (in K^{-1}), ϱ is the density (oven dry basis), and A is a constant with values approximately 56 in the radial direction, 81 in the tangential 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 g/cm^3. This is about half that of polypropylene ($150 \times 10^{-6}\ K^{-1}$) and 3.5 times less than that of low density polyethylene ($250 \times 10^{-6}\ K^{-1}$), both of which are commonly used as matrix materials for wood–plastic composites [28].

The specific heat of dry wood does not have a strong dependence on specific gravity and is roughly 0.324 cal/(g K) or 1360 J/(kg K) [17]. This is about half the specific heat of common polyolefins such as polypropylene and polyethylene, for which values are approximately 2–3000 J/(kg K).

Thermal conductivity, k, of dry wood has been reported to increase linearly with density, ϱ, according to [17]

$$k = 0.200\varrho + 0.024,$$

where k is in units of W/(m K). Assuming a density of compressed wood flour in a composite of 1.5 g/cc, the thermal conductivity is calculated as 0.32 W/(m·K). This is the same order of magnitude as the values reported for polypropylene and polyethylene (0.17–0.51 W/(m·K)).

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, and the product of specific heat, *c*, and density, ϱ [17]:

$$h = k/c\varrho$$

Calculations for wood flour yield a value of 0.16×10^{-6} m²/s compared to $0.11–0.17 \times 10^{-6}$ m²/s 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 disperse nature of these suppliers, there are currently few good resources that list wood flour manufacturers.

Wood–plastic composite manufacturers obtain wood flour either 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 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 [29]. Several major suppliers of wood flour to the North American wood–plastic composite industry include

- American wood Fibers (Schofield, WI, USA)
- Lang Fiber (Marshfield, WI, USA)
- Marth Manufacturing (Marathon, WI, USA)
- P.J. Murphy Forest Products (Montville, NJ, USA)
- P.W.I. Industries Inc. (Saint Hyacinthe, QC, Canada).

15.5
Cost/Availability

As with most materials, wood flour costs are variable and depend on various factors such as volume, availability, particle size, and shipping distance. However, wood flour is typically about $0.11–0.22/kg ($0.05–0.10/lb) in the United States. Narrow particle size distributions and fine sizes tend to increase cost. As there are many small manufacturers and the volume is relatively lower than 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 risks in using wood flour lies in the fact that (i) it has low thermal stability and can degrade and burn resulting in a fire and explosion hazard that is greater than with solid wood, and (ii) 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 materials' safety data sheets. Regulating bodies such as the Occupational Safety and Health Association (OSHA) also have good information on health and safety information on wood dust (e.g., see 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 durability of a given resin. As filler, it is added to thermoset adhesives to control penetration when bonding wood and to improve 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 then 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 twentieth century, often under the trade names such as "Bakelite," its use has diminished considerably over the years. 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

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 density excessively. Wood is much stiffer than the commodity thermoplastics usually used as matrices. Additionally, wood and pulp fibers can nucleate crystal growth in polyolefins 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 strength. Tensile and flexural strengths are, at best, maintained and more often decreased in the absence of a coupling agent. Many different coupling agents have been investigated for use in wood–plastic composites and are reviewed elsewhere [35, 36]. When a coupling agent is desired, maleated polyolefins 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 15.12). It is often unclear 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 in wood–plastic formulations to improve mechanical performance [37].

Table 15.4 summarizes some typical mechanical property changes when various species of wood flour are 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 wt% wood flour, that is, approximately four times that of the unfilled polypropylene. Heat deflection temperature is also approximately doubled by adding 60 wt% 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.

The effects of wood flour particle size on the mechanical performance of filled polypropylene are summarized in Table 15.5. The largest particle size range (0.425–0.600 μm) yields the lowest performance except for notched impact strength. For the three smaller particle size ranges, properties generally decrease as the particle size is reduced except for the unnotched impact strength. Similar trends were found

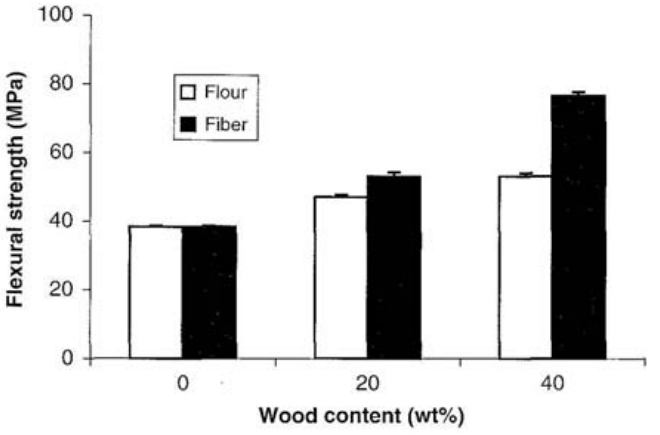

Figure 15.12 Comparison between wood flour and wood fiber as a reinforcement in polypropylene. Injection molded composites. 3% maleated polypropylene added as a coupling agent. (Derived from Ref. [52].)

when broader particle size ranges, more typical of commercially available blends, were investigated [38].

Customer 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. Mixing wood flour with plastic is seen as a way to use wood in these applications, yet improve its durability without chemical treatment or the need for painting or staining. Adding wood flour to thermoplastics results in a composite with a wood color, although often pigments and light stabilizers are added to mitigate color-fade in exterior applications. Though not nearly as stiff as solid wood, these composites are stiffer than unfilled plastics. Many of the composites do not 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.

Wood–plastic composites are heavier than wood and do not have as good mechanical performance, often having much lower stiffness [39]. The swelling of wood flour with moisture can lead to damage in its composites. Adequate dispersion of the wood flour and encapsulation by the matrix is critical and wood flour content is typically limited to approximately 50–65 wt% in exterior applications. These highly filled plastics require judicious use of additives and processing methodology. For example, the high wood content results in high viscosity and low melt strength that require significant amounts of lubricants for reasonable production rates and to prevent melt fracture. Extruders capable of removing considerable moisture from the wood flour have been developed that avoid the need for predrying. Considerable research and development is centered on economically increasing structural performance, improving durability, and decreasing weight. As improvements are being

Table 15.4 Effect of adding wood flour on the mechanical performance of injection molded polypropylene[a] [44].

	Izod impact strength[b]		Flexural properties[c]		Tensile properties[d]			
Filler content (wt %)	Notched (J/m)	Unnotched (J/m)	Flexural strength (MPa)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation at maximum strength (%)	Heat deflection temperature[e] (°C)
No filler								
0	15.0	600	34.7	1.03	28.5	1.31	10.4	55
Ponderosa pine[f]								
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[f]								
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
60	10.4	31	34.1	3.81	17.8	4.32	0.9	77
Maple[f]								
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

(*Continued*)

Table 15.4 (Continued)

	Izod impact strength[b]		Flexural properties[c]		Tensile properties[d]			
Filler content (wt %)	Notched (J/m)	Unnotched (J/m)	Flexural strength (MPa)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation at maximum strength (%)	Heat deflection temperature[e] (°C)
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[f]								
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
Average COV[g]	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 flours were commercial grades from American Wood Fibers, Schofield, WI, USA.
g) COV, the coefficient of variation is 100 × (standard deviation)/(average).

Table 15.5 Mechanical properties of composites made from polypropylene[a]) filled with 40 wt% wood flour [38].

	Izod impact strength[b])		Flexural properties[c])		Tensile properties[d])		
Particle size range (μm)	Notched (J/m)	Unnotched (J/m)	Flexural strength (MPa)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation at maximum strength (%)
No filler							
—	15.0	600	34.7	1.03	28.5	1.31	10.4
Composites with 40 wt% 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
Average COV[f])	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.
f) COV, the coefficient of variation is 100 × (standard deviation)/(average).

made, wood plastic composites' use is extending to other exterior building applications such as roofing, fencing, and siding. It is also increasingly being used in furniture and injection molded consumer products.

Environmental considerations can influence the use of wood flour. Wood flour is manufactured from industrial by products, mitigating a disposal issue. It is also lighter than inorganic fillers, which can lead to benefits such as fuel savings when its composites are used in transportation and packaging applications. With changing consumer perceptions, some manufacturers have used the natural look of wood flour composites as a marketing tool. Others add wood flour to increase bio-based material content. 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.

References

1 Reineke, L.H. (1966) Wood flour, U.S. Forest Service Research Note FPL-0113, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, pp. 13.

2 Panshin, A.J. *et al.* (1962) Wood Flour, Chapter 13, in *Forest Products: Their Sources, Production, and Utilization,* McGraw-Hill, New York, pp. 265–271.

3 Gordon, J.E. (1988) *The New Science of Strong Materials (or why you don't fall through the floor),* 2nd edn, Princeton University Press, Princeton, NJ, p. 179.

4 Morton, J., Quarmley, J., and Rossi, L. (2003) Current and emerging applications for natural and wood fiber composites. Proceedings of the 7th International Conference on Woodfiber-Plastic Composites, Madison, WI, Forest Products Society, pp. 3–6.

5 Rowe, J.W. and Conner, A.H. (1979) Extractives in Eastern Hardwoods - a review, General Technical Report FPL 18, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, p. 17.

6 Bigg, D.M. *et al.* (1988) High performance thermoplastic composites. *J. Themoplast. Compos.,* **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, PJ Murphy Forest Products Corp., Montville, NJ.

9 Miller, R.B. (1999) Structure of wood, Chapter 2. *Wood Handbook: Wood as an Engineering Material,* General Technical Report, FPL-GTR-113, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, pp. 463.

10 Panshin, A.J. and de Zeeuw, C. (1980) *Textbook of Wood Technology,* 4th edn, McGraw-Hill, New York.

11 Hoadley, R.B. (1990) Identifying wood, *Accurate Results with Simple Tools,* Taunton Press, Newtown, CT.

12 Rowell, R.M. (1983) Chemical modification of wood. *For. Prod. Abstr.,* **6** (12), 363–382.

13 Imai, T. and Sugiyama, J. (1998) Nanodomains of Iα and Iβ Cellulose in Algal Microfibrils. *Macromolecules.* **31,** 6275–6279.

14 Wada, M. *et al.* (1994) The monoclinic phase is dominant in wood cellulose. *Mokuzai Gakkaishi,* **40** (1), 50–56.

15 Pettersen, R.C. (1984) The chemical composition of wood, Chapter 2, in *The Chemistry of Solid Wood* (ed. R.M. Rowell), American Chemical Society, Washington, DC, pp. 76–81.

16 Parham, R.A. and Gray, R.L. (1984) Formation and structure of wood, in The *Chemistiy of Solid Wood* (ed. R.M. Rowell), American Chemical Society, Washington, DC, pp. 1–56.

17 Kellogg, R.M. (1981) Physical properties of wood, in *Wood: Its Structure and Properties*

(ed. F.F. Wangaard), Pennsylvania State University, College Park, PA, pp. 191–223.
18 Simpson, W. and TenWolde, A. (1999) Physical properties and moisture relations of wood, Chapter 3. *The Wood Handbook: Wood as an Engineering Material*, General Technical Report, FPL-GTR-113, USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, pp. 2-1–2-4.
19 Karayan, V. (2001) The effect of chemical foaming agents on the processing and properties of polypropylene-woodflour composites. Proceedings of the Sixth International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, pp. 249–252.
20 Turng, L-S. *et al.* (2003) Applications of nano-composites and woodfiber plastics for microcellular injection molding. Proceedings of the Seventh International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, pp. 217–226.
21 Matuana-Malanda, L. *et al.* (1996) Characterization of microcellular foamed PVC/cellulosic fiber composites. *J. Cell. Plast.*, 32(5), 449-469.
22 Winandy, J.E. and Rowell, R.M. (1984) The chemistry of wood strength, Chapter 5, in *The Chemistry of solid Wood* (ed. R.M. Rowell), American Chemical Society, Washington, DC, p. 218.
23 Peyer, S. and Wolcott, M. (2000) 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, pp. 14.
24 Stark, N.S. (2001) Influence of moisture absorption on mechanical properties of wood flour-polypropylene composites, *J. Themoplast.* Compos., 14 (5), 421–432.
25 Balatinecz, J.J. and Park, B.-D. (1997) The effects of temperature and moisture exposure on the properties of woodfiber thermoplastic composites. *J. Themoplast.* Compos., 10, 476-487.
26 Rowell, R.M. (1984) Penetration and reactivity of cell wall components, Chapter 4, in *The Chemistry of Solid Wood* (ed. R.M. Rowell American Chemical Society, Washington, DC, p. 176.
27 Sears, K.D. *et al.* (2001) Reinforcement of engineering thermoplastics with high purity cellulose fibers. Proceedings of the Sixth International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, pp. 27–34.
28 Osswald, T.A. and Menges, G. (1996) *Materials Science of Polymers for Engineers*, Carl Hanser Verlag, New York City, NY, pp.458-459.
29 Anonymous (2003) Special report: who's who in WPC, *Natural and Wood Fiber Compos.*, 2 (8), p. 4.
30 Suddell, B.C. and Evans, G. (2003) The increasing use and application of natural fibre composite materials within the automotive industry. Proceedings of the 7th International Conference on Woodfiber-Plastic Composites, Madison, WI, pp. 7–14.
31 Marra, A.A. (1992) *Technology of Wood Bonding: Principles in Practice*, Van Nostrand Reinhold, New York, NY, p. 438.
32 Dahl, W.S. (1948) *Woodflour*, The Mercury Press, The Parade, Northampton, England, p. 119.
33 Quillin, D.T. et *al.* (1993) Crystallinity in the polypropylene/cellulose system. I. Nucleation and crystalline morphology. *J. Appl. Polym. Sci.*, **50,** 1187–1194.
34 Lee, S.Y. *et al.* (2001) Influence of surface characteristics of TMP fibers to the growth of TCL on the linear fibers surface (I): aspect in the surface roughness. Proceedings of the Sixth International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, pp. 107–118.
35 Lu, J.Z. *et al.* (2000) Chemical coupling in wood fiber and polymer composites: a review of coupling agents and treatments. *Wood Fiber Sci.*, **32** (1), 88–104.
36 Bledski, A.K. *et al.* (1998) Thermoplastics reinforced with wood fillers: A literature review. *Polym. Plast. Technol. Eng.*, **37** (4), 451–468.
37 Wolcott, M.P. and Adcock, T. (2000) New advances in wood fiber-polymer formulations. Proceedings of the Wood-Plastic Conference, Baltimore, MD, Plastics Technology Magazine and

Polymer Process Communications, pp. 107–114.

38 Stark, N.M. and Berger, M.J. (1997) Effect of particle size on properties of wood flour reinforced polypropylene composites. Proceedings of the Fourth International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, pp. 134–143.

39 English, B.W. and Falk, R.H. (1995) Factors that affect the application of woodfiber-plastic composites. Proceedings of the Woodfiber-Plastic Composites: Virgin and Recycled Wood Fiber and Polymers for Composites Conference, The Forest Products Society, Madison, WI, pp. 189–194.

40 ASTM International (2001) Test Method ASTM Ell-01. *Standard Specification for Wire Cloth and Sieves for Testing Purposes, Annual Book of ASTM Standards,* vol. **14.02,** ASTM International, West Conshohocken, PA.

41 ASTM International (2001) 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

42 ASTM (2001) Test Method ASTM D1106-96. *Standard Test Method for Acid-Insoluble Lignin in Wood.*

43 ASTM (2001) Test Method ASTM D1107-96. *Standard Test Method for Ethanol-Toluene Solubility of Wood.*

44 Berger, M.J. and Stark, N.M. (1997) Investigations of species effects in an injection-molding-grade, wood-filled polypropylene. Proceedings of the Fourth International Conference on Woodfiber-Plastic Composites, Forest Products Society, Madison, WI, pp. 19–25.

45 ASTM International (2002) Test Method D256-02el. *Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics, Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA.

46 ASTM International (2002) Test Method D790-03. *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA.

47 ASTM International (2002) Test Method D638-02a. *Standard Test Method for Tensile Properties of Plastics, Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA.

48 ASTM International (2002) Test Method D648-01. *Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position, Annual* Book d *ASTM Standards,* ASTM International, West Conshohocken, PA.

49 English, B. *et al.* (1996) Waste-wood derived fillers for plastics. General Technical Report FPL-GTR-91, U.S. Department of Agriculture, Forest Service, Forest Products, Laboratory, Madison, WI, pp. 282–291.

50 Clemons, C.M. and Ibach, R.E. (2004) The effects of processing method and moisture history on the laboratory fungal resistance of wood-HDPE composites. *Forest Prod. J.,* **54,** (4), 50–57.

51 Nakagawa, S. and Shafizadeh, F. (1984) Thermal properties, in *Handbook of Physical and Mechanical Testing of Paper and Paperboard* (ed. R.E. Mark), Marcel Decker, New York.

52 Stark, N.M. (1999) Wood fiber derived from scrap pallets used in polypropylene composites. *Forest Prod. J.,* **49** (6), 39–45,

Edited by
Marino Xanthos

Functional Fillers for Plastics

Second, updated and enlarged edition

WILEY-VCH Verlag GmbH & Co. KGaA

The Editor

Dr. Marino Xanthos
New Jersey Inst. of Technology
Dept. of Chemical Engineering
Tiernan Hall, Univ. Heights
Newark, NJ 07102
USA

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form - by photoprinting, microfilm, or any other means - nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Cover Design Grafik-Design Schulz, Fußgönnheim
Typesetting Thomson Digital, Noida, India
Printing and Binding Strauss GmbH, Mörlenbach

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN: 978-3-527-32361-6