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WOOD AND NATURAL FIBER-BASED COMPOSITES (NFCs)

Jorge R. Robledo-Ortíz, Francisco J. Fuentes-Talavera, Rubén González-Núñez, and José A. Silva-Guzmán

26.1 INTRODUCTION

Customer preferences for recycled products have encouraged a more efficient use of wood and natural fibers. One potential approach to preserve wood and use natural fibers is the development of commodity-engineered composites that blend wood and natural fibers with other materials, such as plastic. The idea of combining wood and plastic is to produce a product with performance characteristics that combine the positive attributes of both materials. Wood and other natural fibers have been used as fillers and/or reinforcement to improve the mechanical properties of a variety of products. The combination of wood and plastic creates the ability to develop diverse products using many different manufacturing processes.

This chapter includes several technical topics associated with natural fiber composites. First, a background is provided that briefly discusses the historical development of natural fiber-based composites (NFCs). Key points related to the success of NFCs are discussed. In the following section, the types of natural fibers are outlined as well as the factors that promote their increasing use in commercial products. The types of polymers and additives used are also described in this section. Only plastics that melt below 200 °C (392 °F) are commonly used in NFCs because wood and natural fibers cannot withstand higher extrusion temperatures. The effects of the polymer/natural fiber interface, natural fiber/polymer mass ratio, particle size, and moisture content on the composites' performance are also addressed. Next, the processes used to manufacture natural fiber composites are described. Molding and injection processes are the most common processes used and are emphasized in that section. The properties and durability of natural fiber composites are discussed afterwards. Durability is a major concern because of the natural fiber component in the composite. Natural fibers remain susceptible to moisture uptake in spite of the presence of a polymer barrier, thus limiting applications on exterior environments where moisture could be a potential problem. The factors that influence durability and performance of these materials along with the methods used for testing durability are discussed in detail. Finally, current and future uses of NFCs are overviewed. Figure 26.1 shows the typical components present in an NFC.

26.2 BACKGROUND

Wood and natural fibers have been used as fillers or reinforcement materials in order to improve the mechanical properties of a variety of products. The combination of wood and plastic allows the development of products with enhanced properties by using many different manufacturing processes, such as injection and molding, as well as the ability to create an infinite array of products that vary in wood content as well as type of plastic.

Combining lignocellulosic materials with thermoplastics is not new. The first wood–thermoset composites date to the early 1900s [1]. Wood/plastic composites (WPCs) were widely investigated in the 1960s. Substantial amounts of wood/plastic flooring were produced for airport terminals and office buildings in the 1960s [2].

The term *wood/plastic composite* refers to any composite material that contains wood and thermosets (plastic that

Handbook of Polymer Synthesis, Characterization, and Processing, First Edition. Edited by Enrique Saldívar-Guerra and Eduardo Vivaldo-Lima.

Figure 26.1 Typical composite components: (a) fiber, (b) polymer and additives. (*See insert for the color representation of the figure*.)

does not melt by reheating) or thermoplastics (plastic that can be repeatedly melted). WPCs are also known as *natural fiber composites*, *wood fiber plastic composites*, *wood fiber thermoplastic composites*, *polymer/wood composites*, and *wood-filled plastics* [3]. Because wood is by far the raw material most used to manufacture natural fiber composites, in this chapter the term *WPC* (for wood/fiber composite) is used more frequently than NFC. The objective in the development of WPCs is to produce a product with performance characteristics that combine the positive attributes of both wood and plastics [4]. The addition of wood significantly improves the thermal stability as well as mechanical (stiffness) and working properties of WPCs. The disadvantages of using wood fibers are their low bulk density, high tendency to absorb moisture, and susceptibility to fungal attack [1]. Plastic coating of wood particles in a WPC can reduce moisture uptake while enhancing dimensional stability and protection against fungal attack [4]. Furthermore, wood particles also reduce the need to use more costly thermoplastics [5].

In the mid-1980s, high lumber prices and the desire of customers for recycled products stimulated the production of lumber substitutes produced from recycled thermoplastics. However, the totally thermoplastic lumber exhibited limited applications and suffered from poor thermal stability, high heat retention, poor creep resistance, and low fastener-holding properties [4]. These problems stimulated the interest in using wood as filler or reinforcement in combination with thermoplastics because of the advantages offered by wood fibers over inorganic fillers (calcium carbonate and mica) and reinforcements (glass or carbon fibers) in thermoplastics. In contrast to the glass and carbon fiber fillers, wood fibers are abundant, renewable, strong (high stiffness), lightweight (low density), less abrasive to processing equipment, nonhazardous, nontoxic to mammals, relatively inexpensive, easy to process, and available from a variety of sources [6].

Perhaps the most likely reason for the historically low use of these natural fibers in thermoplastics was unfamiliarity. The birth of the wood plastic industry involved the interfacing of two industries that historically had little in common [1]. Initial failures in the early stages of WPC development occurred because thermoplastic manufacturers were unaware of the effects of the high hygroscopicity and thermal degradation of wood on composite production [7]. WPCs are currently produced for commercial purposes in many countries [2]; however, production has been limited because of poor interfaces between wood and plastic, low thermal resistance of plastics, high thickness swelling, and thermal degradation of wood fibers at high temperatures [8].

Plastics are generally resistant to fungal attack; however, a major concern with these materials is that wood in the composite remains susceptible to biological degradation. Many manufacturers avoid this risk by producing products for interior uses where little or no water is present, thereby minimizing the risk of fungal attack. There is little data on decay patterns or effects of fungal attack on the physical and mechanical properties of WPCs, although new reports are emerging in this rapidly expanding area. Initially, it was presumed that plastic encapsulated the wood fibers, protecting them from wetting and further decay, but a number of tests suggest that wood encapsulation by plastic is incomplete [9]. As a result, the wood component in these materials reaches moisture levels suitable for fungal attack [8, 10].

The expanding commercial production and marketing of WPCs for use in exterior applications has encouraged research on the durability and service life of WPCs.

26.3 RAW MATERIALS

26.3.1 Natural Fibers

According to Mohanty et al. [11], natural fibers could be classified into the following categories:

- Straw—rice, wheat, cornstalks, sugar cane, etc.
- Bast—flax, hemp, jute, and kenaf
- Leaf—sisal, henequen, pineapple, and banana
- Seed/Fruit—cotton, kapok, and coir (from coconut husks)
- Grass—bamboo, switch, elephant
- Wood

By far, wood particles are the major raw material source used for manufacturing WPCs. Wood particles can originate from sawdust, planer shavings, short solid pieces of lumber, conventional wood composite scrap [6], and scrap pallets [12]. Both softwoods and hardwoods can be used for WPC production. Currently, most WPCs using softwoods are made with southern yellow pine, while WPCs produced with hardwoods are made with oak, maple, or aspen. The anatomical features as well as physical, mechanical, and chemical properties of softwoods and hardwoods differ considerably among species, and may affect the wood–polymer interface, and, as a consequence, the composite's properties and performance.

The effect of wood species on the wood–polymer interface and on properties of WPCs has received little attention in the literature. Stark and Berger [13] evaluated the effect of ponderosa pine, loblolly pine, maple, or oak on the mechanical properties of polypropylene WPCs. In general, WPCs made with maple or oak exhibit slightly better tensile and flexural properties and heat deflection temperatures than either of the pines. Composites elaborated with coconut fiber and polyurethanes have shown good results. Coconut fiber acts as reinforcement and active part of the matrix system, improving the interface [14]. Composites were prepared using waste tire powder, sugar bagasse cane, high density polyethylene (HDPE), and a coupling agent in order to obtain value-added products. Results indicate that these composites accomplish similar values as the standards for using in diverse exterior environments. It is an interesting opportunity for recycling of waste tires and the use of agricultural fibers [15].

26.3.2 Types of Polymers Used in Wood/Plastic Composites Manufacturing

Thermoplastic linear or branched polymers become rigid when cooled, and soften at varying elevated temperatures (depending on the polymer). Only thermoplastics that melt below 200 °C (392 °F) are commonly used in WPCs because wood cannot withstand higher extrusion temperatures. Several thermoplastic polymers including polypropylene, polyethylene, and poly(vinyl chloride) are currently used to produce WPCs [16]. The polymer contained in WPCs transfers stress between reinforcement fibers, acts as a glue to hold fibers together, protects fibers from mechanical and environmental damage, and improves durability. Both virgin and recycled polymers can be used to produce WPCs. This flexibility creates the potential for using recycled plastics, although care must be taken to ensure reasonable uniformity in the recycled products in order to avoid plastics with higher melting temperatures because of concerns about cellulose decomposition. One great advantage of WPCs is that they can be melt-processed or extruded for further processing. This feature creates the potential to recycle the material by grinding or beading for later heating and extrusion.

26.3.3 Additives

There are several important reasons for using additives when producing WPCs. Additives improve the manufacturing process and/or enhance composite performance, durability, and aesthetics [17]. Susceptibility to ultraviolet (UV) light degradation and fungal attack remain the two primary reasons for additive use in WPCs for exterior applications. Additives include adhesives, lubricants, and/or surfactants. Other additives used in WPCs include colorants, fungicides, foamers, and UV light stabilizers, which are essential for exterior applications since they prevent crazing (development of ultrafine cracks) as well as disintegration due to UV absorption and improve aesthetics. Additionally, additives can modify surface energy, improve fiber dispersion and orientation, and increase interfacial adhesion through mechanical interlocking (see also Chapter 11 for a general discussion on additives) [2, 5, 18].

26.3.4 Polymer–Natural Fiber Interface

One key factor for producing acceptable WPCs is the interaction between the wood and thermoplastic components (wood–polymer interface). It is difficult to achieve wood/plastic interaction because the hydrophobic thermoplastic (nonpolar) and hydrophilic wood (polar) are energetically different [2, 4]. During wood/plastic mixing, the thermoplastic must first coat or spread over the wood fiber surface to interact [4]. It is observed in Figure 26.2 that the polymer–fiber interface and a poor surface adhesion lead to fiber slipping from the matrix.

Sanadi et al. [2] indicate that there is no evidence of chemical reaction at the interface between wood and polymer; the interfacial adhesion between both materials appears to be solely through mechanical interlocking. However, according to Wålinder and Gardner [19], there are five main adhesion mechanisms recognized in the interface between wood particles and plastic: (i) adsorption (also referred to as *wetting*), (ii) mechanical interlocking, (iii) diffusion, (iv) electrostatic forces, and (v) weak boundary layers and interfaces. These mechanisms may contribute to the intrinsic adhesion forces acting across the interface between wood fibers and plastics. Adsorption appears to be the most likely adhesion mechanism for WPC [20], where "adsorption" is defined as "macroscopic manifestations of molecular interaction between liquids and solids in direct contact at the interface between them" [18]. The dominance of adsorption as an adhesion mechanism helps to explain why wood particle geometry affects the wood–polymer interface.

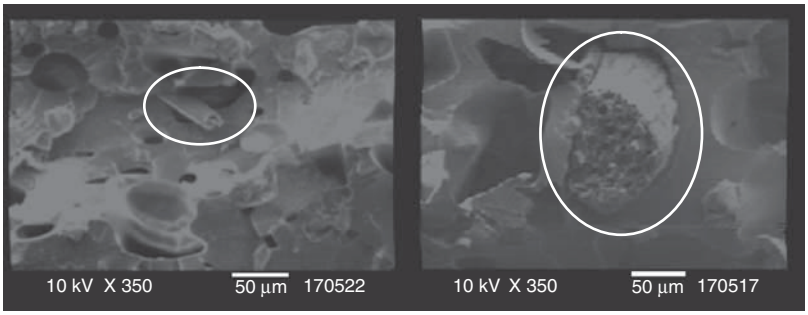

Figure 26.2 SEM micrographs of an LDPE–agave fiber interface for 10 wt% (a) and 20 wt% (b) of fiber composition.

Large wood particles tend to be associated with the formation of voids at the interface between wood fiber and polymer [10], while small particles improve the interface between wood fibers and polymer, limiting void formation on the interface and reducing fiber–fiber surface contact [20]. Large particles are less likely to be uniformly coated or wetted, leading to voids in the resulting WPC. There are a few reports describing the nature of the interface between the wood particles and the plastic. According to Tze et al. [21], the interfacial properties of cellulose fiber–polymer composites can be evaluated by the micro-Raman (Raman spectroscopy) technique. This technique identifies the strain distribution along the cellulose fiber/plastic interface by using a frequency of 895 cm^{-1} (corresponding to a cellulose mode) with applied strain to map the local tensile strain.

Thermoplastic composite manufacturing is often a two-step process, wherein the raw materials are mixed in a process called *compounding*, where fibers and additives are dispersed in the molten polymer. This process may be carried out in either batch or continuous mixers. The molten product is then either extruded or injection-molded into its final shape [1]. Thermal degradation of wood during extrusion and the presence of excessive moisture in wood have major effects on subsequent WPC properties. The temperatures required for many low melting point plastics are still too high for wood, and, as a consequence, some thermal degradation of wood is expected during processing [3]. New equipment has been developed for processing, including material handling, drying and feeding systems, extruders, die designs, and downstream equipment (after extrusion equipment), making the manufacturing process more efficient and versatile and improving the final quality of the resulting composite [1]. Typically, the melt temperatures (temperature of molten material) used for processing WPCs are below 204 °C (400 °F). Degradation (smoke, odor, discoloration) becomes evident above this limit. In general, polyethylene-based formulations are successfully compounded at temperatures of 180 °C (356 °F) or less, whereas polypropylene-based materials work well at temperatures near 190 °C (374 °F) [6].

26.3.5 Wood/Polymer Ratio, Particle Size, and Moisture Content

Since the plastic is largely immune to fungal attack, the amount of wood and plastic (wood/plastic ratio) has a direct effect on WPC decay resistance. Currently, the most common wood/plastic ratio used to manufacture WPCs is 50 : 50 wood/polymer, but 40 : 60 and even 70 : 30 ratios are also used [1, 22]. The optimal wood/plastic ratio depends on the end use of the composite, and represents a delicate balance between the lower cost of using wood versus the increased risk of wetting as the wood/plastic ratio rises. High wood contents are associated with faster water uptake because more lignocellulosic material is available for moisture sorption [1, 22]. The wood/plastic ratio also affects processing parameters and the physicomechanical properties of WPCs. Increased wood flour content improves flexural and tensile modulus, density, heat deflection temperature, and notched impact energy (energy required for crack propagation) [20]. Increasing the plastic content improves flexural and tensile strength, tensile elongation, mold shrinkage, and melt flow index, while the unnotched impact energy (minimum energy needed to initiate a crack) decreases [20].

A variety of wood particle sizes are used to produce WPCs depending on the type of product. The dimensions of wood particles are usually measured in mesh size as the particles resulting from passing through a mesh with a given number of mesh squares in a square inch. The wood used in WPCs is most often in particulate form (wood flour) or very short fibers rather than longer individual fibers. Commonly, mesh sizes 20, 40, 60, and 80 are used in WPC production.

Particle size can affect the stiffness, moisture resistance (ability to withstand water uptake), wood/plastic interactions, and susceptibility to fungal attack of the resulting WPC [13, 23]. WPCs produced from smaller particle sizes

tend to exhibit increased water resistance and modulus of rupture (MOR) [24]. Stark and Rowlands [20] found that aspect ratio, not particle size, had the greatest effect on strength and stiffness. Particle size affects the formation of the wood–polymer interface. Large wood particles have been associated with the formation of voids on the wood fiber–polymer interface. These voids can serve as pathways for moisture movement and fungal colonization [10]. In contrast, small particles improve the interface between the wood fibers and the polymer, and decrease the fiber–fiber contact and voids in the interface area by increasing the probability of a particle getting coated by the plastic. These characteristics limit the potential for moisture uptake as well as fungal growth. Small, well-dispersed particles are also associated with better composite properties; however, wood particles are often difficult to disperse because of their tendency to agglomerate [5]. Early WPC manufacturers tended to use larger wood particles (10–30 mesh) owing to their lower processing costs, but the industry has reduced particle sizes to as small as 80 mesh. These changes appear to produce a material with better performance and more fungal resistance [1].

The moisture content in air-dry wood fibers ranges from 6% to 7%, but the processes for plastics manufacturing tolerate little or no water. Even 1% or 2% moisture is considered too high [1, 6]. Removal of water is critical because any moisture remaining in the wood–plastic blend turns to steam and manifests itself in the form of foam, disrupting processes, resulting in poor surface quality, weak wood–plastic interface, and voids that are unacceptable for final sale [3, 25]. As a result, particles must be predried for blending.

26.4 MANUFACTURING PROCESS

Profile extrusion is the most common process for WPC production. The composite material is first heated so that the thermoplastic component can flow; then it is pumped and forced through a die of a given cross-sectional configuration. The material is supported as it cools, usually in a cold-water bath, and then cut to a given length. Pipes, tubing, furniture, moldings, and sheet goods are the common products made using profile extrusion [26]. WPCs tend to be produced by extrusion because of the process throughput that is possible with this approach.

In the injection-molding process, the material is heated and pumped into a permanent mold, where it takes its final shape and cools. The mold is then opened and the finished part discharged [26]. WPCs produced by injection-molding have been extensively studied, showing that the final properties are strongly affected by the processing conditions, composition, and the presence of coupling and dispersion agents [27]. Adding fibers to low density polyethylene (LDPE) increased flexural and tensile moduli and strength for samples without weld lines [18].

Currently, rotational molding (or rotomolding) processes have been used for WPC production. In this process, the material is charged in a mold and afterwards taken to a heated chamber and rotated at controlled speed around two perpendicular axes. The rotational movement produces the material to melt and stick to the inner surface of the mold. When the material has built a uniform layer, the mold is cooled maintaining constant rotation. The raw materials can be used in powder or liquid forms. Polyethylene powders with sisal, wood, or flax fibers are some examples of WPCs produced by rotomolding [28–30]. Calendaring, thermoforming, and compression molding are also processing methods used in the production of WPCs [31].

26.5 PROPERTIES OF COMPOSITE MATERIALS

26.5.1 Water Absorption in Natural Fiber Plastic Composites

Wood plastic composites tend to have better dimensional stability than solid wood when exposed to moisture [1]. WPCs with higher wood/plastic ratios (>50%) experience water uptake when exposed to moisture sources. WPCs have a higher resistance to moisture absorption and thickness swelling (<1%) than wood-based panels such as plywood and laminated veneer lumber or oriented strand board (>40%) [32]. The plastic covering the wood particles in a WPC tends to reduce moisture uptake; however, a number of tests suggest that wood fiber encapsulation by the polymer is incomplete, especially near the surface. As a result, the wood component in these materials absorbs water when exposed to moisture sources [8]. According to Wålinder and Gardner [19], the wood substrate interacts with water during prolonged exposure to moisture, resulting in debonding of the wood/polymer interface by the intrusion of water. Water movement through WPCs generally takes longer than through solid wood before reaching equilibrium, and cannot be directly achieved by vacuum/pressure cycles [8, 33]. The slow moisture uptake by WPCs creates moisture gradients between the surface and the core. Apparently, moisture levels nearest the surface are more suitable for fungal growth, while moisture levels in the core are too low to support microbial activity [34]. This wetting pattern will ultimately affect the mode and patterns of subsequent fungal attack.

Higher levels of water uptake are associated with poor wood–fiber interfaces. Water sorption by WPCs can severely weaken wood adhesion to thermoplastic matrices, decreasing the mechanical properties of WPCs [35]. Low moisture uptake was observed in composites made with sugar bagasse cane, HDPE, and a coupling agent [36].

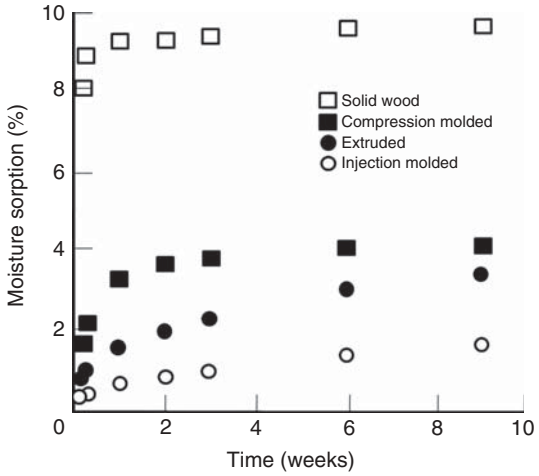

Figure 26.3 Moisture sorption for solid wood and NFCs produced by different manufacturing processes (Clemons [1]).

Swelling by moisture absorption of WPCs exposed in external environments is associated with an increase in UV degradation, as swelling develops new surfaces, exposing more polymer to degradation [37]. Moisture sorption in WPCs is associated with permanent reductions in strength and stiffness (modulus of elasticity (MOE) and MOR), proportional to the moisture content of the wood in the composite [1, 38]. As shown in Figure 26.3, the processing methods and additives used have a significant influence on moisture diffusion in WPCs, and, as result, on the potential for further effects on composite properties [1, 38].

26.5.2 Mechanical Properties

Most commercial WPCs are considerably more flexible than solid wood. WPCs creep more than solid wood, are less tough, and can handle less fatigue before failure [5, 38]. The use of wood fibers as reinforcing agents rather than just as fillers increases MOE, MOR, and the ultimate tensile strength (UTS) [39] as well as the unnotched energy [12]. Composites manufactured using sugar bagasse cane, recycled HDPE, and a coupling agent exhibited good properties (MOE and MOR) according to standards [40]. These mechanical properties are strongly influenced by the amount, size, and type of wood particles added to the matrix, and also by the additives incorporated during processing [12]. Despite the potential improvements, the MOEs of most WPCs are less than half those of solid wood [6]. In contrast, the tensile strength of WPCs is significantly reduced when wood fiber is added to the plastic matrix [32].

The processes used to produce WPCs may influence the mechanical performance of the material. Extruded materials have higher stiffness and strength than materials produced by injection molding [38]. Polypropylene blends tend to perform better than polyethylene blends [6]. As noted previously, the mechanical properties can be greatly improved by using additives to enhance wood/plastic adhesion [5, 18]. Table 26.1 shows the mechanical properties for neat polypropylene and composites produced with wood flour and fibers. It is observed that adding fibers rather than flour increases mechanical properties such as strength, elongation, and unnotched Izod impact energy [1].

26.6 DURABILITY

26.6.1 Decay

The resistance of conventional plastics to fungal attack is due primarily to the low surface area and relative impermeability of plastics, as well as to the very high molecular weight of the plastic material [8]. Microorganisms tend to attack the ends of large molecules. Because the number of ends is inversely proportional to the molecular weight, it would be necessary to break large molecules into very small fragments with a large surface area in order to make the plastic degradable [7]. In addition, fungi tend to lack the enzymes capable of degrading these materials. Polyethylene, polystyrene, and poly(vinyl chloride) are not susceptible to fungal attack [8].

The perceived resistance of WPCs to fungal attack is based on the belief that plastic encapsulates the individual wood fibers in a continuous plastic matrix and acts as a barrier to protect wood fibers from wetting. However, a number of tests suggest that wood fiber is not completely encapsulated by the polymer, especially near the surface. As a result, the wood component in these materials does reach moisture levels suitable for fungal attack (>30%) [1, 8, 10]. For example, WPC specimens exposed for 16 weeks to decay fungi in laboratory tests experienced weight loss exceeding 40% [23, 41]. Morris and Cooper [42] found WPCs manufactured from recycled wood and plastic that were attacked by brown-rot, white-rot, and blue stain fungi in the Everglades National Park, Florida, USA. According to Naghipour [8], the brown-rot fungus *Gloeophyllum trabeum* was able to grow on WPC samples, whereas pure polyethylene and polypropylene were immune to fungal attack. Weight losses were less than 5% at the 60% wood level, while WPCs with wood levels of 50% or less showed good resistance to fungal attack [8].

Decay activity in WPCs is concentrated on the exterior surfaces of the composite, resulting in gradual roughening of the composite surface [22]. Breakdown on the polymer surface leads to more wood particles being exposed, thereby increasing moisture uptake [43]. Surface wood particles exposed directly to fungal attack are generally totally decayed [41]. This decay mechanism is similar to that observed for microbial degradation of polyethylene–starch composites [22].

TABLE 26.1 Mechanical Properties of Wood–Polypropylene Composites*

	Tensile				Flexural		Izod Impact Energy		Heat
Composite†	Density (g/cm^3 [pcf])	Strength (MPa [psi])	Modulus (GPa [psi])	Elongation (%)	Strength (MPa [psi])	Modulus (GPa [psi])	Notched (J/m [ft-lb/in])	Unnotched (J/m [ft-lb/in])	Deflection Temperature (°C [°F])
Polypropylene	0.9 [56.2]	28.5 [4130]	1.53 [221,000]	5.9	38.3 [5550]	1.19 [173,000]	20.9 [0.39]	656 [12.3]	57 [135]
PP + 40% wood flour	1.05 [56.2]	25.4 [3680]	3.87 [561,000]	1.9	44.2 [6410]	3.03 [439,000]	22.2 [0.42]	73 [1.4]	89 [192]
PP + 40% hardwood fiber	1.03 [64.3]	28.2 [4090]	4.20 [609,000]	2.0	47.9 [6950]	3.25 [471,000]	26.2 [0.49]	91 [1.7]	100 [212]
PP + 40% hardwood fiber + 3% coupling agent	1.03 [64.3]	52.3 [7580]	4.23 [613,000]	3.2	72.4 [10,500]	3.22 [467,000]	21.6 [0.41]	162 [3.0]	105 [221]

PP, polypropylene.
*Ref 1.
†Percentages based on weight.

Microscopic observations of decayed WPC specimens showed mycelium concentrated in the interfacial voids between the wood and the thermoplastic component. This observation supported the premise that the primary mode of fungal degradation was via hyphal penetration through the voids on the wood/polymer interfaces [10, 22]. The materials used in these studies tended to have large wood particles, which resulted in lesser wood/plastic adhesion and more voids for fungal entry.

Resistance to fungal attack of WPCs could be evaluated using agar tests. Both, malt extract agar (MEA) and potato dextrose agar (PDA) are suitable media for accelerated WPCs decay. Both media could produce acceptable results in a relatively short period [9]. The traditional soil block method used for testing durability of solid wood is generally less effective for evaluating WPCs than solid wood. This test produces low weight losses on WPCs in comparison to solid wood. While the soil block test can provide valuable information, it is evident that a new method will be required for assessing the decay resistance of WPCs which accounts for the characteristics and properties of this composite.

The American Society for Testing and Material (ASTM) subcommittee composed of materials scientists, wood scientists, and polymer scientists attempted to develop standards for performance ratings for WPC deck boards, but there is little published on actual method development.

The absence of definitive information on decay resistance of WPCs ultimately will limit the ability to reliably and rapidly assess the durability of new materials.

26.7 FACTORS THAT AFFECT DECAY OF WOOD–PLASTIC COMPOSITES

26.7.1 Moisture

Moisture is essential for fungal colonization and decay of lignocellulosic materials. Water absorption on the surface is the key parameter because this is where fungal attack is initiated [8]. WPCs with high wood contents (>50%) clearly absorb water [8, 10]. Naghipour [8] showed that WPCs had slower moisture uptake than plastic composites, but were permeable and, as a consequence, subject to fungal decay, particularly at high wood/polymer ratios (>50% wood). Polyethylene composites absorbed more water than those made with polypropylene at comparable wood/plastic ratios [8]. Surface deterioration and delamination in WPCs have been associated with weathering [8, 43]. Moisture sorption can lead to void formation at wood/polymer interfaces [8]. The voids and cracks that are present before water exposure will expand after exposure. These voids could create pathways for entry by water and fungal hyphae. Short-term boiling can be used to rapidly increase moisture absorption [8, 33]; however, care needs to be taken to avoid altering the wood/plastic interface or leaching of any fungicides. Ibach and Clemons [33] reported that chemical modification of the wood cell wall would reduce WPC moisture uptake below the level required for fungal attack. They evaluated the resistance to fungal attack of WPCs made with chemically modified fiber or flour and polypropylene. Overall, weight losses were consistent with the lower moisture absorption of the composite. According to Ibach et al. [44], moisture contents of WPCs above 15% lead to significant weight losses, but these levels must be viewed cautiously because they do not appear to be favorable for inducing fungal attack. Wang and Morrell [34] exposed samples to water for long periods and found that the conditions on the surface of commercial WPCs were suitable for fungal attack, while moisture levels 5 mm below the surface had changed only slightly. Clearly, test specimen sizes that maximize the surface to volume ratios will result in conditions more suitable for decay development.

26.7.2 Wood Particle Size and Wood/Plastic Ratios

WPCs containing large particles tend to experience more severe decay at similar wood ratios (>50% wood) [23]. Large wood particles create more pathways into the plastic matrix, exposing more surface area to water and fungal hyphae. Simonsen et al. [45] noted similar effects using polyethylene and polypropylene. While small particles are preferable for slow moisture uptake, they are more costly to produce and therefore increase the final cost of the product.

Mankowski and Morrell [10] examined the influence of the wood/plastic ratio and wood particle size on the decay of commercial WPCs made with pine and HDPE. A 20% wood weight loss was observed in the WPCs made with 70% wood (small wood particles) after exposure to a brown-rot fungus. In contrast, little or no degradation was observed in two samples of WPCs made with 50% wood content, despite the use of larger wood particles. These results suggest that the amount rather than size of the wood particles may have a greater effect on WPC durability [13, 22].

26.7.3 Wood/Polymer Interface

Differences between the hydrophilic wood and the hydrophobic thermoplastic during processing can limit bond development, resulting in poor adhesion between wood fibers and the plastic polymer. Without chemical or physical bonding, failures on the wood–polymer interface and interfacial voids can develop because of poor processing or as a result of external factors, such as moisture uptake or UV degradation. These failures in the wood–polymer interface

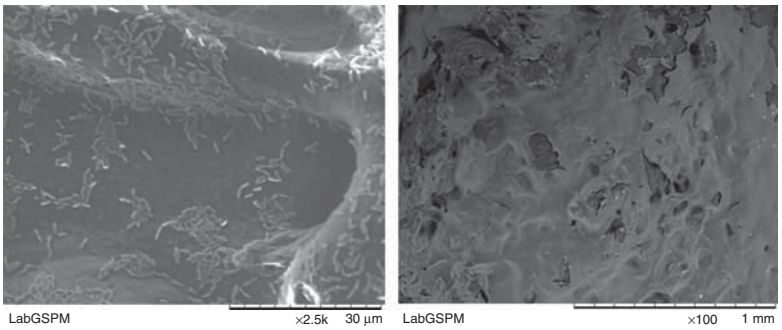

Figure 26.4 Composite surface with adhered bacteria (a) and coated with chitosan (b).

are of critical importance for assessing the WPC performance [22]. Nearly all WPCs contain additives designed to produce some chemical interaction at the wood/plastic interface, but most are proprietary and their effects on decay resistance of the final product are poorly understood.

26.8 USES OF WOOD–PLASTIC COMPOSITES

By far, the most noted marketplace for WPCs in North America is the outdoor decking market [46], followed by windows, door framing, and railings. Roofing, fencing, sea walls, garden structures, and patio furniture are emerging applications for these composites [47]. The largest market segment for natural fiber composites in Europe is automotive parts, agricultural fibers being the norm. Legislation in Europe requires the recyclability of automobiles and other products [46], thus promoting the use of natural fibers. Although WPC decking is more expensive than pressure-treated wood, manufacturers promote its lower maintenance, lack of cracking, and high durability. The actual lifetime of WPC lumber is currently being debated, but most manufacturers offer a 10-year warranty [1].

The automotive industry has long used natural fibers in combination with plastics [1, 48, 49]. Currently, WPCs are primarily used for exterior decking, window and door framing, decorative trim, and railings [7, 47]. Roofing, fencing, sea walls, garden structures, and patio furniture are emerging applications for these composites [47]. Significant markets are also emerging for railroad ties, flowerpots, furniture, and marine piers [7, 47]. The lower creep resistance, stiffness, and strength compared to solid wood and other structural materials severely limit the use of WPCs in applications that require considerable structural performance [1]. Although much work is being done on assessing the durability of WPCs, the methods remain less than ideal. Industry has the potential to produce an array of WPCs with properties tailored to meet specific use conditions. However, these developments are limited by the slow rate of biological testing. For example, process laboratories capable of producing 50 test materials per day must wait 4–6 months to learn whether these materials are durable. Clearly, methods must be developed or refined that accelerate both moisture uptake and decay potential.

Recently, WPCs have been used as carriers for biopolymers and microorganisms (Fig. 26.4). Robledo-Ortíz et al. [50] used a composite material of recycled HDPE and agave fibers for bacterial immobilization. According to the results reported, the natural adhesion of *Pseudomonas putida* F1 onto the composite surface is strongly affected by temperature, pH, ionic strength, and initial biomass concentration. Vázquez et al. [51] coated the same material (agave fibers/HDPE) with chitosan to be applied in heavy-metal adsorption. These studies showed that composite materials represent an attractive low-cost recycled support for bacterial and biopolymers with potential applications in biotechnological and environmental cleanup processes.

Until 2008, there was an explosive growth in wood and natural fiber composites in the United States. Because of the crisis in the building-products market, the demand for these composites dropped sharply. However, it is expected that economics, environmental concerns, and improved properties in the coming years will increase the demand for natural fiber composites.

REFERENCES

1. Clemons CM. Forest Prod J 2002;52(6):10.
2. Sanadi A, Caulfield DF, Rowell RM. Lignocellulosic/plastic composites. The fibril angle, Spring 1998 Newsletter. American Chemical Society; Dallas, TX: 1998. p 8.
3. Forest Products Laboratory. Wood handbook: Wood as an engineering material. Gen. Tech. Rep. FPL-GTR-113. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; Madison (WI): 1999.
4. Wolcott M, editor. The role of thermoplastics in conventional wood composites. 30th International Particleboard/Composite Materials Symposium; 1996; Pullman (WA): Washington State University; 1996.

5. Oksman K, Clemons C. J Appl Polym Sci 1998;67(9): 1503.
6. English B. Wood fiber-reinforced plastics in construction. Proceedings No. 7286, The use of recycled wood and paper in building applications; Madison, WI. Wisconsin: USDA Forest Service and The Forest Products Society; 1996. p 79–81.
7. Clemons CM. Wood fiber-plastic composites in the United States – History and current and future markets. Proceedings 3rd International Wood and Natural Fibre Composites Symposium; Kassel, Germany: 2000. p 1.1.
8. Naghipour B. Effects of extreme environmental conditions and fungal exposure on the properties of wood-plastic composites [dissertation]. Toronto (ON): University of Toronto; 1996.
9. Silva A. Development of an Accelerated Method for Assessing Decay of Wood Plastic Composites (WPC's) [dissertation]. Corvallis (OR): College of Forestry Science and Forestry, Oregon State University; 2004.
10. Mankowski M, Morrell JJ. Wood Fiber Sci 2000;32(3):340.
11. Mohanty AK, Misra M, Drzal LT, editors. *Natural Fibers, Biopolymers and Biocomposites*. Boca Raton (FL): CRC Press; 2005.
12. Stark N. Forest Prod J 1999;49(6):39.
13. Stark N, Berger MJ. Effect of species and particle size on properties of wood-flour-filled polypropylene composites. Proceedings of the Functional fillers for thermoplastics & thermosets; 1997; Madison, WI. Wisconsin: USDA Forest Service. Forest Products Laboratory; 1997. p 1.
14. Trujillo M. Desarrollo de un material compuesto de fibras naturales entrecruzadas con poliuretano [dissertation]. Guadalajara, México: Universidad de Guadalajara; 2005.
15. Rodríguez AR. Elaboración de materiales compuestos utilizando residuos de llanta, bagazo de caña y polietileno de alta densidad [dissertation]. Guadalajara, México: Universidad de Guadalajara; 2004.
16. Patterson J. J Vinyl Addit Technol 2001;7(3):138.
17. Fulmer MS. Compounding and processing additives for woodfiber-plastic composites. Proceedings of the 5th International Conference on Woodfiber-Plastic Composites; Madison, WI. Wisconsin: Forest Products Society; 1999. p 23.
18. Leduc S, Galindo JR, Gonzalez-Nunez R, Ramos-Quirarte J, Riedl B, Rodrigue D. Polym Polym Comp 2008;16(2): 115.
19. Wålinder MEP, Gardner DJ. Surface energy and acid-base characterization of components used for wood-polymer composites. Proceedings of the 6th International Conference on Woodfiber-Plastic Composites; 2001; Madison, WI. Wisconsin: Forest Products Society; 2002. p 185.
20. Stark NM, Rowlands RE. Wood Fiber Sci 2003;35(2):167.
21. Tze WTY, Gardner DJ, Tripp CP, Shaler SM, O'Neill SC. Interfacial adhesion studies of cellulose-fiber/polymer composites using a Micro-Raman technique. Proceedings of the 6th International Conference on Woodfiber-Plastic Composites 2001; Madison, WI. Wisconsin: Forest Products Society; 2002. p 177.
22. Pendleton DE, Hoffard TA, Addock T, Woodward B, Wolcott MP. Forest Prod J 2002;52(6):21.
23. Verhey SA, Lacks PE, Richter DL. The effect of composition on the decay resistance of model woodfiber-thermoplastic composites. Proceedings of the 6th International Conference on Woodfiber-Plastic Composites; 2001; Madison, WI. Wisconsin: Forest Products Society; 2002. p 79.
24. Takatani M, Ito H, Ohsugi S, Kitayama T, Saegusa M, Kawai S, Okamoto T. Holzforshung 2000;54(2):197.
25. English B, Clemons CM, Stark N, Schneider JP. Wastewood-derived fillers for plastics. Gen. Tech. Rep. FPL-GTR-91. Madison, (WI): U. S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1996.
26. B E, P C, D SB. Processing into composites. In: RM R, RA Y, JK R, editors. *Paper and Composites from Agro-Based Resources*. Boca Raton (FL): CRC Lewis Publishers; 1997. p 269.
27. Sun SY, Hai SH, Gan CD. J Reinf Plast Compos 2010;29(5): 637.
28. Ward J, Panigrahi S, Tabil LG, Crerar WJ, Powell T. Rotational molding of flax fiber reinforced thermoplastics. Proceedings 2002, The Society for Engineering in Agricultural, Food and Biological Systems; Chicago, IL; 2002. Paper No: MBSK 02-209.
29. Torres FG, Aragon CL. Polym Test 2006;25(4):568.
30. Jayaraman K, Lin R, Bose D, Maarouf M. Adv Mater Res 2007;29-30(4):307.
31. Youngquist JA. Wood-based composites and panel products. Wood handbook: wood as an engineering material. Gen. Tech. Rep. FPL-GTR-113. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; Madison (WI); 1999.
32. Falk RH, Lundin T, Felton C. The effects of weathering on wood-thermoplastic composites intended for outdoor applications. Proceedings of the 2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing, Madison, WI. Wisconsin: Forest Products Society; 2001. p 175.
33. Ibach RE, Clemons CM. Biological resistance of polyethylene composites made with chemically modified fiber or flour. Proceedings of the 6th Pacific Rim Bio-based Composites Symposium and Workshop on the Chemical Modification of Cellulosics; 2002 Nov 10–13; Portland, OR. Portland (OR): Oregon State University; 2002. p 574.
34. Wang W, Morrell JJ. Forest Prod J 2004;54(12):209.
35. Uerkanrak K. High density polyethylene/wood fiber composites: measuring the effect of processing parameters on their physical and mechanical properties [dissertation]. East Lansing (MI): School of Packaging, Michigan State University; 2001.
36. Fuentes TF, Silva GJ, Richter HG, Sanjuán DR, Ramos QJ. Indust Crops Prod 2007;26(1):1.
37. Lange SE, Rowell RM. Weathering performance of aspen-polypropylene composites. Proceedings of the 7th International Conference on Woodfiber-Plastic Composites, 2003; Madison, WI. Wisconsin: Forest Products Society; 2004. p 317.

38. Rangaraj S. Durability assessment and modeling of wood-thermoplastic composites [dissertation]. Pullman (WA): School of Mechanical and Materials Engineering, Washington State University; 1999.
39. Simonsen WJ. Forest Prod J 1997;47(1):74.
40. Fuentes FJ, Silva A, Sanjuán R, Ramos J. Properties of composite materials manufactured with sugar cane bagasse particles and recycled plastic. Proceedings 8th International Conference on Woodfiber-Plastic Composites. Madison, WI. Wisconsin: Forest Products Society; 2006. p 355.
41. Silva A, Gartner B, Morrell J. J Test Eval 2007;35(2):203.
42. Morris PI, Cooper P. Forest Prod J 1998;48(1):86.
43. Peyer S, Wolcott MP. Damage in woodfiber-plastic composites: a look-up close and personal. Proceedings of the 6th International Conference on Woodfiber-Plastic Composites; 2001; Madison, (WI). Wisconsin: Forest Products Society; 2002. p 280.
44. Ibach RE, Clemons CM, Stark NM. Combined UV and water exposure as a preconditioning method in laboratory fungal durability testing. Proceedings of the 7th International Conference on Woodfiber-Plastic Composites; 2003 May 19–20; Madison, WI. Wisconsin: Forest Products Society; 2004. p 61.
45. Simonsen J, Freitag CM, Morrell JJ. The effect of wood-plastic ratio on the performance of borate biocides against brown-rot fungi. Proceedings of the 6th International Conference on Woodfiber-Plastic Composites; 2001, Madison, WI. Wisconsin: Forest Products Society; 2002. p 69.
46. Hansen E. Market and innovation considerations in development of natural/wood fibre composites. In: Pickering K, editor. *Properties and Performance of Natural-Fibre Composites*. Cambridge, England: Woodhead Publishing; 2008. p 356.
47. Morton J, Quarmley J, Rossi L. Current and emerging applications for natural and woodfiber composites. Proceedings of the 7th International Conference on Woodfiber-Plastic Composites; 2003; Madison, WI. Wisconsin: Forest Products Society; 2004. p 3.
48. Rowell R. The state of the art and future development of bio-based composites science and technology towards the 21st century. Proceedings: The Fourth Pacific Rim Bio-Based Composites Symposium; 1998; Bogor, Indonesia. Indonesia: Bogor Agricultural University; 1998. p 1.
49. Lee EC, Baldwin K. Material damping characteristics of natural fiber reinforced plastics by DMTA and modal analysis. Proceedings of the 6th International Conference on Woodfiber-Plastic Composites; 2001; Madison, WI. Wisconsin: Forest Products Society; 2002. p 6.
50. Robledo-Ortíz JR, Ramírez-Arreola DE, Gómez C, González-Reynoso O, González-Núñez R. Bacterial immobilization by adhesion onto agave fiber/polymer foamed composites. Bioresour Technol 2010;101(4):1293.
51. Vázquez MO, Herrera VS, Gómez C, Gómez-Salazar S, Rodrigue D, González-Núñez R, Luna-Bárcenas JG, Mani-González PG, Herrera-Gómez A. J Appl Polym Sci 2010;115(5):2971.