

CHAPTER 6

WOOD THERMOPLASTIC COMPOSITES

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INTRODUCTION

The wood industry can expand into new sustainable markets with the formation of a new class of composites with the marriage of the wood industry and the plastics industry. The wood component, usually a flour or fiber, is combined with a thermoplastic to form an extrudable, injectable or thermoformable composite that can be used in many non-structural applications (Klyosov 2007).

The term "wood-plastic composites" refers to any number of composites that contain wood (of any form) and either thermoset- or thermoplastic-polymers. "Thermosets" or thermoset polymers are plastics that, once cured, cannot be re-melted by heating. These include cured resins such as epoxies and phenolics, plastics with which the forest products industry is most familiar. Wood-thermoset composites date to the early 1900s. An early commercial composite marketed under the trade name Bakelite was composed of phenol-formaldehyde and wood flour. Its first commercial use was reportedly as a gearshift knob for Rolls Royce in 1916 (Gordon 1988). "Thermoplastics" are plastics that can be repeatedly melted, such as polyethylene, polypropylene and polyvinyl chloride (PVC). Thermoplastics are used to make many diverse commercial products such as milk jugs, grocery bags, and siding for homes. In contrast to the wood-thermoset composites, wood-thermoplastic composites have seen phenomenal growth in the United States in recent years. This chapter deals exclusively with wood-thermoplastic composites, which are now most often simply referred to as wood-plastic composites (WPCs) with the common understanding that the plastic always refers to a thermoplastic.

The birth of the WPC industry involved the interfacing of two industries that have historically known little about each other and have very different knowledge-bases, expertise, and perspectives. The forest products industry has greater experience and resources in the building products market and its production methods center around the typical wood processes; sawing, veneering, chipping, flaking and gluing. The plastics industry has knowledge of plastics processing, that centers around extrusion, compression-molding and injection-molding technologies. Not surprisingly, some of the earliest companies to produce WPCs were window manufacturers that had experience with both wood and plastics.

BRIEF HISTORY

In the United States, WPCs have been produced for several decades, but they were produced even earlier in Europe. However, major growth in the United States did not occur until fairly recently. In 1983, American Woodstock, now part of Lear Corporation in Sheboygan, Wisconsin, began producing WPC panel substrates for automotive interiors using Italian extrusion technology (Schut 1999). Polypropylene with approximately 50 percent wood flour was extruded into a flat sheet that was then formed into various shapes for interior automotive paneling. This was one of the first major applications of WPC technology in the United States.

In the early 1990s, Advanced Environmental Recycling Technologies (AERT, Junction, Texas) and a division of Mobil Chemical Company that later became Trex (Winchester, Virginia) began producing solid WPCs consisting of approximately 50 percent wood fiber in polyethylene. These composites were sold as deck boards, landscape timbers, picnic tables, and industrial flooring (Youngquist 1995). Similar composites were milled into window and door component profiles. Today, the decking market is the largest and fastest growing WPC market.

Also in the early 1990s Strandex Corporation (Madison, Wisconsin) patented technology for extruding high wood fiber content composites directly to final shape without the need for milling or further forming. Strandex has continued to license its evolving technology.

Andersen Corporation (Bayport, Minnesota) began producing wood fiber-reinforced PVC subsills for French doors in 1993. Further development led to a wood-PVC composite window line (Schut 1999). These products allowed Andersen to recycle wastes from both wood and plastic processing operations. The market for WPC window and door profiles has continued to grow.

In 1996, several U.S. companies began producing a pelletized feedstock from wood (or other natural fibers) and plastic. These companies provide compounded pellets for many processors who do not want to blend their own material. Since the mid-1990s, activity in the WPC industry has increased dramatically. Technology is developing quickly and many manufacturers have begun to produce WPCs. Although the WPC industry is still only a fraction of a percent of the total wood products industry (Smith 2001), it has made significant inroads in certain markets. Current end product manufacturers are an interesting mix of large and small manufacturers from both the plastics and forest products industries. According to a

recent market study, the WPC market was 320,000 metric tons (700 million lb.) in 2001, and the volume is expected to more than double by 2005 (Mapleston 2001b). The status and developments in the WPC industry is now also closely monitored by Principia Partners, an international business consulting firm for the industry. In 2003, Principia Partners reviewed recent developments and trends. (Morton et al. 2003). In North America more than 67 WPC enterprises produce 590,000 tonnes valued at \$700,000. The vast majority of production is extruded materials for decks, with lesser amounts of extruded profiles for windows, railings, transportation and other infrastructural uses. Demand is projected to increase by an annual rate of 14% over the next few years, reaching a total increase of 290% by 2010. Significant production increases in Europe and Japan are also anticipated.

In 1991, the First International Conference on Woodfiber-Plastic Composites was convened in Madison, Wisconsin, (about 50 attendees) with the intent of bringing together researchers and industrial representatives from both the plastics and forest products industries to share ideas and technology on WPCs. A similar, sister conference (Progress in Woodfiber-Plastic Composites) began in Toronto, Ontario, the following year and is being held in alternating years. These conferences have grown steadily through the 1990s, and in 2003 in Madison the 7th International Conference on Wood- and Natural-fiber-Plastic Composites Conference was attended by over 400 conferees. Additional conferences have been held in North America and elsewhere around the world as both interest and the market has grown.

MATERIALS

WOOD FLOUR

The wood used in WPCs is most often in particulate form (e.g., wood flour) or very short fibers and bundled fibers, rather than long individual wood fibers. Products typically contain approximately 50 percent wood, although some composites contain very little wood and others as much as 70 percent. The relatively high bulk density and free-flowing nature of wood flour compared with wood fibers or other longer natural fibers, as well as its low cost, familiarity, and availability, is attractive to WPC manufacturers and users. Common species used include pine, maple, and oak. Typical particle sizes are 10 to 80 mesh. 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 diverse nature of wood flour suppliers, there are currently few good resources that list wood flour manufacturers. Wood-plastic composite manufacturers obtain wood flour either: 1) directly from forest products companies such as lumber mills and furniture, millwork, or window and door manufacturers that produce it as a byproduct or 2) buy it 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.

As with most materials, wood flour costs are variable and depend on such factors as volume, availability, particle size, and shipping distance. However, wood flour is typically about \$0.11-0.22/kg (\$0.05-0.10/lb) in the United States. Narrow particle size distributions and fine wood flour sizes tend to increase cost.

Because there are many small manufacturers of wood flour and the volume is small relative to other wood products (solid wood, wood composites, and paper), reliable statistical information on wood flour availability is scarce.

WOOD FIBER

Because of the potential of improved mechanical properties with fillers of greater l/d ratios, there has been a continuing interest in the use individual wood fibers rather than wood flour as reinforcement in WPC. Recently, two wood-pulp fiber suppliers, Rayonier Corp. (Savannah GA) and Creafill Fiber Corp. (Chesterton, Md) have been marketing wood-pulp fibers for use as reinforcements for thermoplastics. The fibers that they supply have been promoted for use in WPC of higher performance potentials. Adding fibers rather than flour increases mechanical properties such as strength, elongation, and unnotched Izod impact energy. However, processing difficulties, such as feeding and metering low-bulk-density fibers, have limited the use of fibers in WPCs. There have been some developments in pelletizing fibers for ease of handling and processing (Jacobson et al. 2002).

THERMOPLASTIC MATRIX MATERIALS

The WPC presently consumes over 685,000 tonnes of thermoplastic resins annually (Morton et al. 2003). There are some differences in processing technologies between Europe and North America and this is reflected in the consumption totals for the various resins. Polyethylene resin (PE) is the dominant resin in North America amounting to 83% of the 685,000 tonnes consumed. Nine percent of the total is polypropylene (PP), and 7% of the thermoplastic resin used in the WPC industry is polyvinyl chloride (PVC). Only about 1% of other resins are used.

ADDED COMPOUNDS

Wood and thermoplastic are not the only components in WPCs. These composites also contain additional materials that are added in small amounts to affect processing and performance. Although formulations are highly proprietary, additives such as coupling agents, light stabilizers, pigments, lubricants, fungicides, and foaming agents are all used to some extent. Some additive suppliers are specifically targeting the WPC industry (Mapleston 2001 a).

COMPATIBILIZERS

Since the wood component of a wood-thermoplastic composite is hydrophilic and the plastic is hydrophobic, a compatibilizer is often used to improve interfacial bonding of the two different phases. Many compatibilizers have been investigated and are reviewed elsewhere (Lu et al. 2000). However, one of the

most common compatibilizers used for wood-thermoplastic composites are maleic anhydride grafted polypropylenes (MAPPs). They differ in molecular weight and the degree of maleic anhydride substitution but those used for compatibilization typically have a number-average molecular weight of about 20,000, a weight-average molecular weight of about 40,000 and contain approximately 6 weight percent maleic anhydride.

The anhydride portion of the compatibilizer reacts with a hydroxyl group of the wood cell wall forming an ester bond (Figure 1). The polypropylene segments of the MAPP can incorporate themselves into the bulk PP matrix (Figure 2). Figure 3 shows a fracture surface of a composite where a compatibilizer has been used. The fiber has been fractured rather than pulled out of the thermoplastic matrix suggesting good fiber-matrix adhesion. There is a small gap at the base of the fiber where the wood has debonded from the PP matrix also suggesting weak interfacial bonding.

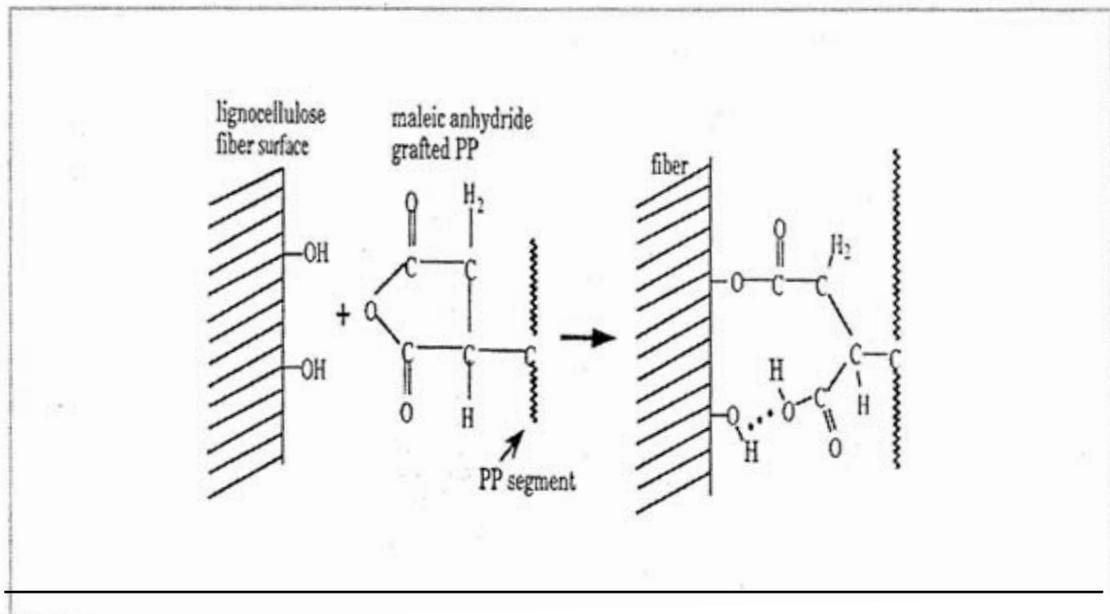


FIGURE 1 – Reaction of an anhydride end group on MAPP with a cell wall hydroxyl group.

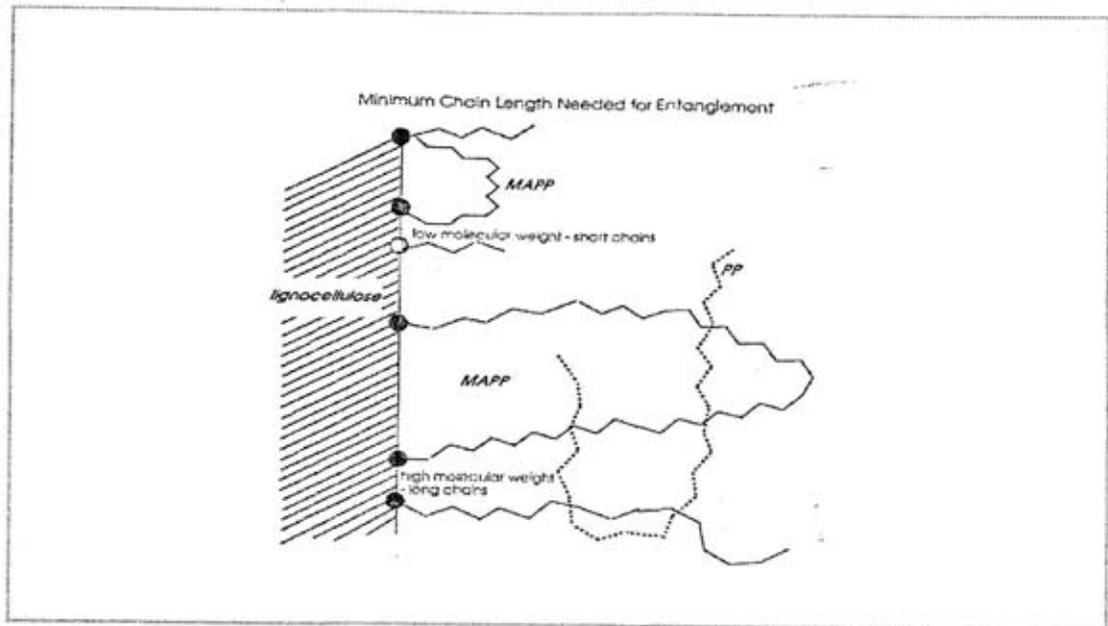


FIGURE 2 - Entanglement of the PP on MAPP with the matrix PP.

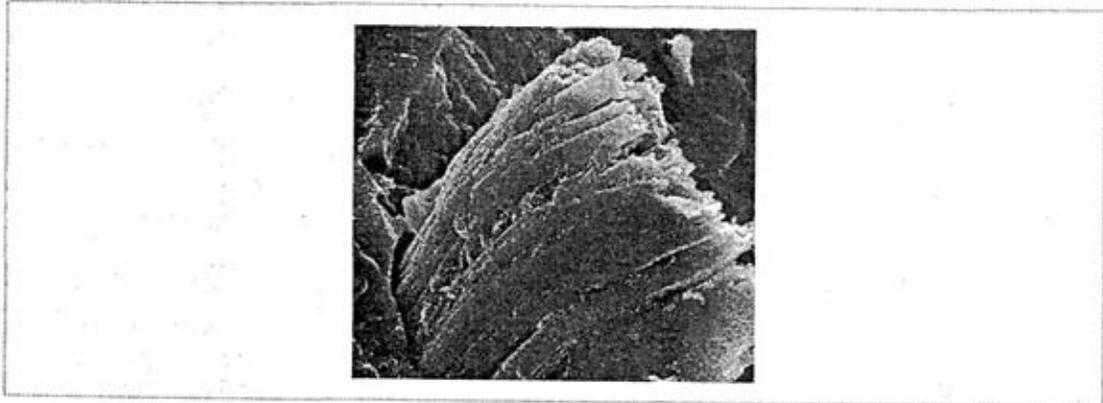


FIGURE 3 - Fiber broken in a test for compatibilization

PROCESSING

The plastics industry has traditionally used inorganic materials like talc, calcium carbonate, mica, and glass fibers to fill and to modify the performance of plastic; about 2.5 billion kg of fillers and reinforcements are used annually (Eckert 2000). The industry was reluctant to use wood or wood fiber as filler because of its low bulk density, low thermal stability, and tendency to absorb moisture. The majority of thermoplastics arrive at a manufacturer as free-flowing pellets or granules with a bulk density of about 500 kg/m. The

plastics processor is faced with the problem of how to consistently meter and force the low bulk density wood fiber into small feed openings typical of plastics processing equipment. In addition, the processing temperature for even low melting point plastics is often too high for incorporating wood fiber without thermal degradation. The high moisture content of wood and other natural fibers is also problematic to the plastics industry, which considers about 1 to 2 percent moisture content high. Even plastics processors with vented equipment capable of removing moisture during processing were averse to removing 5 to 7 percent moisture from wood fibers. Resin dryers, which are occasionally needed to dry plastics, are not appropriate for wood particles or fibers, and drying the fine wood particles poses a fire hazard. Plastics processors who tried to use wood or other natural fibers often lacked knowledge about wood, and their failed attempts made the industry generally skeptical of combining wood and plastic.

For the wood products industry, thermoplastics were a foreign world, albeit one that occasionally intruded on traditional markets (e.g., vinyl siding). Competing in different markets, forest products and plastics industries had few material and equipment suppliers in common and they processed materials very differently and on entirely different scales (Youngquist 1995).

The perspective of some plastics industries has changed dramatically in the last decade. Interest has been fueled by the success of several WPC products, greater awareness and understanding of wood, developments from equipment manufacturers and additive suppliers, and opportunities to enter new markets, particularly in the large-volume building applications sector. Forest products industries are changing their perspective as well. They view WPCs as a way to increase the durability of wood with little maintenance on the consumer's part (one of the greatest selling points). Some forest products companies are beginning to manufacture WPC lumber and others are distributing this product. These ventures into WPCs are being driven by customer demand and opportunities based on the industry's experience in building products (Anonymous 2001).

Because of the limited thermal stability of wood, it was believed initially that only thermoplastics that melt or can be processed at temperatures below 200°C could be used in WPCs and currently that is the practice. Most WPCs are made with polyethylene, both recycled and virgin, for use in exterior building components. However, WPCs made with wood-polypropylene are typically used in automotive applications and consumer products, and these composites have recently been investigated for use in non-structural building profiles. Wood-PVC composites typically used in window manufacture are now being sometimes used in decks and railings as well. Polystyrene and acrylonitrile-butadiene-styrene (ABS) are also being used. The plastic is often selected based on its inherent properties, product need, availability, cost, and the manufacturer's familiarity with the material. Small amounts of thermoset resins such as phenol-formaldehyde or diphenyl methane diisocyanate are also sometimes used in composites with a high wood content (Wolcott and Adcock 2000).

The manufacture of thermoplastic composites is often a two-step process. The raw materials are first mixed together in a process called compounding, and the compounded material is then formed into a product. Compounding is the feeding and dispersing of fillers and additives in the molten polymer (Figure 4). Many options are available for compounding, using either batch or continuous mixers. The

compounded material can be immediately pressed or shaped into an end product or formed into pellets for future processing. Some product manufacturing options for WPCs force molten material through a die (sheet or profile extrusion), into a cold mold (injection molding), between calenders (calendering), or between mold halves (thermoforming and compression molding) (Youngquist 1999). Combining the compounding and product manufacturing steps is called in-line processing.

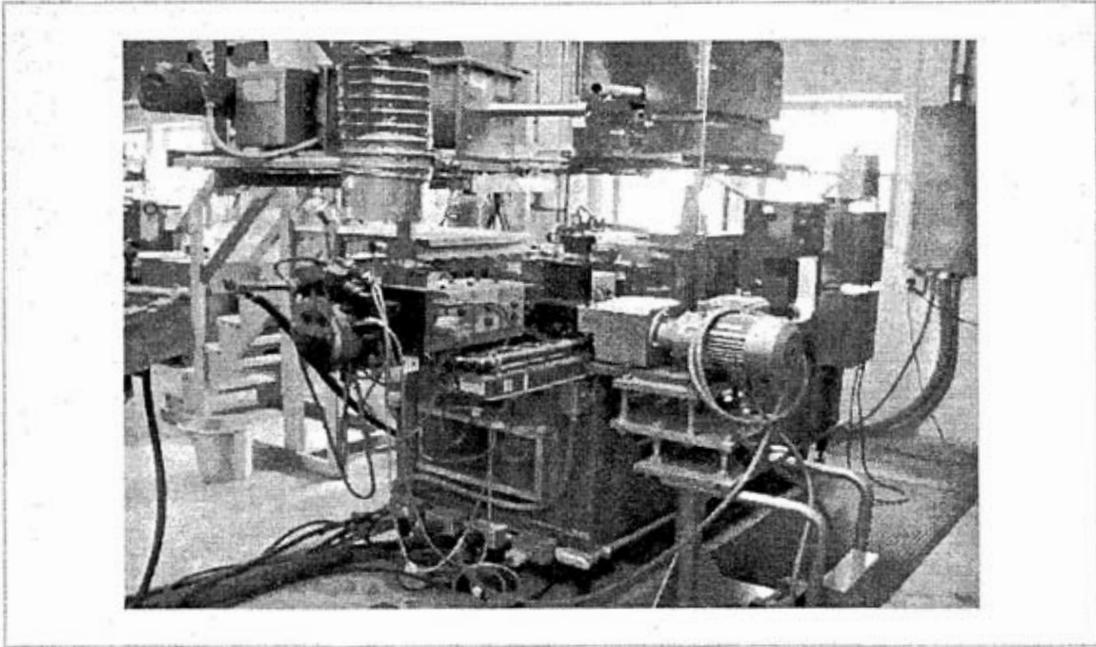


FIGURE 4 - Davis Standard twin-screw extruder with side-stuffer crammer for introducing wood-flour or wood fiber into molten thermoplastic matrix.

The majority of WPCs are manufactured by profile extrusion, in which molten composite material is forced through a die to make a continuous profile of the desired shape (Figure 5). Extrusion lends itself to processing the high viscosity of the molten WPC blends and to shaping the long, continuous profiles common to building materials. These profiles can be a simple solid shape, or highly engineered and hollow. Outputs up to 3 m/min. (10 ft./min.) are currently possible (Mapleston 2001b).

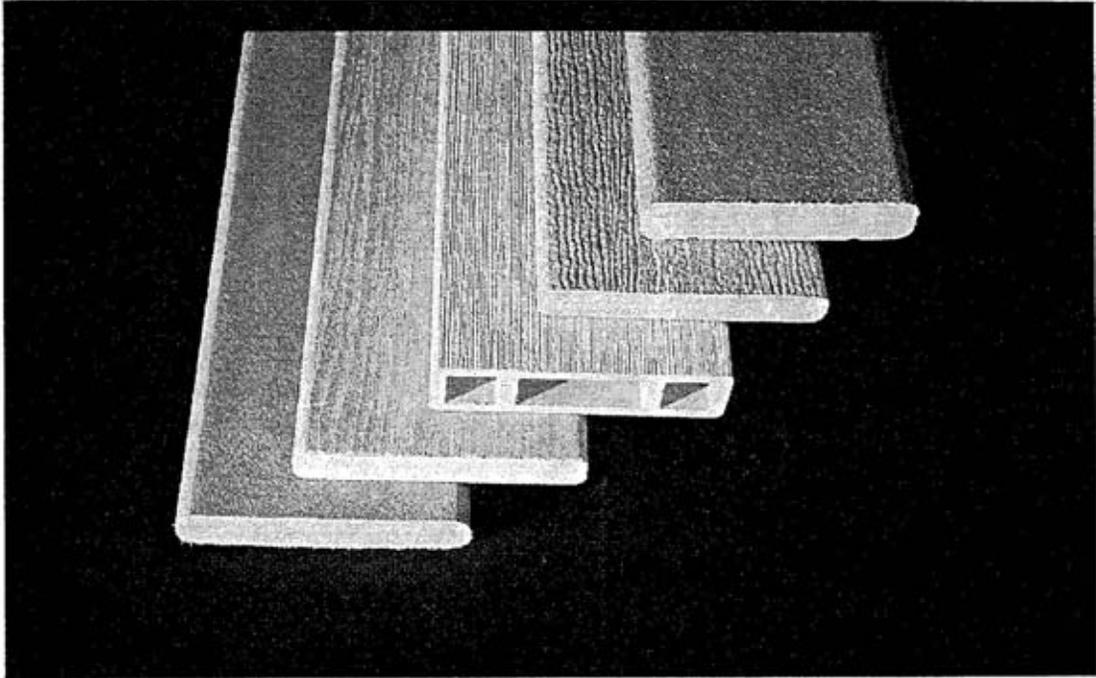


FIGURE 5 - Examples of extruded wood fiber plastics.

Although extrusion is by far the most common processing method for WPCs, the processors use a variety of extruder types and processing strategies (Mapleston 2001c). Some processors run compounded pellets through single-screw extruders to form the final shape. Others compound and extrude final shapes in one step using twin-screw extruders. Some processors use several extruders in tandem, one for compounding and the others for profiling (Mapleston 2001c). Moisture can be removed from the wood component before processing, during a separate compounding step (or in the first extruder in a tandem process), or by using the first part of an extruder as a dryer in some in-line process. Equipment has been developed for many aspects of WPC processing, including materials handling, drying and feeding systems, extruder design, die design, and downstream equipment (i.e., equipment needed after extrusion, such as cooling tanks, pullers, and cut-off saws). Equipment manufacturers have partnered to develop complete processing lines specifically for WPCs. Some manufacturers are licensing new extrusion technologies that are very different from conventional extrusion processing (Mapleston 2001c,d).

Compounders specializing in wood and other natural fibers mixed with thermoplastics have fueled growth in several markets. These compounders supply preblended, free-flowing pellets, that can be reheated and formed into products by a variety of processing methods. The pellets are a boon to manufacturers who do not typically do their own compounding or do not wish to compound in-line (for example, most single-screw profilers or injection molding companies).

Other processing technologies such as injection molding and compression molding are also used to produce WPCs, but the total poundage [produced] is much less (English et al. 1996). These alternative processing methods have advantages when processing of a continuous piece is not desired or a more complicated shape is needed. Composite formulation must be adjusted to meet processing requirements (e.g., the low viscosity needed for injection molding can limit wood content).

PERFORMANCE

The wide variety of WPCs have been made which makes it difficult to discuss the performance of these composites. Performance depends on the inherent properties of the constituent materials, interactions between these materials, processing, product design, and service environment. Moreover, new technologies are continuing to improve performance (Maplestone 2001d).

MECHANICAL PROPERTIES

As an example of mechanical properties a wood fiber-thermoplastic composite, Table 1 shows the composition of aspen fiber, propylene, with and without MAPP compounded using a high intensity thermokinetic mixer where the only source of heat is generated through the kinetic energy of rotating blades (Rowell 2007). The blending was accomplished at 4600 rpm and then automatically discharged at 190 C. The total residence time of the blending operation averaged about 2 min. The mixed blends were then granulated and dried at 105 C for 4 hours. Test specimen were injection molded at 190 °C using pressures varying from 2.75 MPa to 8.3 MPa depending on the constituents of the blend. Test specimen dimensions were according to the respective ASTM standards. The specimens were stored under controlled conditions (20 % Relative Humidity and 32 C) for three days before testing. Tensile tests were conducted according to ASTM 638-90, Izod impact strength tests according to ASTM D 256-90, and flexural testing using the ASTM 790-90 standard. The cross-head speed during the tension and flexural testing was 12.5 mm/min.

TABLE 1 - Composition of aspen-polypropylene composite specimens.

% by weight		
30	70	0
30	68	2
40	60	3
40	58	2
50	50	0
50	48	2
60	10	0
60	38	2

Table 2 shows the results of mechanical tests done on the composite specimens compounded according to Table 1. The addition of MAPP has a great positive effect on flexural strength and modulus and tensile strength and modulus and Izod unnotched toughness. As the percent of aspen fiber increases, flexural strength and modulus and tensile modulus increase. Unnotched Izod results show a decrease in toughness as the percentage of aspen fiber increases.

TABLE 2 - Mechanical properties of aspen fiber-polypropylene composites.

Specimen	Flexural strength (MPa)	Flexural modulus (GPa)	Tensile strength (MPa)	Tensile modulus (GPa)	Izod notched (J/m)	Izod unnotched (J/m)
PP	27.9	1.38	26.2	1.69	22.4	713.5
PP/MAPP	34.6	1.79	29.3	1.82	18.6	563.3
30A/70PP	49.5	4.12	29.3	4.52	24.8	101.7
30A/68PP/MAPP	60.2	3.82	44.9	4.10	21.1	128.3
40A/60PP	54.6	4.60	34.9	5.22	19.6	85.5
40A/58PP/MAPP	66.4	4.66	47.7	5.14	19.8	108.7
50A/50PP	50.2	5.48	28.4	5.81	26.4	67.1
50A/48PP/MAPP	75.7	5.88	53.1	6.68	21.9	98.5
60A/40PP	45.9	6.09	25.6	6.95	23.9	55.2
60A/38PP/MAPP	75.8	6.73	48.1	7.19	21.3	81.1

MOISTURE PROPERTIES

The specimens listed in Table 1 were subjected to 90% relative humidity (RH) for an extended period of time (Rowell 2007). Table 3 shows that even after 200 days, all of the composites continued to gain weight and equilibrium was not reached. The higher the wood fiber content, the more moisture was picked up by the specimen.

Table 4 shows data on a cyclic humidity test where the specimens were subjected to 30% RH for 60 days, measured and then subjected to 90% RH for an additional 60 days (Rowell 2007). This cycle was repeated four times. As with the static 90% RH tests, the specimens continued to gain weight with each 90% RH cycle.

TABLE 3. Weight gain in aspen-polypropylene composites at 90% relative humidity after D days.

Aspen/ PP/ MAPP	Weight Gain					
	25 D	50 D	75 D	100 D	150 D	200 D
	%					
0/100/0	0	0	0	0	0.2	0.4
30/70/0	0.7	1.4	1.7	2.1	2.4	2.8
30/68/2	0.7	0.7	1.1	1.5	1.5	2.2
40/60/0	0.7	1.4	1.7	2.0	2.4	3.0
40/58/2	0.4	1.2	1.5	1.9	2.7	3.5
50/50/0	1.3	2.0	2.6	3.6	4.3	5.3
50/48/2	1.5	1.8	2.2	2.9	4.0	5.1
60/40/0	3.7	4.5	5.6	6.0	6.3	6.7
60/38/2	1.6	2.2	3.5	4.4	5.1	6.0

TABLE 4 - Weight changes in repeated humidity tests on aspen-polypropylene composites cycled between 30% and 90% relative humidity.

Aspen/ PP/ MAPP	Weight Gain							
	30%	90%	30%	90%	30%	90%	30%	90%
	%							
0/100/0	0	0	0	0	0	0.2	0	0.4
30/70/0	0.6	0.9	0.7	1.4	0.7	1.4	0.9	1.9
30/68/2	0.4	0.9	0.7	1.2	0.7	1.3	0.9	1.8
40/60/0	0.4	0.9	0.7	1.4	0.7	1.6	0.7	2.1
40/58/2	0.2	1.2	0.8	1.6	1.0	2.0	1.2	2.2
50/50/0	0.5	1.5	1.2	2.5	1.2	2.7	1.2	3.2
50/48/2	0.6	1.3	1.1	2.2	1.3	2.2	1.3	2.6
60/40/0	0.7	2.5	1.5	4.1	1.6	4.1	1.3	4.8
60/38/2	0.2	1.5	1.0	2.6	1.3	2.6	1.3	3.3

Soaking the specimens listed in Table 1 in liquid water showed that the composites continued to gain small amounts of weight during 200 day test (Rowell 2007). As with the RH tests, equilibrium was not reached in the 200 days. The maximum weight gain due to water soaking was approximately 11% in the specimens with the highest percentage of wood fiber.

from the moisture data, it is clear that as the percentage of hydrophilic wood fiber increases in the wood-thermoplastic composites, there is a corresponding increase in moisture gain. The moisture gain is slow, even in liquid water, but continues over a very long period of time. The data also suggests that at about 50% wood, the rate and extent of moisture pickup increases. At this point, the fiber content has

reached a point where there is a lot of fibers touching each other to wick water faster and further into the composite.

Figure 6 shows a wood fiber-thermoplastic composite using acetylated fiber (see Chapter 8) (Larsson Breilid et al. 2006). The moisture sorption is greatly reduced using a chemically modified fiber in the mix.

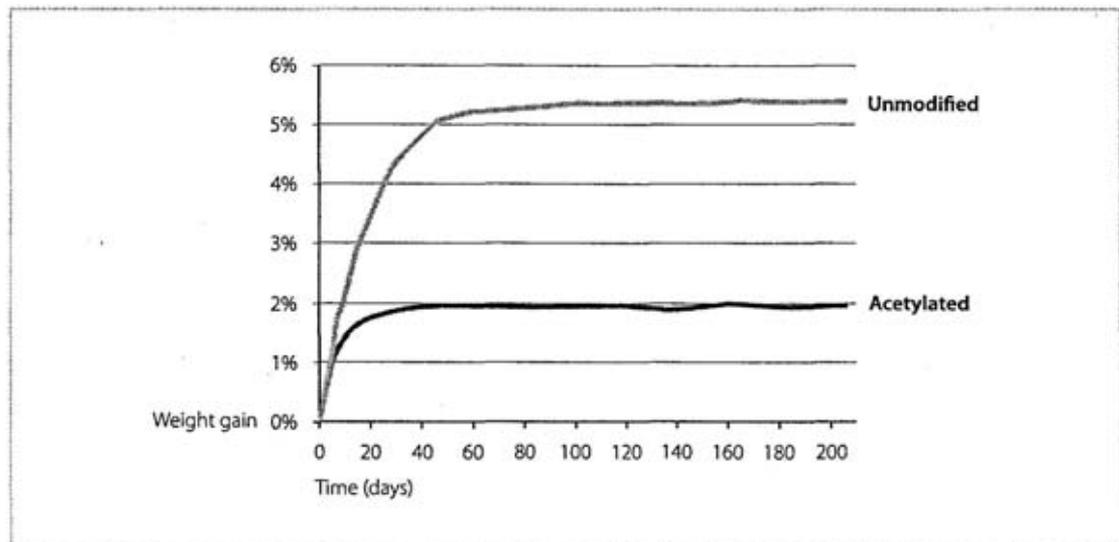


FIGURE 6 -Acetylated and control fiber in PP composite.

BIOLOGICAL PROPERTIES

Because WPCs absorb less moisture and do so more slowly than solid wood, they have better fungal resistance and dimensional stability when exposed to moisture (Rowell 2007). For composites with high wood contents, some manufacturers incorporate additives such as zinc borate to improve fungal resistance. Unfilled plastics absorb little, if any, moisture, are very resistant to fungal attack, and have good dimensional stability when exposed to moisture. However, most plastics expand when heated and adding wood decreases thermal expansion.

ASTM standard laboratory tests using isolated brown- and white-rot fungi show a very small weight loss during a 12 week test. These test, however, are complicated in that the test specimens are not first soaked in water to bring the moisture content of the test specimens up to a moisture content where fungi are able to attack. Outdoor tests show that wood-thermo-plastics are subject to mold growth.

WEATHERING AND FIRE PROPERTIES

Light stability in outdoor exposures is an area of considerable investigation (Rowell et al. 2000, Lundin 2001). Most WPCs tend to lighten over time (Falk et al. 2002). Some manufacturers add pigments to slow this effect. Others add a gray pigment so that color change is less noticeable. Still others co-extrude a UV-stable plastic layer over the WPCs. In laboratory weatherometer tests, wood-PP composites lightened within 400 to 600 hours of UV exposure. After 2000 hours of UV and water exposure, specimens were white and the white color continued through out the 10 mm specimen. This "in depth color change may be due to stabilization of the free radicals formed from UV radiation by the lignin in the wood allowing the free radicals to penetrate deeper into the wood.

The fire performance of WPC materials and products is just beginning to be investigated (Malvar et al. 2001, Stark et al. 1997). These composites are different from many building materials in that they can melt as well as burn, making testing for fire resistance difficult.

HIGHER PERFORMANCE MATERIALS

There has been a continuing interest in achieving improved mechanical properties for WPC. This has involved the use long individual fibers for their reinforcing potential, and the use of thermoplastics with better engineering properties. Thermoplastics with improved strength properties tend to be higher melting thermoplastics like polyamides (nylons). The earliest reported attempt to use cellulose flour and cellulosic fibers to reinforce polyamides was that of (Klason et al. 1984). That paper followed-up an earlier report by these authors that demonstrated the potential of wood flour and cellulosic fibers in commodity thermoplastics like polyethylene and polypropylene. The initial results with polyamides were generally discouraging. Although there was some success in reinforcing PA-12 (melting range 176-180°C) with cellulose, when PA-6 was used (melting point 215°C), cellulosic fibers showed poorer reinforcing potential than wood flour and cellulosic flour. In all cases the PA-6 materials exhibited severe discoloration and pronounced pyrolytic degradation. These authors concluded that for the higher melting thermoplastics like PA-6, "cellulosic fibers do not produce any significant degree of reinforcement despite their obvious stiffness and strength potential." Since those initial experiments, it was commonly believed that the use of cellulosic fibers as reinforcement in thermoplastics is limited to the low-melting commodity thermoplastics (melting points below 180°C). Furthermore, it has been believed that the higher melting engineering thermoplastics (m.p. >220°C) cannot be effectively reinforced with cellulosic fibers because of the severe thermal degradation of the cellulose that occurs at temperatures needed to process these high-melting engineering thermoplastics.

In recent patents, it was demonstrated that these common beliefs are erroneous. The patents described materials and methods for achieving composites containing cellulosic fibers in high-melting engineering thermoplastics (Sears et al. 2001, 2004). Other reports demonstrated that not only the high-melting engineering plastics, nylon-6 and nylon-66 but other high-melting point thermoplastics, ECM (an aliphatic polyketone) and PBT (a polyester) can be reinforced by wood pulp fibers (Caulfield et al. 2001) to produce composites of promising structural potential (See Table 5).

TABLE 5 - Comparison of some plastic/ composite mechanical properties.

	TENSILE STRENGTH	FLEXURAL STRENGTH	TENSILE MODULUS	FLEXURAL MODULUS	NOTCHED IZOD	UNNOTCHED IZOD
	MPa	MPa	GPa	GPa	J/m	J/m
POLYPROPYLENE	27.6	28.7	1.39	1.39	16.1	556.4
PP + 33% WOOD FLOUR	33.1	49.3	3.38	3.19	18.7	75.4
NYLON 6 (PA-6)	60.2	64.2	2.75	2.38	24	746.3
PA-6 + 33% WOLLASTONITE	62.7	105.7	6.51	6.27	25.8	173.9
PA-6 + 33% GLASS FIBRE	111.2	146.7	8.02	7.55	45.9	406.1
PA-6 + 33% HARDWOOD FIBRE	86.5	121.6	5.71	5.88	25.3	318.3
PA-6 + 33% SOFTWOOD FIBRE	81.9	113.9	5.35	5.45	25.1	247.2
CLEAR PINE	90.4	88.3	7.6	12.34	---	---

Control of viscous shear heating during the extrusion processing of these composites is essential for avoiding the thermal degradation of the cellulosic component. These composites (without compatibilizers and other additives) possess stiffness and bending strength properties that are intermediate between similar composites prepared with wollastonite and glassfiber reinforcements. It is expected that with continuing research on coupling agents/compatibilizers that significant improvements in mechanical properties, especially tensile strength will be achieved.

Products can be made using co-extrusion (See Figure 7) where the core is extruded with a second coating extruded over the core (Rowell 2007). Most of the properties can be incorporated in the outer coating.

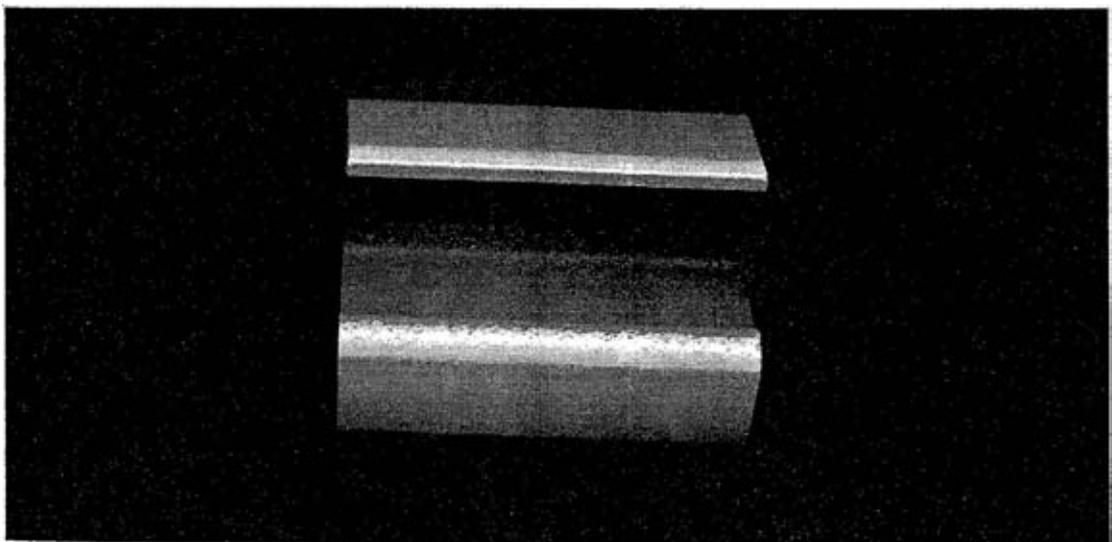


FIGURE 7 - Coextruded wood fiber thermoplastic composite.

MARKETS

The greatest growth potential for WPCs is in building products that have limited structural requirements. Products include decking (See Figure 8), fencing, industrial flooring, landscape timbers, railings, moldings and roofing (See Figure 9). Pressure-treated lumber remains by far the most commonly used decking and railing material (80% of the approximately \$3.2 billion market) but the market for WPC decking is growing rapidly (Smith 2002). Market share grew from 2 percent of the decking market in 1997 to 8 percent in 2001 (Smith 2002), and it is expected to more than double by 2005 (Eckert 2000, Smith 2002, Mapleston 2001e).

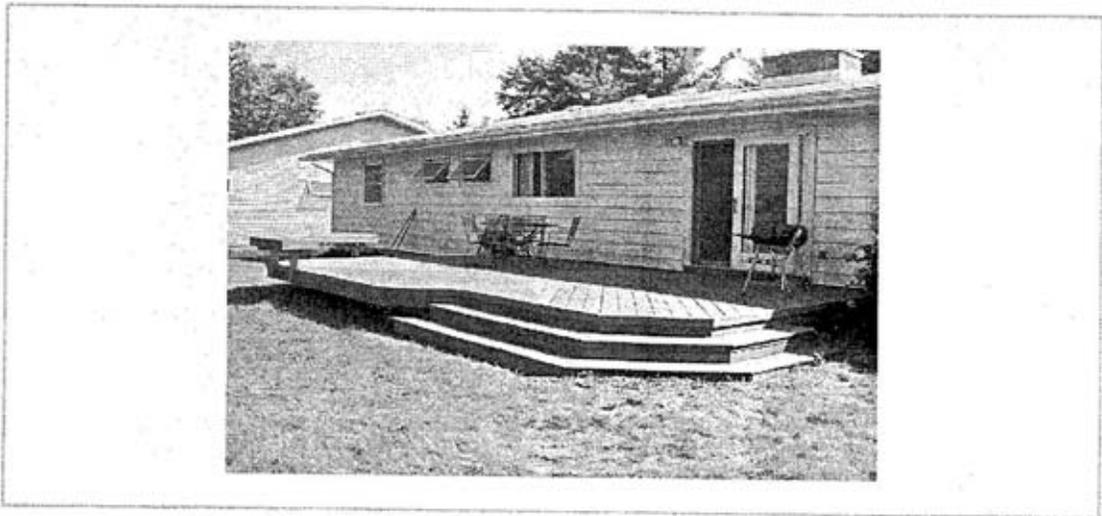


FIGURE 8 - Wood-plastic deck.



FIGURE 9 - Wood fiber plastic roofing tiles.

Although WPC decking is more expensive than pressure-treated wood, manufacturers promote its lower maintenance, lack of cracking or splintering, and high durability. The actual lifetime of WPC lumber is currently being debated; most manufacturers offer a 10-year warranty. Compared with unfilled plastic lumber, the advantages of WPC lumber include increased stiffness and reduced thermal expansion. However, mechanical properties such as creep resistance, stiffness, and strength are lower than those of solid wood. Hence, these composites are not currently being used in applications that require considerable structural performance. For example, WPCs are used for deck boards but not the substructure. Solid, rectangular profiles are manufactured as well as more complex hollow and ribbed profiles. Wood fiber, wood flour, and rice hulls are the most common organic fillers used in decking. About 50 percent wood is typically used, and some products contain as much as 70 percent wood. A polyethylene matrix is used most often, but manufacturers of decking made with PVC and polypropylene have recently entered the market. At least 20 manufacturers produce decking from WPCs; the market is currently dominated by large manufacturers (Smith 2002).

Window and door profile manufacturers form another large industrial segment that uses WPCs. Fiber contents vary considerably. PVC is most often used as the thermoplastic matrix in window applications, but other plastics and plastic blends are also used. Although more expensive than unfilled PVC, wood-filled PVC is gaining favor because of its balance of thermal stability, moisture resistance, and stiffness (Defosse 1999).

Several industry leaders are offering WPC profiles in their product line. Their approaches vary. One manufacturer co-extrudes a wood-filled PVC with an unfilled PVC outside layer for increased durability. Another manufacturer co-extrudes a PVC core with a wood-filled PVC surface that can be painted or stained (Schut 1999). Yet another manufacturer offers two different composites: a wood-filled PVC and a composite with a foamed interior for easy nailing and screwing (Defosse 1999).

In Europe, decks are not yet common and the WPC decking market is in its infancy. However, other product areas are possible. Anti-PVC sentiment (because PVC is a chlorinated compound) and fears over possible legislation are concerning PVC window manufacturers and creating possibilities for replacing PVC with WPCs (Mapleston 2001d). The European market for wood profiles, particularly door frames and furniture, is actively being pursued.

In Japan, promising end uses such as decking, walls, flooring, louvers, and indoor furniture have been reported (Leaversuch 2000). At least one Japanese company is licensing WPC extrusion technology in the United States (Mapleston 2001c).

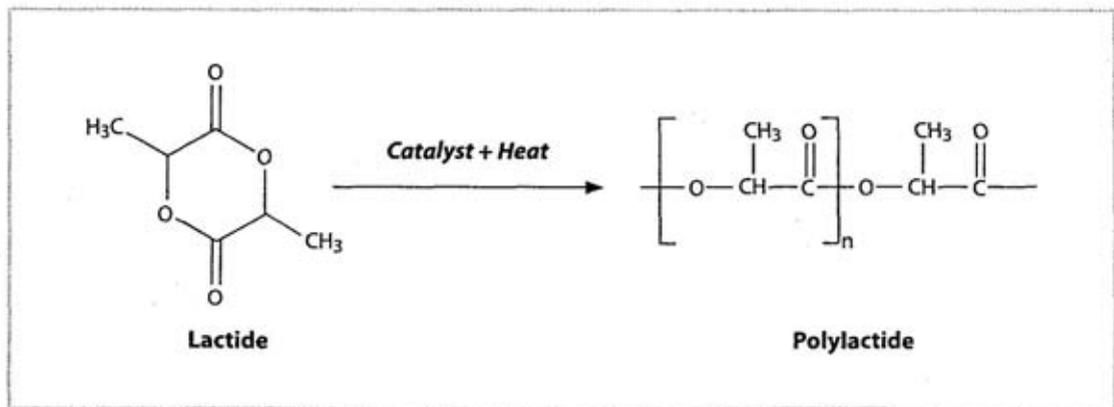
Wood-polypropylene sheets for automobile interior substrates are still made in the United States, but European manufacturers are beginning to use natural fibers other than wood (e.g., kenaf or flax) in air-laid processes. Growth in the use of natural-fiber-reinforced thermoplastics, rather than unfilled plastics, in automotive applications has been slower in the United States than in Europe, where environmental considerations are a stronger driving force. One market analyst cites the lack of delivery channels and high transportation costs as major factors that slow growth in the United States (Eckert 2000). One major

U.S. company has used German technology to produce automotive door quarter panels from natural fiber composites with polypropylene and polyester; the doors achieved a 4-star side impact rating (Manolis 1999). A number of other interior automotive components are being made with similar technology. Nonwoven mat technology have been used to make rear shelf trim panels with flax-reinforced polypropylene (Manolis 1999). Other products being tested include instrument panels, package shelves, load floors, and cab back panels (Manolis 1999).

It is also possible to use very high wood fiber loadings (Seegerholm et al. 2009). Fiber loadings of 70% have been used to make composites with excellent properties. The higher the wood content, the cheaper the composite. It is also possible to use modified wood as part of the wood plastic composite (Westin et al. 2008).

BIODEGRADABLE PLASTIC FIBER COMPOSITES

It is possible to use a biodegradable plastic (see Chapter 7) such as the poly lactides as the matrix polymer (Plackett and Södergård 2005, Ikeda et al. 2008). Polylactic acid or polylactide (PLA) is an alternative to petrochemical-derived products, since the lactides from which it is ultimately produced can be derived from the fermentation of agricultural by-products such as corn starch or other carbohydrate-rich substances like maize, sugar or wheat. This type of thermoplastic offers sustainability, industrial ecology, eco-efficiency, and green chemistry and engineering into the development of a new generation of composites that would be compostable after use. PLA is more expensive than many petroleum-derived commodity plastics, but its price has been falling as production increases. The demand for corn is growing, both due to the use of corn for bioethanol and for corn-dependent commodities, including PLA.



Several forms of polylactide exist: poly-L-lactide (PLLA) is the product resulting from polymerization of L,L-lactide (also known as L-lactide). PLLA has a crystallinity of around 37%, a glass transition temperature between 50-80 °C and a melting temperature between 173-178 °C.

Environmentally friendly wood fiber reinforced poly(lactic acid) (PLA) composites were produced by extrusion followed by injection molding (Misra et al. 2005). PLA/wood fiber composites have mechanical properties are similar in magnitude as conventional thermoplastic composites. The tensile and flexural properties of the PLA/wood fiber composites were significantly higher when compared with the virgin resin. The addition of 20 wt% of wood fibers in PLA/wood fiber composite improved the flexural strength of PLA by 19 %, the flexural modulus by 115 %, and the tensile strength and tensile modulus by 5 % and 77 % respectively. The flexural modulus (8.9 GPa) of the PLA/wood fiber composite (30 wt% fiber content) was comparable to that of traditional polypropylene/wood fiber composites (3.4 GPa). Incorporation of the wood fibers in PLA resulted in a considerable increase of the storage modulus (stiffness) and a decrease in the tan delta values. The addition of the maleated polyolefin coupling agent improved the flexural properties, Izod impact, and heat deflection temperature of the wood fiber reinforced composites. The morphology as indicated by scanning electron microscopy (SEM), showed good dispersion of wood fiber in the PLA matrix. Microstructure studies also indicated a significant interfacial bonding between the matrix and the wood fibers.

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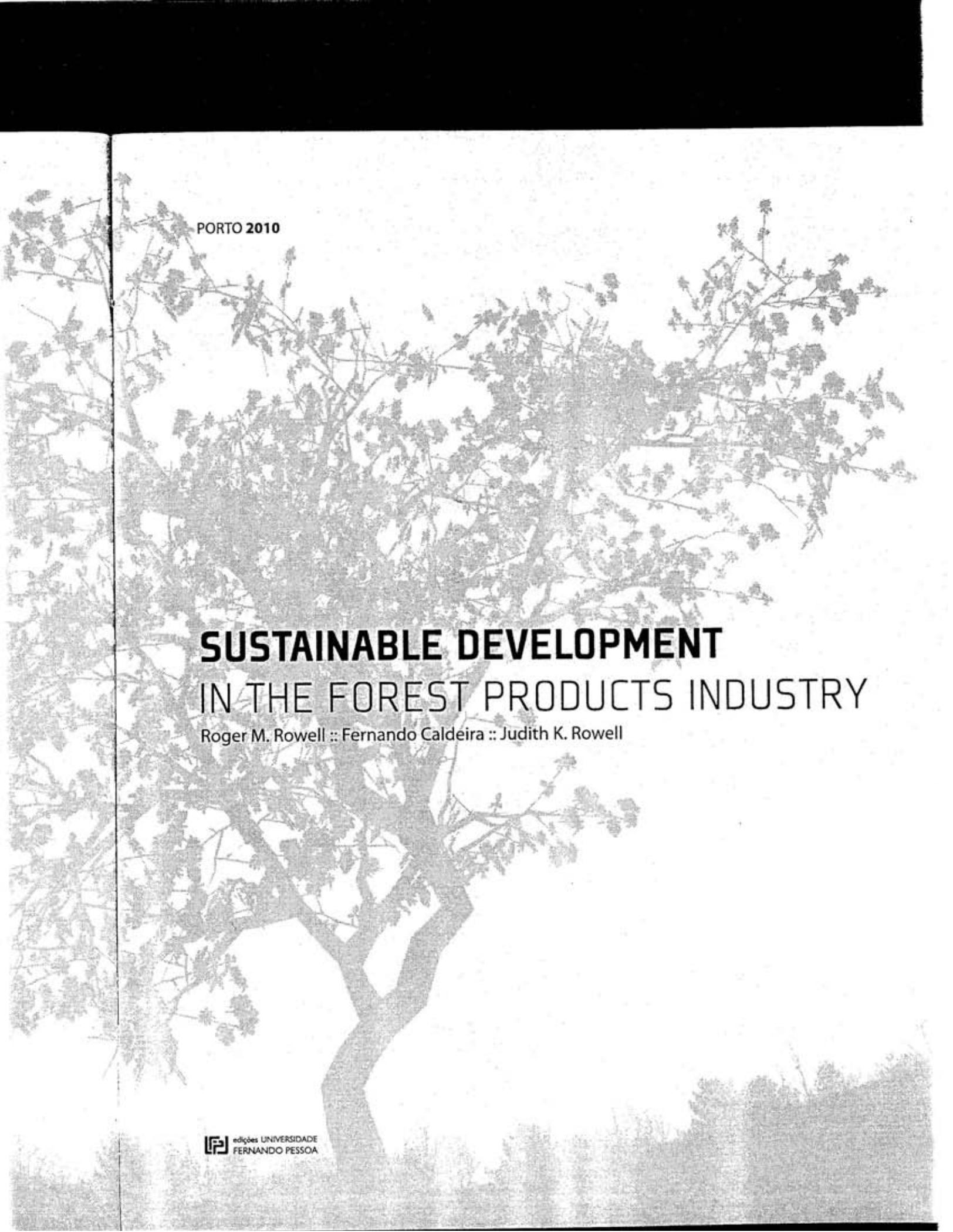
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