CHAPTER 6

Lignocellulosic Composites

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6.1 Introduction

Any substance that contains both cellulose and lignin is a lignocellulosic. Lignocellulosics include wood agricultural crops, like jute or kenaf; agricultural residues, such as bagasse or corn stalks; grasses; and other plant substances. In general, what is true for wood is also true for other lignocellulosics even though they may differ in chemical composition and matrix morphology. Wood is anisotropic (different properties in all three growing directions of a tree). It may contain sapwood heartwood latewood earlywood juvenile wood, and abnormal reaction wood. Wood may also have defects such as knots, cracks, splits, and checks and may be bent, twisted, or bowed. These variations and effects occur in solid wood or lumber but need not exist in wood composites. In a broad sense, a composite can be defined as any combination of two or more materials, in any form, and for any use. In the wood industry, the terms composite and reconstituted wood are usually used to describe any wood product that is "glued" together. The composite products in the wood industry range from fiberboard to laminated beams and structural components.

The objective of composite development is to produce a product with performance characteristics that combine the positive attributes of each constituent component. Like other lignocellulosic material, wood is strong, lightweight, abundant, nonhazardous, and relatively inexpensive. Any lignocellulosic can be chemically modified to enhance properties such as dimensional stability and resistance to biodeterioration. This provides incentive for producing a variety of value-added products from different raw materials combined to provide improvements in cost or performance, or both.

This chapter first briefly reviews various chemical treatments to wood and wood composites. Traditional veneer-, particle-, and fiber-based lignocellulosic composite materials and technology are discussed next. Then, forecasted improvements in existing technology are presented. Greater detail is then presented by reviewing developing opportunities for producing new types of value-added thermoformable lignocellulosic composites using blends of different materials. Current research in this area is illustrated and properties of selected materials are given.

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6.2 Chemical Treatments

Wood is one of the few natural products that humans have used throughout history without modifying its properties. In recent years, however, several treatments have been developed to modify wood for special applications. Chemical modification of wood can be defined as any chemical reaction between some reactive part of a wood cell wall component and a chemical reagent, with or without catalyst, that results in a covalent bond forming between the components. Because the most abundant reactive chemical sites in the wood cell wall polymers are hydroxyl groups, reaction involving hydroxyl reactivity has been most studied.

A USDA Forest Service, Forest Products Laboratory (FPL) report by Rowell and Kondol [1] describes five treatments that alter the physical properties of wood and thus affect its strength, stability, stiffness, and water repellency: (1) treatment of wood with a water-soluble polymer or synthetic resin, (2) compression of wood while heating or curing with resin, (3) heat, (4) bonding of wood cell wall polymers with organic chemicals or cross-linking agents, and (5) polymerization of liquid monomers within wood cell lumens. These treatments will be briefly discussed in the following sections.

Research has demonstrated that it is possible to eliminate or substantially decrease the rate of biodegradation and the dimensional instability of wood by chemically modifying individual cell wall polymer components. Both formaldehyde cross-linking and acetylation research being conducted at FPL and other research institutions provide an excellent opportunity for new specialty product development.

6.2.1 Water-Soluble Polymer or Synthetic Resin Treatment

Polyethylene glycol (PEG) is a white, wax-like chemical that resembles paraffin. Poly-ethylene glycol used for treating wood has an average molecular weight of 1000 (small enough to penetrate the cell wall), melts at 40°C, dissolves easily in warns water, is noncorrosive, odorless, and colorless, and has a very high flash point (305°C).

Polyethylene glycol is usually used with green wood. Pressure is not needed because the treatment is based on diffusion. Polyethylene glycol is dissolved in water at a concentration of 30-50 wt%. Treatment is usually done at temperatures ranging from 20 to 60°C. Diffusion of PEG into wood can be greatly accelerated by increasing the temperature as well as the concentration of the treating solution. Polyethylene glycol is not cured in the wood and remains water soluble. The application of PEG prevents the cracking that frequently occurs in untreated wood.

6.2.2 Compression

Compression of wood while heating or curing with resins greatly improves dimensional stability, strength, and stiffness. The process consists of compressing the wood under conditions that cause sufficient flow of lignin to relieve the internal stresses resulting from

compression. This process greatly reduces the tendency of the wood to swell when wet. Before compression, thin veneers are conditioned to **30–65%** relative humidity. They are then pressed at high pressures at a temperature of 170–177°C. The wood is usually compressed to a specific gravity of at least 1.3.

6.2.3 Heat

Heating wood in a vacuum at high temperatures causes lignin to flow and hemicellulose to decompose, which produces water-insoluble polymers. This treatment increases dimensional stability but decreases strength. The process is done by heating wood at temperatures between 93 and 160°C in a bath of molten lead, tin, and cadmium alloy. This alloy does not stick to the wood. Heating times range from a few minutes to a few hours. Because strength properties are lost in the manufacturing process, heat stabilization of wood using this particular method has not been used commercially.

6.2.4 Bonding of Cell Wall Polymers

The cell wall polymers of lignocellulosics can be permanently bonded by reacting an organic chemical with the hydroxyl groups (bulking agent) or by using a cross-linking agent. These treatments increase dimensional stability but can reduce strength.

Anhydrides, epoxides, isocyanates, acid chlorides, carboxylic acids, lactones, alkyl chlorides, and nitriles have been used for bulking agents. Acetylation of wood with acetic anhydride has undergone the most study. The greatest single application of bonded chemical bulking of the cell wall is in reconstituted products such as fiberboard flakeboard, or particleboard in which standard operating procedures call for dry wood materials and small particle size.

If structural units of the wood cell wall are chemically bound together (cross-linked), the bonds restrain the units from swelling when moisture is present. One of the most widely studied chemical systems for cross-linking is the reaction between wood cell wall hydroxyls and formaldehyde. Cross-linking can take place between the hydroxyl groups on the same or different cellulose, hemicellulose, and lignin polymers. The reaction is usually catalyzed with strong acids. Although formaldehyde cross-linking has been used experimentally to increase the wet strength of paper, commercial applications do not exist at present.

6.2.5 Polymerization of Liquid Monomers within Cell Lumens

In the chemical modifications described so far, most of the chemical resides in the cell walls. The lumens (the spaces enclosed by the cell walls) are essentially empty. Two lumen-fill systems are commercially available: methyl methacrylation and epoxy resin treatment. Both treatments increase strength and stiffness, but neither enhances dimensional stability to any great extent.

At present the main commercial use of methyl methacrylated wood is parquet flooring. Other applications include archery bows, billiard cues, golf clubs, musical instruments, and office equipment. Epoxy resins are used in boat hulls and the outer ply of plywood. Epoxy resin treatments have been used to strengthen soft or decayed wood.

6.3 Types of Commercial Lignocellulosic Composites

Traditional lignocellulosic composites can be placed into three main groups based on particle size: veneer-based, particle-based and fiber-based materials. These groups, and subgroups within them, are important because the smaller the size of the components, the smaller the property variation within the board becomes. For example, plywood is less uniform than waferboard, which is less uniform than particleboard, which is less uniform than fiberboard. Fiberboard whether wood-based or agricultural-based, is made from lignocellulosic fiber. Fiberboards can be very uniform, reproducible, and consistent. A more complete description of the these materials, including strength and property data, is found in the ***Wood Handbook*** [2].

6.3.1 Veneer-Based Materials

Veneer is used to produce a number of glued wood products including structural panels for covering applications, panels for decorative use, and components for structural lumber substitutes such as beams and trusses.

6.3.1.1 Plywood

Plywood is a glued wood panel made up of relatively thin layers of veneer (0.5–5 mm) with the grain of adjacent layers usually at a 90°C angle. The layers vary in number, thickness, and grade, depending on the end-use requirements. Compared with solid wood, the chief advantages of plywood are (1) nearly equal properties along the length and width of the panel, (2) greater resistance to splitting, and (3) capability of manufacture into large sheets. Using plywood results in improved utilization of wood because it covers large areas with a minimum amount of material. The properties of plywood depend on wood species, quality of veneer, order of layer placement in the panel, and type of adhesive used.

6.3.1.2 Laminated Veneer Lumber

Materials made by parallel lamination of veneers into boards with thicknesses common to solid-sawn lumber (19.0–63.5 mm) are called laminated veneer lumber (LVL). Laminated

veneer lumber represents a new technology in wood utilization; the processes and uses for this material are still evolving. The industry presently uses veneers 2.5–3.2 mm thick, which are hot pressed with phenol-formaldehyde adhesive into lengths from 2.4 to 18.0 m or more. In laying up the individual veneers for LVL manufacture, joints, knots, and other flaws are staggered to avoid gross strength-reducing defects.

Some of the first applications of LVL were inspired by rising costs and shortages of high-grade, solid-sawn lumber for parallel-chord trusses and scaffold planks. Truss manufacture found the LVL concept capable of opening new markets. Strength-reducing defects are virtually nonexistent, making possible the use of LVL in light tresses and I-sections. The I-sections have a web composed of a structural panel product, such as plywood or hardboard, glued into a machined groove in the LVL flanges. These I-section beams are currently being used as joists and rafters in light frame construction.

6.3.2 Particle-Based Materials

The class of particle-baaed panel materials includes many subgroups known as chipboard, particleboard, waferboard, oriented strandboard (OSB), and cementboard. In final form, these panel materials retain a few properties of the original wood but because of the manufacturing methods, the panels gain many new and different properties. Unlike solid wood, these manufactured wood products can be tailored to satisfy the property requirements of a specific use or a broad group of end uses.

6.3.2.1 Waferboard and Oriented Strandboard

Two major exterior types of particle panel products are waferboard and oriented strandboard (OSB). Particle sizes range from 25 to 75 mm long by 10 to 30 mm wide by 0.5 to 2 mm thick. In waferboard, the particles are not intentionally oriented, and the board is bonded with an exterior-type resin. Oriented strandboard emerged in the marketplace during the early 1980s. Exterior-type resin is applied to wood strands (long and narrow flakes) that are formed into a mat of the to five layers. The strands in each layer are aligned 90° from the adjacent layer. Strand alignment gives OSB bending properties (in the aligned direction) that are generally superior to those of a randomly oriented waferboard. As with any particle panel product, the properties are highly dependent on the manufacturing process. The properties of waferboard and OSB make them suitable for many applications now dominated by softwood plywood.

6.3.2.2 Particleboard

The particle panel product that is typically made from small wood particles of mill residue such as sawdust, shavings, or flakes, or from lignocellulosic particles like rice hulls, is designated particleboard. Particleboards are difficult to categorize because of the infinite number of processing variables used to manufacture the product.

6.3.2.3 Cementboard

Portland cement is commercially used as a binder for a special class of lignocellulosic particle panels called cementboards. The wood particles typically used are called excelsior, or wood-wool, because they are long (up to 250 mm) and stringy. Medium- to lowdensity wood species are reduced to excelsior, blended with cement, formed into mats, and pressed to a density of 480 to 640 kg/m^3. Other nonwood lignocellulosics are used in the production of cementboard and include bagasse, rattan, and coconut husk fiber. The processing for these lignocellulosics is very similar to that of wood-wool. A common use for cementboard is roof decking because of its sound-absorbing and fire-resistive properties. Other cement-bonded particle products include building blocks and panels made with flakes that can be used in doors, flows, load-bearing walls, partitions, concrete forms, and exterior siding.

6.3.2.4 Fiber-Based Panel Materials

These panel materials are all made from reconstituted wood or other lignocellulosics like bagasse. The wood is first reduced to fibers or fiber bundles and then put back together by special forms of manufacture into panels of relatively large size and moderate thickness.

Properties of fiber-based panel products are determined according to American National Standards Institute (ANSI) standards, and to a considerable extent, these properties either suggest or limit their uses. In the following sections, fiber-based panel materials are divided into various categories by manufacturing process, properties, and use.

6.3.2.5 Insulation Board

This is a generic term for a homogeneous panel that is made from wet-formed, interfered lignocellulosic fibers (usually wood or bagasse). The panels are consolidated under heat and pressure to a specific gravity range between 0.16 and 0.50. There are many different types, names, and uses of insulation board.

6.3.2.6 Medium-Density Fiberboard

Medium-density fiberboard (MDF) is manufactured from lignocellulosic fibers usually combined with a synthetic resin or other suitable binder. Specific gravity values for MDF range from 0.60 to 0.80. The technology utilized to manufacture MDF is a combination of that used in the particleboard and hardboard industry.

The furniture industry is by far the dominant MDF market. Medium-density fiberboard frequently takes the place of solid wood, plywood, and particleboard for many furniture applications. Compared to particleboard, MDF has a very smooth surface, which facilitates wood-grain printing, overlaying with sheet materials, and veneering. Medium-density fiberboard has tight edges, which need not be banded, and can be routed and molded

like solid wood. Wood-grain printed and embossed, MDF is used in many furniture lines. The potential for MDF in other interior and exterior markets such as doors, moldings, exterior trim, and pallet decking is currently being explored by the industry, Many industry people expect MDF markets will expand significantly during the next decade.

6.3.2.7 Hardboard

Hardboard is a generic term for a panel that is manufactured primarily from wet- or dry-formed, interfelted lignocellulosic fibers and has been consolidated under heat and pressure to a specific gravity of 0.50 to 1.45. Hardboards are classified by density, surface finish, thickness, and minimum physical properties.

The uses for hardboard are diverse, but they generally can be subdivided according to uses developed for construction, furniture and furnishings, cabinet and store fixture work appliances, and automotive and rolling stock. Much of the recent success of hardboard resulted from the development of products for a specific use and the specifications of treatments, fabrication, and finishes for each product. Typical hardboard products are prefinished paneling, house siding, floor underlayment, and concrete form hardboard.

6.4 Promising Technological Improvements

Intense competition among various products has long typified the North American materials industries. Although this competition is generally recognized by those working in the materials field, occasionally reviewing developments of the recent past is worthwhile because they provide some perspective about the future. In each of the following categories, only one or two specific examples of possible future changes are listed. In most instances, many more examples could be cited.

6.4.1 Adhesives

The economic health of the wood products industry in North America is controlled to a great extent by the rate of housing construction which in turn is controlled by the health of the overall U.S. economy and by demographics. Within the wood products industry, the greatest use of wood adhesives by far is for manufacturing wood composites [3].

What can be said about wood adhesives in the future? New technologies and new products are continually being introduced. In addition, using low-quality, forest-derived materials more efficiently and cost effectively is a possibility. Expectations are that urea-formaldehyde and phenol-formaldehyde systems will continue to be the dominant wood adhesives in the United States. Two uncertain areas are the possibility of much more stringent regulation of formaldehyde-containing products and the possibility of limitations or

interruptions in the supply of petrochemicals. One result of these uncertainties is that considerable research has been conducted in the area of developing new wood adhesive systems from renewable resources.

Although research results have indicated that a number of new adhesive systems have promise, their commercial use is currently very limited, One example is the use of isocyanate adhesives. The slow adoption of this material is due to the relatively high cost and toxicity concerns. This material does have some definite advantages, including rapid cure at moderate temperatures, insensitivity of cure to moderately high moisture, good durability, and the absence of formaldehyde emissions. Another relatively recent innovation is the use of a two-part adhesive system that allows plywood to be bonded at 12–13% moisture content or higher compared to the previously required moisture content of 3 4%. The use of foamed adhesives for bonding plywood is also becoming more widely used. In addition, the amount of adhesive being applied can be better controlled, leading to a 20–30% savings in adhesive use.

6.4.2 Steam and Chemical Injection

A steam injection process has been developed that reduces press times for flakeboard, particleboard, and medium-density fiberboard production [4]. The process begins by coating wood flakes with a resin and forming them into a mat. The mat is then loaded into a press and a burst of saturated steam is injected into it through perforated platens. Within several seconds, the temperature in the center of the board rises to approximately 104°C. As the board is compacted, the internal pressure increases, allowing the temperature in the center of the board to rise to between 138 and 157°C. This high temperature accelerates the resin cure. Several seconds after the end of the steaming period, the temperature falls to about 107°C and stabilizes there for the remainder of the press cycle. A computer used to control the steam injection schedule also monitors the rapidly changing press operation. It records time, temperature, and several other variables at 0.5-s intervals.

Research conducted at FPL indicated that press time for a 13-mm-thick board can be reduced from 4.5 min to about 90 s. Also, the 45 min needed to conventionally press a 50-mm-thick board can be reduced to less than 5 min with steam injection.

The new process uses smaller equipment and less energy than conventional pressing methods. Steam injection also offers the possibility of injecting chemical additives that increase the durability and fire resistance of the board. The development of steam injection pressing and the techniques for understanding the fundamental relations governing the chemistry and physics of resin cure and wood bonding during hot pressing will provide a rational basis for designing improved structural composites with controlled densities and density profiles.

6.4.3 Structural Paper Products

Researchers at FPL have developed a structural fiber concept called Spaceboard [5]. To make this three-dimensional structural board, wet fibers are press dried against rubber molds

with wafflelike configurations to produce symmetrical halves. An adhesive is used to bond the halves, creating numerous small, shaped cells in the center of the board. Using this technique, Spaceboard can be made as a laminate or a sandwich. It can be thin enough for strong, lightweight corrugated containers or thick enough for wall sections. The result is a fiber composite structural material that is strong in every direction.

Laboratory tests show that Spaceboard is between 30 and **200**% stronger than conventional corrugated fiberboard. Its strength is due to the special configuration of the core and the superior strength imparted by the press-dry method that molds the core and facing together.

6.4.4 Surface Treatments

Wood finishing research is stimulated by the lack of detailed knowledge about fundamental chemical and physical factors that affect the performance of exterior finishes on different wood species, composites, and new wood-based products. Further complicating the problem is the wide range of new finishing materials being applied to the new wood-based substrates. Problems with substrate-finish durability sometimes result with these new materials. The increasing use of wood treated with preservative or fire retardant poses special challenges to the use of exterior wood finishes. Finish durability problems may be further compounded by environmental concerns and restrictions on traditional paint and stain systems and by restrictions on paint additives. The following technical challenges and problems will be significant to the future of finished wood for exterior use:

1. New wood species will be used, and the use of composites and overlays will increase (changing substrates).
2. Use of waterborne finishes, finishes with higher solids contents, finishes incorporating low-volatility organic compounds, and new multipurpose resins for new finishes will increase (changing finishes).
3. New chemicals will be used for mildew and mold control.
4. Use of factory finishing will increase.
5. Environmental restrictions on many finish components will increase.
6. Safety and health concerns will increase.

Continuing research on wood finishing and weathering will focus on demonstrating the wide range of performance of several wood and wood-based panel products, depending on which pretreatment-primer-finish systems are used. Included in the research will be several new finish materials and new wood composite materials that are being introduced in the commercial market [6].

6.4.5 Thermoformable Lignocellulosic Composites

Thermoformable composites are classified into two general types based on the manufacturing process. Both processes, melt-blending and air-laid mat formation, allow and require differences in composition and the lignocellulosic component.

Currently, the primary application of thermoformed composites, both melt-blended and air-laid, is for interior door panels and trunk liners in automobiles. Additional large-volume, low-to-moderate cost applications are expected in areas such as packaging (trays and cartons), interior building panels, and door skins.

Researchers are virtually certain that virgin ingredients can be replaced by some recycled ingredients in melt-blending and air-laid mat formation for many applications. For example, the thermoplastic polymer might be totally or partially replaced by high-density polyethylene (HDPE) from milk bottles, polyethylene terephthalate, or polyester, (PET) from beverage bottles, or even nonsegregated plastic mixtures from municipal solid waste. Large quantities of a variety of industrial waste plastics are also available and should be considered. The virgin lignocellulosic component might be replaced by fibers from wastepaper or waste wood. These substitutions offer potential benefits in reducing both the municipal solid waste stream and the cost of the composites. In some cases, the properties of the composite will probably be improved; for example, by substituting wastepaper fibers for wood flour in the melt-blending process. Specific research in this area will be presented later in this chapter.

6.4.6 Additional Comments

A revolution appears to be underway in the structural panel products business with significant changes being made in production of plywood and the development of waferboards, oriented strandboards, and other types of composite panels. Current production trends clearly indicate increased use of both structural and nonstructural wood-based composite panels for many applications. Structural lumber substitutes, combinations of wood and nonwood materials, and combinations of panels with lumber substitutes are being made into components and are seen as a growing business that will reach commodity proportions in the near future.

6.5 Melt-Blended Composites

Lignocellulosic fillers are regularly used in plastics to make composite materials. Thermo-setting plastics have been filled with wood flour since the turn of the century The fillers have served mainly as extenders to the more expensive plastic resins. Recent developments have increased the interest in using wood flour and fibers as both fillers and reinforcements in thermoplastics.

Thermoplastics can usually be filled to about 60 wt% before limits on viscosity are reached. Thermoplastics with relatively low melting points (polypropylene, polythylene, etc.) are used because the thermodegradation of lignocellulosics begins at around 200°C. In the melt-blending process, the lignocellulosic-based fiber or flour is blended with the melted thermoplastic matrix by high-intensity shearing or kneading. Currently, the primary commercial processes employ twin screw extruders or high shear thermokinetic type

mixers. The mixture is extruded into sheets or pelletized for subsequent operations. Fiber length is limited by fiber breakage as a result of the high shear forces during melt-blending.

Publications are appearing that address the effect of recycled ingredients on the behavior of melt-blended lignocellulosic polyolefin composites. For example, Selke and others [7] showed that composites from aspen fiber and once-recycled blow-molding HDPE from milk bottles possessed essentially equivalent strength and modulus properties as those of composites made from virgin HDPE; however, impact energy was reduced [8]. Woodhams and others [9] found that composites made from polypropylene and pulp fibers or fiberized old newspaper possessed strength and impact properties very similar and apparently much superior to those of composites made from wood flour polypropylene systems.

6.5.1 Properties of Selected Melt-Blended Composites

Many composite scientists believe melt-blending is an area with great opportunity in thermoformable wood plastic composites. Both recycled and virgin materials are being studied. Research in this area has focused on the effects of process parameters, composition, product properties, and coupling agents.

Melt-blending provides options for balancing performance properties and costs. However, poor attraction and low interfacial bonding between the hydrophilic wood and the hydrophobic polymer limit the reinforcement imparted to the plastic matrix by the wood component. This reinforcement could be enhanced if the polar nature of the cellulosic surface were modified so that the wood surface characteristics were more compatible with the nonpolar nature of the polymer matrix. One approach to developing greater comparability is to use a coupling agent that possesses a dual functionality, enabling it to interact or react with both components [10].

The primary commercial product made by melt-blending is an extruded blend of 50% virgin polypropylene (PP) and wood flour (WF). Early research findings at FPL (unpublished) and at the University of Toronto [9] showed that certain properties could be increased by substituting old newspaper fiber or cellulose fiber for the wood flour. Research was conducted at FPL to determine this effect more thoroughly, as well as to determine the effect of coupling agents and the use of recycled HDPE [11]. A brief discussion of this work follows.

The PP was Fortilene 1602 from Solvay Polymers, Inc.* (Deer Park, TX). The HDPE was recycled from milk bottles. The wood flour was western pine [-40, +80 mesh (-420, + 177 μm)] from American Woodfiber Co (Schofield, WI), Cellulose fiber was Solka-Floc BW-40 from James River Corp. (Hackensack, NJ). The old newsprint (ONP) was hammermilled to 15-mm flakes. The coupling agent was E-43 powder, a maleated PP, obtained from Eastman Chemical products., Inc. (Kingsport, TN).

A 1-liter thermokinetic high shear mixer (K-mixer) was used to blend the composites. Component ratio for all of the composites was 57.5% polymer, 37.5% filler, and 5% coupling agent. Each filler was mixed alone for 1 min. The polymer and coupling agent were

* The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

then added and mixed for an additional minute. The HDPE composites were ejected from the K-mixer at a temperature of 185°C at 2800 rpm. The PP composites were ejected at 200°C at 3000 rpm. The material was then injection-molded and the specimens were tested according to ASTM standards. Results are shown in Table 6.1.

6.5.2 Additional Comments

Addition of fillers to polymers has a significant negative effect on unnotched impact strengths. In most cases, the tensile strength values are improved over the unfilled polymer. With either polymer, both the BW-40 fibers and the ONP fibers result in greater tensile properties of composites than does the wood flour. However, the filler fibers increase the impact energy with PP but decrease the impact with HDPE. This difference may be because of better compatibility of the coupling agent with PP than with HDPE. Consistent with the properties of the unfilled polymers, the filled PP composites has higher tensile strength and modulus and lower notched impact energies than does the filled HDPE composites.

Table 6.1 Mechanical Properties of Selected Melt-Blended Composites Using E-43 a Coupling Agenty and of Two Unfilled Virgin Polymers

| Polymer | Filler | Izod impact energy (J/m)[a] | | Tensile tests[b] | |
		Notched	Unnotched	Modulus (GPa)	Strength (MPa)
Virgin polypropylene	WF	18.7	72 3.72	34.1	
Recycled high-density polyethylene	WF	36.4	81	2.60	27.7
Virgin polypropylene 48.2	BW-40		24.7	114	4.80
Recycled high-density	BW-40	30.7	68	3.78	36.3
Virgin polypropylene	ONP	20.8	109	4.89	47.1
Recycled high-density polyethylene	ONP	28.6	73	3.79	37.6
Virgin polypropylene[c]	None	16.0	640	—	33.1
Virgin high-density polyethylene[c]	None	130.0	—[d]	—	29.6

[a] ASTM D 256-84[12]
[b] ASTM D 638-84[13]
[c] Data from manufacturers
[d] Data not available

6.6 Air-Laid Mat Technology

In contrast to melt-blending, air-laid mat technology involves room temperature air mixing of lignocellulosic fibers and fiber bundles with thermoplastic fibers or granules. The resultant mixture passes through a needling step that produces a low-density mat in which the fibers are mechanically entangled. The mat is then shaped and densified by pressing in a heated mold or between flat plattens, With this technology, the amount of lignocellulosic fiber can be greater than 90 wt%. in addition, the lignocellulosic fiber can be precoated with a thermosetting resin, like phenol-formaldehyde. After pressing, the product with thermo-setting resin possesses good temperature resistance. Because longer fibers are required, the air-laid product can achieve better mechanical properties than that obtained with the melt-blending process. However, high wood fiber content leads to increased moisture sensitivity.

Numerous articles and technical papers have been written and several patents have been issued on both the manufacture and use of air-laid mats containing combinations of textile and cellulosic fibers. This technology is particularly well known in the consumer products industry. For example, Bither [14] found that polyolefin pulps can serve as effective binders in air-laid products.

6.6.1 Properties of Selected Air-Laid Composites

The Forest Products Laboratory has made and tested a wide variety of air-laid composite materials. These materials include both recycled and virgin wood fibers, recycled and virgin synthetic fibers, agricultural fibers, phenolic powders, and plastic granules. Almost any dry fiber can be air laid into a mat that can be subsequently pressed into a panel or molded shape. Another advantage of this process is that the properties of the composite can be tailored to many end uses. For the purpose of this chapter, only a brief discussion will be offered on several selected materials.

A comparison was made between two wood fibers derived from virgin western hemlock *(Tsuga heterophylla)* and recycled demolition wood. The wood fibers were blended with either recycled or virgin PET fibers and a phenolic resin.

Hemlock wood fibers, obtained from Canfor, LTD (Vancouver, B.C.), were produced from 100% pulp-grade chips, steamed for 2 min at 0.759 MPa, disk refined, and flash dried at 160°C in a tube dryer. This processing sequence produced fibrous strands made of individual fibers, pieces of fiber, and fiber bundles. In this chapter, these fibrous strands are referred to as fibers. The demolition wood fiber, obtained from Wood Recycling, Incorporated (Peabody, MA) was prepared from demolished houses taken from the Boston, Massachusetts, area. The demolition waste was shredded, hammermilled, and cleaned before it was pressure refined in a manner similar to the hemlock.

Two types of PET fibers were obtained from commercial sources. The virgin fibers were 5.5 denier (6.1×10^7 kg/m), 38 mm long, and crimped and had a bonding at greater than 215°C. The recycled fibers were of a similar configuration. The phenolic resin had a solids content of 52%, a viscosity of 50 to 100 cps (0.05–0.1 Pa-s) at 25°C, and a pH of 9.5–10.0.

The processing began by spraying the phenolic resin onto the wood fibers at a 10% weight basis. The wood and plastic fibers were then mixed by passing them through a spiked drum, transferred through an air stream to a moving support bed, and subsequently formed into a continuous, low-density mat of intertwined fibers. The mat then went through a needling process where barbed-shank needles passed through the mat thickness, and in so doing, increased the interlocking of the fibers. The mats were 330 mm wide and of various lengths. The mats were then cut into 330- by 330-mm squares. The squares were stacked to get the target specific gravity. A manually controlled, steam-heated press was used to press all panels at 190°C to a thickness of 3.2 mm and a specific gravity of 1.0.

Panels were conditioned at 65% relative humidity at 20°C. After conditioning, the panels were cut into test specimens and tested in conformance with ASTM D 1037-87 [15] (for static bending, tensile, water soak (water absorption and thickness swell), and linear expansion. lmpact testing was done in accordance to TAPPI T-803 om-88. Results are shown in Table 6.2. The ANSI minimum standards are included as a point of reference [16].

Table 6.2.   Mechanical and Physical Properties of Air-Laid Composites from Recycled and Virgin Materials[a]

Property	Composite (10% resin)				ANSI standard
	80% Hem		80% Demo		
	10% V-PET	10% R-PET	10% V-Pet	10% R-Pet	
Static bending modulus of rupture (MPa)	50.6	41.1	43.2	47.8	≥31.0
Static bending modulus of elasticity (GPa)	3.66	4.36	3.23	3.74	—
Tensile strength (MPa)	33.0	28.4	28.3	30.0	15.2
Tensile moduls of elasticity (GPa)	4.84	5.12	4.26	4.56	—
Impact energy (J)	36.1	28.7	34.2	30.7	—
Water-soak 24-h water absorption (%)	43.4	41.3	48.3	44.1	≤35.0
Water-soak 24-h thickness swell (%)	25.2	22.3	29.8	26.9	≤25.0
Linear expansion overdried to					
30% RH (%)	0.25	0.21	0.20	0.20	—
65% RH (%)	0.46	0.44	0.43	0.45	—
90% RH (%)	0.65	0.70	0.64	0.71	—

[a] Hem, bemlock; Demo, demolition wood; V-PET, virgin polyester; R-PET, recycled polyester; —, no applicable standard; RH, relative humidity

The above composite materials exceeded the ANSI national standards for basic hardboard strength properties. Except for the **80% Hem, 10%** R-Pet formulation, none of the specimens met standards for water absorption or thickness swell. The addition of a small amount of wax (a standard procedure in the hardboard industry) may improve these values. Some debate exists about the applicability of hardboard standards for wood fiber plastic composites. Since the composites in Table 6.2 closely resemble hard-board, ASTM testing methods were used to determine their properties, and ANSI standards were used for evaluation.

6.6.2 Additional Comments

Air-laid mat technology permits the use of a wide range of lignocellulosic and synthetic fibers. The lignocellulosic components can range from recycled or virgin wood materials to agricultural fibers. The lignocellulosic component can be chemically modified to improve the performance of the composite in adverse conditions, as appropriate. Products can be made from **100%** plastic fibers, **100%** lignocellulosic fibers, or many different combinations of the two materials. Thermosetting resins can be either coated on the lignocellulosic fibers or added in powder form during web formation. Additionally, granulated plastics may be added.

6.7 Concluding Remarks

Lignocellulosics will be used in the future to produce a wide spectrum of composite products ranging from very inexpensive, low-performance materials to materials that are relatively expensive and have high-performance characteristics. Taking advantage of the wide distribution, renewability, and recyclability of lignocellulosics, more markets will develop for low-cost renewable materials. By chemically modifying the lignocellulosic cell wall to overcome some of its disadvantageous properties, new markets for high-performance composites will develop.

Combining lignocellulosics with other materials provides a stategy for producing advanced composites that take advantage of the enhanced properties of all types of materials. Lignocellulosic composites allow scientists to design materials based on end-use require-ments within the framework of cost, availability, renewability, recyclability, energy use, and environmental   considerations.

Acknowledgments

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