CHAPTER 8

Processing into Composites

Brent English, Poo Chow, and Dilpreet Singh Bajwa

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1. INTRODUCTION

Globally, many lignocellulosic fiber options exist for the production of composite products. A literature search was conducted at the USDA Forest Service, Forest Products Laboratory to survey the worldwide use of agricultural fibers in composite building products. A total of 1,039 citations were selected from the vast number available. Youngquist et al. (1993a) summarized the work on composite products from agricultural fibers and part of this report was used here.

2. CHARACTERISTICS OF LIGNOCELLULOSIC COMPOSITES

In a broad sense, a composite can be defined as any combination of two or more resources, in any form, and for any use. For the purposes of this discussion, the term "composite" describes two situations. The first is when the lignocellulosic serves as the main ingredient in the composite. The second is when the lignocellulosic serves as a reinforcing filler or aggregate within a matrix material. Whatever scenario is used, the objective of composite development is to produce a product whose performance characteristics combine the beneficial aspects of each constituent component.

2.1 General Manufacturing Issues

Successful manufacture of any product requires control over raw materials. Ideally, raw materials are uniform, consistent, and predictable. Lignocellulosics do not offer these qualities but instead vary widely between species. Plants of the same species also have differences. Plant stems differ from leaves, which differ from seed husks. Within the bast fibers differ greatly from pith fibers; even the harvest time affects fiber quality.

For the purpose of producing a composite product, uniformity, consistency, and predictability are accomplished by reducing separated portions of the plants into small, relatively uniform and consistent particles, or fibers where effects of differences will average out. Depending on the lignocellulosic material, size reduction is sometimes augmented by chemical treatments designed to weaken the bonds between the components. The degree of size reduction and the shape of the individual lignocellulosic component will depend on the application. Different composites tolerate or demand different sizes and shapes.

Another limiting factor in the use of agro-based resources for large scale industrial purposes is bulk density. Low bulk density can significantly increase transportation costs. For instance, chunked wood (sawed into short lengths and stacked) has a dry basis gross bulk density of 240-320 kg/m^3. In the United States, the economics of processing and transporting wood with such bulk density indicate a practical procurement radius of about 65 km (Vaagen, 1991). In contrast, annual fiber stems of a plant such as kenaf or straw cannot be compacted much beyond 135 kg/m^3, which may limit the feasible supply basin to a range of 25-35 km (Sandwell, 1991).

2.2 General Lignocellulosic Composite Classifications

While there is a broad range of lignocellulosic composites, and many applications for them, for the purposes of this chapter they will be grouped into three general categories. Complete books have been written about each of the categories, and the constraints of this chapter necessitate that our discussion be general and brief. References are provided to lead the reader to more detailed information.

The first category of lignocellulosics that we discuss is that of conventional composites. Conventional composites are already in the marketplace with a high degree of customer acceptance. Here, the lignocellulosic serves as the main ingredient, and a small percentage (generally less than 10%) of a heat-curing adhesive holds the composite together. Particleboards and fiberboards are common examples of this type of lignocellulosic composite.

The second classification is that of inorganic-bonded composites. In these composites, inorganic materials like gypsum or Portland cement hold the composite together. The lignocellulosic might be the main ingredient or serve as an aggregate.

The third composite classification to be discussed here is that of lignocellulosic/thermoplastic composites. In this class, the lignocellulosic can serve as a reinforcing filler in a thermoplastic matrix, or conversely, the thermoplastic may serve as a binder to the lignocellulosic.

Whether used as the main ingredient of the composite or used as a reinforcing filler, much of the raw material factors are the same. Some of these are discussed in the next section, followed by individual sections on conventional panel type composites, inorganic-bonded composites and lignocellulosic/thermoplastic composites.

3. RAW MATERIALS: CHARACTERIZATION, STORAGE, AND PREPARATION

Agro-based lignocellulosics suitable for composites stem from two main sources. The first is agricultural residues. These materials, like rice husks or cereal straws, are the by-products of food or feed crops. While value-added used are found for portions of some of these residues, most are used for more mundane purposes like animal bedding or fuel. Others are simply left on the field or burnt to reduce mass. The second class is those lignocellulosics grown specifically for their fiber. Two examples are jute and kenaf. These plants also have residues, which are often used for bedding or fuel as well.

Technically speaking, almost any agricultural fiber can be used to manufacture composition panels. However, it becomes more difficult to use certain kinds of fibers when restrictions in quality and economy are imposed. The literature has shown that several kinds of fibers have existed in sufficient quantity, in the right place, at the right price and at the right time to have merited at least occasional commercial use. While others may exist, we choose to discuss bagasse, cereal straw, coconut coir, corn stalks, cotton stalks, jute, kenaf, and rice husks. The remainder of this section briefly addresses the issues of fiber harvesting, storage, and fiber preparation to use these fiber sources in composite production.

3.1 Bagasse

Bagasse is the residue fiber remaining when surgarcane is pressed to extract the sugar. Some bagasse is burned to supply heat to the sugar refining operation. some is returned to the fields, and some finds it way into various board products. Bagasse is composed of fiber and pith. The fiber is thick walled and relatively long (1-4 mm). For use in composites, fibers are obtained mostly from the rind, but there are fibrovascular bundles dispersed throughout the interior of the stalk as well (Hamid et al., 1983). In what could be considered a definitive work. Atchinson and Lengel (1985) told of the history and growth of bagasse fiberboard and particleboard at the 19th Washington State Particleboard Symposium. Their paper describes the various success and failure stories of bagasse utilization in composite panel production.

Bagasse is available wherever sugarcane is grown. As such, almost no harvesting problems exist, and large volumes are available at sugar mills. In northern climates, the cane harvest usually lasts about 2.5 months. In warm climates, bagasse may be available for as long as 10 months out of the year. During this time, bagasse supply is relatively constant: the remainder of the year, it must be stored. Special care must be taken during storage to prevent fermentation bagasse does have a high sugar content. To reduce the sugar content and increase storage life, bagasse is usually depithed before storage. The pith is an excellent fuel source for the sugar refining operation. Generally, if the bagasse is depithed, dried, and densely baled it can be stored outside handled in a careful manner, bagasse can also be stored wet. In the wet method large bales of bagasse are specially fabricated and stacked to insure adequate air flow. Heat from fermenting sugars effectively sterilizes the bales. Bagasse can be stored for several years using this method (Chapman, 1956). Other storage options are available, including some that keep the bagasse wet beyond the fiber saturation point.

As previously mentioned, only bagasse fiber is utilized for the production of high-quality composition panels. Various schemes are available to separate the bagasse fiber from the pith, some of which are described in Chapter 6. The fibers after depithing are more accurately described as fiber bundles that can be used "as is" to make particleboard, or they can be refined to produce fibers for fiberboard. Recently, the Tilby process (Sugartree, 1992) has been developed for the separation of the bagasse fiber and pith before the stalk is crushed to extract the juice. This system uses rollers to flatten and then guide the stalk over blades that cleanly separate the two materials. It is claimed that reclamation is increased for both the fiber and the juice.

3.2 Cereal Straw

After bagasse, cereal straw is probably the second most important agricultural fiber for composite panel production. For the purpose of this paper, cereal straw is meant to include straw from wheat, rye, barley, oats, and rice. Straw, like bagasse. is an agricultural residue. Unlike bagasse, large quantities of cereal straw are generally not available at one location. Storage is usually accomplished by bailng. The bales must then be transported to a manufacturing facility. Straws have a high ash content thus tending to fill fireboxes in boilers. Their high inherent silica content results in increased tool wear compared to other lignocellulosic composites. Conversely, the high silica content also tends to make them naturally fire-resistant.

Plants have existed in several countries to make thick (5-15 cm) straw panels with kraft paper faces (UNIDO, 1975). The panels are made by heating the straw to about 200°C, at which point springback properties are virtually nil. The straw is fed through a reciprocating arm extruder and made into a continuous low density (0.25 specific gravity) panel. Kraft paper is then glued to the faces and edges of the panels. These panels can then be cut for prefabrication into housing and other structures. The low density of these panels makes them fairly resilient, and test data show that housing built using these panels is especially earthquake resistant. In the 1980s, such a plant was set up in California to produce straw panels from wheat and rye straw (Galassco, 1992).

Straw can be used to supplement part of the fiber content in wood particleboard. A large particleboard plant in the United States, located in La Grande, Oregon, substituted straw at a rate of 8% and found no major problems except that the sander dust from the faces deposited additional ash in the boiler. This plant then stopped using straw in the face and used it only in the core. At a rate of 10% or less, the effect on tool wear was not significant (Knowles, 1992).

The time of harvest for the straw is important to board quality (Rexen, 1977). The quality of the straw is highest when the grain is at its optimum ripeness for harvesting. Under-ripe straw has not yet yielded its full potential, and over-ripe straw becomes brittle. For praticleboards, straw is reduced by hammer milling or knife milling. For the production of fiber-based products, straw can be pulped by using alkali treatments and refining (see Chapter 6). Ryegrass straw particleboard was commercially produced in the United States in Oregon (Loken et al., 1991).

3.3 Coconut Coir

coconut coir is the long fiber (15-35 cm) from the husk of the mature coconut and the average husk weighs 400 grams (Singh, 1979). Coir is a fiber source for many cottage industries and it is readily woven into mats and made into ropes and other articles for both domestic use and export.

Coir has been used to produce a variety of composite products including particleboards and fiberboards. When used as a reinforcing fiber in inorganic-bonded composites, coir is very resistant to alkalinity and variations in moisture, when compared to other lignocellulosics (Savastano, 1990).

3.4 Corn Stalks

Based on our literature search, there is currently no commercial utilization of corn stalks or cobs in lignocellulosic composite production. However, a low-density insulation board was produced in Dubuque, Iowa for several decades in the middle of this century. In addition, a three-layer board having a corn cob core and wood veneer face was produced for a short time in Czechoslovakia after World War II (UNIDO, 1975).

Corn stalks, like many agricultural fiber sources, consist of a pithy core with an outer layer of long fibers. Currently in the United States, corn stalks are chopped and used for forage, Left on the field, or baled for animal bedding. The cobs are occasionally used for fuel. Research shows that corn stalks and cobs can be made into reasonably good particleboard and fiberboard (Chow, 1974). In the research, corn stalks and cobs were either hammermilled into particles or reduced to fibers in a pressurized refiner.

3.5 Cotton Stalks

Cotton is cultivated primarily for textile fibers, and little use is made of the cotton plant stalk. Stalk harvest yields tend to be low and storage can be a problem. The cotton stalk is plagued with parasites, and stored stalks can serve as a breeding ground\ for the parasites to winter over for next year's crop. Attempted commercialization of cotton stalk particleboard in Iran was unsuccessful for this reason (Brooks, 1992).

If the parasite issue could be addressed, cotton stalks could be an excellent source of fiber. With respect to structure and dimensions, cotton stalk fiber is similar to common species of hardwood fiber (Mobarak and Nada, 1975). As such, debarked cotton stalks can be used to make high grades of paper. The stalk is about 33% bark and quite fibrous. Newsprint quality paper can be made from whole cotton stalks. For particleboard production, cotton stalks can be hammermilled like other materials. For fiberboards, cotton stalks can be refined with or without chemical treatment, depending on the quality of fiber desired.

3.6 Jute

Jute is an annual plant in the genus *Corchorus.* The major types grown are generically known as white jute and tossa jute. Jute, grown mainly in India and Bangladesh, is harvested at 2 to 3 months of growth, at which time it is 3-5 meters tall. Jute has a pithy corer, known as jute stick and the bast fibers grow lengthwise around this core.

Jute bast fiber is separated from the pith in a process known retting. Retting is accomplished by placing cut jute stalks in ponds for several weeks. Microbial action in the pond softens the jute fiber and weakens the bonds between the individual fibers and the pith. The fiber strands are then manually stripped from the jute stick and hung on racks to dry. Very long fiber strands can be obtained this way. If treated with various oils or conditioners to increase flexibility, the retted jute fiber strands are suitable for manufacturing into textiles.

Most composites made using jute exploit the long fiber strand length. Commercially, both woven and non-woven jute textiles are resin- or epoxy-impregnated and molded into fairly complex shapes. In addition, jute textiles are used as overlays over other composites. Jute stick is used for fuel, and in poor areas it is stacked on end, tied into bundles, and used as fences and walls.

3.7 Kenaf

Kenaf is a hibiscus, and is similar to jute or hemp in that it has a pithy stem surrounded by fibers. The fibers make up 20-25% of the dry weight of the plant (LaMahieu et al., 1991). Kenaf grows well in warm climates and does not have the narcotic effect found in the non-fibrous parts of the hemp plant. Mature kenaf plants can be 5 m high.

Kenaf is currently generating much interest from government and industry. The U.S. Department of Agriculture is promoting kenaf, and other non-food, non-feed agricultural crops, because these crops are not subject to subsidies (AARC, 1992). As an indication of the interest in kenaf, a recent bibliography devoted solely to kenaf had 241 scientific citations (USDA, 1992). Also, the International Kenaf Association was formed and is devoted to the study and promotion of kenaf.

Historically, kenaf fiber was first used as cordage. Industry is now exploring the use of kenaf in papermaking and nonwoven textiles. Like jute, most kenaf composite products exploit the long aspect ratio of kenaf fibers and fiber bundles. One way to do this is to form the kenaf into a nonwoven textile mat that can be used for erosion control, seedling mulches, or oil spill absorbents. After a resin is added to the kenaf mats, they can be pressed into flat panels or molded into shapes, such as interior car door substrates. In addition, low-density particleboard based on kenaf pith is produced in Spain (Riccio, 1993). Kenaf pith is used in other parts of the world for animal bedding and other absorbent applications.

Environmental concerns prevent the retting of kenaf fiber in the United states; therefore, alternate means of separating the bast from the pith are employed. If dry, separation begins by chopping the kenaf stalk into shorter lengths, which fractures the pith. Standard screening and air separation techniques can then be used to separate the two different materials. Commercially, kenaf bast fiber separated this way can be purchased 98% pith-free. The Tilby process has also been employed experimentally for separating green kenaf stalk. Kenaf is generally stored in a dried and baled state.

3.8 Rice Husks

Rice husks are an agricultural residue that are available in fairly large quantities in one area. Trees “store on the stump” and with rare exception other lignocellulosics do not share this luxury. Rice husks are a notable exception because they are stored on the grain. The grain is stored to be milled year round, making the availability of rice husks reasonably uniform, at least in the United States (Haislip, 1994).

Rice usually comes to the mill at about an 8% moisture content level (Vasishth and Chandramouli, 1974). Rice husks are quite fibrous by nature and little energy input is required to prepare the husks for board manufacturer. To make high-quality boards, the inner and outer husks are separated and broken at their “spine.” This can be accomplished by hammer milling or refining. Rice husks have a high silica content, and present the same cutting tool problems outlined in section 3.3.

3.9 Other Fiber Sources

Other important fiber sources include flax shives, bamboo, papyrus, and reed stalks. Many countries like France, Sweden, Belgium, and Germany use flax shives to produce resin-bonded particleboards. In the United States, flax is also used in the manufacture of insulation board by mixing with wood pulp. There are two varieties of flax; one is for fiber and the other is for linseed oil production. Bamboo is an important source of raw material for fiberboards in tropical countries. Most varieties of bamboo are fast-growing and produce strong fibers; particleboards from bamboo have also been made.

Papyrus is used in making hardboard in East Africa. Suitable quality insulation boards and hardboards have also been made in a pilot plant in Sefan, Israel. Particleboards have been produced from reed/typha mixtures that meet or exceed specifications. Insulation boards and plastic-bonded boards have also been prepared from reeds. Other miscellaneous fibers include: banana leaves, grasses, palm, sorghum, ect. while many fibers have been used successfully in the laboratory to produce boards, most of these material have not been used commercially because of cost or other factors.

4. CONVENTIONAL PANEL-TYPE COMPOSITES

Many conventional lignocellulosic composites are in the marketplace with a high degree of customer acceptance. They are usually available in panel form and are widely used in housing and furniture. Conventional composites typically use a heat curing adhesive to hold the lignocellulosic component together.

Conventional composites fall into two main categories based on the physical configuration of the communited lignocellulosic: fiberboards and particleboards. Within these categories are low, medium, and high-density classifications. Within the fiberboard category, both wet and dry processes exist.

Within limits, the performance of a conventional type composite can be tailored to the end use. Varying the physical configuration of the communited lignocellulosic and adjusting the density of the composites are just two ways to accomplish this. Other ways include varying the resin type and amount, and incorporating additives to increase water resistance or to resist specific environmental factors. On an experimental basis, lignocellulosics have also been chemically modified to change performance.

4.1 Resins and Additives for Conventional Composites

Worldwide, the most common resin for lignocellulosic composites is urea formaldehyde (UF). About 90% of all lignocellulosic composite panel products are bonded with UF (Maloney, 1989). UF is inexpensive, reacts quickly when the composite is hot-pressed, and is easy to use. UF is water-resistant, but not waterproof. As such, its use is limited to interior applications unless special treatments or coatings are applied. A more durable adhesive is phenol formaldehyde (PF). PF is two to three times as expensive as UF, but the increased durability for exterior applications makes it a poplar resin. A third common resin, melamine formaldehyde (MF), falls roughly midway between UF and PF on both cost and performance.

Natural options exist that might someday replace or supplement the synthetic resins listed above. Tannins, which are natural phenols, can be modified and reacted with formaldehyde to produce a satisfactory resin. Resins have also been developed by acidifying spent sulfite liquor, generated when wood is pulped for paper. Wet process fiberboards frequently use the lignin inherent in the lignocellulosic as the resin (Suchsland and Woodson, 1986).

Except for two major uncertainties, expectations are that urea-formaldehyde and phenol-formaldehyde systems will continue to be the dominant wood adhesives for lignocellulosic composites. The two uncertainties 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 developing new adhesive systems from renewable resources.

Although research results have indicated that a number of new adhesive systems have promise, their commercial use is currently limited. One example is the use of isocyanate adhesives. The slow adoption of this material is due to the relatively high cost and to 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.

The most common additive to lignocellulosic composite panels other than resin is wax. Even small amounts. 0.5-1%, act to retard the rate of liquid water pick up. This is important when the composite is exposed to wet environments for short periods of time. Wax addition, however, has little effect on high-term equilibrium moisture content Flame retardants, biocides, and dimensional stabilizers are also added to panel products. They are discussed in more detail elsewhere in this chapter.

4.2 Particleboards

The wood particleboard industry grew out of a need to dispose of large quantities of sawdust, planer shavings, plywood trim, and other relatively homogeneous waste materials produced by other wood industries. Simply put, particleboard is produced by hammermilling the material into small particles, spray application of adhesive to the particles, and consolidating a loose mat of the particles into a panel product with heat and pressure (Figure 8.1). All particleboards are currently made using a dry process, where air is used to randomize and distribute the particles prior to pressing.

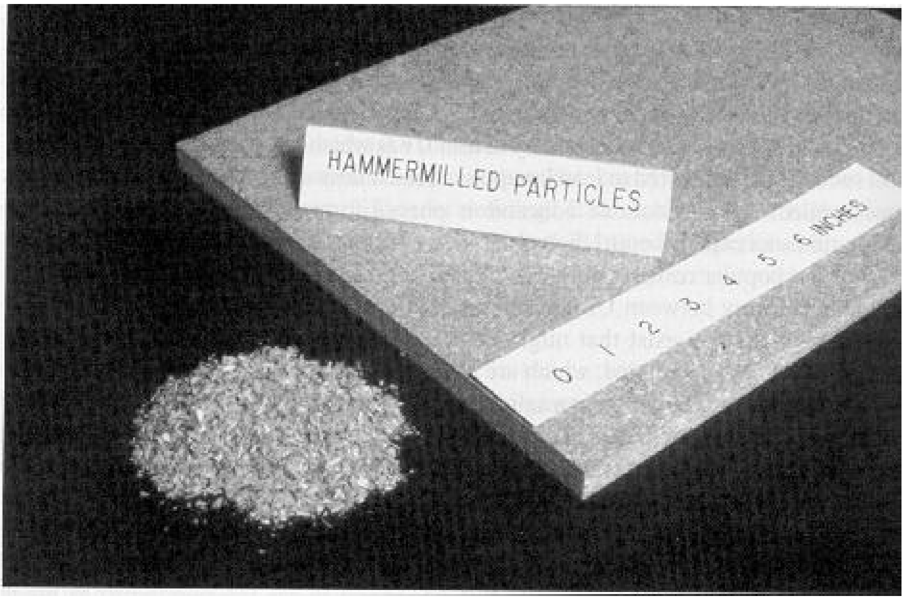

Figure 8.1 Particles are also used to produce composites like particleboards. they are typically produced by hammermilling.

Particleboards are often made in three layers. The faces of the boards are made up of the fines from the communition, while the core is made of the coarser material. Producing a panel this way gives better material utilization and the smooth face presents a better surface for overlaying or veneering. Particleboards are readily made from a variety of agricultural residues. Low density insulating or sound-absorbing particleboards can be made from kenaf core or jute stick. Low, medium, high density panels can be produced with cereal straw. Rice husks are commercially manufactured into medium and high density products in the Middle East.

All other things being equal, reducing lignocellulosic materials to particles requires less energy than reducing the same material into fibers. Particleboards are generally not as strong as fiberboards, however, because the fibrous nature of lignocellulosics is not exploited as well. Particleboards find use as furniture cores, where they are often overlaid with other materials for decorative purposes. Thick particleboard can be used in flooring systems and as underlayment. Thin panels can be used as paneling substrate. Most particleboard applications are interior, and so they are usually bonded with UF, although some use of PF and MF exists for applications requiring more durability. The various steps involved in particleboard manufacturing are included below.

4.2.1 Particle Preparation

There are two basic particle types: hammermill-type particles and flake-type particles. Hammermilled particles are often roughly granular or cubic in shape, and thus have no significant length-to-width ratio. For non-woody materials, flake-type particles are the most common. Their sizes are usually in the range of 0.2-0.4 mm in thickness, 3.0-30 mm in width, and 10.0-60.0 mm in length. Particle geometry significantly influences the board properties: the length of flake-type particles is probably most important as it influences maximum strength.

The most common type of machines used to produce flake-type particles are the cylinder type and the rotating disc type. The cylinder type has knives mounted either on the exterior of the cylinder similar to a planer or on the interior of a hollow cylinder. For the rotating disc type, the knives are mounted on the face of the disc at various angles. The knife angle and spacing influence the nature of the flake obtained.

4.2.2 Classification and Conveying of Particles

It is desirable to classify the particles before they proceed to further operations. Very small particles increase furnish surface area and thus increase resin requirements. Oversized particles can adversely affect the quality of final product because of intenal flaws in the particles. While some ciassification is accomplished using air streams, screen classification methods are the most common. In screen classification, the particles are fed over a vibrating flat screen, or series of screens. The screens may be wire cloth, plates with holes or slots, or plates set on edge.

The two basic methods of particle conveying are mechanical and air conveying. The choice of conveying method depends upon the size of particles. In air conveying, care should be taken that the material does not pass through many fans resulting in particle size reduction. In some types of flakes, damp conditions are maintained to reduce break-up during conveying.

4.2.3 Drying

The moisture content of particles is critical during hot pressing operations. Thus, it is essential to carefully select the proper dryers and control equipment. The moisture content of the material depends on whether resin is to be added dry or in the form of a solution or emulsion. The moisture content of materials leaving the dryers is usually in the range of 4–8%. The main methods used in drying particles include rotary, disc, and suspension drying.

A rotary dryer consists of a large horizontal rotating drum that is heated either by steam or direct heat from 100–200°C. The drum is set at a slight angle, and material is fed in on the high end and discharged at the low end. The rotary movement of the drum allows movement of the material from the input to the output end.

A disc drier consists of a large veritical drum. It is equipped with a vertical shaft mounted with several horizontal discs with flaps. The particles move from the upper disc to the lower disc as drying progresses. Air is circulated from the bottom to the top. Drying time is usually from 15–45 min while the temperature is about 100°C.

A suspension drier consists of a vertical tube where the particles are introduced. The particles are kept in suspension by ascending air, resulting in rapid drying. As drying progresses, the particles leave the tube and are carried away by the air stream to be deposited as dried material. The drying temperature varies from 90°C to 180°C. High flashpoint drying is similar to suspension drying. It consists of a looped length of ducting approximately 40 cm in diameter. The temperature applied is high, approximately 400°C. It may be necessary to pass the dried particles through a cooling drum to reduce the fire hazard and to bring the particles to the proper temperature for resin addition.

4.2.4 Resins and Wax Addition

Frequently used resins for parlicleboards include urea formaldehyde, phenol formaldehyde, and to a much lesser extent melamine formaldehyde, as described in Section 4.1. The type and amount of resin used for particleboards depend on the type of product desired. Based on the weight of dry resin solids and ovendry weight of the particles, resin content is usually in the range of 4–15%, but most likely 6–9%. Resins are usually introduced in water solutions containing about 50–60% solids. Besides resin, paraffin wax emulsion is added to improve moisture resistance. The amount of wax ranges from 0.3–1% based on the oven-dry weight of the particles.

4.2.5 Mat-Forming

After the particles have been prepared, they must be laid into an even and consistent mat to be pressed into a panel. This can be accomplished in a batch mode or by continuous formation. The batch system employs a caul or tray on which a deckle frame is placed. Mat formation is induced either by the back and forth movement of the tray or the back and forth movement of the hopper feeder. After formation, the mat is usually pre-pressed prior to hot-pressing. Three layer boards can also be produced in this system, in which case, three forming stations are necessary. For three layer boards, the two outer layers consist of particles differing in geometry from those of the core. The resin content of the outer layers is usually higher, about 8–15%, with the core having a resin content of about 4–8%.

In continuous mat forming systems, the particles are distributed in one or several layers on traveling cauls or on a moving belt. Mat thickness is controlled volumetrically. Like batch forming, the formed mats are usually pre-pressed, commonly with a single-opening platen press. Pre-pressing reduces the mat height and helps to consolidate the mat for pressing.

4.2.6 Hot-Pressing

After pre-pressing, the mats are hot-pressed into panels. Hot press temperatures are usually in the range of 100–140°C. Urea-based resins are usually cured between 100 and 130°C. Pressure depends on a number of factors, but is usually in the range of 14 to 35 kg/cm^2 for medium density boards. Upon entering the hot press, the mats usually have moisture content of 10–15% but are reduced to about 5–12 percent during pressing.

Alternatively, some particleboards are made by the extrusion process. In this system, formation and pressing occur in one operation. The particles are forced into a long, heated die (made of two sets of platens) by means of reciprocating pistons. The board is extruded between the platens. The particles are oriented in a plane perpendicular to the plane of the board, resulting in properties which differ from those obtained with flat-pressing.

4.2.7 Board Finishing

After pressing, the board is trimmed to bring the board to the desired length and widths, and to square the edges. Trim losses usually amount to 0.5–8%, depending on the size of the board, the process employed, and the control exercised. Trimmers usually consist of saws with tungsten carbide tips. After trimming, the boards are sanded or planed prior to packaging and shipping. The particleboards may also be veneered or overlaid with other materials to provide better surface and improve strength properties. In such products, further finishing with lacquer or paint coatings may be done, or some fire-resistant chemicals may be applied.

4.3 Fiberboards

Several things differentiate fiberboards from particleboards (Figure 8.2); the most notable of these is the physical configuration of the comminuted material. Because lignocellulosics are fibrous by nature, fiberboards exploit their inherent strength to a higher degree than particleboards. To make fibers for composite production, bonds between the fibers in the plant must be broken. ln its simplest form, this is accomplished by attrition milling. Attrition milling is an age-old concept whereby material is fed between two discs, one rotattng, one stationary. As the material is forced through the pre-set gap between the discs, it is sheared, cut and abraded into fibers and fiber bundles. Grain has been ground this way for centuries.

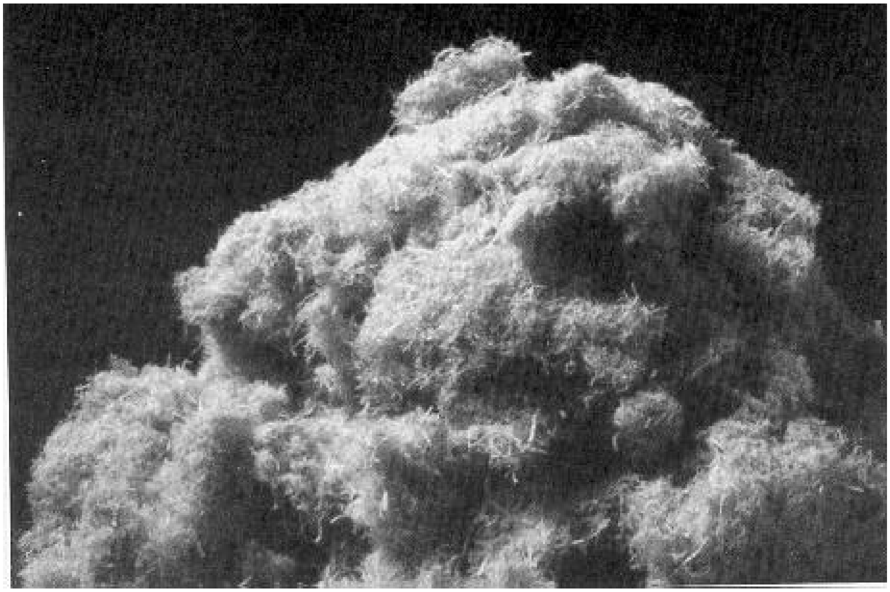

Figure 8.2 Fibers can be made from many lignocellulosics and they form the raw materials for many composites, most notably fiberboards. They are typically produced by the refining process.

Attrition milling, or as it is commonly called, refining, can be augmented by water soaking, steam cooking, or chemical treatments. By steaming the lignocellulosic, the lignin bonds between the cellulosic fibers are weakened. As a result, the fibers more readily separate, usually with less damage. Chemical treatments, usually alkali, are also used to weaken the lignin bonds. All of these treatments help increase fiber quality and reduced energy requirements, but may reduce yield as well. Refiners are available with single- or double-rotating discs, as well as steam-pressurized and unpressurized configurations. Fibers can also be produced by steam explosion. In this system, lignocellulosic material is subjected to high pressure steam for a short period of time, usually less than a minute. The pressure is then rapidly dropped. The pressure differential within the lignocellulosic explodes it into fibers and forces the fibers from the pressure vessel.

Fiberboards are normally classified by density and can be made by either dry or wet processes. Dry processes are applicable to boards with high density (hardboards) and medium density (medium density hardboard or MDF). Wet processes are applicable to high density hardboards and low density insulation boards as well. The following subsections briefly describe the manufacturing of high and medium density dry process hardboards, wet process hardboards, and wet process, low density insulation boards.

4.3.1 Dry Process Fiberboards

Dry process fiberboards are made in a similar fashion to particleboards. Resin (UF, PF) and other additives may be applied to the fibers by spraying in short retention blenders, or introduced as the wet fibers from the refiner are fed into a blow line dryer. Alternatively, some fiberboard plants add the resin in the refiner. The adhesive coated fibers are then air-laid into a mat for subsequent pressing much the same as particleboard (Section 4.2.5).

Pressing procedures for dry process fiberboards differ somewhat from particleboards. After the fiber mat is formed (Figure 8.3), it is typically prepressed in a band press. The densified mat is then trimmed by disc cutters and transferred to caul plates for the pressing operation. Dry-formed boards are pressed in multi-opening presses with temperatures of around 190–210°C (Figure 8.4). Continuous-pressing large, high pressure band presses are also gaining in popularity. Board density is a basic property and is an indicator of board quality. Moisture content greatly influences density; thus, the moisture content is constantly monitored by moisture sensors using infrared light.

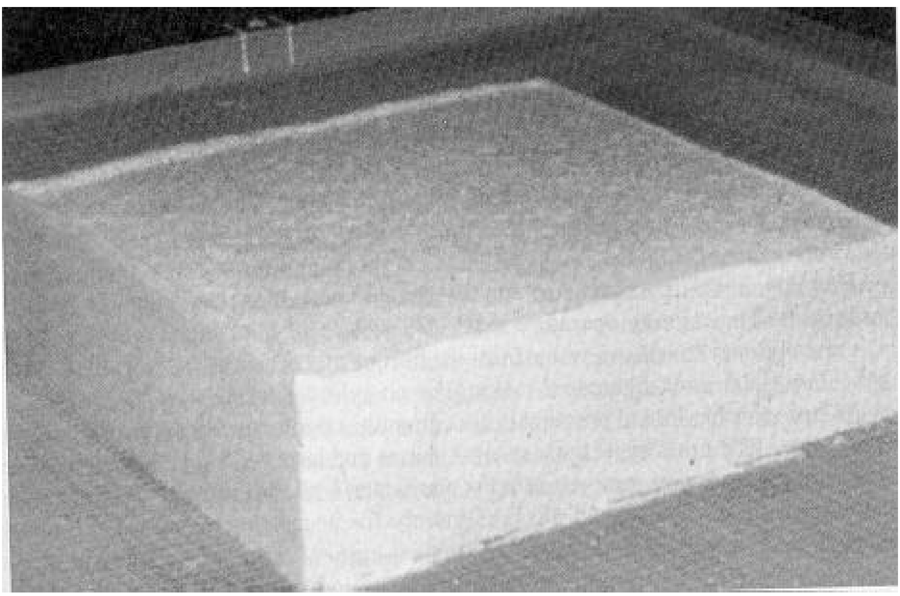

Figure 8.3 A laboratory produced air-laid mat before pressing. Approximate dimensions are 600 x 600 mm x 150 mm thick. Resin was applied to the fibers before mat production. This mat will be made into a high density fiberboard approximately 3 mm thick.

4.3.2 Wet Process Hardboards

Wet process hardboards differ from dry process fiberboards in several significant ways. First, water is used as the distribution medium for the fibers to be formed into

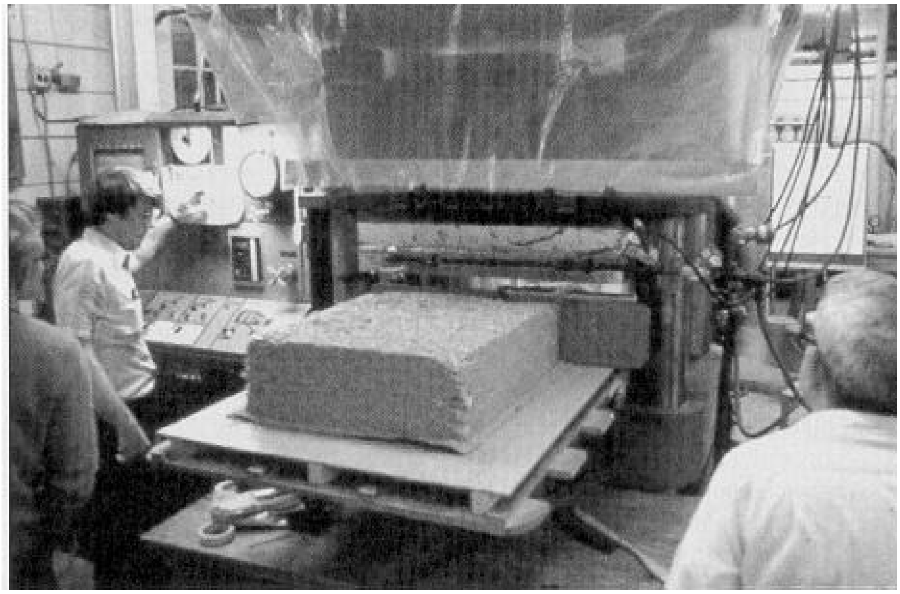

Figure 8.4 A similar mat to that in Figure 8.3 about to enter the press.

a mat. As such, this technology is really an extension of paper manufacturing technology. Secondly, some wet process boards are made without additional binders. If the lignocellulosic contains sufficient lignin, and if the lignin is retained during the refining operation, the lignin can serve as the binder. Under heat and pressure, the lignin will flow and act as a thermosetting adhesive, enhancing the naturally occuring hydrogen bonds.

Refining is an important step for the development of strength in wet process hardboards. The refining operation must also yield a fiber of high "freeness," that is, it must be easy to remove water from the fibrous mat. The mat is typically formed on a Fourdrinier wire, like paper making, or on cylinder formers.

Wet process hardboard presssing is done in multi-opening presses heated by steam or hot water. The press cycle consists of 3 phases and lasts 6–15 min. The first phase is at high pressure and removes most of the water while bringing the board to the desired thickness. The second phase is mainly for water vapor removal. The final phase is relatively short and results in the final cure. Maximum pressures used are about 5 MPa. Heat is essential during pressing to induce fiber-to-fiber bond. High temperatures of up to 210°C are used to increase production by faster evaporation of the water. Lack of sufficient moisture removal during pressing adversely affects strength and may result in "spring back" or blistering.

4.3.3 Post Treatments of Wet and Dry Process Hardboards

Several treatments exist to increase dimensional stability and mechanical performance of hardboard. They are heat treatment, tempering. and humidification and may be done singularly, or in conjunction with each other. Heat treatment is the exposure of the pressed fiberboards to dry heat that improves the dimensional stability and mechanical properties of the boards. The process also reduces water adsorption and improves the bond between fibers.

Tempering is the heat treatment of pressed boards, preceded by the addition of oil. Tempering improved the board's surface hardness and is often done on S2S (smooth two sides) wet-formed hardboard. It also further imporves resistance to abrasion, scratching, scarring, and improves the resistance to water. The most common oils used include linseed oil, tung oil, and tall oil.

Humidification is the addition of water to bring the board moisture content into equilibrium of the air. Initially, a pressed board has almost no moisture content. When it is exposed to air, it expands linearly by taking on 3–7% moisture. The most common humidifiers for this purpose are the continuous or progressive type. Air of high humidity is forced through the stacks where it provides water vapor to the boards. The entire process is controlled by a dry bulb/wet bulb controller. Other methods include spraying water on the back side of board and the application of vacuum to force the moist air through the board.

4.3.4 Insulation Boards

Insulation boards are low density, wet-laid panel products used for insulation, sound deadening, carpet underlayment, and similar applications. In the manufacturer of insulation board, the need for refining and screening is a function of the raw material available, the equipment used, and the desired end product. Insulation boards typically do not use a binder, and rely on hydrogen bonds to hold the board together. Sizes are usually added to the furnish at about 1 percent to provide the finished board with a modest degree of water resistance and dimensional stability. Sizes often used include rosin, paraffin, cumarone, resin, asphalt, and asphalt emulsions.

Like wet process hardboard, insulation board manufacture is a modification of paper making. A thick fibrous sheet is made from a low consistency pulp suspension in a process known as wet felting. Felting can be accomplished through use of a deckle box, Fourdrinier, or cylinder screen. A deckle box is a bottomless frame that sets over a screen A measured amount of stock is put in the box to form one sheet; vacuum is then applied to remove most of the water. Use of Fourdrinier screen for felting is similar to paper making, except that line speeds are reduced to 1.5–15 m/min.

Like the Fourdrinier, the cylinder method uses a screen, except with this system the screen is placed around a cylinder. The cylinder screen rotates in a pulp slurry, picking up fiber through vacuum.

Insulation boards are usually cold pressed to remove most of the free water after forming. From there, the wet mats are dried to the finished moisture content. Dryers may be a continuous tunnel, or a multi-deck arrangement. The board is generally dried in stages; temperatures employed range from 120–190°C. It takes about 2–4 h to bring the moisture content to about 1–3%.

After drying, some of the boards are treated for various applications. Boards may be given tongue and groove or shiplap edges or grooved to produce a plank effect. Some are laminated by means of asphalt to produce roof insulation boards.

In the United States, about one-third of production is treated with a sealer coat to facilitate painting.

4.3.5 Fiberboard Finishing

Trimming: Consists of reducing the products into standard sizes and shapes. Generally, double-saw trimmers are used to saw the boards. Trimmers consist of overhead mounted saws or movable saw drives. The trimmed boards are stacked in piles for future processing.

Sanding: If thickness tolerance is critical, the hardboard is sanded prior to finishing, S1S boards require this process. Sanding reduces thickness variation and improves surface paintability. In sanding, single head, wide belt sanders are used, with abrasive grits varying from 24–36.

Finishing: Finishing involves surface treatments to give the board a good appearance and improve performance. The boards are cleaned using water sprays followed by drying at about 240°C for 30 sec. The board's surfaces are then modified using paper overlay, paints, stains, or prints.

Punching: Punched boards are perforated sheets used as peg board. Most punching machines punch 3 rows of holes at a time while the board advances in position

Embossing: Embossing consists of pressing the board with a textured form. This process results in a slightly contoured board surface that can enhance the resemblance of the board to sawed wood, weathered wood, brick, and others.

4.4 Special Purpose Conventional Composites

Special purpose composites are produced to obtain desirable properties like water resistance, mechanical strength, acidity control, and decay and insect resistance. Overlays and veneers can also be added for both structural and appearance enhancement, as in Figure 8.5.

4.4.1 Moisture Resistance Conventional Composites

Sizes cover the surface of fibers, reduce their surface energy, and render the fibers relatively hydrophobic. The application of a sizing agent can occur in two ways. In the first, water is used as a medium to assure the thorough mixing of size and fiber. The size is forced to precipitate out of the water and is fixed to the fiber surface. In the second method, the size is applied directly to the fibers. Rosin is a common sizing agent: it is obtained from living pine trees, pine stumps, and as a by-product from kraft pulping of pines. Rosin size is added in amounts of less than 3% solids based on dry fiber weight

Waxes are high molecular weight hydrocarbons derived from crude oil. Wax sizes are used in dry fiberboard processes, and wax is added in solid form or sometimes together with liquid resin solutions. Wax sizes tend to lower strength properties to a greater extent than rosin.

Asphalt is also used to increase water resistance, especially in low-density wet process insulation boards. Asphalt is a black-brown solid a semi-solid cement

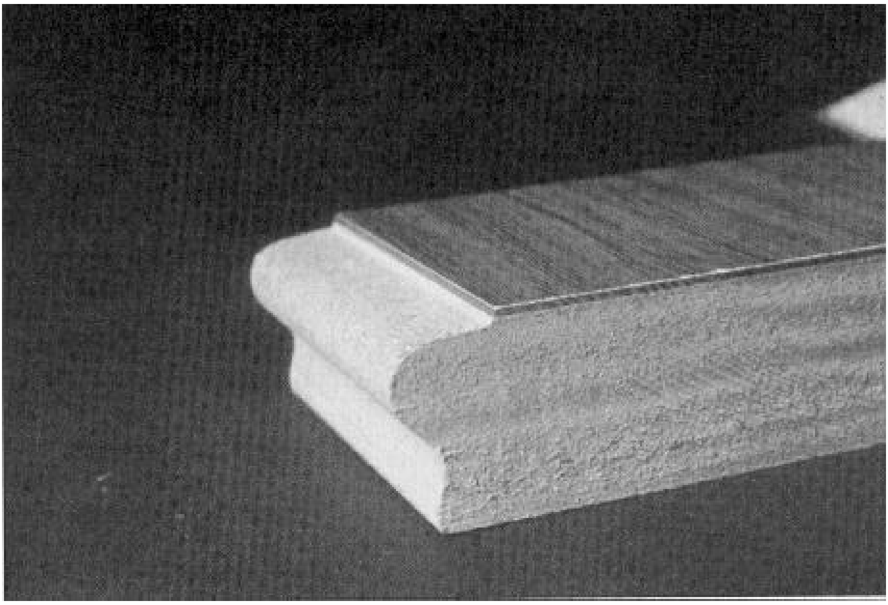

Figure 8.5 A medium density fiberboard with a veneer overlay. The edges can be shaped and finished as required by the end-product.

material which liquifies when heated. The predominant component of asphalt is bituminous. It is precipitated onto the fiber by the addition of alum.

4.4.2 Flame Retardant Conventional Composites

Lignocellulosic products are combustible and develop combustible gases that, at high temperature can be a fire hazard. Most fire-retardant chemicals are thermally stable inorganic salts like aluminum trihydrate or borate ester. By coating the surface of the lignocellulosic, they inhibit the release of combustible gases.

4.4.3 Preservative Treated Conventional Composites

Wood is highly susceptible to attack by fungi and insects; thus, treatment is essential for maximum durability in adverse conditions. Common preservative treatments include chromated copper arsenate (CCA), creosote, and pentachlorophenol (PCP). which was recently prohibited in the United States because of its toxicity. Generally, application of 0.50–0.75 weight percent of these compounds provides adquate protection.

5. INORGANIC-BONDED COMPOSITES

Inorganic-bonded wood composites have a long and varied history being first manufactured commercially in Austria in 1914. A plethora of building materials can be made using inorganic binders and lignocellulosics, and they run the normal gamut of panel products, siding, roofing tiles and pre-cast building members, (Figure 8.6.)

Figure 8.6 A laboratory produced low-density, cement-bonded composite panel. full scale panels such as these are used in construction.

There are three main categories of inorganic binders. They are gypsum, Magnesia cement, and Portland cement. Gypsum and magnesia cement are moisture-sensitive, and their use is generally restricted to interior applications. Portland cement-bonded composites are more durable and are used in both interior and exterior applications. Inorganic-bonded composites are made by blending proportionate amounts of the lignocellulosic with inorganic materials in the presence of water and allowing the inorganic material to cure or "set up" to make a rigid composite. All inorganic-bonded composites are very stable, highly insect and vermin resistant, and very fire resistant.

A unique feature of inorganic-bonded composites is their manufacture adaptable to either end of the cost and technology spectra. This is facilitated by the fact that no heat is required to cure the inorganic material. For example, in the Philippines, Portland cement-bonded composites are fabricated using mostly manual labor and are used in low cost housing. In Japan, the fabrication of these composites is automated, and they are used in very expensive modular housing.

The versatility of inorganic composite manufacture makes it ideally suited to a variety of lignocellulosic materials. With a very small capital investment and the most rudimentary of tools, satisfactory inorganic-bonded lignocellulosic composite building materials can be produced on a small scale using largely unskilled labor. If the market for the composite increases, technology can be introduced to increase manufacturing throughput. The labor force can be trained concurrently with the gradual introduction of the more sophisticated technology.

5.1 Gypsum Bonded Composites

Gypsum can either be derived by mining from natural sources or can be obtained as flue gas gypsum. Flue gas gypsum, now being produced in very large quantities in the United States because of Clean Air Act regulations, is the result of the introduction of lime into the combustion process to reduce sulfur dioxide emissions. By 1995, more than 100 power plants throughout the United States will be producing gypsum. Flue gas gypsum can be used in lieu of mined gypsum.

Gypsum panels are frequently used to finish interior wall and ceiling surfaces. In the United States, these products are generically called “dry wall” because they replace wet plaster systems. To increase the bending strength and stiffness of the gypsum panel, it is frequently wrapped in paper, which provides a tension surface. An alternative to wrapping the gypsum with fiber to increase strength and stiffness is to put the fiber within the panel. Several firms in the United States and Europe are doing this with recycled paper fiber. There is no reason that other lignocellulosics cannot be used. Gypsum is widely available and does not have the highly alkaline environment presented by cement. Experimentally, sisal and coir have been successfully used in gypsum panels (Mattone, 1990).

Gypsum panels are normally made from a slurry of gypsum, water, and lignocellulosic fiber. In large scale production, the slurry is extruded onto a belt. The belt carries the slurry through a drying oven to drive off the water and facilitate the cure of the gypsum. The panel is then cut to length, and trimmed if necessary.

5.2 Magnesia Cement-Bonded Composites

Magnesia cement-bonded boards have not seen the high level of commercial activity that cement-bonded or gypsum-bonded panels have, mainly due to price. Magnesia cement do, however, offer several manufacturing advantages over Portland cement. First, the various sugars in lignocellulosics do not seem to have as much effect on the curing and bonding of the binder. Second, Magnesia cements are more tolerant of high water content during production (Pazner and Klemarevski, 1989). This opens up possibilities to use lignocellulosics not amenable to Portland cement composites, without leaching or other modification, and opens up alternative manufacturing processes, and thus, products. In addition, while Magnesia cement-bonded composites are considered water-sensitive, they are much less so than gypsum-bonded composites.

One successful application of Magnesia cements is a low density panel made for interior ceiling and wall applications. In the production of this panel product, wood wool, or excelsior, is laid out in a low density mat. The mat is then sprayed with a aqueous solution of Magnesia cement, then the mat is pressed and cut into panels. It is easy to envision this technique being used for lignocellulosics with long fibers, like jute, hemp, or kenaf.

In Finland, Magnesia cement-bonded particleboard is manufactured using a converted conventional particleboard plant. The Magnesia oxide is applied to the lignocellulosic particles in a batch blender along with water and other chemicals. Depending on application and other factors, the boards may be cold- or hot-pressed (Loiri, 1989).

Other manufacturing processes have been suggested. One possible application may be to spray a slurry of Magnesia cement; water, and lignocellulosic fiber onto existing structures as fireproofing. Extrusion into pipes or other profiles is also possible

5.3 Portland Cement-Bonded Composites

The most apparent and widely used example of inorganic-bonded composites is cement. Portland cement, when combined with water, immediately reacts in a process called hydration to eventually solidify into a solid stonelike mass. Successfully marketed Portland cement-bonded composites consist of both low density products made with excelsior or coir and high density products made with particles and fibers.

The low density products may be used as interior ceiling and wall panels in commercial buildings. Along with the previously mentioned advantages, they offer sound control and can be quite decorative. In some parts of the world, these panels function as complete wall and roof decking systems. The exterior of the panels is then stuccoed, while the interior is plastered. High density panels can be used as flooring, roof sheathing, fire doors, load bearing walls, and cement forms. Fairly complex molded shapes can be molded or extruded. Thus, decorative roofing tiles or non-pressure pipes can be made.

While the entire sphere of inorganic-bonded lignocellulosic composites is attractive, with cement-bonded ones being especially so, there are limitations and trade-offs when cement is considered. Marked embrittlement of the lignocellulosic component is known to occur and to be caused directly by the alkaline environment provided by the cement matrix. In addition, hemicellulose, starch, sugar, tannins, and lignin, all to a varying degree, affect the cure rate and ultimate strength of the composites. To make strong and durable composites, measures must be taken to ensure long-term stability of the lignocellulosic in the cement matrix.

To overcome these problems, various schemes have been developed. The most common is leaching, whereby the lignocellulosic is soaked in water for a day or two to extract some of the detrimental components. However, in some parts of the world, the water containing the leachate is difficult to dispose. Low water-cement ratios are helpful, as are the use of set accelerators like calcium carbonate. Conversely, low alkali cements have been developed, but they are not readily available in all parts of the world. Two other strategies—natural pozzolans and carbon dioxide treatment are discussed below

5.3.1 Role of Natural Pozzolans

Pozzolans are defined as siliceous or siliceous and aluminous marerials that can react chemically with calcium hydroxide (lime) at normal temperatures, in the presence of water to form cement compounds (ASTM, 1988). Some common pozzolanic materials include volcanic ash, fly ash, rice husk ash, and condensed silica fume. All of these can react with lime at normal temperatures to make a water resistant, natural cement.

As a general statement, when blended with Portland cement, pozzolans increase the strength of the cement, but slow the cure time. More important is that pozzolans decrease Portland cement alkalinity (Swamy, 1990), which indicates that addition of lignocellulosic-based material (rice husk ash) to cement-bonded lignocellulosic composites may be advantageous.

5.3.2 Carbon Dioxide Treatment of Portand Cement-bonded Composites

In the manufacture of a cement-bonded wood fiber composite, the cement hydration process normally requires from 8 to 24 hours to develop sufficient board strength and cohesiveness to permit the release of consolidation pressure. By exposing the cement to CO_2 the initial hardening stage can be reduced to under 5 minutes. The phenomenon results from the chemical reaction of CO_2 with calcium hydroxide to form calcium carbonate and water.

Reduction of initial cure time of the cement-bonded wood fiber composite is not the only advantage of using CO_2 injection. The inhibiting effects of sugars, tannins, etc. on cement hydration are also greatly reduced which is especially important with the variety of lignocellulosics available. In addition, research has demonstrated that CO2-treated composites can be twice as stiff and strong as untreated composites (Geimer et al., 1993). Finally, CO_2-treated composites do not experience efflorescence, a condition whereby calcium hydroxide migrates to the surface of the material, so the appearance of the final product is not changed.

6. LIGNOCELLULOSIC/THERMOPLASTIC COMPOSITES

As described elsewhere in this chapter, there is a long history of the use of lignocellulosics with thermosetting polymeric materials, like phenol or urea formaldehyde in the production of composites. The use of lignocellulosics with thermoplastics, however, is a more recent innovation (see Chapter 12). Broadly defined, a thermoplastic is any material that softens when heated and hardens when cooled. Thermoplastics selected for use with lignocellulosics must melt at or below the degradation point of the lignocellulosic component, normally 200-220°C. This group includes polypropylene, polystyrene, vinyls, both low- and high-density polyethylenes, and others.

There are two main strategies for the use of thermoplastics in lignocellulosic composites. In the first, the lignocellulosic component serves as a reinforcing filler in a continuous thermoplastic matrix. In the second, the thermoplastic serves as a binder to the majority Iignocellulosic component.

In an ideal system with regular and oriented filler material, the point where the thermoplastic matrix ceases to be continuous may be as low as 20% matrix material.

from a practical view, the point where the thermoplastic phase ceases to be continuous in a lignocellulosic composite is thought to be around 35–40%. This is because of the random and irregular nature of the lignocellulosic component.

The presence or absence of a continuous thermoplastic matrix may also determine the processability of the composite material. As a general statement, if a continuous matrix exists, it may be possible to process the composite using conventional thermoplastic processing equipment; however, if no continous matrix exists, other processes may be required. For the purposes of discussion, we will present these two scenarios as high thermoplastic content composites and low thermoplastic content composites.

6.1 High Thermoplastic Content Composites

High thermoplastic content composites are those in which the thermoplastic component exists in a continuous matrix and the lignocellulosic component serves as a reinforcing filler (Figure 8.7). The great majority of reinforced thermoplastic composites available commercially used inorganic materials as their reinforcing fillers, e.g., glass, clays, and minerals. These materials are heavy, abrasive to processing equipment and non-renewable. Lignocellulosics are lighter, much less abrasive, and of course, renewable. As a reinforcement, lignocellulosic stiffen, and somewhat strengthen the thermoplastic when compared to unfilled material. As a filler material, the lignocellulosic can usually be prepared for composite production for one third to one half the cost of the thermoplastic.

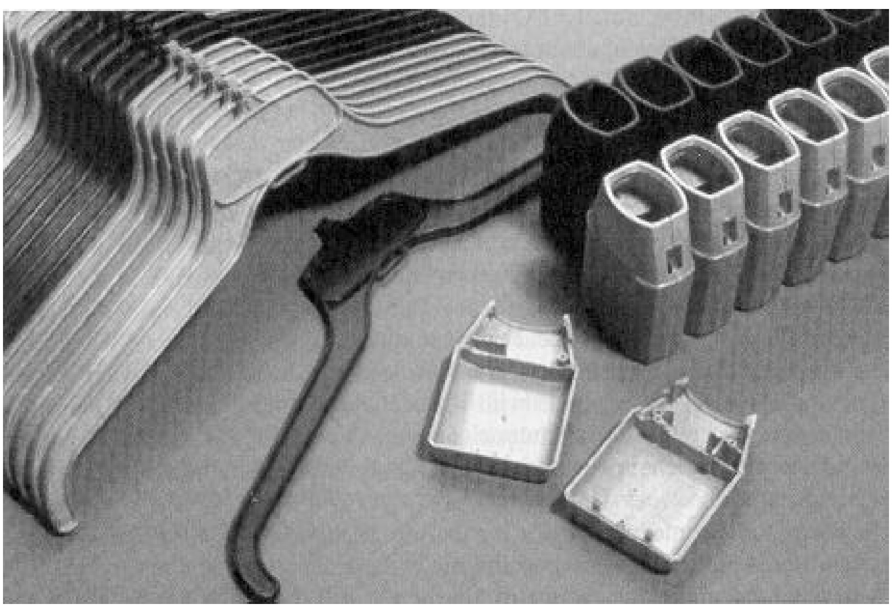

Figure 8.7 Using lignocellulosics as reinforcing fillers in thermoplastics allows them to be molded into a wide variety of shapes and forms.

These composites are not without trade-offs. Impact resistance of the composite decreases significantly when compared to the unfilled thermoplastic, but for most applications, this is not significant. By point of comparison though, the impact resistance is often better than similar composites made with thermosetting resins. The composite is also somewhat more sensitive to moisture than the unfilled material or an inorganic-filled composite. From a practical standpoint, though, the temperature sensitivity of the composite, because of the thermoplastic component is usually more significant than any change in properties brought about by moisture absorption.

The lignocellulosic may be in fiber or particleform. Particles are easier to prepare and are usually used more as a filler, although they do have a reinforcing effect. Fibers are used more as a reinforcement, although their relatively low cost (when compared to the thermoplastic) still makes them viable fillers. The lignocellulosic component size can also vary widely. One commercial product uses rather large wood filler in the 20 mesh size range. Conversely, the lignocellulosic component might exist as individual fibers or fiber fragments.

6.1.1 Compounding

Perhaps the greatest challenge to continued commercialization of thermoplastic content lignocellulosic composites is their compounding, or blending. Compounding consists of the feeding and dispersion of the lignocellulosic component throughout the thermoplastic matrix. The ultimate goal of any compounding operation is usually the production of a compounded, pelletized feedstock. The feed pellets are suitable for use in almost any plastic processing operation and this is the normal form in which they are sold. Problems in this area focus on the differences in bulk density of the two components and the degree of shear of the compounding equipment and thus fiber length retention or loss.

Thermoplastics in pellet form have a bulk density in the range of 500–600 kg/m^3. Lignocellulosics have an uncompacted bulk density of 50–250 kg/m^3. Fibers are at the low end of the lignocellulosic bulk density continuum: particles are at the high end. Dry blending of the thermoplastic and the lignocellulosic generally results in settling of the heavier component. This problem is exasperated if the thermoplastic is in molten form, at which time its bulk density or specific gravity will be closer to 900–1000 kg/m^3.

Bulk density issues are simplified by selecting a lignocellulosic component with a bulk density as close to the thermoplastic component as possible. This usually involves selecting a particle or flour as opposed to a fiber. Wood flour is commercially used in the United States, and feeding problems are minimal. The extension of the wood flour feeding to ground nut shell flours and other particulate materials like finely hammermilled rice hulls would seem reasonable. Particles do not give the level of reinforcement as that obtained from fibers: however, additional measures must be taken for fiber handling.

The feeding of fibers can be made easier if batch-style, kneading-type compounding equipment is selected. Kneading-type compounding equipment is used by the chemical, pharmaceutical, cosmetics, foodstuffs, rubber and plastics industries as well as many other special fields for compounding a diverse range of materials.

The operation of this type of equipment is quite simple. Pre-weighed amounts of various materials are loaded into a heated mixing chamber. A ram feeder facilitates the feeding of low bulk density materials like lignocellulosics. In the chamber are two low-speed, high-torque kneading rotors. The chamber is closed, the rotors turn, and the mixing is conducted. After mixing, the compounded material is discharged from the chamber en masse. The compounded mass is usually fed through a single screw extruder and pelletizing line for production of a pellet. The three compounding variables controllable by this type of equipment are mixing time, batch temperature, and energy consumption.

Batch-style, kneading-type compounding equipment offers several advantages. This equipment can accommodate a wide range of feedstocks and work with extremely high viscosity materials. special ram feeders can accommodate very low bulk density materials. Relatively low shear forces help retain fiber length, and importantly, excellent quality control is reached because the formulation components of each batch can be weighed individually.

On the down side, batch-style equipment has lower output than continous compounders at the same power rating and the en masse discharge requires expensive downstream processing equipment for practical material utilization by pelletization. also, the addition of time sensitive components to the formulation is not feasible due to the batch nature of the compounding.

Instead of discharging en masse, a discharge screw can be added to empty the mixing chamber. This enables the material to be extruded into a sheet or strand that can be fed into a pelletizer for subsequent operations. This simplifies, but does not eliminate, the downstream equipment needed for further processing.

Continuous kneading mixers are also available: they differ substantially from batch-style equipment and can be used to some advantage. In operation, this equipment generally consists of two long, intermeshing rotors in a heated barrel. Control of the formation depends on accurate feeding of the raw materials. In operation, materials are fed into one end of the barrels either through gravity or ram feeders. The action of the rotors forces the material through the mixing chamber where it is blended and subsequently discharged through a sheet or strand die, usually directly into a pelletizer. As compared to the batch-style equipment, some advantages and disadvantages become apparent.

First, output is increased over batch-style machines of the same power rating. Second, the discharged material can be fed directly into a pelletizer. In addition, time-sensitive components, like thermosetting crosslinking agents, can be introduced at various stages of the compounding operation. Shear is relatively moderate, so fiber length retention is generally good. Disadvantages include a degee of loss of formulation control because the formulation is dependent on the ability to consistently feed the components. These types of compounders also do not function as pumps: therefore, they cannot be used to extrude or mold finished products.

Both batch and continuous kneading compounders need downstream processing equipment to make a product. A more sophisticated and more expensive compounder is a twin screw extruder. Similar in operation to a continuous kneader, twin screw extruders have two screws, or augers running in a common barrel. Materials can be fed into the extruder at various points to accommodate various compounding schemes. Special ram feeders, or crammers, are needed for lignocellulosic materials. Twin screws act as pumps, and are often used in profile extrusion. They can also be used for injection molding.

If fiber length retention is not a concern, other high shear compounding equipment may be used. Two batch-style machines, a thermokinetic mixer known as a K-mixer (Myers and Clemons, 1993) and film densification equipment (English and Schneider, l994), can be used. Both of these use kinetic energy from a high speed rotor enclosed in a chamber to melt the thermoplastic component and blend in the lignocelluiosic component.

6.1.2 Profile Extrusion

After the materials have been compounded, they can be made into products. One process to accomplish this is profile extrusion where the composite material is first heated so that the thermoplastic component can flow. It is then continually pumped and forced through a die of a given cross section configuration. The material is supported as it cools, normally in a cold water bath, and then cut to length. As mentioned above, twin screw extruders can be used as compounders and as pumps for profile extrusion. Many products are made this way; common ones include pipe and tubing, furniture edging and moldings, and sheet goods.

6.1.3 Injection Molding

Injection molding differs from profile extrusion in that after the material is heated, it is pumped into a permanent mold, where it takes shape and cools. The mold is then opened and the finished part discharged. Injection-molded parts range from buttons to computer cases to automotive components.

Currently, the primary application of high thermoplastic content lignocellulosic composites is for interior door panels and trunk liners in automobiles. Some producers of plastic lumber are also adding lignocellulosic fiber to their product to increase stiffness and reduce creep. Additional large-volume, low-to-moderate cost applications are expected in areas such as packaging (trays, cartons, pallets), interior building panels, and door skins.

6.2 Low Thermoplastic Content Composites

Low thermoplastic content composites can be made in a variety of ways. In their simplest form, the thermoplastic component acts much the same way as a thermosetting resin, that is, as a binder to the lignocellulosic component. An alternative way is to use the thermoplastic in the form of a textile fiber. The thermoplastic textile fiber enables a variety of lignocellulosics to be incorporated into a low-density, nonwoven textile-like mat. The mat may be a product in itself. or it may be consolidated into a high density product.

6.2.1. Conventional-Type Low Thermoplastic Content Composites

Experimentally, low thermoplastic content composites have been made that are very similar to conventional lignocellulosic composites in many performance characteristics (Youngquist et al., 1993b). In their simplest form, lignocellulosic particles or fibers can be dry-blended with thermoplastic granules, flakes or fibers and pressed into panel products. Because the thermoplastic component remains molten when hot, different pressing strategies must be used than when using thermosetting binders.

Two options have been developed to accommodate these types of composites. In the first, the material is placed in the hot press at ambient temperature. The press then closes and consolidates the material, and heat is transferred through conduction to melt the thermoplastic component, which flows around the lignocellulosic component. The press is then cooled, "freezing" the thermoplastic so that the composite can be removed from the press.

Alternatively, the material can be first heated in an oven or hot press. The hot material is then transferred to a cool press where it is quickly consolidated and cooled to make a rigid panel. Some commercial non-structural lignocellulosic/thermoplastic composites are made this way.

6.2.2 Nonwoven Textile-Type Composites

In contrast to high-thermoplastic content composites and conventional low-thermoplastic content composites, nonwoven textile type composites typically require long fibrous materials for their manufacture. These fibers might be treated jute or kenaf, but more typically are synthetic thermoplastic materials. Nonwoven processes allow and tollerate a wider range of lignocellulosic materials and synthetic fibers dependent on application. After the fibers are dry blended, they are air-laid into a continuous, loosely consolidated mat. The mat then passes through a secondary operation in which the fibers are mechanically entangled or otherwise bonded together. This low density mat may be a product in itself, or the mat may be shaped and densified in a thermoforming step.

If left as a low density mat and used without significant modification by post processing these mats have a bulk density of 50–250 kg per cubic meter. These products are particularly well-known in the consumer products industry, where nonwoven technology is used to make a variety of absorbent personal care products, wipes, and other disposable items. These products use high quality pulps in conjunction with additives to increase their absorptive properties. Other applications, as described below, can use a much wider variety of lignocellulosics.

One interesting application for low-density, nonwoven mats is for mulch around newly planted seedlings. The mats provide the benefits of natural mulch; in addition, controlled-release fertilizers, repellents, insecticides, and herbicides can be added to the mats as discussed in Chapter 7. Research on the combination of mulch and pesticides in agronomic crops have been promising (Cutchfield et al., 1985). The addition of such chemicals could be based on silvicultural prescriptions to ensure seedling survival and early development on planting sites where severe nutritional deficiencies, animal damage, insect attack, and weed problems are anticipated.

Low-density nonwoven mats can also be used to replace dirt or sod for grass seeding around new homesites or along highway embankments. The grass seed can be incorporated directly into the mat. These mats promote seed germination and good moisture retention. Low-density mats can also be used for filters. The density of the mats can be varied, depending on the material being filtered and the volume of material that passes through the mat per unit of time.

High density fiber mats can be defined as composites made using the aforementioned nonwoven mat process which are post formed into rigid shapes by heat and pressure. To insure good bonding, the lignocellulosic can be precoated with a thermal setting resin, e.g., phenol-formaldehyde, or it can be blended with synthetic fibers, thermal plastic granules, or any combination of these. These products typically have a specific gravity of 0.60–1.40. After thermoforming, the products possess good temperature resistance. Because longer fibers are used, these products exhibit better mechanical properties than those obained with high thermoplastic content composites; however, high lignocellulosic content leads to increased moisture sensitivity.

7. CONCLUSIONS

Agricultural fibers have been successfully utilized in a variety of composite panels, most notably conventional composite panels and inorganic-bonded composites. Lignocellulosic/thermoplastic composites are a newer area of lignocellulosic utilization. It is anticipated that interest and commercial development will continue in this area. More than enough agricultural fiber residues are available to support composite manufacturing needs, although the agro-based materials may not have a suitable geographical distribution to provide an economically feasible endeavor.

Lignocellulosics are attractive material sources for composites because they are lightweight, economical, and require low amounts of energy for processing. In addition, their growth, use, and disposal are generally considered environmentally friendly. As renewable materials, they can be used to replace or extend non-renewable materials such as those based on petroleum.

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Edited by

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Raymond A. Young
Judith K. Rowell

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