Because wood properties vary among species, between trees of the same species, and between pieces from the same tree, solid wood cannot match reconstituted wood in the range of properties that can be controlled. Wood with localized defects (such as knots) can often be utilized effectively in wood-based composites. When wood with defects is reduced to wood elements, the influence of these characteristics in the manufactured product is reduced. To reinforce sustainable harvesting efforts, wood derived from small-diameter timber, forest residues, or exotic and invasive species may also be used in wood-based composites.

Wood-based composite materials can be made up of various wood elements, including fibers, particles, flakes, veneers, or laminates. Properties of such materials can be changed by combining, reorganizing, or stratifying these elements. When raw material selection is paired with properly selected processing variables, the end result can surpass nature’s best effort.

The basic element for composite wood products is the fiber, with larger particles composed of many fibers (Fig. 11–1). Elements used in production of wood-based composites can be made in a great variety of sizes and geometries and can be used alone or in combination. The choices are almost unlimited. The control of these characteristics—size and geometry—provide the chief means by which composite materials can be fabricated with predetermined properties.

Currently, the term composite is being used to describe any wood material adhesively bonded together. This encompasses a range of products from fiberboard to laminated beams and components. Table 11–1 shows a logical basis for classifying wood composites proposed by Maloney (1986). For this chapter, these classifications were slightly modified from those in the original version to reflect the latest product developments. Composites are used for a number of nonstructural and structural applications in product lines ranging from panels for interior covering...
purposes to panels for exterior uses and in furniture and support structures in many different types of buildings (Fig. 11–2).

This chapter describes the general composition of wood-based composite products and the materials and processes used to manufacture them. It describes conventional wood-based composite panels and structural composite materials intended for general construction, interior use, or both. This chapter also describes wood–nonwood composites. The mechanical properties of these types of composites are presented and discussed in Chapter 12. Because wood-based composites come in a variety of forms, we briefly describe several of the most common commercial products.

This chapter is organized into three sections. The first section covers conventional wood-based composite panels. Woody material types, adhesives, and additives common to conventional wood-based composites are summarized. Specific products addressed include panel products such as plywood, oriented strandboard, particleboard, and fiberboard. Specialty composites are also discussed.

The second section covers structural composite lumber and timber products, including glued laminated timber, laminated veneer lumber, parallel strand lumber, laminated strand lumber, and oriented strand lumber. Wood–nonwood composites are discussed in the third section, including inorganic-bonded composites and wood-thermoplastic composites. Books have been written about each of these categories, and the constraints of this chapter necessitate that the discussion be general and brief. References are provided for more detailed information.

### Conventional Wood-Based Composite Panels

Conventional wood-based composites are used for a number of structural and nonstructural applications, including panels for exterior uses, panels for interior uses, and furniture. Performance standards are in place for many conventional wood-based composite products (Table 11–2).

Conventional wood-based composites are manufactured products made primarily from wood with only a few percent resin as the bonding agent. Product types of conventional wood-based composites made from various constituent materials can be sub-categorized based on the physical...
configuration of the wood elements used to make these products: veneer, particle, strand, or fiber. Morphology of the wood elements influences the properties of composite materials and can be controlled by selection of the wood raw material and by the processing techniques used to generate the wood elements. Composite properties can also be controlled by segregation and stratification of wood elements having different morphologies in different layers of the composite material. In conventional wood-based composites, properties can also be controlled by use of adhesives with different cure rates in different layers. Varying the physical configuration of the wood element, adjusting the density of the composite, adjusting adhesive resin, or adding chemical additives are just a few of the many ways to influence properties.

Wood Elements

In any discussion of the characteristics or utility of wood-based composites, the first consideration is the constituent materials from which these composite products are made (Jayne 1972, Bodig and Jayne 1982). The variety of wood elements that can be used in wood-based composites is shown in Figure 11–3. Figure 11–3 shows the relative size of the wood elements.

A useful way to classify conventional wood-based composites based on material characteristics is shown in Figure 11–4. It presents an overview of the most common types of commercial products discussed in this chapter and a quick reference to how these composite materials compare to solid wood from the standpoint of density and general processing considerations. The raw material classifications of fibers, particles, and veneers are shown on the left y-axis. Specific gravity and density are shown on the top and bottom horizontal axes (x-axes), respectively. The right y-axis, wet and dry processes, describes in general terms the processing method used to produce a particular product. Figure 11–5 shows examples of some commercial wood-based composites.

Adhesives

Bonding in most conventional wood-based composites is provided by thermosetting (heat-curing) adhesive resins. Chapter 10 provides a more thorough discussion of thermoset adhesive resins. Commonly used resin–binder systems include phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, and isocyanate.
Phenol-Formaldehyde
Phenol-formaldehyde (PF) resins are typically used in the manufacture of construction plywood and oriented strandboard. These products may be intended for use where exposure to weather during construction is a concern, or in applications where weather exposure is temporary or not a factor. Other moisture exposure situations, such as occasional plumbing leaks or wet foot traffic, may also necessitate the use of PF resins. PF resins are commonly referred to as phenolic resins. Phenolic resins are relatively slow-curing compared with other thermosetting resins. In hot-pressed wood-based composites, use of phenolic resin necessitates longer press times and higher press temperatures. Hot-stacking of pressed material shortly after emergence from the press is a fairly common industrial practice, used to attain adequate resin cure without greatly extending press time. Significant heat exposure associated with pressing of phenolic-bonded composites commonly results in a noticeable reduction in their hygroscopicity. Cured phenolic resins remain chemically stable at elevated temperatures, even under wet conditions; their bonds are sometimes referred to as being “boil-proof.” The inherently darker color of PF resin compared with other resins may make them aesthetically unsuitable for product applications such as interior paneling and furniture.

Urea-Formaldehyde
Urea-formaldehyde (UF) resins are typically used in the manufacture of products used in interior applications, primarily particleboard and medium-density fiberboard (MDF), because moisture exposure leads to a breakdown of the bond-forming reactions. Excessive heat exposure will also result in chemical breakdown of cured UF resins, therefore UF-bonded panels are typically cooled after emergence from the press. Advantages of UF resins include lower curing temperatures than PF resins and ease of use under a variety of curing conditions. Urea-formaldehyde resins are the lowest cost thermosetting adhesive resins. They offer light color, which often is a requirement in the manufacture of decorative products. However, the release of formaldehyde from products bonded with UF is a growing health concern.

Melamine-Formaldehyde
Melamine-formaldehyde (MF) resins are used primarily for decorative laminates, paper treating, and paper coating. They are typically more expensive than PF resins. MF resins may, despite their high cost, be used in bonding conventional wood-based composites. When used in this application, they typically are blended with UF resins. Melamine–UF resins are used where an inconspicuous (light color) adhesive is needed and where greater water resistance than can be attained with UF resin is required.

Isocyanates
Isocyanate as diphenylmethane di-isocyanate (MDI) resin is commonly used as an alternative to PF resin, primarily in composite products fabricated from strands. Polymeric
Figure 11–4. Classification of wood composite panels by particle size, density, and process (Suchsland and Woodson 1986). Note that insulation board is now known as cellulosic fiberboard.

Figure 11–5. Examples of various composite products. From top left, clockwise: LVL, PSL, LSL, plywood, OSB, particleboard, and fiberboard.
MDI (pMDI) resin, which is closely related to MDI resin, is also commonly used in this application. Isocyanate resins are typically more costly than PF resins but have more rapid cure rates and will tolerate higher moisture contents in the wood source. Isocyanate resin is sometimes used in core layers of strand-based composites, with slower-curing PF resin used in surface layers. Facilities that use MDI are required to take special precautionary protective measures because the uncured resin can result in chemical sensitization of persons exposed to it. Cured isocyanate resin poses no recognized health concerns.

**Bio-Based Adhesives**

Bio-based adhesives, primarily protein glues, were widely used prior to the early 1970s in construction plywood. In the mid-1970s, they were supplanted by PF adhesives, on the basis of the superior bond durability provided by phenolics. Several soy-protein-based resin systems, with bond durabilities similar to those provided by PF resins, have recently been developed and commercialized. Durable adhesive systems may also be derived from tannins or from lignin. Tannins are natural phenol compounds that are present in the bark of a number of tree species. The tannins can be extracted from bark, modified, and reacted with formaldehyde to produce an intermediate polymer that is a satisfactory thermosetting adhesive. Lignin-based resins have also been developed from spent pulping liquor, which is generated when wood is pulped for paper or chemical feedstocks. Significant research on thermosetting resins derived from tannin and from pulping liquors was undertaken in the late 1970s and early 1980s. However, technology resulting from the research did not become, or at least did not remain, commercially successful. The reason was that petroleum prices decreased in the late 1980s, making petroleum-derived phenol inexpensive, and thus alternatives to it economically unattractive. In the manufacture of wet-process fiberboard, lignin, which is an inherent component of lignocellulosic material, is frequently used as binder (Suchsland and Woodson 1986), although “natural” lignin bonding is sometimes augmented with small amounts of PF resin.

**Resin Choice**

Often a particular resin will dominate for a particular product, but each has its advantages. Factors taken into account include materials to be bonded together, moisture content at time of bonding, mechanical property and durability requirements of the composite products, anticipated end-use of the product, and resin system costs.

In the near future, PF, UF, and MDI resins systems are expected to remain the predominant adhesives used for bonded wood-based composites. However, cost and reliable availability of petrochemicals may affect the relative predominance of PF and isocyanate adhesives versus bio-based adhesives. More stringent regulation concerning emissions from formaldehyde-containing products (driven by concern over indoor air quality) may affect the continued commercial predominance of UF resin in interior products. For example, the California Air Resources Board (CARB) has established formaldehyde emission standards that cover hardwood plywood, particleboard, and MDF through their Wood Products Airborne Toxic Control Measure (ATCM). As a result, bio-based adhesive and resin systems are gaining market share compared with petroleum-based synthetic resins.

**Additives**

A number of additives are used in the production of conventional composite products. The most common additive is wax, which is used to provide products with some resistance to liquid water absorption. In particle- and fiberboard products, wax emulsions provide limited-term water resistance and dimensional stability when the board is wetted. Even small amounts (0.5% to 1%) act to retard the rate of liquid water pickup for limited time periods. These improved short-term water penetration properties are important for ensuring the success of subsequent secondary gluing operations and for providing protection upon accidental wetting of the product during and after construction. The addition of wax has practically no effect on water vapor sorption or dimensional changes associated with changes in humidity. Other additives used for specialty products include preservatives, moldicides, and fire retardants. Composites containing additives are more thoroughly discussed in the section on Specialty Products.

**Plywood**

Plywood is a flat panel built up wholly or primarily of sheets of veneer called plies. It is constructed with an odd number of layers with the grain direction of adjacent layers oriented perpendicular to one another. A layer can consist of a single ply or of two or more plies laminated with their grain direction parallel. A panel can contain an odd or even number of plies but always an odd number of layers. The outside plies are called faces, or face and back plies. Inner plies are plies other than the face or back plies. Inner plies whose grain direction runs parallel to that of the faces are termed “centers” whereas inner plies whose grain direction runs perpendicular to that of the faces are termed “crossbands.” To distinguish the number of plies (individual sheets of veneer in a panel) from the number of layers (number of times the grain orientation changes), panels are sometimes described as three-ply, three-layer or four-ply, three-layer. The outer layers and all odd-numbered layers have their grain direction oriented parallel to the long dimension of the panel. The grain in even-numbered layers is perpendicular to the length of the panel. The center layer may be composed of veneer, lumber, particleboard, or fiberboard; however, all-veneer construction is most common in construction and industrial plywood.
Plywood panels are used in various applications, including construction sheathing, furniture, cabinet panels, doors, musical instruments, and sporting equipment. Plywood is also used as a component in other engineered wood products and systems in applications such as prefabricated I-joists, box beams, stressed-skin panels, and panelized roofs.

**Characteristics**

The properties of plywood depend on the quality of the veneer plies in panel layers, the order of layer placement, the adhesive used, and the degree to which bonding conditions are controlled during production. The durability of the adhesive-to-wood bond depends largely on the adhesive used but also on control of bonding conditions and on veneer quality. The grade of the panel depends upon the quality of the veneers used, particularly of the face and back.

Plywood panels have significant bending strength along the panel and across the panel, and the differences in strength and stiffness along the panel length versus across the panel are much smaller than those differences in solid wood. Plywood also has excellent dimensional stability along its length and across its width. Minimal edge-swelling makes plywood a good choice for adhesive-bonded tongue-and-groove joints, even where some wetting is expected. Unlike most panels fabricated from particles, it undergoes minimal irreversible thickness swelling if wetted. Because the alternating grain direction of its layers significantly reduces splitting, plywood is an excellent choice for uses that call for fasteners to be placed very near the edges of a panel. In uses where internal knotholes and voids may pose a problem, such as in small pieces, plywood can be ordered with a solid core and face veneers.

**Classes of Plywood**

Two classes of plywood are commonly available, covered by separate standards: (a) construction and industrial plywood and (b) hardwood and decorative plywood.

Most construction and industrial plywood used in the United States is produced domestically, and U.S. manufacturers export some material. The bulk of construction and industrial plywood is used where strength, stiffness, and construction utility are more important than appearance. However, some grades of construction and industrial plywood are made with faces selected primarily for appearance and are used either with clear natural finishes or lightly pigmented finishes. Construction and industrial plywood have traditionally been made from softwoods such as Douglas-fir and southern yellow pine. However, true firs, western hemlock, and western pines are also used (Bowyer and others 2007). A large number of hardwoods qualify for use under the standard. PF resin is the primary adhesive type used in construction and industrial plywood. Construction and industrial plywood is categorized by exposure capability and grade using Voluntary Product Standard PS 1–09 (APA 2010a).

Hardwood and decorative plywood is made of many different species, both in the United States and overseas. Well over half of all panels used in the United States are imported. Hardwood plywood is normally used in applications including decorative wall panels, furniture and cabinet panels, and musical instruments where appearance may be more important than strength. Most of the production is intended for interior or protected uses and therefore uses formaldehyde-free adhesives, although a very small proportion is made with adhesives suitable for exterior service, such as in marine applications. A substantial portion of all hardwood plywood is available completely finished. Hardwood and decorative plywood is categorized by species and characteristics of face veneer, bond durability, and composition of center layers (veneer, lumber, particleboard, MDF, or hardboard) (ANSI/HPVA HP-1-2016) (DHA 2016).

**Exposure Capability**

Construction and industrial plywood is classified as either Exposure 1 or Exterior in Voluntary Product Standard PS 1–09 (APA 2010a). Exposure 1 plywood is intended for applications not permanently exposed to weather, whereas Exterior plywood is suitable for repeated wetting and drying, or long-term exposure to weather. Bond quality of plywood of either bond classification (Exposure 1 or Exterior) is evaluated by the same test procedure, but a higher level of performance in the test procedure is required for Exterior plywood. The test procedure involves water saturation, boiling, and high-temperature exposure (in excess of boiling temperature). This means that all construction and industrial plywood is now bonded with boil-proof adhesive. The majority of construction and industrial plywood sold in North America is of Exposure 1 classification. Exposure 1 panels may undergo rain-wetting during building construction but will be protected from wetting after the building is enclosed.

Two exposure classes of hardwood and decorative plywood are recognized by ANSI/HPVA HP-1–2016, Exterior and Interior. The standard actually lists two different Exterior classes, Technical and Type I, but the bond performance requirements for these classes, as determined by test procedures outlined in the standard, are the same.

**Plywood Grades**

Plywood grades may indicate the intended use, a type of surface treatment, or the grades of the face and back veneers, and in some cases, a combination of these. Agencies that provide quality certification services for plywood mills have coined their own trademarked grade names for specified end uses through proprietary product standards. Grade stamps are used to identify plywood products (Figs. 11–6 and 11–7a). An example of plywood CARB third-party identification is shown in Figure 11–7b. Veneer quality is a factor in construction and industrial plywood based on visually observable characteristics.
Figure 11–6. Typical grade stamps for plywood and OSB. (Courtesy of PFS-TECO Corporation, Cottage Grove, Wisconsin. Used by permission.)
Figure 11–7. Typical grade stamps for hardwood plywood. (Courtesy of Decorative Hardwoods Association, Sterling, Virginia. Used by permission.)
Knots, decay, splits, insect holes, surface roughness, number of surface repairs, and other defects are considered. Veneer species and characteristics are also a major factor in categorization of hardwood and decorative plywood.

Specialty Plywood Panels
Plywood is easily pressure-treated with waterborne preservatives and fire retardants. Because plywood is not prone to irreversible thickness swelling, its bond integrity is unaffected by pressure treatment with waterborne chemicals. Treatment is typically performed by commercial entities specializing in treatment rather than by the plywood manufacturer. Treatments for plywood have been standardized (AWPA 2019). This allows specification by reference to a commercial standard. Special grades of plywood are produced for specific uses such as boat construction, concrete form work, or special exterior applications such as highway signage.

Oriented Strandboard
Oriented strandboard (OSB) is an engineered structural-use panel manufactured from thin wood strands bonded together with waterproof resin, typically PF or MDI. It is used extensively for roof, wall, and floor sheathing in residential and commercial construction. The wood strands typically have an aspect ratio (strand length divided by width) of at least 3. OSB panels are usually made up of three layers of strands, the outer faces having longer strands aligned in the long-direction of the panel and a core layer that is counter-aligned or laid randomly using the smaller strands or fines. The orientation of different layers of aligned strands gives OSB its unique characteristics, including greater bending strength and stiffness in the oriented or aligned direction. Control of strand size, orientation, and layered construction allows OSB to be engineered to suit different uses.

OSB technology and the raw material used originally evolved from waferboard technology, for which aspen was the predominant wood species used. As the industry learned to control strand size, placement, and orientation, the performance and utility of OSB products improved to the point that their performance was similar to that of structural plywood. As a result, product acceptance and the industry expanded as OSB replaced softwood plywood in many construction applications.

Raw Materials
In North America, aspen is the predominant wood used for OSB. Species other than aspen, such as Southern Pine, spruce, birch, yellow-poplar, sweetgum, sassafrass, and beech, are also suitable raw materials for OSB production. High-density species such as beech and birch are often mixed with low-density species such as aspen to maintain panel properties (Bowyer and others 2007).

Manufacturing Process
To manufacture OSB, debarked logs are sliced into long, thin wood elements called strands. The strands are dried, blended with resin and wax, and formed into thick, loosely consolidated mats that are pressed under heat and pressure into large panels. Figure 11–8 shows an OSB manufacturing process. A more detailed description of each individual manufacturing step follows.

During stranding, logs are debarked and then sent to a soaking pond or directly to the stranding process. Long log disk or ring stranders are commonly used to produce wood strands typically measuring 114 to 152 mm (4.5 to 6 in.) long, 12.7 mm (0.5 in.) wide, and 0.6 to 0.7 mm (0.023 to 0.027 in.) thick. Green strands are stored in wet bins and dried in a traditional triple-pass dryer, a single-pass dryer, a combination triple-pass/single-pass dryer, or a three-section conveyor dryer. A recent development is a continuous chain dryer, in which the strands are laid on a chain mat that is mated with an upper chain mat and the strands are held in place as they move through the dryer. The introduction of new drying techniques allows the use of longer strands, reduces surface inactivation of strands, and lowers dryer outfeed temperatures. Dried strands are screened and sent to dry bins.

Dried strands are blended with adhesive and wax in a highly controlled operation, with separate rotating blenders used for face and core strands. Typically, different resin formulations are used for face and core layers. Face resins may be liquid or powdered phenolics, whereas core resins may be phenolics or isocyanates. Several different resin application systems are used; spinning disk resin applicators are frequently used.

The strands with adhesive applied are sent to mat formers. Mat formers take on a number of configurations, ranging from electrostatic equipment to mechanical devices containing spinning disks to align strands along the panel’s length and star-type cross-orienters to position strands across the panel’s width. All formers use the long and narrow characteristic of the strand to place it between the spinning disks or troughs before it is ejected onto a moving screen or conveyor belt below the forming heads. Oriented layers of strands within the mat are dropped sequentially onto a moving conveyor. The conveyor carries the mat into the press.

Once the mat is formed, it is hot-pressed. In hot-pressing, the loose layered mat of oriented strands is compressed under heat and pressure to cure the resin. As many as sixteen 3.7- by 7.3-m (12- by 24-ft) panels may be formed simultaneously in a multiple-opening press. A more recent development is the continuous press for OSB. The press compacts and consolidates the oriented and layered mat of strands and heats it to 177 to 204 °C (350 to 400 °F) to cure the resin in 3 to 5 min.
OSB Grade Marks and Product Certification

OSB that has been grade marked is produced to comply with voluntary industry product performance standards. These inspection or certification programs also generally require that the quality control system of a production plant meet specified criteria. OSB panels conforming to these product performance standards are marked with grade stamps (Fig. 11–6).

Particleboard

The particleboard industry initially used cut flakes as a raw material. However, economic concerns prompted development of the ability to use sawdust, planer shavings, and to a lesser extent, mill residues and other relatively homogeneous waste materials produced by other wood industries. Particleboard is produced by mechanically reducing the wood raw material into small particles, applying adhesive to the particles, and consolidating a loose mat of the particles with heat and pressure into a panel product. All particleboard is currently made using a dry process, where air or mechanical formers are used to distribute the particles prior to pressing.

Particleboard is typically made in three layers. But unlike OSB, the faces of particleboard usually consist of fine wood particles and the core is made of coarser material. The result is a smoother surface for laminating, overlaying, painting, or veneering. Particleboard is readily made from virtually any wood material and from a variety of agricultural residues. Low-density insulating or sound-absorbing particleboard can be made from kenaf core or jute stick. Low-, medium-, and high-density panels can be produced with cereal straw, which has begun to be used in North America. 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. However, particleboard is generally not as strong as fiberboard because the fibrous nature of lignocellulosics (that is, their high aspect ratio) is not exploited as well. Particleboard is widely used in furniture, where it is typically overlaid with other materials for decorative purposes. It is the predominant material used in ready-to-assemble furniture. Particleboard can be also used in flooring systems, in manufactured houses, and as underlayment. Thin panels can also be used as a paneling substrate. Since most applications are interior, particleboard is usually bonded with a UF resin, although PF and MF resins are sometimes used for applications requiring more moisture resistance.

Manufacturing Process

The various steps involved in particleboard manufacturing include particle preparation, particle classification and drying, adhesive application, mat formation, pressing, and finishing.

Standard particleboard plants based on particulate material use combinations of hogs, chippers, hammermills, ring flakers, ring mills, and attrition mills. To obtain
The raw materials (or furnish) for these products do not usually arrive at the plant at a low enough moisture content for immediate use. Furnish that arrives at the plant can range from 10% to 200% dry basis moisture content. For use with liquid resins, for example, the furnish must be reduced to about 2% to 7% moisture content. The moisture content of particles is critical during hot-pressing operations and 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% to 8%. The main methods used to dry particles are rotary, disk, and suspension drying. A triple-pass rotary dryer consists of a large horizontal rotating drum that is heated by either steam or direct heat. Operating temperatures depend on the moisture content of the incoming furnish. The drum is set at a slight angle, and material is fed into the high end and discharged at the low end. A series of flights forces the furnish to flow from one end to the other three times before being discharged. The rotary movement of the drum moves the material from input to output.

Frequently used resins for particleboard include UF and, to a much lesser extent, PF, melamine-formaldehyde, and isocyanates. The type and amount of resin used for particleboard depend on the type of product desired. Based on the weight of dry resin solids and ovendry weight of the particles, the resin content can range between 4% and 10%, but usually ranges between 6% and 9% for UF resins. The resin content of the outer face layers is usually slightly higher than that of the core layer. Urea-formaldehyde resin is usually introduced in water solutions containing about 50% to 65% solids. Besides resin, wax is added to improve short-term moisture resistance. The amount of wax ranges from 0.3% to 1% based on the ovendry weight of the particles.

After the particles have been prepared, they are laid into an even and consistent mat to be pressed into a panel. This is accomplished in batch mode or usually by continuous formation. The batch system traditionally employs a caul or tray on which a deckle frame is placed. The mat is formed by the back-and-forth movement of a tray or hopper feeder. The mat is usually cold pressed to reduce mat thickness prior to hot pressing. The production of three-layer boards requires three or more forming stations. The two outer layers consist of particles that differ in geometry from those in the core. The resin content of the outer layers is usually higher (about 8% to 15%) than that of the core (about 4% to 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. The two outer face layers usually consist of particles that differ in geometry from those in the core. Continuous-formed mats are often pre-pressed, which reduces the mat height and helps to consolidate the mat for pressing. After pressing, panels are trimmed to obtain the desired length and to square the edges. After trimming the panels are sanded or planed prior to packaging and shipping.

Alternatively, a few 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 that differ from those obtained with flat pressing.

Particleboards may also be veneered or overlaid with other materials to provide a decorative surface, or they may be finished with lacquer or paint. Treatments with fire-resistant chemicals are also available.

**Particleboard Grade Marks and Product Certification**

A grade mark on particleboard ensures that the product has been periodically tested for compliance with voluntary industry product performance standards. These inspection or certification programs also generally require that the quality control system of a production plant meets strict criteria. Particleboard panels conforming to these product performance standards are marked with grade stamps (Fig. 11–9).
CHAPTER 11 | Wood-Based Composite Materials

Fiberboard

The term fiberboard includes hardboard, medium-density fiberboard (MDF), and cellulosic fiberboard. Several things differentiate fiberboard from particleboard, most notably the physical configuration of the wood element. Because wood is fibrous by nature, fiberboard exploits the inherent strength of wood to a greater extent than does particleboard.

To make fibers for composites, bonds between the wood fibers must be broken. Attrition milling is the easiest way to accomplish this. During attrition milling material is fed between two disks, usually one rotating and the other stationary. As the material is forced through the preset gap between the disks, it is sheared, cut, and abraded into fibers and fiber bundles. Grain has been ground in this way for centuries.

Attrition milling, or refining as it is commonly called, can be augmented by water soaking, steam cooking, or chemical treatments. Steaming the lignocellulosic weakens the lignin bonds between the cellulosic fibers. As a result, fibers are more readily separated and are usually less damaged than fibers processed by dry processing methods. Chemical treatments, usually alkali, are also used to weaken the lignin bonds. All these treatments help increase fiber quality and reduce energy requirements, but they may reduce yield and modify the chemistry as well. Refiners are available with single- or double-rotating disks, as well as steam-pressurized and unpressurized configurations. For MDF, steam-pressurized refining is typical.

Fiberboard is normally classified by density and can be made by either dry or wet processes (Fig. 11–4). Dry processes are applicable to boards with high density (hardboard) and medium density (MDF). Wet processes are applicable to both high-density hardboard and low-density cellulosic fiberboard. The following subsections briefly describe the manufacturing of high- and medium-density dry-process fiberboard, wet-process hardboard, and wet-process low-density cellulosic fiberboard. Suchsland and Woodson (1986) and Maloney (1993) provide more detailed information.

Dry-Process Fiberboard

Dry-process fiberboard is made in a similar fashion to particleboard. Resin (UF or melamine–UF) and other additives may be applied to the fibers by spraying in short-retention blenders or introduced as the wet fibers are fed from the refiner 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 mat formation for particleboard.

Pressing procedures for dry-process fiberboard differ somewhat from particleboard procedures. After the fiber mat is formed, it is typically pre-pressed in a band press. The densified mat is then trimmed by disk cutters and transferred to caul plates for the hardboard pressing operation; for MDF, the trimmed mat is transferred directly to the press. Many dry-formed boards are pressed in multi-opening presses. Continuous pressing using large, high-pressure
band presses is also gaining in popularity. Panel density is a basic property and an indicator of panel quality. Since density is greatly influenced by moisture content, this is constantly monitored by moisture sensors using infrared light.

MDF is frequently used in place of solid wood, plywood, and particleboard in many furniture applications. It is also used for interior door skins, mouldings, and interior trim components. ANSI A208.2 classifies MDF by physical and mechanical properties, and identifies dimensional tolerances and formaldehyde emission limits (CPA 2016b). An example of an MDF formaldehyde emissions certification tag is shown in Figure 11–10.

Wet-Process Hardboard
Wet-process hardboards differ from dry-process fiberboards in several significant ways. First, water is used as the distribution medium for forming the fibers into a mat. The 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 lignin is retained during the refining operation, lignin can serve as the binder. Under heat and pressure, lignin will flow and act as a thermosetting adhesive, enhancing the naturally occurring hydrogen bonds.

Refining is an important step for developing 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 papermaking, or on cylinder formers. The wet process employs a continuously traveling mesh screen, onto which the soupy pulp flows rapidly and smoothly. Water is drawn off through the screen and then through a series of press rolls, which use a wringing action to remove additional water.

Wet-process hardboards are pressed in multi-opening presses heated by steam. The press cycle consists of three phases and lasts 6 to 15 min. The first phase is conducted at high pressure, and it removes most of the water while bringing the board to the desired thickness. The primary purpose of the second phase is to remove water vapor. The final phase is relatively short and results in the final cure. A maximum pressure of about 5 MPa (725 lb in\(^2\)) is used in all three phases. Heat is essential during pressing to induce fiber-to-fiber bond. A high temperature of up to 210 °C (410 °F) is used to increase production by causing faster evaporation of the water. Lack of sufficient moisture removal during pressing adversely affects strength and may result in “springback” or blistering.
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Wet-formed composite technology has lost market share compared with dry-formed technology over the past few decades because of processing speed and perceived environmental issues related to process water. However, wet-formed technology does offer unique opportunities for forming geometric shapes that yield enhanced structural performance and decrease weight, elimination of fiber drying prior to forming, and reduced need for adhesive resins. It also greatly increases the ability to use recycled paper and some other woody fibers. Recent advances in process wastewater recycling and remediation also bode well for wet-formed technologies. Wet-formed composites may soon experience a renaissance and again become a significant technology because of reduced energy-demands, increased composite structural performance and decreased weight, and the virtual elimination of (or drastic reduction in) process water concerns.

Several treatments are used to increase dimensional stability and mechanical performance of hardboard. Heat treatment, tempering, and humidification may be done singularly or in conjunction with one another. Heat treatment—exposure of pressed fiberboard to dry heat—improves dimensional stability and mechanical properties, reduces water adsorption, and improves interfiber bonding. Tempering is the heat treatment of pressed boards, preceded by the addition of oil. Tempering improves board surface hardness, resistance to abrasion, scratching, scarring, and water. The most common oils used include linseed oil, tung oil, and tall oil. Humidification is the addition of moisture to bring the board moisture content to levels roughly equivalent to those anticipated in its end-use environment. Air of high humidity is forced through the stacks where it provides water vapor to the boards. Another method involves spraying water on the back side of the board. Typical hardboard products are prefinished paneling, house siding, floor underlayment, and concrete form board. A typical grade stamp for hardboard siding is shown in Figure 11–11.

Cellulosic Fiberboard

Cellulosic fiberboards are low-density, wet-laid panel products used for insulation, sound deadening, carpet underlayment, and similar applications. In the manufacture of cellulosic fiberboard, the need for refining and screening is a function of the raw material available, the equipment used, and the desired end-product. Cellulosic fiberboards typically do not use a binder, and they rely on hydrogen bonds to hold the board components together. Sizing agents are usually added to the furnish (about 1%) to provide the finished board with a modest degree of water resistance and dimensional stability.

As in the manufacture of wet-process hardboard, cellulosic fiberboard manufacture is a modification of papermaking. 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 screen, or cylinder screen. A deckle box is a bottomless frame that is placed 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. The use of Fourdrinier screen for felting is similar to that for papermaking, except that line speeds are reduced to 8 to 18 m min⁻¹ (25 to 60 ft min⁻¹).

Cellulosic fiberboard formed in a deckle box is cold-pressed to remove the free water after the mat is formed. Compression rollers on the Fourdrinier machines squeeze out the free water. The wet mats are then dried to the final moisture content. Dryers may be a continuous tunnel or a multideck arrangement. The board is generally dried in stages at temperatures ranging from 120 to 190 °C (248 to 374 °F). Typically, about 2 to 4 h is required to reduce moisture content to about 1% to 3%.

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

Cellulosic fiberboard products include sound-deadening board, roof insulation boards, structural and nonstructural sheathings, backer board, and roof decking in various thicknesses. An example of a grade mark stamp for these cellulosic fiberboard products conforming to ASTM C208 (ASTM 2017a) is shown in Figure 11–12.

**Figure 11–11. Typical grade stamp for hardboard siding.** (Courtesy of Composite Panel Association, Leesburg, Virginia. Used by permission.)

**Finishing Techniques**

Several techniques are used to finish fiberboard: trimming, sanding, surface treatment, punching, and embossing. Trimming consists of reducing products into standard sizes and shapes. Generally, double-saw trimmers are used to saw the panels. Trimmers consist of overhead-mounted saws or multiple saw drives. Trimmed panels are stacked in piles for future processing. If thickness tolerance is critical, hardboard is sanded prior to finishing. S1S (smooth on one side) panels require this process. Sanding reduces thickness variation and improves surface paintability. Single-head, wide-belt sanders are used with 24- to 36-grit abrasive. Surface treatments improve the appearance and performance
of boards. Panels are cleaned by spraying with water and then dried at about 240 °C (464 °F) for 30 s. Panel surfaces are then modified with paper overlay, paint, or stain or are printed directly on the panel. Punching changes panels into the perforated sheets used as peg board. Embossing consists of pressing the unconsolidated mat of fibers with a textured form. This process results in a slightly contoured panel surface that can enhance the resemblance of the panel to that of sawn or weathered wood, brick, and other materials.

Specialty Composite Materials
Special-purpose composite materials are produced to obtain enhanced performance properties such as water resistance, mechanical strength, acidity control, and fire, decay and insect resistance. Overlays and veneers can also be added to enhance both structural properties and appearance (Fig. 11–13).

Moisture-Resistant Composites
Sizing agents, wax, and asphalt can be used to make composites resistant to moisture. Sizing agents cover the surface of fibers, reduce surface energy, and render the fibers relatively hydrophobic. Sizing agents can be applied in two ways. In the first method, water is used as a medium to ensure thorough mixing of sizing and fiber. The sizing is precipitated from the water and is fixed to the fiber surface. In the second method, the sizing is applied directly to the fibers.

Rosin is a common sizing agent that is obtained from living pine trees, from pine stumps, and as a by-product of kraft pulping of pines. Rosin sizing 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 sizing is used in dry-process fiberboard production; for wet processes, wax is added in solid form or as an emulsion. Wax sizing tends to lower strength properties to a greater extent than does rosin. Asphalt is also used to increase water resistance, especially in low-density wet-process cellulose fiberboard. Asphalt is a black–brown solid or semi-solid material that liquefies when heated. The predominant component of asphalt is bitumen. Asphalt is precipitated onto fiber by the addition of alum.

Flame-Retardant Composites
Two general application methods are available for improving the fire performance of composites with fire-retardant chemicals. One method consists of pressure impregnating the wood with waterborne or organic solvent-borne fire retardant chemicals (AWPA 2019). The second method consists of applying fire-retardant chemical coatings to the wood surface. The pressure impregnation method is usually more effective and longer lasting; however, this technique is standardized only for plywood. It is not generally used with structural flake, particle, or fiber composites, because it can cause swelling that permanently damages the wood–adhesive bonds in the flake, particle, or fiber composite and results in the degradation of some physical and mechanical properties of the composite.

Preservative-Treated Composites
Composites can be protected from attack by decay fungi and harmful insects by applying selected chemicals as wood preservatives. The degree of protection obtained depends on the kind of preservative used and the ability to achieve proper penetration and retention of the chemicals. Wood preservatives can be applied using pressure or nonpressure processes (AWPA 2019). As in the application of fire-retardant chemicals, the pressurized application of wood preservatives is generally performed after manufacture and is standardized for plywood. Post-manufacture pressure treatments are not standardized for all types of flake,
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particle, or fiber composite because it can sometimes damage wood–adhesive bonds, which in turn reduces physical and mechanical properties of the composite. Preservatives can be added in the composite manufacturing process, but the preservative must be resistant to vaporization during hot pressing. Proprietary flakeboard and fiberboard products with incorporated nonvolatile preservatives have been commercialized. Common preservative treatments include ammoniacal copper quat (ACQ), copper azol (CA), and boron compounds.

Performance and Standards

Performance levels required for conventional wood-based composite products are typically established under a series of internationally accredited consensus review processes involving users, producers, and general interests. Then, commercial wood composites are manufactured to conform to these commercial product or performance standards (Table 11–2). These product or performance standards are written for composites used in specific end uses, and the requirements of these standards focus on particular end uses. Approved uses are established by the International Code Council (ICC), a nonprofit organization that has developed a single national construction code. In the early part of the past century, three regional nonprofit code organizations separately developed three sets of building codes for use throughout the United States. Although regional code development was effective at that time, eventually a single set of codes was needed. In 1994, the nation’s three model code groups responded by creating the ICC, which then developed the International Building Code that had no regional limitations. Because not all composite products have National Standards, the ICC sometimes accepts proprietary construction products when National Standards do not exist. The National Evaluation Services organization of ICC, are approved under the International Building Code. These wood-based composites can be used for construction applications such as sheathing for roofs, sub-flooring, and walls. Plywood and OSB, are span-rated for particular end uses. Similarly, many types of wood-based composite lumber can be used for joists, purlins, stringers, beams, and columns.

Plywood panels conforming to PS 1–09 are marked with grade stamps (Fig. 11–6a,b). Structural flake-based composites, such as OSB, are usually marketed as conforming to a product standard for sheathing or single-layer sub-flooring or underlayment and are also marked with grade stamps (Fig. 11–6c,d). The grade stamps in Figure 11–6 show (1) conformance to product standards, (2) nominal panel thickness, (3) grades of face and back veneers or grade name based on use (plywood only), (4) performance-rated panel standard, (5) recognition as a quality assurance agency by the National Evaluation Service (NES), which is affiliated with the ICC, (6) exposure durability classification, (7) span rating, which refers to maximum allowable roof support spacing and maximum floor joist spacing, and (8) panel sizing for spacing.

Role of Standards in Construction

Structural wood-based composite panels and lumber elements manufactured in conformance with product standards (Table 11–2), or as approved by issuance of a national evaluation report by the National Evaluation Services organization of ICC, are approved under the International Building Code. These wood-based composites can be used for construction applications such as sheathing for roofs, sub-flooring, and walls. Plywood and OSB, are span-rated for particular end uses. Similarly, many types of wood-based composite lumber can be used for joists, purlins, stringers, beams, and columns.

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Structural-use panels are also span-rated. Span-rating of construction plywood and OSB simplifies materials specification in light-frame construction by allowing specification without resorting to specific structural engineering design calculations. Panels in PS 2–10 are designated by application (wall, roof, sub-floor, or single floor) and by span rating. Specification by application and span is more convenient for builders than specification by
species or species group, veneer grade, and panel thickness. Span ratings refer to on-center spacing of support members (expressed in inches), with the long panel dimension (in plywood this is the same direction as the face grain) placed across the supports, assuming that there are at least two spans (a minimum of three supports). A panel may be suitable for use as either roof sheathing or sub-flooring, with different span ratings for the two applications. Such panels will have a dual span-rating, the first (and larger) number indicating allowable span when used as roof sheathing, the second number indicating the allowable span when used as sub-flooring.

Design properties and basic installation guidelines of these structural-use panels are standardized in the International Residential Code (IRC 2018). By reference through these voluntary product standards, the IRC requires independent third-party certification of these panels, and several such third-party certification agencies exist, such as APA–The Engineered Wood Association (www.apawood.org) and TECO (www.tecotested.com). These agencies and others offer a variety of technical information on the proper selection, design, and installation of structural-use panels.

**Glued Laminated Timber**

Structural glued laminated timber (glulam) is one of the oldest glued engineered wood products. Glulam is an engineered, stress-rated product that consists of two or more layers of lumber that are glued together with the grain of all layers, which are referred to as laminations, parallel to the length. Glulam is defined as a material that is made from suitably selected and prepared pieces of wood either in a straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member. The maximum lamination thickness permitted is 50 mm (2 in.), and the laminations are typically made of standard 25- or 50-mm- (nominal 1- or 2-in.-) thick lumber. North American standards require that glulam be manufactured in an approved manufacturing plant. Because the lumber is joined end to end, edge to edge, and face to face, the size of glulam is limited only by the capabilities of the manufacturing plant and the transportation system. Cross-laminated timber (CLT) is a solid engineered wood panel in which layers of glulam are glued together perpendicular to their adjoining layer. (See Chap. 12 for more details on CLT.)

Douglas Fir–Larch, Southern Pine, Hem–Fir, and Spruce–Pine–Fir (SPF) are commonly used for glulam in the United States. Nearly any species can be used for glulam timber, provided the mechanical and physical properties are suitable and gluing properties acceptable. Industry standards cover many softwoods and hardwoods, and procedures are in place for including other species.

**Advantages**

Compared with sawn timbers as well as other structural materials, glulam has several distinct advantages. These include size capability, architectural effects, seasoning, and grades.

**Size Capabilities**

Glulam offers the possibility of manufacturing structural timbers that are much larger than the trees from which the component lumber was sawn. In the past, the United States had access to large trees that could produce relatively large sawn timbers. However, the present trend is to harvest smaller diameter trees on much shorter rotations, and nearly all new sawmills are built to accommodate relatively small logs. By combining the lumber in glulam, the production of large structural elements is possible. Straight members up to 30 m (100 ft) long are not uncommon, and some span up to 43 m (140 ft). Sections deeper than 2 m (7 ft) have been used. Thus, glulam offers the potential to produce large timbers from small trees.

**Architectural Effects**

By curving lumber during the manufacturing process, a variety of architectural effects can be obtained with glulam that are impossible or very difficult with other materials, such as varying cross sections or curved arches (Fig. 11–14). The degree of curvature is controlled by the thickness of the laminations. Thus, glulam with moderate curvature is generally manufactured with standard 19-mm- (nominal 1-in.-) thick lumber. Low curvatures are possible with standard 38-mm (nominal 2-in.) lumber, whereas 13 mm (1/2 in.) or thinner material may be required for very sharp curves. As noted later in this chapter, the radius of curvature is limited to between 100 and 125 times the lamination thickness.

**Seasoning Advantages**

The lumber used in the manufacture of glulam must be seasoned or dried prior to use, so the effects of checking and other drying defects are minimized. This allows design on the basis of seasoned wood, which permits greater design values than can be assigned to unseasoned timber.

**Varying Grades**

One major advantage of glulam is that a large quantity of lower grade lumber can be used within the less highly stressed laminations of the beams. Grades are often varied within the beams so that the highest grades are used in the highly stressed laminations near the top and bottom edges, with the lower grades used in the inner half or more (toward the center) of the beams. Species can also be varied to match the structural requirements of the laminations.
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Figure 11–14. Erected in 1934 at the Forest Products Laboratory in Madison, Wisconsin, this building is one of the first constructed with glued laminated timbers arched, designed and built using engineering principles.

Types of Glulam Combinations

Bending Members
The configuring of various grades of lumber to form a glulam cross section is commonly referred to as a glulam combination. Glulam combinations subjected to flexural loads, called bending combinations, were developed to provide the most efficient and economical section for resisting bending stress caused by loads applied perpendicular to the wide faces of the laminations. This type of glulam is commonly referred to as a horizontally laminated member. Lower grades of laminating lumber are commonly used for the center portion of the combination, or core, where bending stress is low, while a higher grade of material is placed on the outside faces where bending stress is relatively high. To optimize the bending stiffness of this type of glulam member, equal amounts of high-quality laminations on the outside faces should be included to produce a “balanced” combination. To optimize bending strength, the combination can be “unbalanced” with more high-quality laminations placed on the tension side of the member compared with the quality used on the compression side. For high-quality lumber placed on the tension side of the glulam combination, stringent requirements are placed on knot size, slope of grain, and lumber stiffness.

For compression-side laminations, knot size and slope-of-grain requirements are less stringent and only lumber stiffness is given high priority. In the case where the glulam member is used over continuous supports, the combination would need to be designed as a balanced member for strength and stiffness because of the exposure of both the top and bottom of the beam to tensile stresses. The knot and slope-of-grain requirements for this type of combination are generally applied equally to both the top and bottom laminations.

Axial Members
Glulam axial combinations were developed to provide the most efficient and economical section for resisting axial forces and flexural loads applied parallel to the wide faces of the laminations. Members having loads applied parallel to the wide faces of the laminations are commonly referred to as vertically laminated members. Unlike the practice for bending combinations, the same grade of lamination is used throughout the axial combination. Axial combinations may also be loaded perpendicular to the wide face of the laminations, but the nonselective placement of material often results in a less efficient and less economical member than does the bending combination. As with bending combinations, knot and slope-of-grain requirements apply based on whether the axial member will be used as a tension or compression member.

Curved Members
Efficient use of lumber in cross sections of curved glulam combinations is similar to that in cross sections of straight, horizontally laminated combinations. Tension and compression stresses are analyzed as tangential stresses in the curved portion of the member. A unique behavior in these curved members is the formation of radial stresses perpendicular to the wide faces of the laminations. As the radius of curvature of the glulam member decreases, the radial stresses formed in the curved portion of the beam increase. Because of the relatively low strength of lumber in tension perpendicular-to-the-grain compared with tension parallel-to-the-grain, these radial stresses become a critical factor in designing curved glulam combinations. Curved members are commonly manufactured with standard 19- and 38-mm- (nominal 1- and 2-in.-) thick lumber. Naturally, the curvature that is obtainable with the standard 19-mm- (nominal 1-in.-) thick lumber will be sharper than that for the standard 38-mm- (nominal 2-in.-) thick lumber.

Tapered Straight Members
Glulam beams are often tapered to meet architectural requirements, provide pitched roofs, facilitate drainage, and lower wall height requirements at the end supports. The taper is achieved by sawing the member across one or more laminations at the desired slope. It is recommended that the taper cut be made only on the compression side of the glulam member, because violating the continuity of the tension-side laminations would decrease the overall strength of the member.

Standards and Specifications

Manufacture
and to take advantage of the increased structural properties of the glulam timber during transit and storage.

In instances where the glulam will be used in high-moisture-content conditions, the member must also be pressure-treated with preservative.

The manufacturing process can be divided into four major parts: (a) drying and grading the lumber, (b) end jointing the lumber, (c) face bonding, and (d) finishing and fabrication. In instances where the lumber will be used in high-moisture-content conditions, the member must also be pressure-treated with preservative.

A final critical step in ensuring the quality of glulam is protection of the glulam timber during transit and storage.

**Lumber Drying and Grading**

To minimize dimensional changes following manufacture and to take advantage of the increased structural properties assigned to lumber compared with large sawn timbers, the lumber must be properly dried prior to glulam manufacture. This generally means kiln drying. Matching the moisture content of the glulam timber at the time of manufacture to that which it will attain in application minimizes shrinkage and swelling, the main causes of checking. The moisture content of lumber can be determined by sampling from the lumber supply and using a moisture meter. Alternatively, most manufacturers use a continuous in-line moisture meter to check the moisture content of each piece of lumber as it enters the manufacturing process. Pieces with greater than a given moisture level are removed and redried.

Grading standards published by the regional lumber grading associations describe the characteristics that are permitted in various grades of lumber. Manufacturing standards for glulam timber describe the combination of lumber grades necessary for specific design values. The rules for visually graded lumber are based entirely upon the characteristics that are readily apparent. The lumber grade description consists of limiting characteristics for knot sizes, slope of grain, wane, and several other characteristics.

Manufacturers generally purchase graded lumber and verify the grades through visual inspection of each piece and, if E-rated, testing of a sample. To qualify the material for some of the higher design stresses for glulam timber, manufacturers must also conduct additional grading for material to be used in the tension zone of certain beams. Another option is to purchase special lumber that is manufactured under a quality assurance system to provide the required tensile strength. Another option practiced by at least one manufacturer has been to use laminated veneer lumber (LVL) to provide the required tensile strength.

**End Jointing**

To manufacture glulam timber in lengths beyond those commonly available for lumber, laminations must be made by end jointing lumber to the proper length. The most common end joint, a fingerjoint, is about 28 mm (1.1 in.) long. Other configurations are also acceptable, provided they meet specific strength and durability requirements. The advantages of fingerjoints are that they require only a short length of lumber to manufacture (thus reducing waste) and continuous production equipment is readily available. Well-made joints are critical to ensure adequate performance of glulam timber. Careful control at each stage of the process—determining lumber quality, cutting the joint, applying the adhesive, mating, applying end pressure, and curing—is necessary to produce consistent high strength joints.

**Face Bonding**

The assembly of laminations into full-depth members is another critical stage in manufacture. To obtain clear, parallel, and gluable surfaces, laminations must be planed to
strict tolerances. The best procedure is to plane the two wide faces of the laminations just prior to the gluing process. This ensures that the final assembly will be rectangular and that the pressure will be applied evenly. Adhesives that have been pre-qualified are then spread, usually with a glue extruder. Phenol resorcinol is the most commonly used adhesive for face gluing, but other adhesives that have been adequately evaluated and proven to meet performance and durability requirements may also be used.

The laminations are then assembled into the required layup; after the adhesive is given the proper open assembly time, pressure is applied. The most common method for applying pressure is with clamping beds; the pressure is applied with either a mechanical or hydraulic system. This results in a batch-type process, and the adhesive is allowed to cure at room temperature from 6 to 24 h. Some newer automated clamping systems include continuous hydraulic presses and radio-frequency curing to shorten the face gluing process from hours to minutes. Upon completion of the face bonding process, the adhesive is expected to have attained 90% or more of its bond strength. During the next few days, curing continues, but at a much slower rate.

The face bonding process is monitored by controls in the lumber planing, adhesive mixing, and adhesive spreading and clamping processes. Performance is evaluated by conducting shear tests on samples cut off as end trim from the finished glulam timber. Thus, the adhesive bonds are expected to develop nearly the full strength of the wood soon after manufacture.

**Finishing and Fabrication**

After the glulam timber is removed from the clamping system, the wide faces are planed to remove the adhesive that has squeezed out between adjacent laminations and to smooth out any slight irregularities between the edges of adjacent laminations. As a result, the finished glulam timber is slightly narrower than nominal dimension lumber. The remaining two faces of the member can be lightly planed or sanded using portable equipment.

The appearance requirements of the beam dictate the additional finishing necessary at this point. Historically, three classifications of finishing have been included in the industry standard, AITC 110: Industrial, Architectural, and Premium (AITC 2001). Industrial appearance is generally applicable when appearance is not a primary concern, such as industrial plants and warehouses. Architectural appearance is suitable for most applications where appearance is an important requirement. Premium appearance is the highest classification. The primary difference among these classifications is the amount of knot holes and occasional planer skips that are permitted. A recently introduced classification, called Framing, consists of hit-and-miss planing and permits a significant amount of adhesive to remain on the surface. This finishing is intended for uses that require one member to have the same width as the lumber used in manufacture for framing into walls. These members are often covered in the finished structure.

The next step in the manufacturing process is fabrication, where the final cuts are made, holes are drilled, connectors are added, and a finish or sealer is applied, if specified. For various members, different degrees of prefabrication are done at this point. Trusses may be partially or fully assembled. Moment splices can be fully fabricated, then disconnected for transportation and erection. End sealers, surface sealers, primer coats, and wrapping with waterproof paper or plastic all help to stabilize the moisture content of the glulam timber between the time it is manufactured and installed. The extent of protection necessary depends upon the end use and must be specified.

**Preservative Treatment**

In instances where the moisture content of the finished glulam timber will approach or exceed 20% (in most exterior and some interior uses), the glulam timber should be preservative-treated following AITC 109 (AITC 2007). Three main types of preservatives are available: creosote, oilborne, and waterborne. Creosote and oilborne preservatives are applied to the finished glulam timbers. Some light oil solvent treatments can be applied to the lumber prior to gluing, but the suitability must be verified with the manufacturer. Waterborne preservatives are best applied to the lumber prior to the laminating and manufacturing process because they can lead to excessive checking if applied to large finished glulam timbers.

**Structural Composite Lumber and Timber Products**

Structural composite lumber (SCL) was developed in response to the increasing demand for high-quality lumber at a time when it was becoming difficult to obtain this type of lumber from the forest resource. Structural composite lumber products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber.

One type of SCL product is manufactured by laminating veneer with all plies parallel to the length. This product is called laminated veneer lumber (LVL) and consists of specially graded veneer. Another type of SCL product consists of strands of wood or strips of veneer glued together under high pressures and temperatures. Depending upon the component material, this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL). These types of SCL products can be manufactured from raw materials, such as aspen or other underutilized species, that are not commonly used for structural applications. Different widths of lumber can be ripped from SCL for various uses. Compared with similar size solid-sawn lumber, SCL often provides a stronger, more reliable structural member that can often span greater distances and has less dimensional change.
Structural composite lumber is a growing segment of the engineered wood products industry. It is used as a replacement for lumber in various applications and in the manufacture of other engineered wood products, such as prefabricated wood I-joists, which take advantage of engineering design values that can be greater than those commonly assigned to sawn lumber.

**Laminated Veneer Lumber**

Work in the 1940s on LVL targeted the production of high-strength parts for aircraft structures using Sitka spruce veneer. Research on LVL in the 1970s was aimed at defining the effects of processing variables for veneer up to 12.7 mm (1/2 in.) thick. Since the 1990s, production of LVL uses veneers 3.2 to 2.5 mm (1/8 to 1/10 in.) thick, which are hot pressed with phenol-formaldehyde adhesive into lengths from 2.4 to 18.3 m (8 to 60 ft) or more. Today LVL is commonly used as the flanges in composite I-joists.

Veneer for the manufacture of LVL must be carefully selected for the product to achieve the desired engineering properties. Veneers are often sorted using ultrasonic testing to ensure that the finished product will have the desired engineering properties.

End joints between individual veneers may be staggered along the product to minimize their effect on strength. These end joints may be butt joints, or the veneer ends may overlap for some distance to provide load transfer. Some producers provide structural end joints in the veneers using either scarf or fingerjoints. Laminated veneer lumber may also be made in 2.4-m (8-ft) lengths, having no end joints in the veneer; longer pieces are then formed by end jointing these pieces to create the desired length and can be much longer than conventional lumber products.

Sheets of LVL are commonly produced in 0.6- to 1.2-m (2- to 4-ft) widths in a thickness of 38 mm (1.5 in.). Continuous presses can be used to form a potentially endless sheet, which is cut to the desired length. Various widths of lumber can be manufactured at the plant or the retail facility.

**Parallel Strand Lumber**

Parallel strand lumber (PSL) is defined as a composite of wood strand elements with wood fibers oriented primarily along the length of the member. The least dimension of the strands must not exceed 6.4 mm (0.25 in.), and the average length of the strands must be a minimum of 150 times the least dimension. PSL is a proprietary product, commonly sold as Parallam®. It is often used for large beams and columns, typically as a replacement of solid-sawn lumber or glulam.

Parallel strand lumber is manufactured using veneer about 3 mm (1/8 in.) thick, which is then clipped into strands about 19 mm (3/4 in.) wide. These strands are commonly at least 0.6 m (24 in.) long. The manufacturing process was designed to use the material from roundup of the log in the veneer cutting operation as well as other less than full-width veneer (Fig. 11–15). Thus, the process can utilize waste material from a plywood or LVL operation. Species commonly used for PSL include Douglas-fir, southern pines, western hemlock, and yellow-poplar, but there are no restrictions on using other species.

The strands are coated with a waterproof structural adhesive, commonly phenol-resorcinol formaldehyde, and oriented in a press using special equipment to ensure proper orientation and distribution. The pressing operation results in densification of the material, and the adhesive is cured using microwave technology. Billets larger than those of LVL are commonly produced; a typical size is 0.28 by 0.48 m (11 by 19 in.). This product can then be sawn into smaller pieces, if desired. As with LVL, a continuous press is used so that the length of the product is limited by handling restrictions.

**Laminated Strand Lumber and Oriented Strand Lumber**

Laminated strand lumber (LSL) and oriented strand lumber (OSL) products are an extension of the technology used to produce oriented strandboard (OSB) structural panels. The products have more similarities than differences. The main difference is that the aspect ratio of strands used is LSL is higher than for OSL (AF&PA 2006). One type of LSL uses strands that are about 0.3 m (12 in.) long, which is somewhat longer than the strands commonly used for OSB. Waterproof adhesives are used in the manufacture of LSL. One type of product uses an isocyanate type of adhesive that is sprayed on the strands and cured by steam injection. This product needs a greater degree of alignment of the strands than does OSB and higher pressures, which result in increased densification. Both LSL and OSL are proprietary products; LSL is sold as TimberStrand®. Applications such as studs and millwork are common.

**Advantages and Uses**

In contrast with sawn lumber, the strength-reducing characteristics of SCL are dispersed within the veneer or strands and have much less effect on strength properties. Thus, relatively high design values can be assigned to strength properties for both LVL and PSL. Whereas both LSL and OSL have somewhat lower design values, they have the advantage of being produced from a raw material that need not be in a log size large enough for peeling into veneer. All SCL products are made with structural adhesives and are dependent upon a minimum level of strength in these bonds.

All SCL products are made from veneers or strands that are dried to a moisture content that is slightly less than that for most service conditions. Thus, little change in moisture content will occur in many protected service conditions. When used indoors, this results in a product that is less...
likely to warp or shrink in service. However, the porous nature of both LVL and PSL means that these products can quickly absorb water unless they are provided with some protection.

All types of SCL products can be substituted for sawn lumber products in many applications. Laminated veneer lumber is used extensively for scaffold planks and in the flanges of prefabricated I-joists, which take advantage of the relatively high design properties. Both LVL and PSL beams are used as headers and major load-carrying elements in construction. The LSL and OSL products are used for band joists in floor construction and as substitutes for studs and rafters in wall and roof construction. Various types of SCL are also used in a number of nonstructural applications, such as the manufacture of windows and doors.

Standards and Specifications

The ASTM D5456-19 (ASTM 2019a) standard provides methods to develop design properties for SCL products as well as requirements for quality assurance during production. Each manufacturer of SCL products is responsible for developing the required information on properties and ensuring that the minimum levels of quality are maintained during production. An independent inspection agency is required to monitor the quality assurance program.

Unlike lumber, no standard grades or design stresses have been established for SCL. Each manufacturer may have unique design properties and procedures. Thus, the designer should consult information provided by the manufacturer.

Wood–Nonwood Composite Materials

Wood may be combined with nonwood materials to produce composite products with unique properties. Wood–nonwood composites typically contain wood elements such as particles and fibers suspended in a matrix material (for example, cement, ceramic, or thermoplastic). The proportion of wood elements varies depending upon the composite and application and can range from a few percent of the product mass to the majority of the product mass.

The primary impetus for developing such products has come from one or more of the following research and development goals:

- Develop biocomposite products with enhanced sustainability
- Reduce material costs by combining a lower cost material (acting as a filler or extender) with an expensive material
- Develop products that can utilize recycled materials and be recyclable in themselves
- Produce composite products that exhibit specific properties that are superior to those of the component materials alone (for example, increased strength-to-weight ratio, improved abrasion resistance, enhanced resistance to fire, decay and insects)
Composites made from wood and other materials create enormous opportunities to match product performance to end-use requirements. The following discussion includes the most common type of wood–nonwood composites: inorganic bonded and wood–thermoplastic composites.

**Cement-Bonded Composite Materials**

Inorganic-bonded wood composites have a long and varied history that started with commercial production in Austria in 1914. They are now used in many countries in the world, mostly in panel form. 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 precast building members.

Cement-bonded wood composites are molded products or boards that contain between 10% and 70% by weight wood particles or fibers and conversely 90% to 30% inorganic binder. Acceptable properties of an inorganic-bonded wood composite can be obtained only when the wood particles are fully encased within the binder to make a coherent material. This differs considerably from the technique used to manufacture thermosetting-resin-bonded boards, where flakes or particles are “spot welded” by a binder applied as a finely distributed spray or powder. Because of this difference and because hardened inorganic binders have a higher density than that of most thermosetting resins, the required amount of inorganic binder per unit volume of composite material is much higher than that of resin-bonded wood composites. The properties of inorganic-bonded wood composites are significantly influenced by the amount and nature of the inorganic binder and the woody material as well as the density of the composites.

The properties of cement-bonded composites are influenced by wood element characteristics (species, size, geometry, chemical composition), cement type, wood–water–cement ratio, environmental temperature, and cure time (Jorge and others 2004). They are heavier than conventional wood-based composites but lighter than concrete. Therefore they can replace concrete in construction, specifically in applications that are not subjected to loads. Wood–cement composites provide an option for using wood residues, or even agricultural residues. However, species selection can be important because many species contain sugars and extractives that retard the cure of cement (Bowyer and others 2007).

Magnesia and Portland cement are the most common cement binders. Magnesia cement is sensitive to moisture, and its use is generally restricted to interior applications. Composites bonded with Portland cement are more durable than those bonded with magnesia cement and are used in both interior and exterior applications. Cement-bonded composites are made by blending proportionate amounts of the wood element with inorganic materials in the presence of water and allowing the inorganic material to cure or “set up” to make a rigid composite. Some cement-bonded composites are very resistant to deterioration by decay fungi, insects, and vermin. Most have appreciable fire resistance.

A unique feature of cement-bonded composites is that their manufacture is adaptable to either end of the cost and technology spectrum. This is facilitated by the fact that no heat is required to cure the inorganic material. 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 mostly unskilled labor. If the market for such composites increases, technology can be introduced to increase manufacturing throughput. The labor force can be trained concurrently with the gradual introduction of more sophisticated technology.

**Magnesia-Cement-Bonded Composite Materials**

Fewer commercial products bonded with magnesia cement have been produced than those bonded with Portland cement mainly because of higher price and lower durability. However, magnesia cement does offer some manufacturing advantages over Portland cement. First, the various sugars in lignocellulosics apparently do not have as much effect on the curing and bonding of the binder. Second, magnesia cement is reported to be more tolerant of high water content during production. This opens up possibilities to use lignocellulosics not amenable to Portland cement composites, without leaching or other modification, and to use alternative manufacturing processes and products. Although composites bonded with magnesia cement are considered water sensitive, they are much less so than gypsum-bonded composites.

One successful application of magnesia cement is a low-density panel made for interior ceiling and wall applications. In the production of this panel product, wood wool (excelsior) is laid out in a low-density mat. The mat is then sprayed with an aqueous solution of magnesia cement, pressed, and cut into panels (Fig. 11–16).

Other processes have been suggested for manufacturing magnesia-cement-bonded composites. One application may be to spray a slurry of magnesia cement, water, and lignocellulosic fiber onto existing structures as fireproofing. Extrusion into a pipe-type profile or other profiles is also possible.

**Portland-Cement-Bonded Composite Materials**

The most widely used inorganic-bonded composites are those bonded with Portland cement. Portland cement, when combined with water, immediately reacts in a process called hydration to eventually solidify into a solid stone-like mass. Successfully marketed Portland-cement-bonded composites consist of both low-density products made with excelsior and high-density products made with particles and fibers.
Low-density products may be used as interior ceiling and wall panels in commercial buildings. In addition to the advantages described for low-density magnesia-bonded composites, low-density composites bonded with Portland cement 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 coated with stucco, and 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, such as decorative roofing tiles or non-pressure pipes.

Problems and Solutions of Cement-Bonded Composite Materials

The use of cement for wood-based composites involves limitations and tradeoffs. Marked embrittlement of the lignocellulosic component is known to occur and is caused by the alkaline environment provided by the cement matrix. In addition, hemicellulose, starch, sugar, tannins, and lignin, each to a varying degree, affect the cure rate and ultimate strength of these 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 1 or 2 days to extract some of the detrimental components. However, in some parts of the world, the water containing the leachate is difficult to dispose of. Low water–cement ratios are helpful, as is the use of curing accelerators like calcium carbonate. Conversely, low-alkali cements have been developed, but they are not readily available throughout the world. Two other strategies involve the use of natural pozzolans and carbon dioxide treatment.

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

In general, when pozzolans are blended with Portland cement, they increase the strength of the cement but slow the cure time. More important, pozzolans decrease the alkalinity of the product.

Carbon Dioxide Treatment—In the manufacture of a cement-bonded lignocellulosic composite, the cement hydration process normally requires from 8 to 24 h to develop sufficient board strength and cohesiveness to permit the release of consolidation pressure. By exposing the cement to carbon dioxide, the initial hardening stage can be reduced to less than 5 min. This phenomenon results from the chemical reaction of carbon dioxide with calcium hydroxide to form calcium carbonate and water.

Reduction of initial cure time of the cement-bonded lignocellulosic composite is not the only advantage of using carbon dioxide injection. Certain species of wood have various amounts of sugars and tannins that interfere with the hydration or setting of Portland cement. Research has shown that the use of carbon dioxide injection reduces the likelihood that these compounds will inhibit the hydration process, thus allowing the use of a wider range of species in these composites. In addition, research has demonstrated that composites treated with carbon dioxide can be twice as stiff and strong as untreated composites (Geimer and others 1992). Finally, carbon-dioxide-treated composites do not experience efflorescence (migration of calcium hydroxide to surface of material), so the appearance of the surface of the final product is not changed over time.

Applications and Standards

The largest volume of cement-bonded wood-based composite materials manufactured in North America is fiber-cement siding. Fiber-cement siding incorporates delignified wood fiber into the Portland cement matrix. Siding sheets that mimic shingles or lapboard and roof tiles are becoming more common. The largest volume of cement-bonded wood-based composite materials manufactured in North America is fiber-cement siding. Fiber-cement siding incorporates delignified wood fiber into the Portland cement matrix. Siding sheets that mimic shingles or lapboard and roof tiles are becoming more common. There are a number of standards that apply to these products and depend upon the geometry of the final products. Flat sheets used as exterior claddings are covered by ASTM C1186-08(2016),
whereas those that have variable thicknesses, such as weather-exposed shakes and shingles, are covered by ASTM C1530/C1530M-04(2019) and ASTM C1225-08(2016). The test methods used to test fiber-cement products cited in the above specification are described in ASTM C1185-08(2016).

**Ceramic-Bonded Composite Materials**

In the last few years a new class of inorganic binders, non-sintered ceramic inorganic binders, has been developed. These non-sintered ceramic binders are formed by acid–base aqueous reaction between a divalent or trivalent oxide and an acid phosphate or phosphoric acid. The reaction slurry hardens rapidly, but the rate of setting can be controlled. With suitable selection of oxides and acid-phosphates, a range of binders may be produced. Recent research suggests that phosphates may be used as adhesives, cements, or surface augmentation materials to manufacture wood-based composites (Jeong and Wagh 2003, Wagh and Jeong 2003).

As adhesives, the reaction slurry resulting from the acid–base reaction may be used as an adhesive similar to the current polymer resins. Thus, phosphate adhesives can be used to coat individual fibers and form a composite by binding the fibers to each other. These adhesives will behave much like current polymer resins and may be used with existing equipment. The binder content in a product is expected to be low, typically 15% to 20% by weight; therefore, phosphate adhesives have very good potential to replace current polymer-based products.

As a cement, phosphate binders can be used to produce bulk composites. When conventional cement is used in fiber-based products, typical cement loading is approximately 30% or higher; phosphate cements may be used in a similar manner. The slurry formed by the acid–base reaction may be mixed with fiber or any other extender to produce solid composites (Jeong and Wagh 2003).

Phosphate binders may also be used for coating wood-based composite panels to enhance surface properties. The phosphate slurry is very smooth; thin (<1 mm) coatings can be applied, suitable for providing fire or water resistance.

**Wood–Thermoplastic Composite Materials**

In North America and Europe, wood elements have been combined with thermoplastics for several decades. However, it is only in the past decade that wood–thermoplastic composites have become a widely recognized commercial product in construction, automotive, furniture, and other consumer applications (Oksman Niska and Sain 2008). Commercialization in North America has been primarily due to penetration into the construction industry, first as decking and window profiles, followed by railing, siding, and roofing. Interior molding applications are also receiving attention. The automotive industry in Europe has been a leader in using wood–thermoplastic composites for interior panel parts and is leading the way in developing furniture applications. Manufacturers in Asia are targeting the furniture industry, in addition to interior construction applications. Continued research and development will expand the available markets and each application will penetrate the global marketplace.

**Materials**

Broadly defined, a thermoplastic softens when heated and hardens when cooled. Thermoplastics selected for use with lignocellulosics must melt or soften at or below the degradation point of the lignocellulosic component, normally 200 to 220 °C (392 to 428 °F). These thermoplastics include polypropylene, polystyrene, vinyls, and low- and high-density polyethylenes.

The term wood–thermoplastic composites is broad, and the class of materials can include lignocellulosics derived from wood or other natural sources. Geographical location often dictates the raw material choice. In North America, wood is the most common raw material, in Europe natural fibers such as jute, hemp, and kenaf are preferred, while rice hull flour and bamboo fiber are typical in Asia. The wood is incorporated as either fiber bundles with low aspect ratio (wood flour) or as single fibers with higher aspect ratio (wood fiber). Wood flour is processed commercially, often from post-industrial materials such as planer shavings, chips, and sawdust. Several grades are available depending upon wood species and particle size. Wood fibers, although more difficult to process than wood flour, can lead to superior composite properties and act more as a reinforcement than as a filler. A wide variety of wood fibers are available from both virgin and recycled resources.

Other materials can be added to affect processing and product performance of wood–thermoplastic composites. These additives can improve bonding between the thermoplastic and wood component (for example, coupling agents), product performance (impact modifiers, ultraviolet (UV) light stabilizers, flame retardants), and processability (lubricants).

Wood–thermoplastic composites are of two main types. In the first, the lignocellulosic component serves as a reinforcing agent or filler in a continuous thermoplastic matrix. In the second, the thermoplastic serves as a binder to the majority lignocellulosic component. The presence or absence of a continuous thermoplastic matrix may also determine the processability of the composite material. In general, if the matrix is continuous, conventional thermoplastic processing equipment may be used to process composites; however, if the matrix is not continuous, other processes may be required. For the purpose of discussion, we present these two scenarios for composites with high and low thermoplastic content.
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**Composite Materials with High Thermoplastic Content**

The vast majority of commercially available wood–thermoplastic composites have high thermoplastic content. In composites with high thermoplastic content, the thermoplastic component is in a continuous matrix and the lignocellulosic component serves as a reinforcement or filler. These types of composites have been called wood–plastic composites (WPCs). The lignocellulosic content is typically less than 60% by weight. In the great majority of reinforced thermoplastic composites available commercially, inorganic materials (for example, glass, clays, and minerals) are used as reinforcements or fillers. Lignocellulosic materials offer some advantages over inorganic materials: they are lighter, much less abrasive, and renewable. Lignocellulosics serve to reinforce the thermoplastic by stiffening and strengthening and can improve thermal stability of the product compared with that of unfilled material.

The manufacture of WPCs is usually a two-step process. The raw materials are first mixed together, and the composite blend is then formed into a product. The combination of these steps is called in-line processing, and the result is a single processing step that converts raw materials to end products. In-line processing can be very difficult because of control demands and processing trade-offs. As a result, it is often easier and more economical to separate the processing steps (Clemons 2002).

Compounding is the feeding and dispersing of the lignocellulosic component in a molten thermoplastic to produce a homogeneous material. Various additives are added and moisture is removed during compounding. Compounding may be accomplished using either batch mixers (for example, internal and thermokinetic mixers) or continuous mixers (for example, extruders and kneaders).

The compounded material can be immediately pressed or shaped into an end product while still in its molten state or pelletized into small, regular pellets for future reheating and forming. The most common types of product-forming methods for wood–thermoplastic composites involve forcing molten material through a die (sheet or profile extrusion) or into a cold mold (injection molding), or pressing in calenders (calendering) or between mold halves (thermoforming and compression molding). Most wood–thermoplastic composites in North America are formed using profile extrusion. Products such as decking, railings, and window profiles readily lend themselves to extrusion through a two-dimensional die (Fig. 11–17). Injection-molded applications such as consumer household goods and furniture parts are gaining importance (Fig. 11–18). Thermoforming or compression molding is the forming method of choice for the automotive industry.

Several factors must be considered when processing wood with thermoplastics. Moisture can disrupt many thermoplastic processes, resulting in poor surface quality, voids, and unacceptable parts. Either materials must be pre-dried or vented equipment must be used to remove moisture. The low degradation temperature of wood must also be considered. As a general rule, melt temperatures should be kept below 200 °C (392 °F), except for short periods. Higher temperatures can result in the release of volatiles, discoloration, odor, and embrittlement of the wood component. Although processing of wood flour in thermoplastics is relatively easy, the low bulk density and difficulty of dispersing fibrous materials make thermoplastics more difficult to compound. More intensive mixing and the use of special feeding equipment may be necessary to handle longer fibers.

The increase in commercial applications of these products, particularly in construction applications, has led to the development of product standards. The standard for establishing performance ratings for WPC deckboards, stair treads, guards, and handrails is covered in ASTM D7032-17 (ASTM 2017b); the standard that prescribes the test

**Composite Materials with Low Thermoplastic Content**

In composites with low thermoplastic content, the thermoplastic component is not continuous, acting more as a binder for the fiber much the same way as a thermosetting resin rather than a matrix material. Thermoplastic content is typically less than 30% by weight. In their simplest form, lignocellulosic particles or fibers can be dry-blended with thermoplastic granules, flakes, or fibers and pressed into panel products. An alternative 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, non-woven, textile-like mat. The mat may be a product in itself, or it may be consolidated into a high-density product.

Because the thermoplastic component remains molten when hot, different pressing strategies must be used than when thermosetting binders are used. 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 used 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 nonstructural wood–thermoplastic composite panels are made in this way.

**Cellulose Nanocomposites**

A relatively new class of wood composites is cellulose nanocomposites. Cellulose nanomaterials are roughly defined as cellulose fibers or particles with one dimension in the nanoscale. When derived from wood, the most common forms are cellulose nanocrystals (CNCs) or cellulose nanofibrils (CNFs). The production of both forms generally begins with a cellulose raw material such as pulp fiber, which is converted via chemical process (CNCs) or mechanical process (CNFs) into cellulose nanomaterials. Compared with CNFs, CNCs are more discrete rod-like particles with lower aspect ratio but higher mechanical properties. Both have been explored for use in cellulose nanocomposites.

Cellulose nanocomposites are produced using a variety of methods in which cellulose nanomaterial is combined with other nonwood materials such as resins and thermoplastics. The composites can contain less than 1% cellulose nanomaterials to more than 99%, depending upon the application and desired performance. Applications under development include flexible electronic displays, packaging products, automotive products, and cement products. More detailed information on this new and evolving area of wood composites is provided by Postek and others (2013).

**Literature Cited**


Additional Reference

Abstract

Summarizes information on wood as an engineering material. Presents properties of wood and wood-based products of particular concern to the architect and engineer. Includes discussion of designing with wood and wood-based products along with some pertinent uses.

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, preservation, wood-based products, heat sterilization, sustainable use

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