Chapter 10

Wood-based Composites and Panel Products

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Contents

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 in processing. When processing variables are properly selected, the end result can sometimes surpass nature’s best effort. With solid wood, changes in properties are studied at the cellular level. With reconstituted wood materials, changes in properties are studied at the fiber, particle, flake, or veneer level. Properties of such materials can be changed by combining, reorganizing, or stratifying these elements.

The basic element for composite wood products may be the fiber, as it is in paper, but it can also be larger wood particles composed of many fibers and varying in size and geometry. These characteristics, along with control of their variations, provide the chief means by which materials can be fabricated with predetermined properties.

In any discussion of the strength properties of wood-based panels and other adhesive-bonded wood composites, the first consideration is the constituents from which these products are made (O’Halloran and Youngquist 1984; Youngquist 1987, 1988). The basic wood elements that can be used in the production of wood-based panels are shown in Figure 10–1. The elements can be made in a great variety of sizes and shapes and can be used alone or in combination. The choice is almost unlimited.

Currently, the term composite is being used to describe any wood material adhesive-bonded together. This product mix ranges from fiberboard to laminated beams and components. Table 10–1 shows a logical basis for classifying wood composites proposed by Maloney (1986). For the purposes of 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 structural and nonstructural 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.

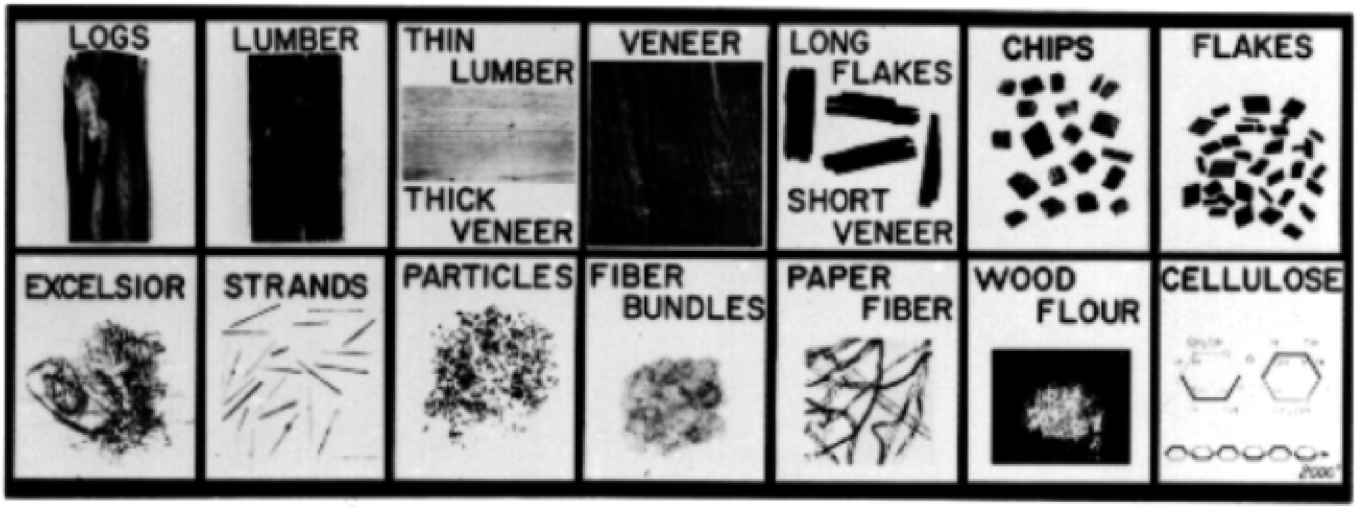


Figure 10–1. Basic wood elements, from largest to smallest (Marra 1979).

Table 10–1. Classification of wood-based composites[a]

Veneer-based material
- Plywood
- Laminated veneer lumber (LVL)
- Parallel-laminated veneer (PLV)

Laminates
- Laminated beams
- Overlayed materials
- Wood–nonwood composites[b]

Composite material
- Cellulosic fiberboard
- Hardboard
- Particleboard
- Waferboard
- Flakeboard
- Oriented strandboard (OSB)
- COM-PLY[c]

Edge-adhesive-bonded material
- Lumber panels

Components
- I-beams
- T-beam panels
- Stress-skin panels

Wood–nonwood composites
- Wood fiber–plastic composites
- Inorganic-bonded composites
- Wood fiber–agricultural fiber composites

[a] Maloney 1986.
[b] Panels or shaped materials combined with nonwood materials such as metal, plastic, and fiberglass.
[c] Registered trademark of APA–The Engineered Wood Association.

Figure 10–2 provides a useful way to further classify wood-based composite materials. This figure presents an overview of the most common types of products discussed in this chapter as well as 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). The right *y* axis, wet and dry processes, describes in general terms the processing method used to produce a particular product. Note that both roundwood and chips can serve as sources of fiber for wet-process hardboard. Roundwood or wood in the form of a waste product from a lumber or planing operation can be used for dry-processed products. For medium-density fiberboard (MDF), resin is usually applied to the fiber after the fiber is released from the pressurized refiner. The fiber is then dried, formed into a mat, and pressed into the final product. For other dry-processed products, the material is fiberized and dried and then adhesive is added in a separate operation prior to hot pressing into the final composite product. Figure 10–3 shows examples of some composite materials that are represented in schematic form in Figure 10–2.

Scope

Although there is a broad range of wood composites and many applications for such products, for the purposes of this chapter, wood composites are grouped into three general categories: plywood, particle and fiber composites, and wood–nonwood 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. Information on adhesive-bonded-laminated (glulam, timbers, and structural composite lumber, including laminated veneer lumber) and adhesive-bonded members for lumber and panel products

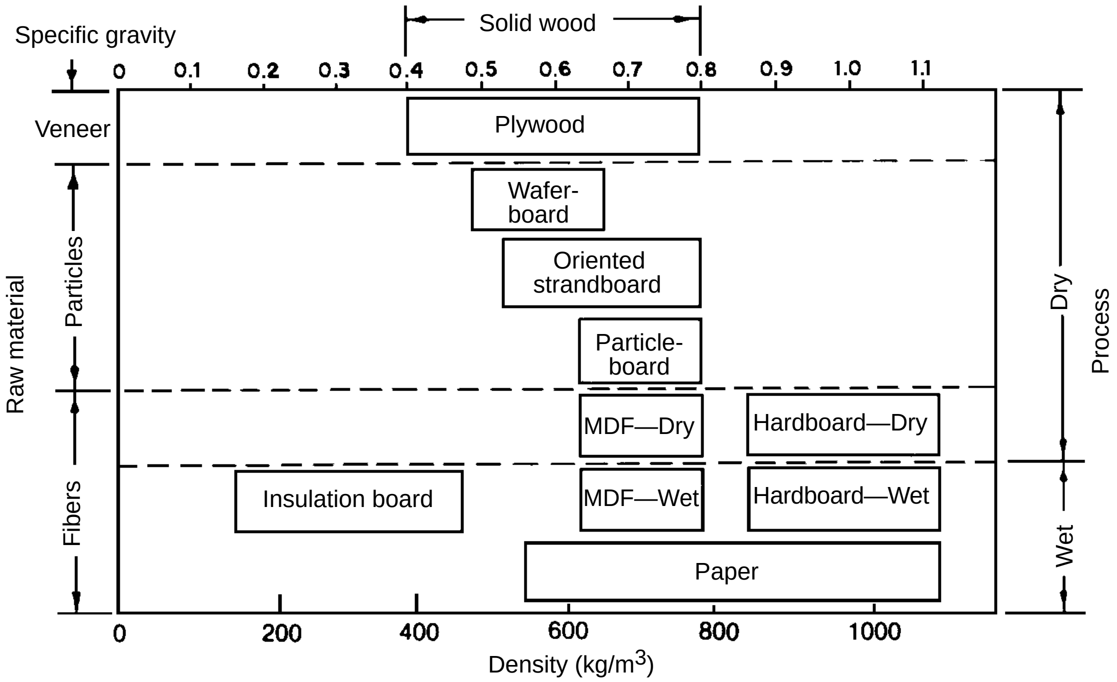


Figure 10–2. Classification of wood composite boards by particle size, density, and process type (Suchsland and Woodson 1986).

is presented in Chapter 11 of this handbook. Many composite materials, like fiberboard, MDF, and particleboard, can be made from wood alone or in combination with agricultural fibers (Youngquist and others 1993a, 1994; Rowell and others 1997).

The first category, plywood, is covered in some detail because the process for manufacturing this kind of material is quite different from that used for other composite materials and because there are many different classes and grades of plywood in the marketplace. The second category, composite materials, includes oriented strandboard (OSB), particleboard, and fiberboard. These types of composites undergo similar processing steps, which are discussed in general terms for all the products in the Particle and Fiber Composites section. The first and second categories of composite materials are further generally classified as conventional composite materials. The third category, wood–nonwood composites, includes products made from combining wood fibers with agricultural fibers, with thermoplastics, and with inorganic materials.

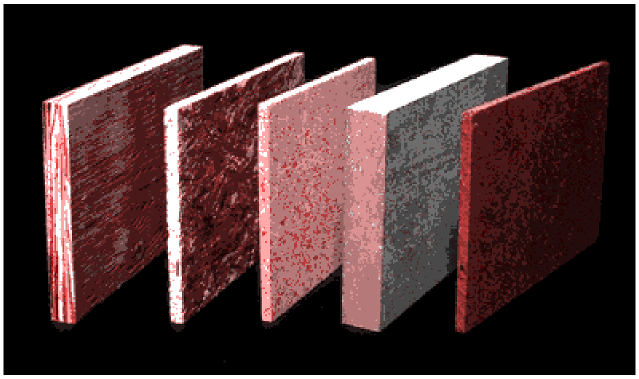


Figure 10–3. Examples of various composite products. From left to right: plywood, OSB, particleboard, MDF, and hardboard.

Types of Conventional Composite Materials

Conventional wood composite materials fall into five main categories based on the physical configuration of the wood used to make the products: plywood, oriented strandboard, particleboard, hardboard, and cellulosic fiberboard. Within limits, the performance of a conventional type of composite can be tailored to the end-use application of the product. Varying the physical configuration of the wood and adjusting the density of the composites are just two ways to accomplish this. Other ways include varying the resin type and amount and incorporating additives to increase water or fire resistance or to resist specific environmental conditions.

Adhesive Considerations

The conventional wood-based composite products discussed in this chapter are typically made with a thermosetting or heat-curing resin or adhesive that holds the lignocellulosic (wood) fiber together. The physical and mechanical properties of wood-based veneer, fiber, and particle panel materials are determined by standard American Society for Testing and Materials (ASTM) test methods. Commonly used resin–binder systems include phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, and isocyanate.

Phenol-formaldehyde (PF) resins are typically used in the manufacture of products requiring some degree of exterior exposure durability, for example, OSB, softwood plywood, and siding. These resins require longer press times and higher press temperatures than do urea-formaldehyde resins, which results in higher energy consumption and lower line speeds (productivity). Products using PF resins (often referred to as phenolics) may have lowered dimensional stability because of lower moisture contents in the finished products. The inherently dark color of PF resins may render them unsuitable for decorative product applications such as paneling and furniture.

Urea-formaldehyde (UF) resins are typically used in the manufacture of products where dimensional uniformity and surface smoothness are of primary concern, for example, particleboard and MDF. Products manufactured with UF resins are designed for interior applications. They can be formulated to cure anywhere from room temperature to 150°C (300°F); press times and temperatures can be moderated accordingly. Urea-formaldehyde resins (often referred to as urea resins) are more economical than PF resins and are the most widely used adhesive for composite wood products. The inherently light color of UF resins make them quite suitable for the manufacture of decorative products.

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 be blended with UF resins for certain applications (melamine urea).

Isocyanate as diphenylmethane di-isocyanate (MDI) is commonly used in the manufacture of composite wood products; MDI is used primarily in the manufacture of OSB. Facilities that use MDI are required to take special precautionary protective measures.

These adhesives have been chosen based upon their suitability for the particular product under consideration. Factors taken into account include the materials to be bonded together, moisture content at time of bonding, mechanical property and durability requirements of the resultant composite products, and of course, resin system costs.

Some natural options may someday replace or supplement these synthetic resins. Tannins, which are natural phenols, can be modified and reacted with formaldehyde to produce a satisfactory resin. Resins have also been developed by acidifying spent sulfite liquor, which is generated when wood is pulped for paper. In the manufacture of wet-process fiberboard, lignin, which is inherent in lignocellulosic material, is frequently used as the resin (Suchsland and Woodson 1986).

Except for two major uncertainties, UF and PF systems are expected to continue to be the dominant wood adhesives for lignocellulosic composites. The two uncertainties are the possibility of much more stringent regulation of formaldehyde-containing products and the possibility of limitations to or interruptions in the supply of petrochemicals. One result of these uncertainties is that considerable research has been conducted in developing new adhesive systems from renewable resources.

Additives

A number of additives are used in the production of conventional composite products. One of the most notable additives is wax, which is used to provide finished products with resistance to aqueous penetration. In particle- and fiberboard products, wax emulsion provides excellent 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. These improved water penetration properties are important for ensuring the success of subsequent secondary gluing operations and for providing protection upon accidental wetting to the product during and after construction. The water repellency provided by the wax has practically no effect upon dimensional changes or water adsorption of composites exposed to equilibrium conditions. Other additives used for specialty products include preservatives, fire retardants, and impregnating resins.

General Manufacturing Issues

Successful manufacture of any composite wood product requires control over raw materials. Ideally, raw materials are uniform, consistent, and predictable. Wood does not offer these qualities but instead varies widely between species. For the purpose of producing a composite product, uniformity, consistency, and predictability are accomplished by reducing separated portions of the wood into small, relatively uniform and consistent particles, flakes, or fibers where effects of differences will average out. Size reduction is sometimes augmented by chemical treatments designed to weaken the bonds between the components. The degree of size reduction and the shape of individual lignocellulosic components will depend on the application. Different composites tolerate or demand different sizes and shapes. Generally speaking, all the conventional composite products discussed in this chapter are made to conform to product or performance standards (English and others 1997).

Standards for Wood–Based Panels

The general types of standards for panel products are product standards and performance standards. Table 10–2 lists standards for common conventional composite products. The term adhesive, as used in the following descriptions of product and performance standards, is synonymous with glue.

Table 10–2. Standards for frequently used panel products

Product category	Applicable standard	Name of standard	Source
Plywood	PS 1–95	Voluntary product standard PS 1–95 Construction and industrial plywood	NIST 1995
	PS 2–92	Voluntary product standard PS 2–92 Performance standard for wood-based structural-use panels	NIST 1992
Oriented strandboard	PS 2–92	Voluntary product standard PS 2–92 Performance standard for wood-based structural-use panels	NIST 1992
Particleboard	ANSI A208.1–1993	Particleboard	NPA 1993
Hardboard	ANSI/AHA A135.4–1995	Basic hardboard	AHA 1995a
	ANSI/AHA A135.5–1995	Prefinished hardboard paneling	AHA 1995b
	ANSI/AHA A135.6–1990	Hardboard siding	AHA 1990
Insulation board	ASTM C208–94	Standard specification for cellulosic fiber insulating board	ASTM current edition
	ANSI/AHA A194.1–1985	Cellulosic fiberboard	AHA 1985
Medium-density fiberboard	ANSI A208.2–1994	Medium-density fiberboard (MDF)	NPA 1994

Product Standards

Product standards may be further classified as manufacturing method standards and laboratory test standards. Probably the best example of a manufacturing method standard is Voluntary Product Standard PS 1–95 for construction and industrial plywood (NIST 1995). This standard specifies such matters as what wood species and grades of veneer may be used, what repairs are permissible, and how repairs must be made. For panels produced according to prescriptive manufacturing requirements, a comparison of wood failure to adhesive failure in small test specimens of plywood is the performance test specified.

A good example of a laboratory test product standard is the American National Standard for mat-formed particleboard, ANSI A208.1 (NPA 1993). The American National Standards Institute (ANSI) product standards for both particleboard and MDF are sponsored by the Composite Panel Association (CPA) in Gaithersburg, Maryland. The CPA is the association resulting from the 1997 consolidation of the U.S.-based National Particleboard Association and the Canadian Particleboard Association. This standard states that in laboratory tests, specimens show certain minimally acceptable physical and mechanical properties, identified by numeric values. The test values give some indication of product quality, but the tests on small specimens were not specifically developed to correlate with performance of whole panels in specific end-uses.

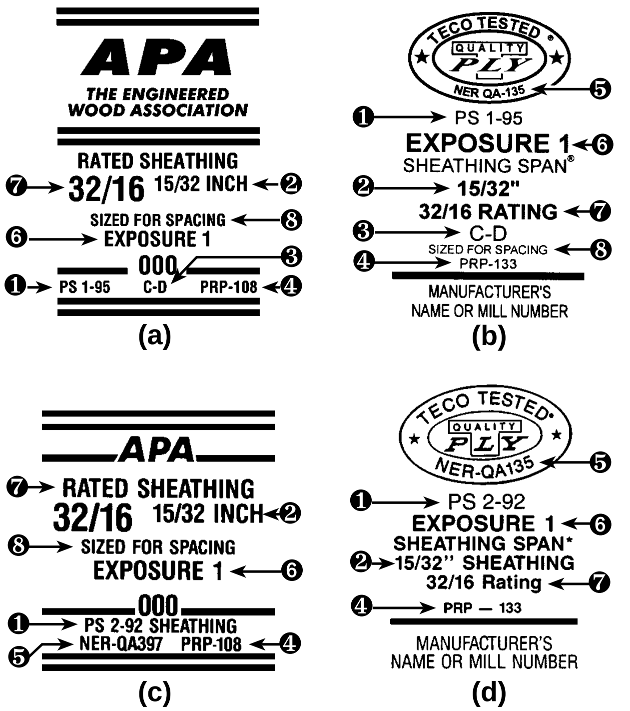
Performance Standards

Performance standards are written for panels in specific end-uses. These standards focus on panel performance in laboratory tests developed to indicate panel performance for particular end-uses. Federal legislation (Abourezk 1977) encourages the development of performance standards in preference to commodity-type standards. The Voluntary Standards and Accreditation Act of 1977 states that “a performance standard does not limit the manufacturer’s freedom to choose any method of design or any form of construction that achieves the desired level of performance” (Abourezk 1977)

The APA–The Engineered Wood Association (formerly American Plywood Association) was the leading proponent of performance-type standards for panel products, and their early work formed the basis for the performance standards in existence today (O’Halloran 1979, 1980; APA 1981). Wood-based panels manufactured in conformance with performance standards (APA–The Engineered Wood Association 1995a, TECO 1991) are approved by the three major model codes by virtue of approval by the Council of American Building Officials through the issuance of a national evaluation report. These wood-based panels can be used for construction applications such as sheathing for roofs, subflooring, and walls.

Similarly, wood-based panels may be used in light-frame construction for many single-layer floor applications. Plywood, OSB, and COM-PLY, a proprietary product, are all span-rated for particular end uses.

Under PS 1–95 (NIST 1995), plywood panels intended for structural uses may be certified or rated using either prescriptive or performance-based criteria. Standard PS 2–92 (NIST 1992) is strictly performance based because it applies to all structural-use wood-based panels, including plywood, waferboard, and OSB; OSB is a second generation panel, with aligned fibers, that evolved from the original product called waferboard. The PS 2–92 standard is not a replacement for PS 1–95, which contains necessary veneer-grade and



❶ Product Standard that governs specifics of production for construction and industrial plywood

❷ Nominal panel thickness subject to acceptable tolerances

❸ Panel grade designation indicating minimum veneer grade used for panel face and back, or grade name based on panel use

❹ Performance-rated panel standard indicating structural-use panel test procedure recognized by National Evaluation Service (NES)

❺ NES report number from Council of American Building Officials (CABO)

❻ Exposure durability classification: Exposure 1 indicates interior panel bonded with exterior glue suitable for uses not permanently exposed to weather

❼ Span rating indicating maximum spacing of roof and floor supports for ordinary residential construction applications; 32/16 rating identifies a panel rated for use on roof supports spaced up to 813 mm (32 in.) o.c., or floor supports spaced up to 406 mm (16 in.) o.c.

❽ Sized for spacing denotes panels that have been sized to allow for spacing of panel edges during installation to reduce the possibility of buckling

Figure 10–4. Typical grade stamps for plywood and OSB.

adhesive-bond requirements as well as prescriptive lay-up provisions and includes many plywood grades not covered under PS 2–92.

A significant portion of the market for construction and industrial plywood is in residential construction. This situation has resulted in the development of performance standards for sheathing and single-layer subflooring or underlayment for residential construction. Plywood panels conforming to these performance standards for sheathing are marked with grade stamps such as those shown in Figure 10–4a,b. Structural flakeboards are usually marketed as conforming to a product standard for sheathing or single-layer subflooring or underlayment and are graded as a performance-rated product (PRP–108) similar to the grading for construction plywood. Voluntary Product Standard PS 2–92 is the performance standard for wood-based structural-use panels, which include such products as plywood, OSB, and waferboard. Panels conforming to these performance standards for sheathing are marked with grade stamps such as those shown in Figure 10–4c,d. As seen in Figure 10–4a,b, the grade stamps must show (1) conformance to plywood product standards, (2) nominal panel thickness, (3) grades of face and back veneers or grade name based on panel use, (4) performance-rated panel standard, (5) recognition as a quality assurance agency by the National Evaluation Service (NES), which is affiliated with the Council of American Building Officials, (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.

Plywood

General Description

Plywood is a flat panel built up of sheets of veneer called plies, united under pressure by a bonding agent to create a panel with an adhesive bond between plies. Plywood can be made from either softwoods or hardwoods. It is always constructed with an odd number of layers with the grain direction of adjacent layers oriented perpendicular to one another. Since layers can consist of a single ply or of two or more plies laminated such that their grain is 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; the inner plies are called cores or centers; and the plies with grain perpendicular to that of the face and back are called crossbands. The core may be veneer, lumber, or particleboard, with the total panel thickness typically not less than 1.6 mm (1/16 in.) or more than 76 mm (3 in.). The plies may vary in number, thickness, species, and grade of wood. 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 (face and back) and all odd-numbered layers (centers) generally have their grain direction oriented parallel to the length or long dimension of the panel. The grain of even-numbered layers (cores) is perpendicular to the length of the panel.

The alternation of grain direction in adjacent plies provides plywood panels with dimensional stability across their width. It also results in fairly similar axial strength and stiffness properties in perpendicular directions within the panel plane. The laminated construction distributes defects, markedly reduces splitting when the plywood is penetrated by fasteners (compared with splitting of solid wood), and improves resistance to checking.

Compared with solid wood, the chief advantages of plywood are that the properties along the length of the panel are more nearly equal to properties along the width, there is greater resistance to splitting, and the form permits many applications where large sheets are desirable. The use of plywood may result in improved utilization of wood. Plywood can cover large areas with a minimum amount of wood fiber because plywood that is thinner than sawn lumber can be used in some applications. The properties of plywood depend on the quality of the different layers of veneer, order of layer placement, adhesive used, and control of bonding conditions. The grade of the panel depends upon the quality of the veneers used, particularly of the face and back. The type of panel refers to the durability of the adhesive-to-wood bond and depends upon the adhesive-bonded joint, particularly its water resistance, and upon veneer grades used. Generally, face veneers with figured grain that are used in panels where appearance is important have numerous short, or otherwise deformed, wood fibers. These may significantly reduce strength and stiffness of the panels. On the other hand, face veneers and other plies may contain certain sizes and distributions of knots, splits, or growth characteristics that have no undesirable effects on strength properties for specific uses, such as sheathing for walls, roofs, or floors.

The plywood industry continues to develop new products. Hence, the reader should always refer directly to current specifications on plywood and its use for specific details.

Types of Plywood

Broadly speaking, two classes of plywood are available, covered by separate standards: (a) construction and industrial, and (b) hardwood and decorative. Construction and industrial plywood has traditionally been made from softwoods such as Douglas-fir, Southern Pine, white fir, larch, western hemlock, and redwood. However, the current standard lists a large number of hardwoods as qualifying for use. At the same time, the standard for hardwood and decorative plywood covers certain decorative softwood species for nonconstruction use.

Most construction and industrial plywood used in the United States is produced domestically, and U.S. manufacturers export some material. Generally speaking, the bulk of construction and industrial plywood is used where strength, stiffness, and construction convenience 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 pigmented finishes.

Hardwood and decorative plywood is made of many different species, both in the United States and overseas. Well over half of all such panels used in the United States are imported. Hardwood plywood is normally used in such applications as decorative wall panels and for furniture and cabinet panels where appearance is more important than strength. Most of the production is intended for interior or protected uses, although a very small proportion is made with adhesives suitable for exterior service, such as in marine applications. A significant portion of all hardwood plywood is available completely finished.

The adhesives used in the manufacture of the two classes of plywood are quite different, but each type is selected to provide the necessary performance required by the appropriate specifications.

Construction and industrial plywood covered by Product Standard PS 1 is classified by exposure capability (type) and grade. The two exposure capabilities are exterior and interior. Exterior plywood is bonded with exterior adhesive, and veneers used in manufacture cannot be less than “C” grade as defined in PS 1. Interior-type plywood may be bonded with interior, intermediate, or exterior (waterproof) adhesive. “D” grade veneer is allowed as inner and back plies of certain interior-type plywoods. Adhesive bond performance requirements are specified in PS 1.

The four types of hardwood and decorative plywood in decreasing order of resistance to water are Technical (Exterior), Type I (Exterior), Type II (Interior), and Type III (Interior); adhesive bond requirements for these are specified in ANSI/HPVA–1–1994 (HPVA 1994).

Processing Considerations

After trees are felled and bucked to length, the logs are graded and sorted to make the most appropriate and efficient use of the wood fiber. For softwood plywood, in the past, logs graded as “peelers” were sent to veneer mills or plywood plants and “sawlogs” were shipped to lumber mills. Because of the dwindling availability of the clear, large-diameter peeler logs on which the plywood industry was founded, this practice has changed. Today, the higher grades of softwood peeler logs are sent to sawmills, and with few exceptions, plywood is made from low-grade sawlogs or peeler logs. This change came about because of the increasing demand for clear sawn lumber, and it has been made possible by innovations in veneer and plywood manufacturing and testing practices that ensure that panels are suitable for their intended use (McKay 1997).

Logs delivered to a veneer mill are sorted by grade and species, then debarked and crosscut into peeler blocks. Peeler blocks are often heated or conditioned by steaming or immersion in hot water prior to peeling, which makes them easier to peel, reduces veneer breakage, and results in smoother, higher quality veneer. The heated blocks are then conveyed to a veneer lathe. To maximize veneer yield, each block is gripped on the ends at the block’s geometric center. While rotating at high speed, the block is fed against a stationary knife parallel to its length. Veneer is peeled from the block in a continuous, uniformly thin sheet, much like unwinding a roll of paper towels, but at a speed of up to 4.1 m/s (13.3 linear ft/s).

Depending on its intended use, veneer may range in thickness from 1.6 to 4.8 mm (1/16 to 3/16 in.) for softwood plywood and much thinner for hardwood and decorative plywood. After being peeled to a diameter from 127 to 51 mm (5 to 2 in.), the peeler core is ejected from the lathe. Peeler cores may be sawn into standard 38- by 89-mm (nominal 2- by 4-in.) lumber, used for fence posts, and landscape timbers, or chipped for use as pulp chips or fuel.

The continuous sheet of veneer is then transported by conveyor to a clipping station where it is clipped into usable widths and defects are removed. The wet veneer is then dried to an average moisture content that is compatible with the adhesive system being used to bond the panels. Since it is critical that veneer moisture content be low at the time adhesive is applied, each sheet is metered as it exits the dryer. Pieces that are too wet or dry are rerouted to be redried or reconditioned, respectively. Properly dried veneer is then sorted into one of as many as 15 to 20 different grades according to the size and number of knots and other natural and processing defects. Each grade has a specific use; some veneer requires special processing before it is assembled into plywood. After grading and/or processing, the veneer is taken to the lay-up area.

Adhesive is applied to veneers in the lay-up area by spray, curtain coating, roller coating, extrusion, and recently, foaming. Veneer is laid up into plywood by hand, machine, or a combination of both. Hand lay-up is the oldest method, and it is still the only practical way of making plywood for some applications. With this method, the face, back, and center veneers are hand-placed by workers called sheet turners. After being coated on both sides with adhesive, the alternating core plies are placed by hand or machine. The lay-up process is almost completely automated in newer plywood plants, although the narrow strips used for cores may still be placed manually. Before veneers are laid up, narrow strips are sometimes joined into full-width sheets with hot-melt adhesive-coated fiberglass thread so that they can be handled by machine. Also, veneers may be upgraded by punching out knots and other defects and replacing them with wood plugs or synthetic patches.

Once assembled, panels are conveyed from the lay-up area to the pressing area. Panels are first subjected to cold prepressing to flatten the veneers and transfer the adhesive to uncoated sheets; panels are then hot pressed. After hot pressing, panels are solid-piled or hot-stacked to ensure complete curing of the adhesive, then sawn to size. Panels are then graded with regard to the product standard under which they were manufactured. Knotholes and splits on the faces and backs of some panels may be repaired with wood plugs or with synthetic patches (by filling the holes and splits with what is essentially liquid plastic that quickly hardens). Those panels that do not meet the specification are downgraded or rejected. Panels needing further processing are sent to the finishing area where, depending on their intended use, they may be sanded to thickness, profiled with tongue and groove edges, surface textured, scarf- or finger-jointed, oiled and edge-sealed, or given other treatments. The panels are then ready for shipping (McKay 1997).

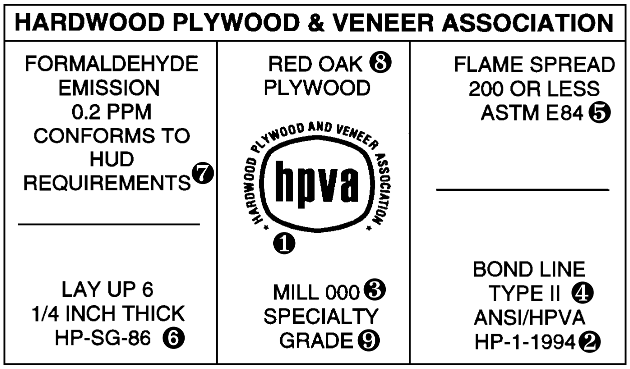
Specifications

The two general classes of plywood—(a) construction and industrial plywood and (b) hardwood and decorative plywood—are covered by separate standards. Construction and industrial plywood are covered by Product Standard PS 1–95 (NIST 1995), and hardwood and decorative plywood by American National Standard ANSI/HPVA–1–1994 (HPVA 1994). Each standard recognizes different exposure durability classifications, which are primarily based on moisture resistance of the adhesive and the grade of veneer used.

Model building codes in the United States stipulate that plywood used for structural applications like subflooring and sheathing must meet the requirements of certain U.S. Department of Commerce standards. Voluntary Product Standard PS 1–95 for construction and industrial plywood (NIST 1995) and Performance Standard PS 2–92 for wood-based structural-use panels (NIST 1992) spell out the ground rules for manufacturing plywood and establishing plywood or OSB properties, respectively. These standards have evolved over time from earlier documents (O'Halloran 1979, 1980; APA 1981) and represent a consensus opinion of the makers, sellers, and users of plywood products as well as other concerned parties. In addition, model building codes require that plywood manufacturers be inspected and their products certified for conformance to PS 1–95, PS 2–92, APA PRP–108, or TECO PRP–133 by qualified independent third-party agencies on a periodic unannounced basis.

With PS 1–95, as long as a plywood panel is manufactured using the veneer grades, adhesive, and construction established in the standard's prescriptive requirements, the panel is by definition acceptable. When plywood is assembled so that the proportion of wood with the grain perpendicular to the panel's face grain is greater than 33% or more than 70% of the panel's thickness, the plywood automatically meets the span rating. In panels with four or more plies, the combined thickness of the inner layers must equal 45% or more of the panel's thickness. Generally speaking, for panels of the same thickness and made with the face and back veneer of the same species, stiffness and strength increase as the thickness of the face and back veneers increases. All other things being equal, the stiffness and strength of plywood also increase as panel thickness increases.

All hardwood plywood represented as conforming to American National Standard ANSI/HPVA–1–1994 (HPVA 1994) is identified by one of two methods: by marking each panel with the Hardwood Plywood & Veneer Association (HPVA) plywood grade stamp (Fig. 10–5) or by including a written statement with this information with the order or shipment. The HPVA grade stamp shows (1) HPVA trademark, (2) standard that governs manufacture, (3) HPVA mill number, (4) plywood adhesive bond type, (5) flame spread index class, (6) description of lay-up, (7) formaldehyde emission characteristics, (8) face species, and (9) veneer grade of face.



HARDWOOD PLYWOOD & VENEER ASSOCIATION		
FORMALDEHYDE EMISSION 0.2 PPM CONFORMS TO HUD REQUIREMENTS❼	RED OAK ❽ PLYWOOD hpva ❶	FLAME SPREAD 200 OR LESS ASTM E84 ❺
LAY UP 6 1/4 INCH THICK HP-SG-86 ❻	MILL 000❸ SPECIALTY GRADE❾	BOND LINE TYPE II ❹ ANSI/HPVA HP-1-1994❷

Explanation of numbering

❶ HPVA trademark

❷ Standard governing manufacture

❸ HPVA mill number

❹ Plywood bondline type

❺ Flame spread index class as determined by testing in accordance with ASTM E84, standard test method for surface burning characteristics of building materials

❻ Lay-up description references structural attributes of wall panels as described in HPMA design guide HP-SG-86, Structural design Guide for Hardwood Plywood Wall Panels as published by the Hardwood Plywood & Veneer Association

❼ Formaldehyde emission characteristics to determine compliance with U.S. Department of Housing and Urban Development requirements for building product use in manufactured homes by testing in accordance with ASTM E1333, Standard Test Method for Determining Formaldehyde Levels From Wood Products Under Defined Test Conditions Using a Large Chamber

❽ Face species (face species designation is not required for wall panels when the surface is a decorative simulation such as that of a wood grain of another species or of a pattern)

❾ Veneer grade of face (grade of veneer of back is shown following grade of face for industrial panels)

Figure 10–5. Grade stamp for hardwood plywood conforming to ANSI/HPVA–1–1994.

The span-rating system for plywood was established to simplify plywood specification without resorting to specific structural engineering design. This system indicates performance without the need to refer to species group or panel thickness. It gives the allowable span when the face grain is placed across supports with a minimum of three supports.

If design calculations are desired, a design guide is provided by the APA–The Engineered Wood Association in *Plywood Design Specification* (PDS) and APA Technical Note N375B (APA–The Engineered Wood Association 1995a,b). The design guide contains tables of grade stamp references, section properties, and allowable stresses for plywood used in construction of buildings and similar structures.

Grades and Classification

Plywood is classified by both exposure durability class and grade. Exposure durability class refers to the ability of a panel to resist the damaging effects of exposure to the weather or moisture. Panel grades are either names that describe the intended use of the panel, such as underlayment or concrete form, or letters that identify the grades of the face and back veneers, such as A–B.

Veneers for plywood are visually graded according to the size, number, and location of natural and processing defects that affect their strength and appearance. Knots, decay, splits, insect holes, surface roughness, number of surface repairs, and other defects are considered. More surface repairs, such as elliptical (boat-shaped) wood patches and bigger knots are allowed in the lower veneer grades. Veneers are graded as N, A, B, C, C-Plugged, and D. N-grade or natural finish veneers are virtually blemish-free, and they contain only a few minor surface repairs. A and B veneers have solid surfaces with neatly made repairs and small, tight knots. Knotholes up to 25 mm (1 in.) in diameter are allowed in C veneers, whereas D veneers may have knotholes as large as 51 mm (2 in.) across. Because their appearance is usually of secondary importance, panels meant for sheathing and other structural uses are made mostly from C and D veneers. The N, A, and B veneers are reserved for panels where appearance is the primary consideration in such uses as exterior trim and soffits, interior paneling, doors, and cabinets.

Construction Plywood Exposure Durability Class

The exposure durability classifications for construction and industrial plywood specified in PS–1 are as follows: exterior, exposure 1, intermediate adhesive, exposure 2, and interior. Exterior plywood is bonded with exterior (waterproof) adhesive and is composed of C-grade or better veneers throughout. Exposure 1 plywood is bonded with exterior adhesives, but it may include D-grade veneers. Exposure 2 plywood is made with adhesive of intermediate resistance to moisture. Interior-type plywood may be bonded with interior, intermediate, or exterior (waterproof) adhesive. D-grade veneer is allowed on inner and back plies of certain interior-type grades.

The exposure durability classifications for hardwood and decorative plywood specified in ANSI/HPVA HP–1–1994 are as follow, in decreasing order of moisture resistance: technical (exterior), type I (exterior), type II (interior), and type III (interior). Hardwood and decorative plywood are not typically used in applications where structural performance is a prominent concern. Therefore, most of the remaining discussion of plywood performance will concern construction and industrial plywood.

Plywood Grades

There are many plywood grade names (Tables 10–3 and 10–4). In addition to the 30 or so generic names listed in PS 1–95, each agency that inspects plywood mills and certifies their products has coined its own trademarked grade names. For example, panels intended for use as single-layer

Table 10–3. Grade names for interior plywood grades[a]

Panel grade designation	Minimum face	Veneer back	Quality inner plies	Surface
N–N	N	N	C	S2S[b]
N–A	N	A	C	S2S
N–B	N	B	C	S2S
N–D	N	D	D	S2S
A–A	A	A	D	S2S
A–B	A	B	D	S2S
A–D	A	D	D	S2S
B–B	B	B	D	S2S
B–D	B	D	D	S2S
Underlayment	C plugged	D	C & D	Touch sanded
C–D plugged	C plugged	D	D	Touch sanded
Structural I C–D				Unsanded
Structural I C–D plugged, underlayment				Touch sanded
C–D	C	D	D	Unsanded
C–D with exterior adhesive	C	D	D	Unsanded

[a] NIST 1995.
[b] Sanded on two sides.

Table 10–4. Grade names for exterior plywood grades[a]

Panel grade designation	Minimum face	Veneer back	Quality inner plies	Surface
Marine, A–A, A–B. B–B, HDO, MDO				See regular grades
Special exterior, A–A, A–B, B–B, HDO, MDO				See regular grades
A–A	A	A	C	S2S[b]
A–B	A	B	C	S2S
A–C	A	C	C	S2S
B–B (concrete form)				
B–B	B	B	C	S2S
B–C	B	C	C	S2S
C–C plugged	C plugged	C	C	Touch sanded
C–C	C	C	C	Unsanded
A–A high-density overlay	A	A	C plugged	—
B–B high-density overlay	B	B	C plugged	—
B–B high-density concrete form overlay	B	B	C plugged	—
B–B medium-density overlay	B	B	C	—
Special overlays	C	C	C	—

[a] NIST 1995.
[b] Sanded on two sides.

flooring (combined subfloor and underlayment) made by TECO-certified manufacturers are called Floorspan, while those made by mills certified by the APA–The Engineered Wood Association are named Sturd-I-Floor. Although the trade names may be different, the minimum stiffness and strength properties of the panels are not. With the exception of custom-order panels, plywood is strictly a commodity product; panels of the same grade and thickness conforming to either PS 1–95 or PS 2–92 are interchangeable among manufacturers.

Span Rating and General Property Values

The more than 70 species of wood used for making softwood plywood (including some hardwoods) are classified into five groups according to their stiffness and strength (Table 10–5). The strongest woods are in Group 1; the weakest, in Group 5. Today, almost all plywood intended for structural use is marked with a two-number span rating (for example, 32/16) instead of a species group number (Fig. 10–4).

As with softwood lumber allowable design values, plywood span ratings were developed by breaking thousands of full-size panels of varying construction and thickness. The left-hand number of the rating represents the maximum

Table 10–5. Softwood plywood species groups by stiffness and strength[a]

Group 1	Group 2	Group 3	Group 4	Group 5
Apitong	Cedar, Port Orford	Alder, red	Aspen	Basswood
Beech, American	Cypress	Birch, paper	Bigtooth	Poplar
Birch	Douglas-fir[b]	Cedar, yellow	Quaking	Balsam
Sweet	Fir	Fir, subalpine	Cativo	
Yellow	Balsam	Hemlock, eastern	Cedar	
Douglas-fir[c]	California red	Maple, bigleaf	Incense	
Kapur	Grand	Pine	Western	
Keruing	Noble	Jack	Red	
Larch, western	Pacific silver	Lodgepole	Cottonwood	
Maple, sugar	White	Ponderosa	Eastern	
Pine	Hemlock, western	Spruce	Black	
Caribbean	Lauan	Redwood	(Western Poplar)	
Ocote	Almon	Spruce	Pine, eastern	
Pine, Southern	Bagtikan	Engelman	White, sugar	
Loblolly	Mayapis	White		
Longleaf	Red lauan			
Shortleaf	Tangile			
Slash	White lauan			
Tanoak	Maple, black			
	Mengkulang			
	Meranti, red			
	Mersawa			
	Pine			
	Pond			
	Red			
	Virginia			
	Western white			
	Spruce			
	Black			
	Red			
	Sitka			
	Sweetgum			
	Tamarack			
	Yellow poplar			

[a] From NIST 1995. Strongest species in Group 1; weakest in Group 5.
[b] Trees grown in Nevada, Utah, Colorado, Arizona, and New Mexico.
[c] Trees grown in Washington, Oregon, California, Idaho, Montana, Wyoming, and Canadian provinces of Alberta and British Columbia.

recommended on-center (OC) spacing for framing when the panel is used as roof sheathing; the right-hand number is the maximum recommended OC spacing for framing when the panel is used as subflooring. Panels intended for single-layer flooring (combined subfloor and underlayment) have only one span-rating number; for example, 24 OC. In all cases, the panels are meant to be installed with their length perpendicular to framing and across three or more supports. Again, panels of the same grade and span rating can be substituted for one another regardless of who made or certified them.

Table 10–6 provides approximate properties of sheathing-grade plywood. Plywood may be used under loading conditions that require the addition of stiffeners to prevent it from buckling. It may also be used in the form of cylinders or curved plates, which are beyond the scope of this handbook but are discussed in U.S. Department of Defense Bulletin ANC–18.

It is obvious from its construction that a strip of plywood cannot be as strong in tension, compression, or bending as a strip of solid wood of the same size. Those layers having

Table 10–6. General property values for sheathing-grade plywood[a]

Property	Value	ASTM test method[b] (where applicable)
Linear hygroscopic expansion (30%–90% RH)	0.15%	
Linear thermal expansion	6.1×10^{-6} cm/cm/°C (3.4×10^{-6} in/in/°F)	
Flexure		
Modulus of rupture	20.7–48.3 MPa (3,000–7,000 lb/in^2)	D3043
Modulus of elasticity	6.89–13.1 GPa ($1–1.9 \times 10^6$ lb/in^2)	
Tensile strength	10.3–27.6 MPa (1,500–4,000 lb/in^2)	D3500
Compressive strength	20.7–34.5 MPa (3,000–5,000 lb/in^2)	D3501
Shear through thickness (edgewise shear)		
Shear strength	4.1–7.6 MPa (600–1,100 lb/in^2)	D2719
Shear modulus	0.47–0.761 GPa ($68–110 \times 10^3$ lb/in^2)	D3044
Shear in plane of plies (rolling shear)		D2718
Shear strength	1.7–2.1 MPa (250–300 lb/in^2)	
Shear modulus	0.14–0.21 GPa ($20–30 \times 10^3$ lb/in^2)	

[a] All mechanical properties are based on gross section properties of plywood panels, with stress applied parallel to grain direction of face plies where applicable. Note: Data are not to be used in developing allowable design values. Information on engineering design methods for plywood courtesy of APA–The Engineered Wood Association, Tacoma, WA.

[b] Standard methods of testing strength and elastic properties of structural panels are given in ASTM standards (see References).

their grain direction oriented at 90° to the direction of stress can contribute only a fraction of the strength contributed by the corresponding areas of a solid strip because they are stressed perpendicular to the grain. Strength properties in the length and width directions tend to be equalized in plywood because adjacent layers are oriented at an angle of 90° to each other.

Characteristics

Although plywood is an engineered wood product, it 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. Plywood has high strength-to-weight and strength-to-thickness ratios, and its stiffness and strength are more equal in width and length than are stiffness and strength of solid wood. Plywood also has excellent dimensional stability along its length and across its width. Minimal edge-swelling makes plywood perhaps the best choice for adhesive-bonded tongue-and-groove joints, even where some wetting is expected. 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.

Other Considerations

Plywood of thin, cross-laminated layers is very resistant to splitting. Therefore, nails and screws can be placed close together and close to the edges of panels. Of course, highly efficient, rigid joints can be obtained by bonding plywood to itself or to heavier wood members, such as those needed in prefabricated wood I-joists, box beams, and stressed-skin panels. Adhesive-bonded joints should not be designed to transmit load in tension primarily normal to the plane of the plywood sheet because of the rather low tensile strength of wood perpendicular to grain. Adhesive-bonded joints should be arranged to transmit loads through shear. It must be recognized that shear strength across the grain of wood (often called rolling shear strength because of the tendency to roll the wood fibers) is only 20% to 30% of that parallel to the grain. Thus, sufficient area must be provided between plywood and flange members of box beams and between plywood and stringers of stressed-skin panels to avoid perpendicular-to-grain shearing failure in the face veneer, in the crossband veneer next to the face veneer, or in the wood member. Various details of design are given in Chapter 11.

Specialty Panels

Some plywood panels are designed for special uses, including marine decorative underlayment and concrete form and special exterior applications. The treating of plywood with preservatives and fire retardants is done by manufacturers outside of the plywood industry. Plywood is easily pressure-treated with waterborne preservatives and fire retardants, and treated plywood is readily available for use where such protection is needed.

Particle and Fiber Composites

Many wood-based composite materials have become popular. These composites are usually available in panel form and are widely used in housing and furniture. Conventional composites are typically made with a heat-curing adhesive that holds the wood fiber components together. The physical and mechanical properties of wood-based fiber and particle panel materials are determined by standard ASTM test methods.

General Processing Considerations

All the products in the family of particle and fiber composite materials are processed in similar ways. Raw material for OSB, waferboard, and fiberboard is obtained by flaking or chipping roundwood. For fiberboard, chips are reduced to wood fiber using refiners that usually use steam to soften the wood. The comminuted wood is then dried, adhesive is applied, and a mat of wood particles, fibers, or strands is formed; the mat is then pressed in a platen-type press under heat and pressure until the adhesive is cured. The bonded product is allowed to cool and is further processed into specified width, length, and surface qualities.

Oriented Strandboard

Oriented strandboard is an engineered structural-use panel manufactured from thin wood strands bonded together with waterproof resin under heat and pressure, and it is used extensively for roof, wall, and floor sheathing in residential and commercial construction. Orientation of wood strands with a typical aspect ratio (that is, strand length divided by width) of at least 3 can produce a panel product with greater bending strength and stiffness in the oriented or aligned direction.

Raw Materials

The raw material for the original waferboard product, which was made from square wafers, was aspen. As this industry expanded and OSB became the predominant product manufactured, other species such as Southern Pine, white birch, red maple, sweetgum, and yellow-poplar were found to be suitable raw materials as well. Small amounts of some other hardwoods can also be used for OSB.

Manufacturing Process

In the general manufacturing process for OSB, debarked logs are often heated in soaking ponds, then sliced into thin wood elements. 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 10–6 shows an OSB manufacturing process. Oriented strandboard is made from long, narrow strands, with the strands of each layer aligned parallel to one another but perpendicular to strands in adjacent layers, like the cross-laminated veneers of plywood. It is this perpendicular orientation of different layers of aligned strands that gives OSB its unique characteristics and allows it to be engineered to suit different uses.

Stranding Process

Typically, logs are debarked and then sent to a soaking pond or directly to the stranding process. Long log disk or ring standers 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.

Drying Process

Green strands are stored in wet bins and then 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 relatively 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.

Adhesive Application or Blending

The blending of strands with adhesive and wax is 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.

Mat Formation

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—face, core, face, for example—are dropped sequentially, each by a different forming head. Modern mat formers either use wire screens laid over a moving conveyor belt to carry the mat into the press or screenless systems in which the mat lies directly on the conveyor belt.

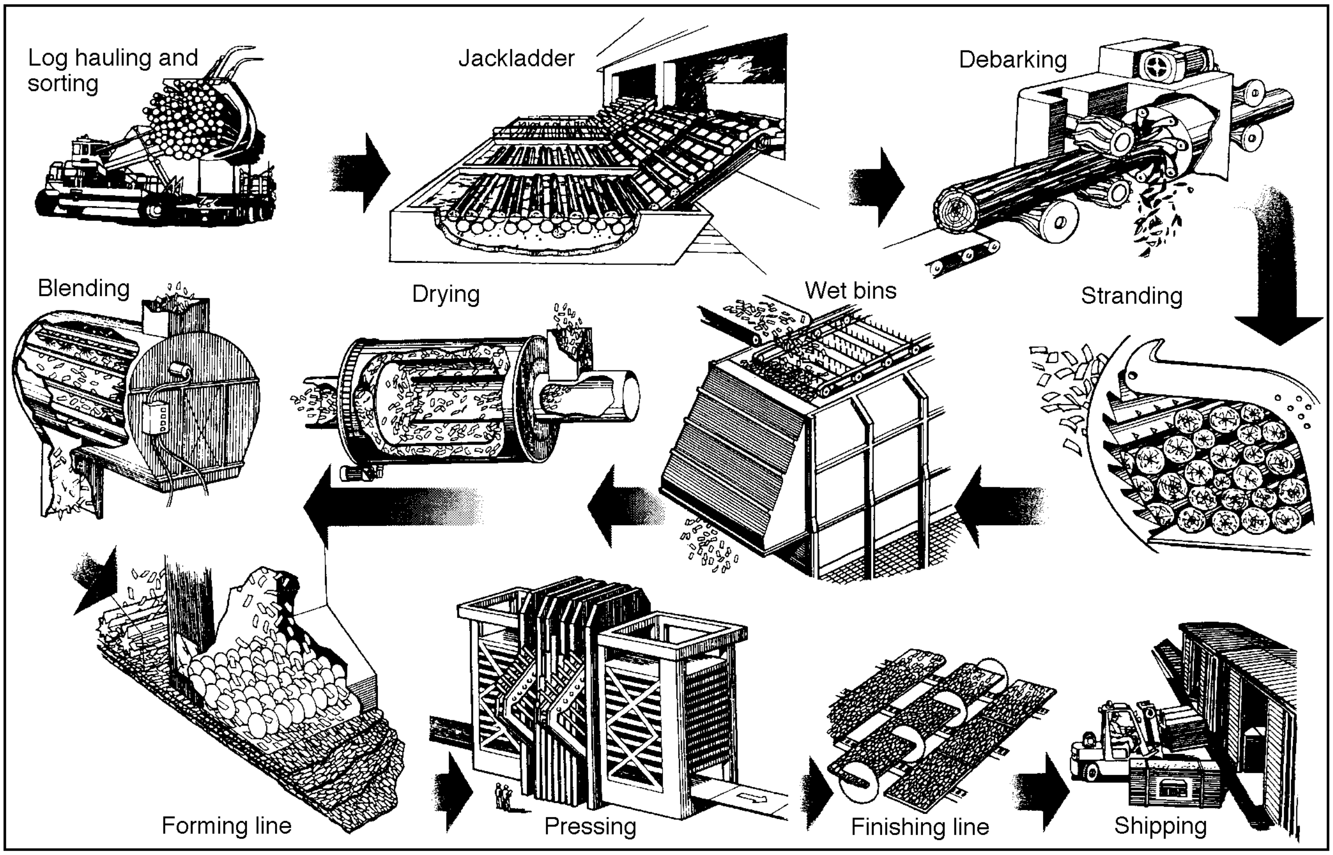


Figure 10–6. Schematic of OSB manufacturing process. (Courtesy of Structural Board Association, Willowdale, Ontario, Canada.)

Hot Pressing

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°C to 204°C (350°F to 400°F) to cure the resin in 3 to 5 min.

Design Capacities and Panel Certification

Design capacities of performance-rated products, which include OSB and waferboard, can be determined by using procedures outlined in Technical Note N375B (APA–The Engineered Wood Association 1995a). In this reference, allowable design strength and stiffness properties, as well as nominal thickness and section properties, are specified based on the span rating of the panel. Additional adjustment factors based on panel grade and construction are also provided. Table 10–7 provides general property values for sheathing-grade OSB.

Under PS 2–92, a manufacturer is required to enter into an agreement with an accredited testing agency to demonstrate that its panels conform with the requirements of the chosen standard. The manufacturer must also maintain an in-plant quality control program in which panel properties are regularly checked, backed by an independent third-party-administered quality assurance program. The third-party agency must visit the mill on a regular unannounced basis. The agency must confirm that the in-plant quality control program is being maintained and that panels meet the minimum requirements of the standard. Today, OSB manufactured to standard PS 2–92 is quality-certified by the following organizations: APA–The Engineered Wood Association, Professional Services and Industries, Inc., Pittsburgh Testing Laboratories, and PFS/TECO Corporations. Examples of grade stamps for performance-rated panels are shown in Figure 10–4c,d.

Particleboard

The wood particleboard industry grew out of a need to dispose of large quantities of sawdust, planer shavings, and to a lesser extent, the use of mill residues and other relatively homogeneous waste materials produced by other wood industries. Simply put, particleboard is produced by mechanically reducing the material into small particles, applying adhesive to the particles, and consolidating a loose mat of

Table 10–7. General property values for sheathing-grade OSB[a]

Property	Value	ASTM test method[b] (where applicable)
Linear hygroscopic expansion (30%–90% RH)	0.15%	
Linear thermal expansion	6.1×10^{-6} cm/cm/°C (3.4×10^{-6} in/in/°F)	
Flexure		
Modulus of rupture	20.7–27.6 MPa (3,000–4,000 lb/in^2)	D3043
Modulus of elasticity	4.83–8.27 GPa ($700–1,200 \times 10^3$ lb/in^2)	
Tensile strength	6.9–l0.3 MPa (1,000–1,500 lb/in^2)	D3500
Compressive strength	10.3–17.2 MPa (1,500–2,500 lb/in^2)	D3501
Shear through thickness (edgewise shear)		
Shear strength	6.9–10.3 MPa (1,000–1,500 lb/in^2)	D2719
Shear modulus	1.24–2.00 GPa ($180–290 \times 10^3$ lb/in^2)	D3044
Shear in plane of plies (rolling shear)		D2718
Shear strength	1.38–2.1 MPa (200–300 lb/in^2)	
Shear modulus	0.14–0.34 GPa ($20–50 \times 10^3$ lb/in^2)	

[a] All mechanical properties are based on gross section properties of OSB panels, with stress applied parallel to panel major axis where applicable. Note: Data are not to be used in developing allowable design values. Information courtesy of APA–The Engineered Wood Association, Tacoma, WA.

[b] Standard methods of testing strength and elastic properties of structural panels are given in ASTM standards (see References).

the particles with heat and pressure into a panel product (Fig. 10–7). 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. The faces of the board consists of fine wood particles, and the core is made of the coarser material. Producing a panel this way improves utilization of the material and the smooth face presents a better surface for laminating, overlaying, painting, or veneering. Particleboard is also readily made 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 is not exploited as well. Particleboard is used for furniture cores, where it is typically overlaid with other materials for decorative purposes. Particleboard can be used in flooring systems, in manufactured houses, for stair treads, and as underlayment. Thin panels can 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. The various steps involved in particleboard manufacturing are described in the following text.

Figure 10–7. Particles, which are sometimes produced by hammermilling, are used to produce composites such as particleboard.

Particle Preparation

Standard particleboard plants based on particulate material use combinations of hogs, chippers, hammermills, ring flakers, ring mills, and attrition mills. To obtain particleboards with good strength, smooth surfaces, and equal swelling, manufacturers ideally use a homogeneous material with a high degree of slenderness (long, thin particles), no oversize particles, no splinters, and no dust. Depending on the manufacturing process, the specifications for the ideal particle size are different. For a graduated board, wider tolerances are acceptable. For a three-layer board, the core particles should be longer and surface particles shorter, thinner, and smaller. For a five-layer or multi-layer board, the furnish for the intermediate layer between surface and core should have long and thin particles for building a good carrier for the fine surface and to give the boards high bending strength and stiffness.

Particle Classification and Conveying

Very small particles increase furnish surface area and thus increase resin requirements. Oversized particles can adversely affect the quality of the final product because of internal flaws in the particles. While some particles are classified through the use of air streams, screen classification methods are the most common. In screen classification, the particles are fed over a vibrating flat screen or a series of screens. The screens may be wire cloth, plates with holes or slots, or plates set on edge.

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

Particle Drying

The furnish drying operation is a critical step in the processing of composite products. The raw materials 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% 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. Thus, it is essential to carefully select proper dryers and control equipment. The moisture content of the material depends on whether resin is to be added dry or in the form of a solution or emulsion. The moisture content of materials leaving the dryers is usually in the range of 4% 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.

Addition of Resins and Wax

Frequently used resins for particleboard include urea-formaldehyde and, to a much lesser extent, phenol-formaldehyde, 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, paraffin or microcrystalline wax emulsion 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.

Mat Formation

After the particles have been prepared, they must be laid into an even and consistent mat to be pressed into a panel. This is typically accomplished in a batch mode or by continuous formation. The batch system employs a caul or tray on which a deckle frame is placed. The mat is formed by the back-and-forth movement of the 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, with either a single-opening platen or a continuous press. Pre-pressing reduces mat height and helps to consolidate the mat for pressing.

Hot Pressing

After pre-pressing, the mats are hot-pressed into panels. Presses can be divided into platen and continuous types. Further development in the industry has made possible the construction of presses for producing increasingly larger panel sizes in both single- and multi-opening presses. Both of these types of presses can be as wide as 3.7 m (12 ft). Multi-opening presses can be as long as 10 m (33 ft) and single-opening presses, up to 30.5 m (100 ft) long. Hot-press temperatures for UF resins usually range from 140°C to 165°C (284°F to 325°F). Pressure depends on a number of factors, but it is usually in the range of 1.37 to 3.43 MPa (199 to 498 lb/in^2) for medium-density boards. Upon entering the hot press, mats usually have a moisture content of 8% to 12%, but this is reduced to about 5% to 9% during pressing.

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

Finishing

After pressing, the board is trimmed to obtain the desired length and width and to square the edges. Trim losses usually amount to 0.5% to 8%, depending on the size of the board, the process employed, and the control exercised. Trimmers usually consist of saws with tungsten carbide tips. After trimming, the boards are sanded or planed prior to packaging and shipping. 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.

Properties

Tables 10–8 and 10–9 show requirements for grades of particleboard and particleboard flooring products, as specified by the American National Standard for Particleboard A208.1 (NPA 1993). This standard is typically updated at least every 5 years. Today, approximately 85% of interior-type particleboard is used as core stock for a wide variety of furniture and cabinet applications. Floor underlayment and manufactured home decking represent particleboard construction products and approximately 10% of the market. Low-density panels produced in thicknesses >27 mm (>1-1/16 in.) are used for solid-core doors.

Particleboard Grade Marks and Product Certification

Particleboard that has been grade marked 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 such as those shown in Figure 10–8.

Fiberboard

The term fiberboard includes hardboard, medium-density fiberboard (MDF), and insulation board. Several things differentiate fiberboard from particleboard, most notably the physical configuration of the comminuted material (Fig. 10–9). 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. In its simplest form, this is

Table 10–8. Particleboard grade requirements[a,b,c]

Grade[d]	MOR (MPa)	MOE (MPa)	Internal bond (MPa)	Hardness (N)	Linear expansion max avg (%)	Screw-holding (N) Face	Screw-holding (N) Edge	Formaldehyde maximum emission (ppm)
H–1	16.5	2,400	0.90	2,225	NS	1,800	1,325	0.30
H–2	20.5	2,400	0.90	4,450	NS	1,900	1,550	0.30
H–3	23.5	2,750	1.00	6,675	NS	2,000	1,550	0.30
M–1	11.0	1,725	0.40	2,225	0.35	NS	NS	0.30
M–S	12.5	1,900	0.40	2,225	0.35	900	800	0.30
M–2	14.5	2,225	0.45	2,225	0.35	1,000	900	0.30
M–3	16.5	2,750	0.55	2,225	0.35	1,100	1,000	0.30
LD–1	3.0	550	0.10	NS	0.35	400	NS	0.30
LD–2	5.0	1,025	0.15	NS	0.35	550	NS	0.30

[a] From NPA (1993). Particleboard made with phenol-formaldehyde-based resins does not emit significant quantities of formaldehyde. Therefore, such products and other particleboard products made with resin without formaldehyde are not subject to formaldehyde emission conformance testing.

[b] Panels designated as “exterior adhesive” must maintain 50% MOR after ASTM D1037 accelerated aging.

[c] MOR = modulus of rupture; MOE = modulus of elasticity. NS = not specified. 1 MPa = 145 lb/in^2; 1 N = 0.22 lb.

[d] H = density > 800 kg/m^3 (> 50 lb/ft^3), M = density 640 to 800 kg/m^3 (40 to 50 lb/ft^3). LD = density < 640 kg/m^3 (< 40 lb/ft^3). Grade M–S refers to medium density; “special” grade added to standard after grades M–1, M–2, and M–3. Grade M–S falls between M–1 and M–2 in physical properties.

Table 10–9. Particleboard flooring product grade requirements[a]

Grade[b]	MOR (MPa)	MOE (MPa)	Internal bond (MPa)	Hardness (N)	Linear expansion max avg (%)	Formaldehyde maximum emission (ppm)
PBU	11.0	1,725	0.40	2,225	0.35	0.20
D–2	16.5	2,750	0.55	2,225	0.30	0.20
D–3	19.5	3,100	0.55	2,225	0.30	0.20

[a] From NPA (1993). Particleboard made with phenol-formaldehyde-based resins does not emit significant quantities of formaldehyde. Therefore, such products and other particleboard products made with resin without formaldehyde are not subject to formaldehyde emission conformance testing. Grades listed here shall also comply with appropriate requirements listed in section 3. Panels designated as "exterior adhesive" must maintain 50% MOR after ASTM D1037 accelerated aging (3.3.3).

[b] PBU = underlayment; D = manufactured home decking.

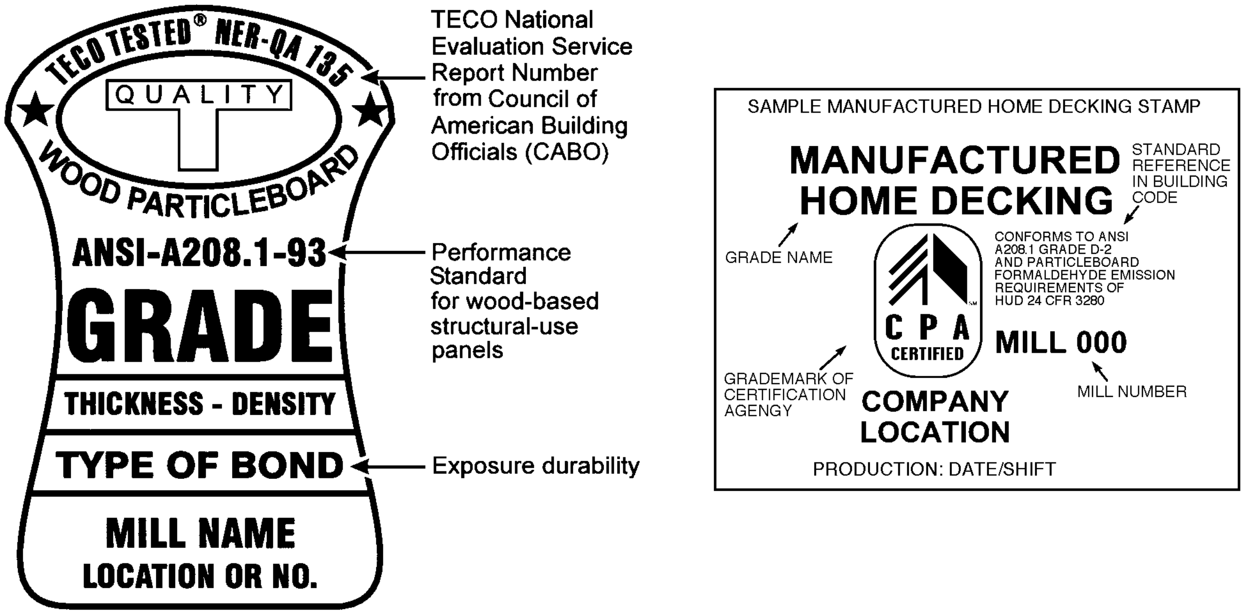


Figure 10–8. Examples of grade stamps for particleboard.

accomplished by attrition milling. Attrition milling is an age-old concept whereby material is fed between two disks, 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, the fibers are more readily separated and usually are less damaged than fibers processed by dry processing methods. Chemical treatments, usually alkali, are also used to weaken the lignin bonds. All of these treatments help increase fiber quality and reduce energy requirements, but they may reduce yield 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. 10–2). 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 insulation board. The following subsections briefly describe the manufacturing of high- and medium-density dry-process fiberboard, wet-process hardboard, and wet-process low-density insulation board. Suchsland and Woodson (1986) and Maloney (1993) provide more detailed information.

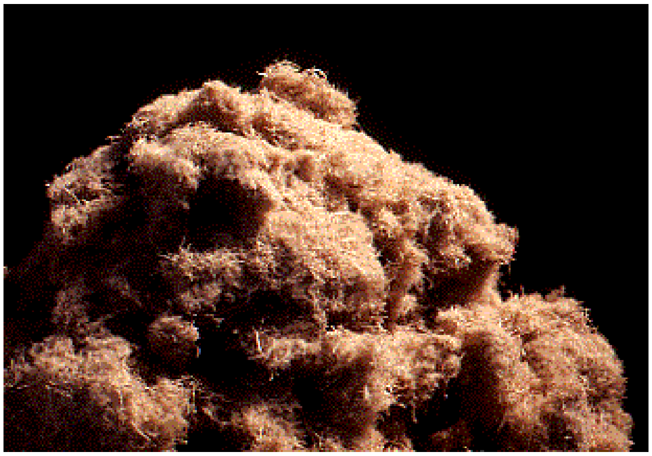


Figure 10–9. Fibers can be made from many lignocellulosics and form the raw materials for many composites, most notably fiberboard. Fibers are typically produced by the refining process.

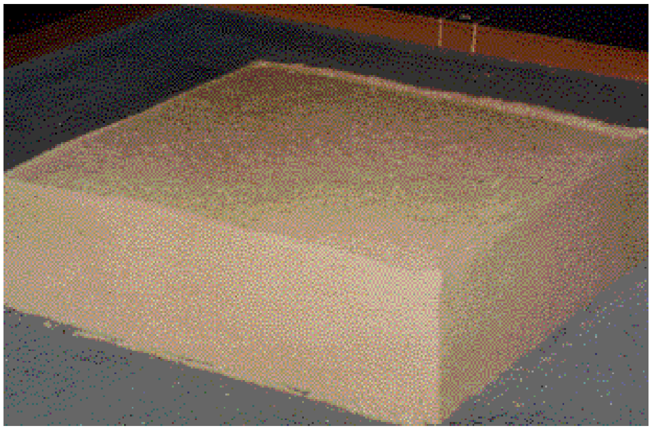
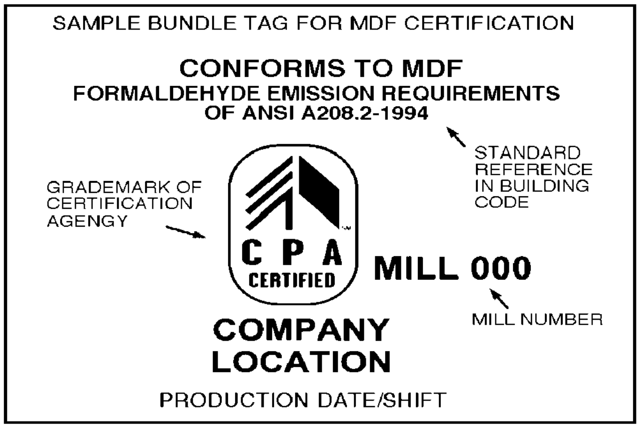


Figure 10–10. Laboratory-produced air-laid mat before pressing. Approximate dimensions are 686 by 686 by 152 mm (27 by 27 by 6 in.) thick. Resin was applied to fibers before mat production. This mat will be made into a high-density fiberboard approximately 3 mm (0.12 in.) thick.

Figure 10–11. Air-laid mat about to enter a laboratory press.



SAMPLE BUNDLE TAG FOR MDF CERTIFICATION

CONFORMS TO MDF
FORMALDEHYDE EMISSION REQUIREMENTS
OF ANSI A208.2-1994

STANDARD
REFERENCE
IN BUILDING
CODE

GRADEMARK OF
CERTIFICATION
AGENGY

C P A
CERTIFIED

MILL 000

MILL NUMBER

COMPANY
LOCATION

PRODUCTION DATE/SHIFT

Figure 10–12. Example of MDF formaldehyde emissions certification tag.

Dry-Process Fiberboard

Dry-process fiberboard is made in a similar fashion to particleboard. Resin (UF, PF) 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 blowline 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 (Fig. 10–10), 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 (Fig. 10–11). All dry-formed boards are pressed in multi-opening presses at approximately 140°C to 165°C (284°F to 329°F) for UF-bonded products and 190°C (410°F) for PF-bonded products. Continuous pressing using large, high-pressure band presses is also gaining in popularity. Board density is a basic property and an indicator of board quality. Since density is greatly influenced by moisture content, this is constantly monitored by moisture sensors using infrared light. An example of an MDF formaldehyde emissions certification tag is shown in Figure 10–12.

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. As such, this technology is really an extension of paper manufacturing technology. Secondly, some wet-process boards are made without additional binders. If the lignocellulosic contains sufficient lignin and if 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. 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.

Post-Treatment of Wet- and Dry-Process Hardboard

Several treatments are used to increase the 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 and is sometimes done on various types of wet-formed hardboards. It also improves 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 water to bring the board moisture content into equilibrium with the air. Initially, a pressed board has almost no moisture content. When the board is exposed to air, it expands linearly by taking on 3% to 7% moisture. Continuous or progressive humidifiers are commonly used for this purpose. Air of high humidity is forced through the stacks where it provides water vapor to the boards. The entire process is controlled by a dry-bulb-wet-bulb controller. Another method involves spraying water on the back side of the board.

Insulation Board

Insulation boards are low-density, wet-laid panel products used for insulation, sound deadening, carpet underlayment, and similar applications. In the manufacture of insulation board, the need for refining and screening is a function of the raw material available, the equipment used, and the desired end-product. Insulation boards typically do not use a binder, and 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. Sizing agents include rosin, starch, paraffin, cumarone, resin, asphalt, and asphalt emulsions.

Like the manufacture of wet-process hardboard, insulation board 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 1.5 to 15 m/min (5 to 49 ft/min).

Insulation board is usually cold-pressed to remove most of the free water after the mat is formed. The wet mats are then dried to the final moisture content. Dryers may be a continuous tunnel or a multi-deck arrangement. The board is generally dried in stages at temperatures ranging from 120°C to 190°C (248°F to 374°F). Typically, about 2 to 4 h are 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.

Properties and Applications

Medium-Density Fiberboard—Minimum property requirements, as specified by the American National Standard for MDF, A208.2 (NPA 1994) are given in Table 10–10. This standard is typically updated every 5 years or less. The furniture industry is by far the dominant MDF market. Medium-density fiberboard 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 (Youngquist and others 1997).

Hardboard—Table 10–11 provides basic hardboard physical properties (ANSI/AHA A135.4–1995 (AHA 1995a)) for selected products. The uses for hardboard can generally be grouped as construction, furniture and furnishings, cabinet and store work, appliances, and automotive and rolling stock. Typical hardboard products are prefinished paneling (ANSI/AHA A135.5–1995 (AHA 1995b)), house siding (ANSI/AHA A135.6–1990 (AHA 1990)), floor underlayment, and concrete form board. Table 10–12 shows physical

Table 10–10. Medium-density fiberboard (MDF) property requirements[a]

Product class[b]	Nominal thickness (mm)	MOR (MPa)	MOE (MPa)	Internal bond (MPa)	Screw-holding (N)		Formaldehyde emission[c] (ppm)
					Face	Edge	
Interior MDF							
HD		34.5	3,450	0.75	1,555	1,335	0.30
MD	≤21	24.0	2,400	0.60	1,445	1,110	0.30
	>21	24.0	2,400	0.55	1,335	1,000	0.30
LD		14.0	1,400	0.30	780	670	0.30
Exterior MDF							
MD–Exterior adhesive	≤21	34.5	3,450	0.90	1,445	1,110	0.30
	>21	31.0	3,100	0.70	1,335	1,000	0.30

[a] From NPA (1994). Metric property values shall be primary in determining product performance requirements.

[b] MD–Exterior adhesive panels shall maintain at least 50% of listed MOR after ASTM D1037–1991, accelerated aging (3.3.4). HD = density > 800 kg/m^3 (> 50 lb/ft^3), MD = density 640 to 800 kg/m^3 (40 to 50 lb/ft^3), LD = density < 640 kg/m^3 (< 40 lb/ft^3).

[c] Maximum emission when tested in accordance with ASTM E1333–1990, Standard test method for determining formaldehyde levels from wood products under defined test conditions using a larger chamber (ASTM).

Table 10–11. Hardboard physical property requirements[a]

Product class	Normal thickness (mm)	Water resistance (max avg/panel)		MOR (min avg/ panel) (MPa)	Tensile strength (min avg/panel) (MPa)	
		Water absorption based on weight (%)	Thickness swelling (%)		Parallel to surface	Perpendicular to surface
Tempered	2.1	30	25	41.4	20.7	0.90
	2.5	25	20	41.4	20.7	0.90
	3.2	25	20	41.4	20.7	0.90
	4.8	25	20	41.4	20.7	0.90
	6.4	20	15	41.4	20.7	0.90
	7.9	15	10	41.4	20.7	0.90
	9.5	10	9	41.4	20.7	0.90
Standard	2.1	40	30	31.0	15.2	0.62
	2.5	35	25	31.0	15.2	0.62
	3.2	35	25	31.0	15.2	0.62
	4.8	35	25	31.0	15.2	0.62
	6.4	25	20	31.0	15.2	0.62
	7.9	20	15	31.0	15.2	0.62
	9.5	15	10	31.0	15.2	0.62
Service-tempered	3.2	35	30	31.0	3.8	0.52
	4.8	30	30	31.0	3.8	0.52
	6.4	30	25	31.0	3.8	0.52
	9.5	20	15	31.0	3.8	0.52

[a] AHA 1995a.

Table 10–12. Physical and mechanical properties of hardboard siding[a]

Property[b]	Requirement	
Water absorption (based on weight)	12% (max avg/panel)	
Thickness swelling	8% (max avg/panel)	
Weatherability of substrate (max residual swell)	20%	
Weatherability of primed substrate	No checking, erosion, flaking, or objectionable fiber raising; adhesion, less than 3.2 mm (0.125 in.) of coating picked up	
Linear expansion 30% to 90% RH (max)	Thickness range (cm)	Maximum linear expansion (%)
	0.220–0.324	0.36
	0.325–0.375	0.38
	0.376–0.450	0.40
	>0.451	0.40
Nail-head pull-through	667 N (150 lb) (min avg/panel)	
Lateral nail resistance	667 N (150 lb) (min avg/panel)	
Modulus of rupture	12.4 MPa (1,800 lb/in^2) for 9.5, 11, and 12.7 mm (3/8, 7/16, and 1/2 in.) thick (min avg/panel)	
	20.7 MPa (3,000 lb/in^2) for 6.4 mm (1/4 in.) thick (min avg/panel)	
Hardness	2002 N (450 lb) (min avg/panel)	
Impact	229 mm (9 in.) (min avg/panel)	
Moisture content[c]	4% to 9% included, and not more than 3% variance between any two boards in any one shipment or order	

[a] From Youngquist and others 1992.

[b] Refer to ANSI/AHA A135.6 I–1990 for test method for determining information on properties.

[c] Since hardboard is a wood-based material, its moisture content varies with environmental humidity conditions. When the environmental humidity conditions in the area of intended use are a critical factor, the purchaser should specify a moisture content range more restrictive than 4% to 9% so that fluctuation in the moisture content of the siding will be kept to a minimum.

properties of hardboard siding. Hardboard siding products come in a great variety of finishes and textures (smooth or embossed) and in different sizes. For application purposes, the AHA siding classifies into three basic types:

Lap siding**—**boards applied horizontally, with each board overlapping the board below it

Square edge panels**—**siding intended for vertical application in full sheets

Shiplap edge panel siding**—**siding intended for vertical application, with the long edges incorporating shiplap joints

The type of panel dictates the application method. The AHA administers a quality conformance program for hardboard for both panel and lap siding. Participation in this program is voluntary and is open to all (not restricted to AHA members). Under this program, hardboard siding products are tested by an independent laboratory in accordance with product standard ANSI/AHA A135.6. Figure 10–13a provides an example of a grade stamp for a siding product meeting this standard.

Insulation Board—Physical and mechanical properties of insulation board are published in the ASTM C208 standard specification for cellulosic fiber insulation board. Physical

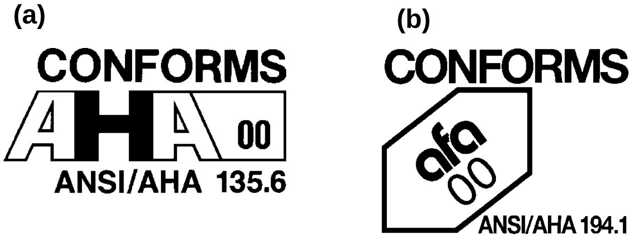


Figure 10–13. Examples of grade stamps: (a) grade stamp for siding conforming to ANSI/AHA A135.6 standard, and (b) grade mark stamp for cellulosic fiberboard products conforming to ANSI/AHA A194.1 standard.

properties are also included in the ANSI standard for cellulosic fiberboard, ANSI/AHA A194.1 (AHA 1985). Insulation board products can be divided into three categories (Suchsland and Woodson 1986): exterior, interior, and industrial.

Exterior products

- Sheathing—board used in exterior construction because of its insulation and noise control qualities, bracing strength, and low price
- Roof decking—three-in-one component that provides roof deck, insulation, and a finished interior ceiling surface; insulation board sheets are laminated together with waterproof adhesive Roof insulation—insulation board designed for use on flat roof decks
- Aluminum siding backer board—fabricated insulation board for improving insulation of aluminum-sided houses

Interior products

- Building board—general purpose product for interior construction
- Ceiling tile—insulation board embossed and decorated for interior use; valued for acoustical qualities; also decorative, nonacoustical tiles
- Sound-deadening board—special product designed to control noise levels in buildings

Industrial products

- Mobile home board
- Expansion joint strips
- Boards for automotive and furniture industries

The AHA administers a quality conformance program for cellulosic fiberboard products including sound-deadening board, roof insulation boards, structural and nonstructural sheathings, backer board, and roof decking in various thicknesses. These products are tested by an independent laboratory in accordance with product standard ANSI/AHA A194.1. An example of the grade mark stamp for these products is shown in Figure 10–13b.

Finishing Techniques

Several techniques are used to finish fiberboard: trimming, sanding, surface treatment, punching, and embossing.

Trimming—Trimming consists of reducing products into standard sizes and shapes. Generally, double-saw trimmers are used to saw the boards. Trimmers consist of overhead-mounted saws or multiple saw drives. Trimmed boards are stacked in piles for future processing.

Sanding—If thickness tolerance is critical, hardboard is sanded prior to finishing. S1S (smooth on one side) boards 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 treatment—Surface treatments improve the appearance and performance of boards. Boards are cleaned by spraying with water and then dried at about 240°C (464°F) for 30 seconds. Board surfaces are then modified with paper overlay, paint, or stain or are printed directly on the panel.

Punching—Punching changes boards into the perforated sheets used as peg board. Most punching machines punch three rows of holes simultaneously while the board advances.

Embossing—Embossing consists of pressing the unconsolidated mat of fibers with a textured form. This process results in a slightly contoured board surface that can enhance the resemblance of the board to that of sawn or weathered wood, brick, and other materials.

Specialty Composites

Special-purpose composites are produced to obtain desirable properties like water resistance, mechanical strength, acidity control, and decay and insect resistance. Overlays and veneers can also be added to enhance both structural properties and appearance (Fig. 10–14).

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 forced to precipitate 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

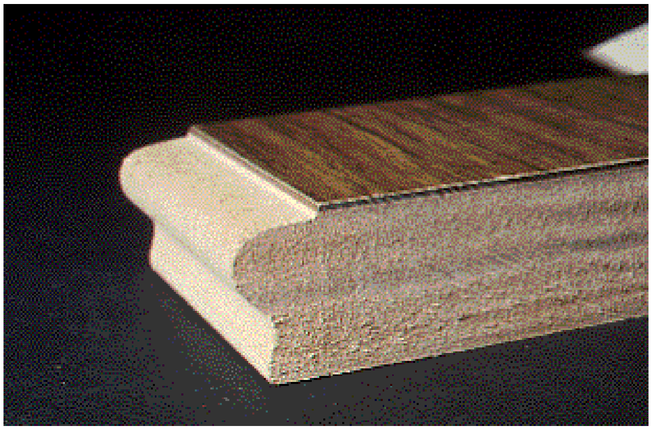


Figure 10–14. Medium-density fiberboard with veneer overlay. Edges can be shaped and finished as required by end product.

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 insulation board. 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 solventborne chemicals. The second method consists of applying fire-retardant chemical coatings to the wood surface. The impregnation method is usually more effective and longer lasting; however, this technique sometimes causes damage to the wood–adhesive bonds in the composite and results in the degradation of some physical and mechanical properties of the composite. For wood in existing constructions, surface application of fire-retardant paints or other finishes offers a practical method to reduce flame spread.

Preservative-Treated Composites

Wood is highly susceptible to attack by fungi and insects; thus, treatment is essential for maximum durability in adverse conditions.

Composites can be protected from the attack of 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 preservative chemicals can be applied using pressure or nonpressure processes. As in the application of fire-retardant chemicals, the application of wood preservatives can sometimes cause damage to wood–adhesive bonds, thus reducing physical and mechanical properties of the composite. Common preservative treatments include chromated copper arsenate (CCA) and boron compounds.

Wood–Nonwood Composites

Interest has burgeoned in combining wood and other raw materials, such as plastics, gypsum, and concrete, into composite products with unique properties and cost benefits (Youngquist and others 1993a, 1993b, 1994; Rowell and others 1997). The primary impetus for developing such products has come from one or more of the following research and development goals:

- 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)

Composites made from wood and other materials create enormous opportunities to match product performance to end-use requirements (Youngquist 1995).

Figure 10–15. Laboratory-produced low-density, cement-bonded composite panel. Full-scale panels such as these are used in construction.

Inorganic–Bonded Composites

Inorganic-bonded wood composites have a long and varied history that started with commercial production in Austria in 1914. A plethora of building materials can be made using inorganic binders and lignocellulosics, and they run the normal gamut of panel products, siding, roofing tiles, and precast building members (Fig. 10–15).

Inorganic-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 with 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.

Inorganic binders fall into three main categories: gypsum, magnesia cement, and Portland cement. Gypsum and magnesia cement are sensitive to moisture, and their use is generally restricted to interior applications. Composites bonded with Portland cement are more durable than those bonded with gypsum or magnesia cement and are used in both interior and exterior applications. Inorganic-bonded composites are made by blending proportionate amounts of lignocellulosic fiber with inorganic materials in the presence of water and allowing the inorganic material to cure or "set up" to make a rigid composite. All inorganic-bonded composites are very resistant to deterioration, particularly by insects, vermin, and fire.

A unique feature of inorganic-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. For example, in the Philippines, Portland cement-bonded composites are mostly fabricated using manual labor and are used in low-cost housing. In Japan, the fabrication of these composites is automated, and they are used in very expensive modular housing.

The versatility of manufacture makes inorganic-bonded composites ideally suited to a variety of lignocellulosic materials. With a very small capital investment and the most rudimentary of tools, satisfactory inorganic-bonded lignocellulosic composite building materials can be produced on a small scale using 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.

Gypsum-Bonded Composites

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

Gypsum panels are frequently used to finish interior wall and ceiling surfaces. In the United States, these products are generically called "dry wall" because they replace wet plaster systems. To increase the bending strength and stiffness, gypsum panels are frequently wrapped in paper, which provides a tension surface. An alternative to wrapping gypsum with fiber is to place the fiber within the panel, as several U.S. and European firms are doing with recycled paper fiber. There is no technical reason that other lignocellulosics cannot be used in this way. Gypsum is widely available and does not have the highly alkaline environment of cement.

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

Magnesia-Cement-Bonded Composites

Fewer boards bonded with magnesia cement have been produced than cement- or gypsum-bonded panels, mainly because of price. 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.

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

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 Composites

The most apparent and 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. General mechanical property values for a low density cement–wood excelsior product are given in Table 10–13.

The 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 stuccoed, 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.

Table 10–13. General properties of low-density cement–wood composites fabricated using an excelsior-type particle[a,b]

Property	From	To
Bending strength	1.7 MPa (250 lb/in^2)	5.5 MPa (800 lb/in^2)
Modulus of elasticity	621 MPa (0.9 × 10^5 lb/in^2)	1,241 MPa (1.8 × 10^5 lb/in^2)
Tensile strength	0.69 MPa (100 lb/in^2)	4.1 MPa (600 lb/in^2)
Compression strength	0.69 MPa (100 lb/in^2)	5.5 MPa (800 lb/in^2)
Shear[c]	0.69 MPa (100 lb/in^2)	1.4 MPa (200 lb/in^2)
E/*G*[d]	40	100

[a] Data represent compilation of raw data from variety of sources for range of board properties. Variables include cement–wood mix, particle configuration, board density, and the forming and curing methods.

[b] Specific gravity range, 0.5 to 1.0.

[c] Shear strength data are limited to a small sample of excelsior boards having a specific gravity of 0.5 to 0.65.

[d] *E*/*G* is ratio of bending modulus of elasticity to modulus of rigidity or shear modulus. For wood, this ratio is often assumed to be around 16.

Problems and Solutions

Although the entire sphere of inorganic-bonded lignocellulosic composites is attractive, and cement-bonded composites are especially so, the use of cement 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, all 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 are natural pozzolans and carbon dioxide treatment.

Natural Pozzolans—Pozzolans are defined as siliceous or siliceous and aluminous materials that can react chemically with calcium hydroxide (lime) at normal temperatures in the presence of water to form cement compounds (ASTM 1988). Some common pozzolanic materials include volcanic ash, fly ash, rice husk ash, and condensed silica fume. All 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 Portland cement, which indicates that adding lignocellulosic-based material (rice husk ash) to cement-bonded lignocellulosic composites may be advantageous.

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 varying 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 of these compounds to 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.

Wood Fiber–Thermoplastic Composites

As described elsewhere in this chapter, the use of lignocellulosic materials with thermosetting polymeric materials, like phenol- or urea-formaldehyde, in the production of composites has a long history. The use of lignocellulosics with thermoplastics, however, is a more recent innovation. 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°C to 220°C (392°F to 428°F). These thermoplastics include polypropylene, polystyrene, vinyls, and low- and high-density polyethylenes.

Wood flour is a readily available resource that can be used as a filler in thermoplastic composites. 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 compared with 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, UV stabilizers, flame retardants), and processability (lubricants).

Several considerations must be kept in mind when processing wood with thermoplastics. Moisture can disrupt many thermoplastic processes, resulting in poor surface quality, voids, and unacceptable parts. Materials must either be predried 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.

There are two main strategies for processing thermoplastics in lignocellulosic composites (Youngquist and others 1993b). 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.

Composites With 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 (Fig. 10–16). 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. As a reinforcement, lignocellulosics can stiffen and strengthen the thermoplastic and can improve thermal stability of the product compared with that of unfilled material.

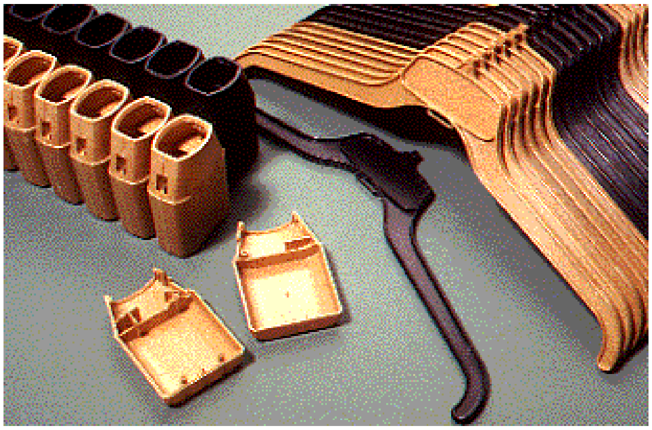


Figure 10–16. The use of lignocelulosics as reinforcing fillers allows thermoplastics to be molded into a wide variety of shapes and forms.

Thermoplastics in pellet form have bulk density in the range of 500 to 600 kg/m^3 (31 to 37 lb/ft^3). Lignocellulosics typically have an uncompacted bulk density of 25 to 250 kg/m^3 (1.6 to 16 lb/ft^3). Wood fibers are at the low end of the lignocellulosic bulk density continuum and wood flours at the high end. 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 manufacture of thermoplastic composites 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.

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). Batch systems allow closer control of residence time, shear, and temperature than do continuous systems. Batch systems are also more appropriate for operations consisting of short runs and frequent change of materials. On the other hand, continuous systems are less operator-dependent than are batch systems and have less batch-to-batch differences (Anon. 1997).

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) into a cold mold (injection molding) or pressing in calenders (calendering) or between mold halves (thermoforming and compression molding).

Properties of wood–plastic composites can vary greatly depending upon such variables as type, form, and weight fractions of constituents, types of additives, and processing history. Table 10–14 shows some of the properties for several unfilled polypropylene and wood–polypropylene composites.

Composites with high thermoplastic content are not without tradeoffs. Impact resistance of such composites decreases compared with that of unfilled thermoplastics, and these composites are also more sensitive to moisture than unfilled material or composites filled with inorganic material. From a practical standpoint, however, the thermoplastic component usually makes the temperature sensitivity of the composite more significant than any change in properties brought about by moisture absorption.

Composites With Low Thermoplastic Content

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

Experimentally, low-thermoplastic-content composites have been made that are very similar to conventional lignocellulosic composites in many performance characteristics (Youngquist and others 1993b). In their simplest form, lignocellulosic particles or fibers can be dry-blended with thermoplastic granules, flakes, or fibers and pressed into panel products.

Because the thermoplastic component remains molten when hot, different pressing strategies must be used than when 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 transferred through conduction to melt the thermoplastic component, which flows around the lignocellulosic component. The press is then cooled, “freezing” the thermoplastic so that the composite can be removed from the press. Alternatively, the material can be first heated in an oven or hot press. The hot material is then transferred to a cool press where it is quickly consolidated and cooled to make a rigid panel. Some commercial nonstructural lignocellulosic–thermoplastic composites are made in this way.

Nonwoven Textile-Type Composites

In contrast to high-thermoplastic-content and conventional low-thermoplastic-content composites, nonwoven textile-type composites typically require long fibrous materials for their manufacture. These fibers might be treated jute or kenaf, but more typically they are synthetic thermoplastic materials. Nonwoven processes allow and tolerate a wider range of lignocellulosic materials and synthetic fibers, depending on product applications. After fibers are dry-blended, they are air-laid into a continuous, loosely consolidated mat. The mat is then passed through a secondary operation in which the fibers are mechanically entangled or otherwise bonded together. This low-density mat may be a product in itself, or the mat may be shaped and densified in a thermoforming step (Youngquist and others 1993b).

If left as low density and used without significant modification by post-processing, the mats have a bulk density of

Table 10–14. Mechanical properties of wood–polypropylene composites[a,b]

		Tensile			Flexural		Izod impact energy		
Composite[c]	Density (g/cm^3 (lb/ft^3))	Strength (MPa (lb/in^2))	Modulus (GPa (lb/in^2))	Elongation (%)	Strength (MPa (lb/in^2))	Modulus (GPa (lb/in^2))	Notched (J/m (ft-lbf/in))	Unnotched (J/m (ft-lbf/in))	Heat deflection temperature (°C (°F))
Polypropylene	0.9 (56.2)	28.5 (4,130)	1.53 (221,000)	5.9	38.3 (5,550)	1.19 (173,000)	20.9 (0.39)	656 (12.3)	57 (135)
PP + 40% wood flour	1.05 (65.5)	25.4 (3,680)	3.87 (561,000)	1.9	44.2 (6,410)	3.03 (439,000)	22.2 (0.42)	73 (1.4)	89 (192)
PP + 40% hardwood fiber	1.03 (64.3)	28.2 (4,090)	4.20 (609,000)	2.0	47.9 (6,950)	3.25 (471,000)	26.2 (0.49)	91 (1.7)	100 (212)
PP + 40% hardwood fiber + 3% coupling agent	1.03 (64.3)	52.3 (7,580)	4.23 (613,000)	3.2	72.4 (10,500)	3.22 (467,000)	21.6 (0.41)	162 (3.0)	105 (221)

[a] Unpublished data.
[b] Properties measured according to ASTM standards for plastics.
[c] PP is polypropylene; percentages based on weight.

50 to 250 kg/m^3 (3 to 16 lb/ft^3). These products are particularly well known in the consumer products industry, where nonwoven technology is used to make a variety of absorbent personal care products, wipes, and other disposable items. The products are made from high-quality pulps in conjunction with additives to increase absorptive properties. A much wider variety of lignocellulosics can be used for other applications, as described in the following text.

One interesting application for low-density nonwoven mats is for mulch around newly planted seedlings. The mats provide the benefits of natural mulch; in addition, controlled-release fertilizers, repellents, insecticides, and herbicides can be added to the mats. The addition of such chemicals could be based on silvicultural prescriptions to ensure seedling survival and early development on planting sites where severe nutritional deficiencies, animal damage, insect attack, and weeds are anticipated.

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

High-density fiber mats can be defined as composites that are made using the nonwoven mat process and then formed into rigid shapes by heat and pressure. To ensure good bonding, the lignocellulosic can be precoated with a thermosetting resin such as phenol–formaldehyde, or it can be blended with synthetic fibers, thermoplastic granules, or any combination of these materials. High-density fiber mats can typically be pressed into products having a specific gravity of 0.60 to 1.40. Table 10–15 presents mechanical and physical property

Table 10–15. Properties of nonwoven web composite panels with specific gravity of 1.0[a]

	Formulation[b]		
Property	90H/10PE	90H/10PP	80H/10PE/PR
Static bending MOR, MPa (lb/in^2)	23.3 (3,380)	25.5 (3,700)	49.3 (7,150)
Cantilever bending MOR, MPa (lb/in^2)	21.1 (3,060)	27.1 (3,930)	45.6 (6,610)
Static bending MOE, GPa (×10^3 lb/in^2)	2.82 (409)	2.99 (434)	3.57 (518)
Dynamic MOE, GPa (×10^3 lb/in^2)	4.75 (689)	5.27 (764)	5.52 (800)
Tensile strength, MPa (lb/in^2)	13.5 (1,960)	12.5 (1,810)	27.7 (4,020)
Tensile MOE, GPa (×10^3 lb/in^2)	3.87 (561)	420 (609)	5.07 (735)
Internal bond, MPa (lb/in^2)	0.14 (20)	0.28 (41)	0.81 (120)
Impact energy, J (ft·lbf)	26.7 (19.7)	21.5 (15.9)	34.3 (25.3)
Water-soak, 24 h			
Thickness swell, %	60.8	40.3	21.8
Water absorption, %	85.0	54.7	45.1
Water boil, 2 h			
Thickness swell, %	260.1	77.5	28.2
Water absorption, %	301.6	99.5	55.7
Linear expansion[c]			
Ovendry to			
30% RH, %	0.13	0.00	0.55
65% RH, %	0.38	0.25	0.76
90% RH, %	0.81	0.78	0.93
Equilibrium MC at			
30% RH, %	3.4	3.4	3.4
65% RH, %	6.4	6.2	6.3
90% RH, %	15.6	14.9	14.1

[a] From Youngquist and others 1992.

[b] Values connected by solid line are not statistically different at 0.05 significance level. 90H/10PE, 90% hemlock and 10% polyester; 90H/10PP, 90% hemlock and 10% polypropylene; 80H/10PE/10PR, 80% hemlock, 10% polyester, and 10% phenolic resin.

[c] RH = relative humidity.

data for nonwoven web composite panels with a specific gravity of 1.0 for three different formulations of wood, synthetic fibers, and phenolic resin. After thermoforming, the products possess good temperature resistance. Because longer fibers are used, these products exhibit better mechanical properties than those obtained with high-thermoplastic-content composites; however, the high lignocellulosic content leads to increased moisture sensitivity.

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