
Adhesive Bonding of Wood Materials

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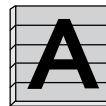
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Adhesive bonding of wood components has played an essential role in the development and growth of the forest products industry and has been a key factor in the efficient utilization of our timber resource. The largest use of adhesives is in the construction industry. By far, the largest amounts of adhesives are used to manufacture building materials, such as plywood, structural flakeboards, particleboards, fiberboards, structural framing and timbers, architectural doors, windows and frames, factory-laminated wood products, and glass fiber insulation. Adhesives are used in smaller amounts to assemble building materials in residential and industrial construction, particularly in panelized floor and wall systems. Significant amounts are also used in nonstructural applications, such as floor coverings, countertops, ceiling and wall tile, trim, and accessories.

Adhesives can effectively transfer and distribute stresses, thereby increasing the strength and stiffness of the composite. Effective transfer of stress from one member to another depends on the strength of the links in an imaginary chain of an adhesive-bonded joint. Thus, performance of the bonded joint depends on how well we understand and control the complexity of factors that constitute the individual links—wood, adhesive, and the interphasing regions between—which ultimately determine the strength of the chain.

Adhesion to Wood

The American Society for Testing and Materials (ASTM) defines an adhesive as a substance capable of holding materials together by surface attachment. An adherend is a substrate held to another substrate by an adhesive. Adhesion is the state in which two surfaces are held together by interfacial forces, which may be valence forces, interlocking action, or both. Valence forces are forces of attraction produced by the interactions of atoms, ions, and molecules that exist within and at the surfaces of both adhesive and adherend. Interlocking action, also called mechanical bonding, means surfaces are held together by an adhesive that has penetrated the porous surface while it is liquid, then anchored itself during solidification. The extent to which valence forces and interlocking action develop between adhesive polymers and wood adherends is uncertain, but both are generally acknowledged as essential for the most effective bonding. Bonding to porous surfaces, such as wood, paper, and textiles, was

thought to be primarily mechanical, but now there is evidence supporting bonding by primary valence forces. In contrast, bonding to hard metal surfaces was believed to involve only valence forces, but this is no longer the accepted view. Metal surfaces roughened by chemical etching or made microscopically porous with a layer of oxide are capable of mechanical interlocking with an adhesive to produce exceptionally strong and durable bonds.

Mechanical interlocking is probably the primary mechanism by which adhesives adhere to porous structures, such as wood. Effective mechanical interlocking takes place when adhesives penetrate beyond the surface debris and damaged fibers into sound wood two to six cells deep. Deeper penetration into the fine microstructure increases the surface area of contact between adhesive and wood for more effective mechanical interlocking. The most durable structural bonds to wood are believed to develop not only when an adhesive penetrates deeply into cell cavities, but also when an adhesive diffuses into cell walls to make molecular-level contact with the hemicellulosics and celluloses of wood. If an adhesive penetrates deeply enough into sound wood and becomes rigid enough upon curing, the strength of the bond can be expected to exceed the strength of the wood.

Physical forces of attraction composed of three intermolecular attraction forces are believed to be important to the formation of bonds between adhesive polymers and molecular structures of wood. Generally called van der Waal's forces, these include dipole-dipole forces, which are positively and negatively charged polar molecules that have strong attractions for other polar molecules; London forces, which include the weaker forces of attraction that nonpolar molecules have for each other; and hydrogen bonding, a special type of dipole-dipole force that accounts for strong attractions between positively charged hydrogen atoms of one polar molecule and the electronegative atom of another molecule. Hydrogen bonding forces are important in the interfacial attraction of polar adhesive polymers for the hemicellulosics and celluloses, which are rich with polar hydroxyl groups. These physical forces of attraction, sometimes referred to as specific adhesion, are particularly important in wetting of water carriers and adsorption of adhesive polymers onto the molecular structures of wood.

Covalent chemical bonds form when atoms of nonmetals interact by sharing electrons to form molecules. The simplest example of a purely covalent bond is the sharing of electrons by two hydrogen atoms to form hydrogen. These covalent bonds are the strongest of chemical bonds; they are more than 11 times the strength of the hydrogen bond. Even though covalent chemical bonds between adhesive polymer and the molecular structure of wood seem a possibility, there is no clear evidence that such bonds constitute an important mechanism in adhesive bonding to wood.

For two wood adherends to be held together with maximum strength, a liquid adhesive must wet and spread freely to make intimate contact with both surfaces. Molecules of the adhesive must diffuse over and into each surface to make contact with the molecular structure of wood so that

intermolecular forces of attraction between adhesive and wood can become effective. As will be discussed later, wood adherends, as well as other materials, differ widely in their attractive energies, bulk properties, surface roughness, and surface chemistry. Wood surfaces may appear to be smooth and flat, but on microscopic examination, they become peaks, valleys, and crevices, littered with loose fibers and other debris. Such surface conditions cause gas pockets and blockages that prevent complete wetting by the adhesive and introduce stress concentrations when the adhesive has cured. Thus, the liquid adhesive must have high wettability, coupled with a viscosity that will produce good capillary flow to penetrate sound wood structure, while displacing and absorbing air, water, and contaminants at the surface. Pressure is normally used to enhance wetting by forcing liquid adhesive to flow over the surfaces, displace air blockages, and penetrate to sound wood.

Wetting of a surface occurs when the contact angle (the angle between the edge of a drop of adhesive and the surface of wood) approaches zero. The contact angle approaches zero when the surface has high attractive energy, the adhesive has an affinity for the adherend, and the surface tension of the adhesive is low. If a drop of adhesive spreads to a thin film approaching zero contact angle, the adhesive has spread well and made intimate contact with the surface. The differences in wettabilities of various wood surfaces are illustrated by a simple water drop test in Figure 9-1.

The process of adhesion is essentially completed after transition of the adhesive from liquid to solid form. After the viscosity of a liquid adhesive has increased and the adhesive has solidified to the point where the film effectively resists shear and tensile forces tending to separate the surfaces, the surfaces are effectively bonded. An adhesive film changes from liquid to solid form by one of three mechanisms, although two may be involved in some curing mechanisms. This transition can be a physical change as in thermoplastic adhesives or it can be a chemical change as in thermosetting adhesives. In thermoplastics, the physical change to solid form may occur by either (a) loss of solvent from the adhesive through evaporation and diffusion into the wood, or (b) cooling of molten adhesive on a cooler surface. In thermosets, the solid form occurs through chemical polymerization into cross-linked structures that resist softening on heating. Most thermosetting wood adhesives contain water as a carrier; therefore, water also must be evaporated and absorbed by the wood so that the adhesive can cure completely.

Surface Properties of Wood Adherends

Because adhesives bond by surface attachment, the physical and chemical conditions of the adherend's surface is extremely important to satisfactory joint performance. Wood surfaces should be smooth, flat, and free of machine marks and other surface irregularities, including planer skips and crushed, torn, and chipped grain. The surface should be free of burnishes, exudates, oils, dirt, and other debris.

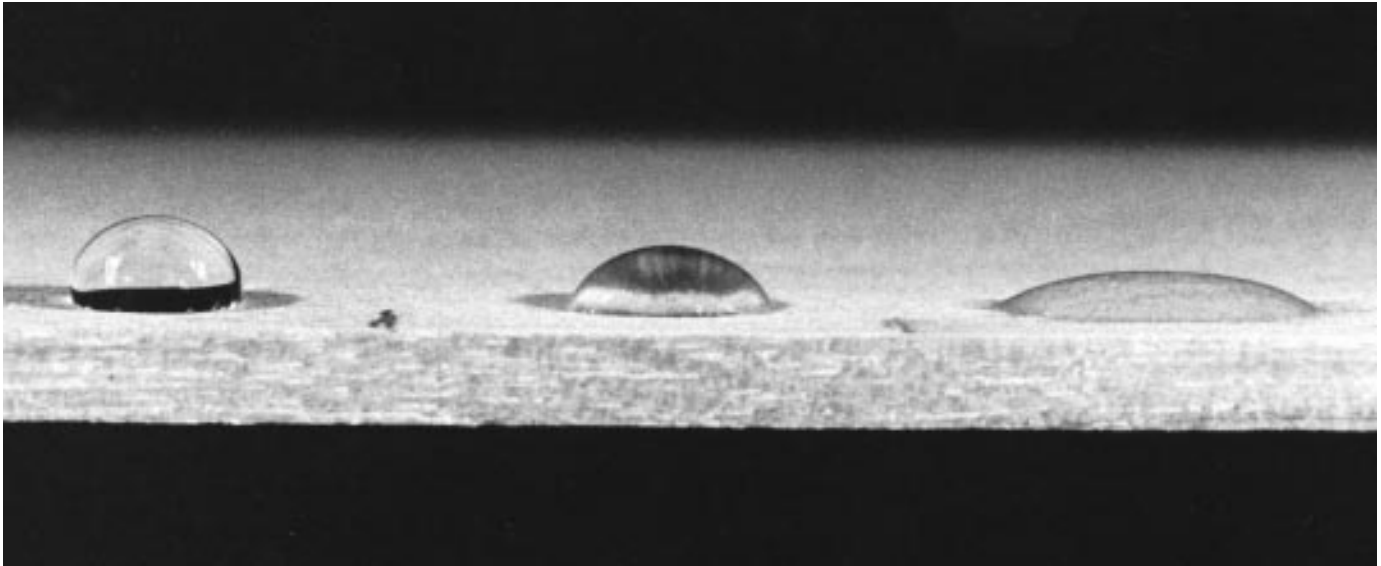


Figure 9–1. A simple water drop test shows differences in the wettability of a yellow birch veneer surface. Three drops were applied to the surface at the same time, then photographed after 30 s. The drop on the left retains a large contact angle on the aged, unsanded surface; the drop in the center has a smaller contact angle and improved wettability after the surface is renewed by two passes with 320-grit sandpaper; the drop on the right shows a small contact angle and good wettability after four passes with the sandpaper.

Overdrying and overheating deteriorates the physical condition of the wood surfaces by forcing extractives to diffuse to the surface, by reorienting surface molecules, and by irreversibly closing the larger micropores of cell walls. Wood surfaces can be chemically inactivated with respect to adhesion by airborne chemical contaminants, hydrophobic and chemically active extractives from the wood, oxidation and pyrolysis of wood bonding sites from overdrying, and impregnation with preservatives, fire retardants, and other chemicals. Unfortunately, some of these surface conditions are difficult to detect. Physical deterioration and chemical contamination interfere with essential wetting, flow, and penetration of adhesive but can also interfere with the cure and resulting cohesive strength of the adhesive.

Extractives on Surfaces

Extensive research indicates that extractives on wood surfaces are the principal physical and chemical contributors to surface inactivation, hence to poor wettability by adhesives. This is particularly true for resinous species, such as the southern pines and Douglas-fir. When subjected to high temperatures during processing, extractives diffuse to the surface where they concentrate and physically block adhesive contact with wood. Furthermore, resinous and oily exudates are hydrophobic; that is, they repel water. Most wood adhesives contain water as a carrier; therefore, they do not properly wet, flow, and penetrate extractive-covered surfaces. The acidity of extractives of some Southeast Asian hardwoods and oak species can interfere with the chemical cure of adhesives. The acid may accelerate the cure of an alkaline phenolic adhesive, causing the adhesive to gel prematurely and reducing its

ability to wet, flow, and penetrate. In contrast, normal polymerization of an acidic adhesive, such as urea-formaldehyde, can be retarded by an alkaline wood surface, which would compromise the integrity of the adhesive film and bond.

A simple water test can reveal much about the state of inactivation of a wood surface and how difficult it may be to wet and bond with adhesive. As a first test, place a small drop of water on the surface and observe how it spreads and absorbs. If the drop remains a bead and does not begin to spread within 30 s, the surface is resistant to adhesive wetting (Fig. 9–1). Another water drop test can be used to estimate the degree of surface inactivation of veneer. Place a drop of water in an area on the earlywood of a flat-grain surface that does not have checks or splits in the area of the drop. Good wettability is indicated if the drop is absorbed within 20 min. If the drop has spread out but some water still remains on the surface after 40 min, then bonding problems are likely to occur. If after 40 min the water drop still retains much of its original shape with little spreading, then bonding problems from surface inactivation is a certainty.

Knife- and Abrasive-Planed Surfaces

Wood should be surfaced or resurfaced within 24 h before bonding to remove extractives and other physical and chemical contaminants that interfere with bonding. Surfacing also removes any unevenness that may have occurred from changes in moisture content. Parallel and flat surfaces allow the adhesive to flow freely and form a uniformly thin layer of adhesive that is essential to the best performance of water-based wood adhesives.

Experience and testing have proven that a smooth, knife-cut surface is best for bonding. Surfaces made by saws usually are rougher than those made by planers and jointers. However, surfaces sawn with special blades on properly set straight-line ripsaws are satisfactory for both structural and nonstructural joints. Precision sawing of wood joints rather than two-step sawing and jointing is commonplace in furniture manufacture for purposes of reducing costs for labor, equipment, and material. Unless the saws and feed works are well maintained, however, joints made with sawed surfaces will be weaker and less uniform in strength than those made with sharp planer or jointer knives. Dull cutting edges of planer or jointer knives crush and burnish the wood surface. The crushed and burnished surface inhibits adhesive wetting and penetration. If the adhesive does not completely penetrate crushed cells to restore their original strength, a weak joint results. Another simple water test can be used to detect a surface that has been damaged during machining. Wipe a very wet rag over a portion of the surface. After waiting for a minute, remove any remaining water by blotting with a paper towel. Then compare the roughness of the wet and dry surfaces. If the wetted area is much rougher than the dry area, then the surface has been damaged in machining. This damage will significantly reduce the strength of adhesive-bonded joints.

Abrasive planing with grit sizes from 24 to 80 causes surface and subsurface crushing of wood cells. Figure 9–2 shows cross sections of bondlines between undamaged, knife-planed Douglas-fir lumber compared with surfaces damaged by abrasive planing. Such damaged surfaces are inherently weak and result in poor bond strength. Similar damage can be caused by dull planer knives or saws. There is some evidence that sanding with grits finer than 100 may improve an abrasive-planed surface. However, abrasive-planing is not recommended for structural joints that will be subjected to high swelling and shrinkage stresses from water soaking and drying. If abrasive-planing is to be used before bonding, then belts must be kept clean and sharp, and sanding dust must be removed completely from the sanded surface.

Veneer Surfaces

The wood properties of veneer are essentially no different from those of lumber; however, manufacturing processes, including cutting, drying, and laminating into plywood, can drastically change physical and chemical surface properties of veneer. Special knowledge and attention to these characteristics are required to ensure good wetting, flow, and penetration of adhesive.

Rotary cutting produces continuous sheets of flat-grain veneer by rotating a log by its ends against a knife. As the knife peels veneer from the log, the knife forces the veneer away from the log at a sharp angle, thereby breaking or checking the veneer on the knife side. The checked side is commonly called the loose side, and the opposite side without checking is called the tight side. When rotary-cut veneer is used for faces in plywood, the loose side should be bonded with the tight side presented to view. Otherwise, open checks in the faces produce imperfections in any finish that may be applied.

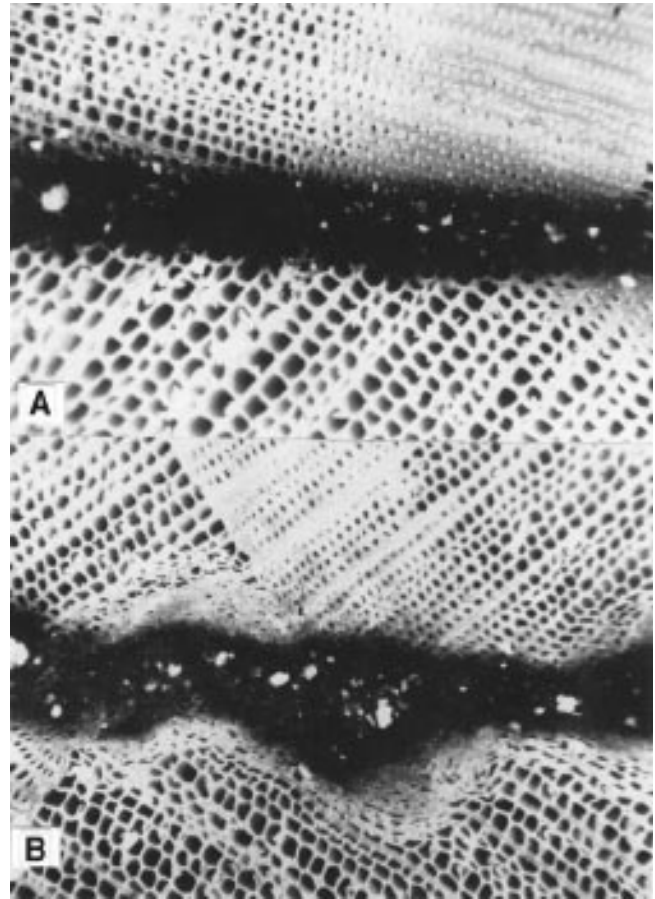


Figure 9–2. (A) Cross section of a bonded joint between two undamaged Douglas-fir surfaces that were planed with a sharp knife (120X). The wood cells are open, and their walls are distinct. The dark area at the center of micrograph is the adhesive bondline. (B) Cross section of a bonded joint between two damaged Douglas-fir surfaces abrasively planed with 36-grit sandpaper. The cells in and adjacent to the bondline are crushed, and their walls are indistinct.

Adhesive overpenetration into lathe checks usually is not a problem if the adhesive spread rate is adjusted correctly.

Sliced veneer is produced in long strips by moving a squared log, called a flitch, against a knife. As in rotary cutting, the veneer is forced by the knife away from the flitch at a sharp angle, causing fine checking of the veneer on the knife side. This checked surface will show imperfections in a finished surface, so the loose side should be bonded and the tight side finished. For book-matched face veneers, where grain patterns of adjacent veneers are near mirror images, half the veneers will be loosely cut and must be finished, so the veneer must be cut as tightly as possible. Generally, hardwood face veneers are sliced to reveal the most attractive grain patterns.

Sawn veneer is produced in long narrow strips from flitches that have been selected and sawn for attractive grain patterns. The two sides of sawn veneer are free from knife checks, so either surface may be bonded or exposed to view with satisfactory results.

Veneer is dried promptly after cutting, using continuous, high temperature dryers that are heated either with steam or hot gases from wood-residue or gas-fired burners. Drying temperatures range from 170°C to 230°C (330°F to 446°F) for short periods. Drying veneer to very low moisture content levels at very high temperatures and drying at moderate temperatures for prolonged periods inactivates surfaces, causing poor wetting of veneer, hence poor bonding of the plywood. Residues deposited on veneer surfaces from incomplete combustion of gases and fuel oils can cause serious adhesion problems in plywood production.

Veneer selected for its attractive appearance, or for use in sanded grades of plywood, should be uniform in thickness, smooth, flat, free from deep checks, knots, holes, and decay, and have face grain suitable for the intended face grade. For plywood of the lower grades, defect requirements are not as restricted. For example, loosely cut veneer with frequent deep checks and large defects is suitable for structural plywood, but more adhesive is required than for tightly cut veneer. Higher spread rates compensate for overpenetration of adhesive into loosely cut veneer. When rotary-cut veneer is bonded into plywood, the tight side is usually bonded to the loose side, except that in one bondline, the loose side must be bonded to the loose side. This orientation permits the face veneer to be presented with its tight side facing outward for sanding and appearance.

Surfaces of Wood and Nonwood Composite Products

The surfaces of wood products such as plywood, structural flakeboard, particleboard, fiberboard, and hardboard generally have poor wettability relative to that of freshly cut, polar wood surfaces. Surfaces of these materials may have a glazed appearance indicating they have been inactivated by pressing at high temperatures. During hot pressing, resinous extractives migrate to the surface, adhesives on the outer surfaces of particles and fibers cure, and caul release agents remain on product surfaces—all of which inactivate or block surfaces from being wetted by water-based wood adhesives. Furthermore, the strength of bonds to the surfaces of these products is limited by the strength with which surface flakes, particles, and fibers are bound to the inner flakes, particles, and fibers of the product. A much lower bond strength can be expected to the surfaces of products of particulate structure than to products of natural wood structure. Adhesion to composite panel products having poor wettability (Fig. 9-1) can be improved by lightly sanding with 320-grit sandpaper. However, too much sanding can change a flat surface to an uneven surface and perhaps produce too much loose-fiber debris that would interfere with adhesion.

Metal foils and plastic films are commonly laminated to wood panels usually by product manufacturers. Although high cohesive strength is not required of adhesives to support these materials in an indoor environment, adhesives still must be reasonably compatible with both the wood and nonwood surfaces. If a bond of greater structural integrity is required to bond wood to heavier, rigid metals and plastics,

then only epoxy, polyurethane, and other isocyanate-based adhesives may be sufficiently compatible with metals and plastics. Even then, cleaning or special preparation of the nonwood surfaces may be required to remove contaminants and chemically activate the surfaces. Composite materials are becoming more common as manufacturers learn to bond dissimilar materials to gain extraordinary composite properties or cost advantages not available from a single component. Composite materials in which nonpolar thermoplastics are successfully bonded to polar wood materials with the aid of coupling agents are becoming commonplace.

Metals are stronger and stiffer than wood and if bonded well enough to effectively transfer stresses between metal and wood, the mechanical properties of wood can be enhanced by the metal so that the resultant composite performs as a single material. Metal has a much higher energy surface than does wood. On exposure to air, oxides of the metal quickly form, and with moisture, gases, and debris adsorbed from the air, the surfaces quickly develop a low energy, weak boundary layer. To restore the high energy surfaces, a series of cleaning procedures are required to prepare the surfaces for structural bonding. Steps in surface preparation include cleaning with liquid or vapor organic solvents, abrading by sandblasting, alkaline washing, chemical etching, and priming with adhesive solutions or coupling agents.

Plastics are organic polymers that may be either thermoplastic (soften on heating) or thermosetting (cross-linked and resist softening on heating). Thermoplastics generally are not as strong and stiff as wood, but thermoset materials approximate and even exceed the mechanical properties of wood. When plastics contain fibrous reinforcing materials, such as fiberglass, strength and stiffness of the composite materials greatly exceed some of the mechanical properties of wood. In so doing, reinforced plastics that are effectively bonded to wood offer stronger and more cost-effective structural composites. The surfaces of plastics generally are low energy, nonpolar, and hydrophobic. Traditional aqueous-based wood adhesives are polar and hydrophilic, so they do not bond well to plastics. Epoxies, polyurethanes, and isocyanate-based adhesives are capable of bonding many plastics to wood. Adhesion to plastic surfaces occurs primarily by physical intermolecular attraction forces and, in some cases, hydrogen bonding. Abrading and chemical etching of plastic surfaces provide some mechanical interlocking, thereby increasing adhesion. Coupling agents are particularly useful for chemically bridging dissimilar materials. They have molecules that are of either unlike or like functionalities that are capable of reacting with both the adhesive and the surface of the adherend. Treatment of plastic surfaces with an inert gas, including oxygen plasma activated by radio-frequency energy, cleans and activates surfaces for enhanced adhesion. Grafting of monomers onto cleaned plastic surfaces by means of plasma polymerization creates a polar surface that is more compatible with adhesives.

Chemical treatment of wood with preservatives, fire retardants, and dimensional stabilizers interferes with adhesion to the treated wood. Types of chemical treatment and adhesives,

conditions of joint assembly and adhesive cure, and pre-bonding chemical surface treatments have varied, interacting, and even strong effects on the strength and durability of bonds. Certain combinations of these factors can lead to excellent bonds, despite the interference from chemical treatments.

Lumber treated with chromated copper arsenate (CCA) preservatives dominates the treated wood market; however, very little of the CCA-treated wood is used in adhesively bonded lumber products. Commercial adhesives do not adhere to CCA-treated wood well enough to consistently meet rigorous industrial standards for resistance to delamination in accelerated exterior service tests. Analytical studies have shown that cellular surfaces of CCA-treated wood are thoroughly covered with microscopic-size deposits of mixtures of chromium, copper, and arsenic oxides that are physicochemically fixed to cell walls. The presence of these insoluble metallic deposits is so pervasive that intermolecular forces of attraction that normally act between polar wood and adhesive are physically blocked (Fig. 9-3). A new hydroxymethylated resorcinol (HMR) coupling agent greatly improves adhesion to CCA-treated wood when HMR is applied as a dilute aqueous primer on lumber surfaces before bonding. The HMR physicochemically couples phenol-resorcinol, epoxy, emulsion polymer-isocyanate, polymeric methylene diphenyl diisocyanate, and melamine-urea adhesives to treated wood so that bonds can meet rigorous industrial standards for strength and durability.

Wood preservatives other than CCA, even nonacidic waterborne preservatives including emulsion types, interfere with adhesion of hot-pressed phenolic plywood adhesives, particularly as levels of chemical retention in the wood increase. Generally, preservatives containing boron, copper, and zinc interfere with the cure of phenolic resins, although assembly conditions can be optimized to improve bonding. Certain alkyl ammonium and fluoride-based salt preservatives have demonstrated limited interference with adhesion.

The most common fire-retarding chemicals used for wood are inorganic salts based on phosphorous, nitrogen, and boron. These acid salts release acid at elevated temperatures to decrease flammable volatiles and increase char in wood, thereby effectively reducing flame spread. A few salts release acid at temperatures lower than fire conditions, and in the presence of elevated temperature and moisture service conditions, increasing acidity leads to destructive hydrolysis of the wood. The acidity of the fire-retardant-treated wood, particularly at the elevated temperature and moisture conditions of hot-press curing, also inhibits the cure and bond formation of alkaline phenolic adhesive. By priming treated-wood surfaces with certain alkaline aqueous solutions before bonding and selecting resins of appropriate molecular-size distribution, strong and durable bonds can be made to certain fire-retardant-treated woods.

Acetylation is a chemical modification of wood that drastically reduces moisture-related dimensional changes and rate of biodeterioration. Acetic anhydride is reacted with the

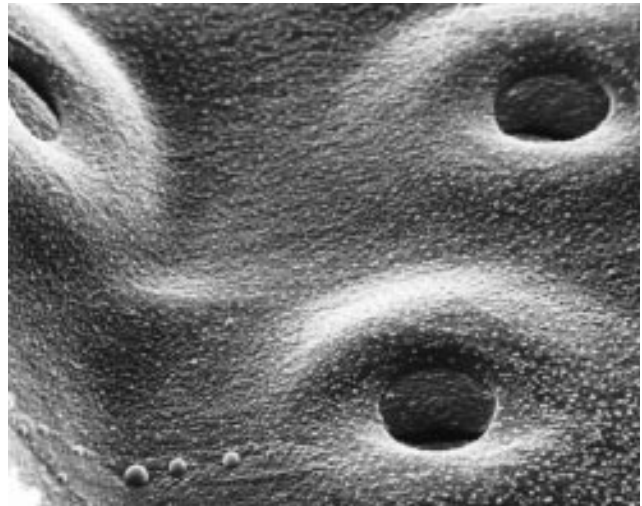


Figure 9-3. Surface of cell lumen of CCA-treated Southern Pine covered with chemically fixed deposits of insoluble mixture of chromium, copper, and arsenic oxides.

hydroxyl groups of hemicelluloses and lignin of wood. For every acetyl group reacted, one hydroxyl group is blocked from hydrogen bonding with a water molecule, and the result is lower affinity of acetylated wood for water. Reduced wettability from fewer available hydroxyl groups means poorer adhesion of aqueous-based wood adhesives. Adhesion is reduced to varying degrees among thermoplastic and thermosetting adhesives in proportion to their compatibility with the amount of nonpolar, hydrophobic acetate groups formed in the acetylated wood. Only room-temperature-curing resorcinolic adhesives and an acid-catalyzed phenolic hot-press adhesive have been found to develop durable bonds to acetylated wood. All other wood adhesives develop poorer bonds to acetylated wood than to untreated wood.

Physical Properties of Wood Adherends

Density and Porosity

The bondability of wood is not only affected by the surface properties of wood adherends but also by wood's physical properties, particularly density, porosity, moisture content, and dimensional movement.

Wood substance without void volume has a density approximating 1.5 g/cm^3 (93.6 lb/ft^3), regardless of the wood species. But density varies greatly between wood species, and even within a species, because species vary in void volume and thickness of cell walls. High density woods have thick walls and small lumen volumes, whereas low density woods have thin walls with large lumen volumes. The strength of wood is directly related to its density because thick-walled cells are capable of withstanding much greater stress than are thin-walled cells. Wood cells are an integral

part of the wood–adhesive interphasing region; therefore, the adhesive bond must be at least as strong as the wood if the strength capability of the wood adherend is to be fully utilized.

The strength of adhesive bonds to wood increases with wood density up to a range of 0.7 to 0.8 g/cm³ (43.7 to 49.9 lb/ft³) (moisture content 12%). Above this level, joint strength decreases. Although strength increases with wood density, wood failure decreases gradually up to a density range of 0.7 to 0.8 g/cm³ (43.7 to 49.9 lb/ft³), then decreases more rapidly above 0.8 g/cm³ (49.9 lb/ft³). As wood density increases, high strength joints with high wood failure are more difficult to achieve consistently. (Wood failure means rupture of wood fibers during strength tests of adhesive bonds to wood. It is usually expressed as a percentage of the total bonded area of the joint.)

High density woods are difficult to bond for several reasons. Because of thicker cell walls and less lumen volume, adhesives do not penetrate easily, so important mechanical interlocking of adhesives is limited to one or two cells deep. Much greater pressure is required to compress stronger, stiffer, high density wood to bring contact between wood surface and adhesive. Higher concentrations of extractives that may interfere with the cure of adhesives are common in high density species, particularly domestic oaks and imported tropical hardwoods. The severe stresses produced by high density species as they change dimensions with changes in moisture content also contribute heavily to bonding difficulties.

Density is perhaps a crude indicator, but as previously noted, it is useful for estimating the bondability of a great variety of wood species. Table 9–1 categorizes commonly used domestic and imported species according to their relative ease of bonding. The categories for domestic woods are based on the average strength of side-grain joints of lumber as determined in laboratory tests and industrial experience. The laboratory tests included animal, casein, starch, urea-formaldehyde, and resorcinol-formaldehyde adhesives. The categories for imported woods are based on information found in the literature on bond strength, species properties, extractives content, and industrial experience. In most cases, the amount of data available for categorizing imported woods is not equivalent to that for domestic woods. However, a species that bonds poorly with one adhesive may develop much better bonds with another adhesive. A similar type of adhesive but with somewhat different working, penetration, curing, and even strength properties can often dramatically improve bondability of a given species. Adhesive suppliers will quite often adjust adhesive formulations to solve specific adhesion problems.

The void volume of wood, which can range from 46% to 80% of total volume, strongly affects the depth and direction that an adhesive flows. To attain the highest joint strength, the adhesive must penetrate and mechanically interlock several cells deep into sound, undamaged cell structure. In

wood, porosity varies according to the grain direction. It is most porous on end-grain surfaces, being many times greater than on radial or tangential surfaces. Adhesives penetrate deeply into open fibers and vessels along the grain, so deeply that overpenetration occurs when pressure is applied to end-grain surfaces. This is a primary reason why it is so difficult to form strong, load-bearing bondlines in butt joints. Across the grain, porosity is limited because of fewer pathways in which adhesive can flow, so overpenetration under pressure generally is not a problem with a properly formulated adhesive.

The porosity of hardwoods and softwoods, both as species groups and as species within a group, varies greatly, which dramatically affects the amount and direction of adhesive flow. Highly porous softwoods, such as the southern pines, have fiber lumens that are interconnected by open pits. Pits are the small openings between fibers that permit lateral transfer of fluids in living trees. They form a complex capillary system that also allows adhesives to penetrate deeply, even in tangential and radial directions. The relatively large vessels in hardwoods have no end walls, so adhesive can penetrate indefinitely along the end grain. The remaining fibers have relatively few pits for lateral transfer of adhesive, except that hardwoods, such as the red oaks, have radially oriented rays that can allow excessive flow and overpenetration. Although adhesives for hardwoods and softwoods generally differ by chemical type according to product markets, adhesives must be specifically formulated for hardwoods or softwoods, including specific species within the groups, or have adjustable working properties for specific manufacturing situations.

Moisture Content and Dimensional Changes

Water occurs naturally in living trees—as free water in cell lumens and as adsorbed water within cell walls. Total water content of wood can range well above 200% (based on oven-dry weight), but when the free water is removed from cell lumens by drying, approximately 30% remains bound within cell walls. Water has strong molecular attraction to wood, primarily through hydrogen bonding with hydroxyl groups of wood cellulose. Therefore, cell walls remain saturated with moisture (called the fiber saturation point) until the moisture content of the surrounding air falls below that of saturated cell walls. Actual moisture content at fiber saturation (roughly 30%) varies, depending on species, tree, temperature, and pressure. This is the critical point at which wood begins to shrink. If wood has dried below the fiber saturation point, then regains moisture, the wood will swell. These dimensional changes differ with the three principal directions, or grain directions in wood, that is, longitudinal, radial, and tangential, with intermediate changes varying with the angle between the principal directions. Longitudinal dimensional change along the grain is least and amounts to less than 1% in drying from fiber saturation point to oven-dry. Dimensional change is greatest across the grain, but the

Table 9–1. Categories of selected wood species according to ease of bonding

U.S. hardwoods	U.S. softwoods	Imported woods	
Bond easily^a			
Alder	Fir	Balsa	Hura
Aspen	White	Catibo	Purpleheart
Basswood	Grand	Courbaril	Roble
Cottonwood	Noble	Determa ^b	
Chestnut, American	Pacific		
Magnolia	Pine		
Willow, black	Eastern white		
	Western white		
	Redcedar, western		
	Redwood		
	Spruce, Sitka		
Bond well^c			
Butternut	Douglas-fir	Afromosia	Meranti (lauan)
Elm	Larch, western ^d	Andiroba	Light red
American	Pine	Angelique	White
Rock	Sugar	Avodire	Yellow
Hackberry	Ponderosa	Banak	Obeche
Maple, soft	Redcedar, eastern	Iroko	Okoume
Sweetgum		Jarrah	Opepe
Sycamore		Limba	Peroba rosa
Tupelo		Mahogany	Sapele
Walnut, black		African	Spanish-cedar
Yellow-poplar		American	Sucupira
			Wallaba
Bond satisfactorily^e			
Ash, white	Yellow-cedar	Angelin	Meranti (lauan), dark red
Beech, American	Port-Orford-cedar	Azobe	Pau marfim
Birch	Pines, southern	Benge	Parana-pine
Sweet		Bubinga	Pine
Yellow		Karri	Caribbean
Cherry			Radiata
Hickory			Ramin
Pecan			
True			
Madrone			
Maple, hard			
Oak			
Red ^b			
White ^b			
Bond with difficulty^f			
Osage-orange		Balata	Keruing
Persimmon		Balau	Lapacho
		Greenheart	Lignumvitae
		Kaneelhart	Rosewood
		Kapur	Teak

^aBond very easily with adhesives of a wide range of properties and under a wide range of bonding conditions.

^bDifficult to bond with phenol-formaldehyde adhesive.

^cBond well with a fairly wide range of adhesives under a moderately wide range of bonding conditions.

^dWood from butt logs with high extractive content is difficult to bond.

^eBond satisfactorily with good-quality adhesives under well-controlled bonding conditions.

^fSatisfactory results require careful selection of adhesives and very close control of bonding conditions; may require special surface treatment.

amounts differ with the direction; dimensional change varies with and within species. As a rule of thumb, tangential dimensional change is about twice that of the radial direction; but again, there are variations by species. (See Ch. 3 for a detailed discussion of wood moisture relations.)

Dimensional changes that accompany changes in moisture content have broad-ranging and significant consequences on performance of bonded joints. As wood in bonded assemblies swells and shrinks, stresses develop that can be great enough to rupture adhesive bond and wood. Ruptures may develop when adjacent pieces of wood in a bonded joint differ in grain direction and shrinkage coefficients, for example, radial grain bonded to tangential grain, or in the worst case, longitudinal grain bonded to either tangential or radial grain. Even if moisture content levels in adjacent pieces are equal, but changing, stresses could be severe. Moreover, if moisture content in one piece is at equilibrium with surrounding air, that is, stable, but the other piece with differing grain direction is shrinking as it approaches equilibrium moisture content (EMC), then resultant stresses would be compounded and almost sure to rupture either the adhesive bond or the wood, whichever is weaker. Some wood adhesives are elastic enough to yield to stresses so that fracture does not occur. Structural wood adhesives have greater moduli of elasticity than wood and can effectively transfer stresses from one adherend to the other without failure. However, if stresses are great enough from extraordinary moisture content changes within adjacent pieces of wood of differing shrinkage coefficients, then fracture in either wood or a poor bond is almost inevitable. Severe stresses on bondlines can be minimized by bonding pieces of wood with compatible grain directions of low shrinkage coefficients at a uniform moisture content equivalent to that which the bonded assembly will encounter in service.

The amount of moisture in wood combined with water in adhesive will greatly influence the wetting, flow, penetration, and even cure of aqueous wood adhesives. In general, these adhesives bond satisfactorily across moisture content levels ranging from 6% to 14% and even below and above this range when adhesives are formulated for specialized processing. The optimum moisture content range for bonding a specific product with a specific adhesive is determined from practical experience and product performance. Aqueous adhesives tend to dry out when applied to wood below 6% moisture content. Wood absorbs water from the adhesive so quickly that adhesive flow and penetration into the wood is drastically inhibited, even under high pressure. Wood may become so dry below 3% moisture content that it temporarily resists wetting by the adhesive because insufficient water remains bound to the wood to establish intermolecular attraction forces with water in the adhesive.

When wood contains excess amounts of moisture, then less water and adhesive can be absorbed by the wood. This leads to excessive adhesive mobility, followed by squeeze-out when pressure is applied. Control of moisture content is particularly critical to bonding in hot presses because excess moisture increases adhesive mobility, followed by

overpenetration of the adhesive. Furthermore, high vapor pressure builds internally as water boils, and on release of platen pressure, sudden release of internal pressure actually separates laminates along the bondlines, called blows. Even if blows do not occur, excess moisture within thermosetting adhesives can prevent complete cross-linking with accompanying weakened adhesive film and bond. Appropriate moisture content levels of wood for bonding by hot-press methods are well known, as are target moisture content levels for satisfactory service of wood products throughout the United States. However, control of moisture content in bonding wood materials is not easily achieved. This is discussed in the Moisture Content Control section.

Adhesives Composition

Organic polymers of either natural or synthetic origin are the major chemical ingredients in all formulations of wood adhesives. According to ASTM, a polymer is a compound formed by the reaction of simple molecules having functional groups that permit their combination to proceed to higher molecular weights under suitable conditions. Polysaccharides and proteins are high molecular weight natural polymers derived from plants and animals. Animal, blood, hide, casein, starch, soybean, dextrin, and cellulosic adhesives are all derived from the natural polymers found in these indicated sources. They have been used as adhesives for centuries and are still in use today, although they have been replaced mostly by adhesives made with synthetic polymers. The first wood adhesives based on synthetic polymers were produced commercially during the 1930s. This marked the beginning of fundamental changes in composition of adhesives from natural to synthesized polymers. These adhesives could not only be stronger, more rigid, and more durable than wood, but also have much greater resistance to water than adhesives from natural polymers.

Synthetic polymers are chemically designed and formulated into adhesives to perform a great variety of bonding functions. Whether the base polymer is thermoplastic or thermosetting has a major influence on how an adhesive will perform in service. Thermoplastics are long-chain polymers that soften and flow on heating, then harden again by cooling. They generally have less resistance to heat, moisture, and long-term static loading than do thermosetting polymers. Common wood adhesives that are based on thermoplastic polymers include polyvinyl acetate emulsions, elastomerics, contacts, and hot-melts. Thermosetting polymers make excellent structural adhesives because they undergo irreversible chemical change, and on reheating, they do not soften and flow again. They form cross-linked polymers that have high strength, have resistance to moisture and other chemicals, and are rigid enough to support high, long-term static loads without deforming. Phenolic, resorcinolic, melamine, isocyanate, urea, and epoxy are examples of types of wood adhesives that are based on thermosetting polymers.

A formulation of wood adhesive consists of a mixture of several chemically active and inert materials that vary in proportion with the basic adhesive polymer, which enhances performance, whether it be working characteristics, strength properties, shelf life, or durability. Solvents disperse or dissolve adhesive polymers, act as carriers of polymer and additives, aid wetting, and control flow and penetration of the adhesive. Water is used as the carrier for most wood adhesives, primarily because water readily absorbs into wood, is inexpensive, and is free of toxicity problems. Adhesive polymers can be brought into intimate, even molecular, contact with wood by water as the carrier. Organic solvents are used with elastomeric and contact adhesives, although water-based adhesive systems have lower toxicity and flammability. Fillers of both organic and inorganic origins contribute to rheological control of the fluid system, particularly in reducing the spreading and penetrating of the adhesive into wood. Reinforcing fibers, mostly inert and of organic origins, can enhance an adhesive film's mechanical properties, especially toughness, impact resistance, and shrinkage. Extenders are filler-like organic materials that may have sufficient chemical activity to improve adhesion to a small degree, but they are used primarily to control flow and other working characteristics, without excess sacrifice of adhesion capability, as is the case with most fillers.

Certain chemicals and polymeric systems plasticize adhesive polymers, and others are used to enhance tackiness. Plasticizers, such as dibutyl phthalate, are used to soften brittle vinyl acetate homopolymer in polyvinyl acetate emulsion adhesives, which facilitates diffusion of adhesive and formation of a flexible adhesive film from the emulsion at and below room temperature. Phenolic polymers are used as tackifiers and adhesion promoters in neoprene and nitrile rubber contact adhesives. Reactive polymeric fortifiers, such as melamine-formaldehyde, can be substituted in limited proportions in urea-formaldehyde adhesives to improve resistance to moisture and heat. Phenol-formaldehyde may be substituted for resorcinol-formaldehyde to reduce adhesive costs, without sacrificing adhesive strength and durability.

Catalysts are chemicals used to accelerate the rate of chemical reaction of polymeric components. Acids, bases, salts, peroxides, and sulfur compounds are a few examples of catalysts. Catalysts do not become a part of the reacted compound; they simply increase the rate of reaction. Hardeners are added to base polymers as reactive components, and they do become a part of the reacted compound. Examples are an amine hardener added to epoxy and formaldehyde added to resorcinol—all produce cross-linking reactions to solidify the adhesive. Other chemicals, such as antioxidants, acid scavengers, preservatives, wetting agents, defoamers, even colorants, may be added to control or eliminate some of the less desirable characteristics of certain adhesive formulations.

Health and Safety

Wood adhesives contain chemicals that are toxic to people if they are exposed to sufficient concentrations for prolonged periods. Generally, it is accepted that wood adhesives in a

cured state do not present toxicity problems. A notable exception is urea-formaldehyde adhesive, which can release low concentrations of formaldehyde from bonded wood products under certain service conditions. Formaldehyde is a toxic gas that can react with proteins of the body to cause irritation and, in some cases, inflammation of membranes of eyes, nose, and throat. It is a suspected carcinogen, based on laboratory experiments with rats. Considerable research has led to new adhesive formulations with significantly reduced levels of formaldehyde emissions in both manufacturing operations and bonded wood products. Phenol-formaldehyde adhesives, which are used to manufacture plywood, flakeboard, and fiberglass insulation, also contain formaldehyde. However, formaldehyde is efficiently consumed in the curing reaction, and the highly durable phenol-formaldehyde, resorcinol-formaldehyde, and phenol-resorcinol-formaldehyde polymers do not chemically break down in service to release toxic gas.

Diisocyanates are highly reactive chemicals that polymerize rapidly on contact with strong alkali, mineral acids, and water. Polymeric methylene diphenyl diisocyanate (PMDI) adhesives develop strong and durable bonds to wood, so they are now widely used to manufacture composite wood products. They are potentially hazardous if mishandled, but the low vapor pressure of PMDI adhesives coupled with adequate ventilation to remove airborne PMDI on dust particles, permits manufacturing plants to operate safely. Properly cured PMDI adhesives are not considered hazardous in bonded wood products.

Construction and contact adhesives contain organic solvents that have low flash points. If these adhesives are used in unventilated areas where concentrations build to dangerously high levels, explosions can occur with an ignition source. Some adhesive producers now offer less flammable formulations based on chlorinated solvents. Organic solvents in these adhesives are toxic, but by following the manufacturer's handling and use instructions, coupled with adequate ventilation, harmful effects can be avoided.

Health and safety regulations require that toxic and hazardous chemicals be identified and visibly labeled to warn of their dangers. Material safety data sheets (MSDS) or instructions are provided with adhesive products to advise of proper handling procedures, protective gear and clothing, and procedures for dealing with spills and fire, as well as to offer guidance for first-aid and professional treatment of injuries. The statements made in this section concerning safety of adhesives and effects on the health of the user are general and not meant to be all inclusive. The user should consult the MSDS and follow the manufacturer's instructions and precautions before using any adhesive.

Strength and Durability

The ability of an adhesive to transfer load from one member of an assembly to another and to maintain integrity of the assembly under the expected conditions of service will govern the choice of adhesive for a given application.

In building construction, adhesives that contribute strength and stiffness during the life of the structure are considered structural. They generally are stronger and stiffer than the wood members. Structural bonds are critical because bond failure could result in serious damage to the structure, even loss of life. Examples of structural applications include glued-laminated beams, prefabricated I-joists, and stressed-skin panels. Adhesives that are strongest, most rigid, and most resistant to deterioration in service, unfortunately, are those least tolerant of wide variations in wood surface condition, wood moisture content, and assembly conditions including pressures, temperatures, and curing conditions. Examples of rigid structural adhesives include phenolic, resorcinol, melamine, urea, and casein (Table 9–2).

Adhesives are further categorized in Table 9–2 as to how well they transfer load relative to wood as the service environment becomes more severe. Structural adhesives that maintain their strength and rigidity under the most severe cyclic water-saturation and drying are considered fully exterior adhesives. Rigid adhesives that lose their ability to

transfer load faster than does wood as service conditions worsen, particularly with regard to moisture, are considered interior adhesives. Between exterior and interior adhesives are the intermediate adhesives that maintain strength and rigidity in short-term water soaking but deteriorate faster than wood during long-term exposure to water and heat. Adhesives that are the weakest, least rigid, and least resistant to severe service conditions are those most tolerant of wide variations in wood surface, assembly, and curing conditions.

Semistructural adhesives impart strength and stiffness to an adhesive-bonded assembly, and in some instances, they may be as strong and rigid as wood. However, semistructural adhesives generally do not withstand long-term static loading without deformation. They are capable of short-term exposure to water but not long-term saturation, hence their limited exterior classification. Examples are cross-linking polyvinyl acetate and polyurethane adhesives. Another example of the semistructural adhesive application is the nailed–glued assembly where failure of the bond would not cause serious loss of structural integrity because the load would be carried by mechanical fasteners.

Table 9–2. Wood adhesives categorized according to their expected structural performance at varying levels of environmental exposure^{a,b}

Structural integrity	Service environment	Adhesive type
Structural	Fully exterior (withstands long-term water soaking and drying)	Phenol-formaldehyde Resorcinol-formaldehyde Phenol-resorcinol-formaldehyde Emulsion polymer/isocyanate Melamine-formaldehyde
	Limited exterior (withstands short-term water soaking)	Melamine-urea-formaldehyde Isocyanate Epoxy
	Interior (withstands short-term high humidity)	Urea-formaldehyde Casein
Semistructural	Limited exterior	Cross-linked polyvinyl acetate Polyurethane
Nonstructural	Interior	Polyvinyl acetate Animal Soybean Elastomeric construction Elastomeric contact Hot-melt Starch

^aAssignment of an adhesive type to only one structural/service environment category does not exclude certain adhesive formulations from falling into the next higher or lower category.

^bPriming wood surfaces with hydroxymethylated resorcinol coupling agent improves resistance to delamination of epoxy, isocyanate, emulsion polymer/isocyanate, melamine and urea, phenolic, and resorcinolic adhesives in exterior service environment, particularly bonds to CCA-treated lumber.

Nonstructural adhesives typically support the dead weight of the material being bonded and can equal the strength and rigidity of wood in the dry condition. However, on exposure to water or high humidity, nonstructural adhesives quickly lose their load transfer ability. Examples are adhesives used for bonding wall tiles and fixtures.

Elastomeric construction adhesives are categorized as nonstructural. However, they are used normally for field assembly of panelized floor and wall systems in the light-frame construction industry. Nails are used in the assembly so that if failure did occur in the adhesive bond, the structural load would be carried by nails. The adhesive enables the nailed assembly to act as a composite with increased stiffness. With nails providing structural safety in this application, elastomeric adhesives could be included in the semistructural category.

Some adhesives listed in Table 9–2 could be included easily in more than one category because they can be formulated for a broad range of applications. Isocyanate and polyurethane adhesives are examples. Polymeric methylene diphenyl diisocyanates of low molecular weight develop highly durable bonds in structural flakeboards, although flakeboard products deteriorate from swelling and shrinkage stresses. One-part polyurethane adhesives have highly durable adhesive films, but as molecular weight increases, adhesion to porous wood generally decreases and bonds become increasingly susceptible to deterioration from swelling and shrinkage stresses. Polyurethane adhesives liberate carbon dioxide on reaction with water. As a result, they foam, and in thick bondlines, polyurethane bonds become more deformable under static loading. Two-part polyurethanes can be formulated for rigidity, depending on the degree of structural loading required.

Adhesive Selection

Adhesive selection begins by considering the types of wood adhesives, along with their strength and durability, preparation and use characteristics, and typical applications, as shown in abbreviated form in Table 9–3. Their relative strength and durability are categorized into levels of structural integrity (Table 9–2) and were discussed previously. Adhesive selection for a wood product manufacturer may begin as a cooperative effort between the manufacturer and an adhesive supplier. Together, they completely review the product, its intended service environment, and all production processes and equipment before choosing an appropriate adhesive. Whatever the approach to adhesive selection might be, the following general discussion should be helpful.

A broad array of adhesive types, with significant variations within each type, are available for bonding wood materials, even for bonding wood to nonwood materials. The selection process begins with determining which adhesives are compatible with the physical and chemical properties of the adherends, particularly their surface properties. The polar, aqueous wood adhesive must be capable of wetting the usually polar wood surface, within its normal variations in

hydrophilicity. As the adhesive wets, it must have flow properties that enable it to spread over surfaces of variable roughness and to penetrate wood structures that differ in porosity, with respect to grain orientation at the bondline. The adhesive must make molecular contact with the lignocellulosics of wood and penetrate deeply enough to mechanically interlock with the wood's cell structure. Metals and plastics cannot be penetrated, so these materials generally cannot be bonded with aqueous wood adhesives. However, nonaqueous, 100% solids adhesives, including epoxy, isocyanate, and polyurethane, are capable of sound bonds to nonwood and wood materials.

The structural integrity expected of the adhesive bond under anticipated service loads in the presence of expected environmental exposure conditions should be one of the foremost considerations. To intelligently select an adhesive for a given bonded assembly, it is necessary to have an approximation of the nature, direction, level, and duration of loading that the assembly and bondlines must withstand. Furthermore, it is essential to know the range and duration of temperature and moisture content levels to which bondlines will be subjected. For example, prolonged exposure to high moisture content levels will significantly reduce the load-carrying ability of any adhesive in a wood joint. Failure to give full consideration to these factors could risk structural failure of the bonded assembly, even severe personal injury.

There may be need for tradeoffs between bonding requirements of adhesives and their resistance to stress, duration of load, and service environment. Adhesives that are the strongest, most rigid, and durable are generally those least tolerant of bonding conditions, including wood moisture content, surface roughness, cleanliness, inactivation, grain orientation, bondline thickness, and pressure and temperature of cure. Adhesives that are the weakest, least rigid, and least resistant to service conditions are those most tolerant of bonding conditions. Many adhesives are positioned between these extremes of bonding requirements and performance (Tables 9–2 and 9–3).

When a group of adhesives with suitable performance capabilities for a particular bonded assembly has been determined, the user also must choose within that group an adhesive that can be mixed, applied, and cured with available equipment or consider the cost of purchasing equipment to meet specific working properties of another adhesive. Important working properties must be considered when making cost decisions. The working life of an adhesive is the time between mixing and the end of its useful life when it becomes too viscous to properly wet and flow over a surface.

If an adhesive requires mixing with a hardener or catalyst, then mixing and application equipment appropriate for the working life must be considered. Given the consistency of an adhesive, specific types of application equipment are required. Depending on the size of the spreading operation, the equipment can range from brush to roll-spreader to extruder to spray to meter-mixed extrusion. Wood adhesives, including phenolic, melamine, urea, and isocyanate adhesives,

Table 9–3. Working and strength properties of adhesives, with typical uses

Type	Form and color	Preparation and application	Strength properties	Typical uses
Natural origin				
Animal, protein	Solid and liquid; brown to white bondline	Solid form added to water, soaked, and melted; adhesive kept warm during application; liquid form applied directly; both pressed at room temperature; bonding process must be adjusted for small changes in temperature	High dry strength; low resistance to water and damp atmosphere	Assembly of furniture and stringed instruments; repairs of antique furniture
Blood, protein	Solid and partially dried whole blood; dark red to black bondline	Mixed with cold water, lime, caustic soda, and other chemicals; applied at room temperature; pressed either at room temperature or 120°C (250°F) and higher	High dry strength; moderate resistance to water and damp atmosphere and to microorganisms	Interior-type softwood plywood, some times in combination with soybean adhesive; mostly replaced by phenolic adhesive
Casein, protein	Powder with added chemicals; white to tan bondline	Mixed with water; applied and pressed at room temperature	High dry strength; moderate resistance to water, damp atmospheres, and intermediate temperatures; not suitable for exterior uses	Interior doors; discontinued use in laminated timbers
Soybean, protein	Powder with added chemicals; white to tan, similar color in bondline	Mixed with cold water, lime, caustic soda, and other chemicals; applied and pressed at room temperatures, but more frequently hot pressed when blended with blood adhesive	Moderate to low dry strength; moderate to low resistance to water and damp atmospheres; moderate resistance to intermediate temperatures	Softwood plywood for interior use, now replaced by phenolic adhesive. New fast-setting resorcinol-soybean adhesives for fingerjointing of lumber being developed
Lignocellulosic residues and extracts	Powder or liquid; may be blended with phenolic adhesive; dark brown bondline	Blended with extender and filler by user; adhesive cured in hot-press 130°C to 150°C (266°F to 300°F) similar to phenolic adhesive	Good dry strength; moderate to good wet strength; durability improved by blending with phenolic adhesive	Partial replacement for phenolic adhesive in composite and plywood panel products
Synthetic origin				
Cross-linkable polyvinyl acetate emulsion	Liquid, similar to polyvinyl acetate emulsions but includes copolymers capable of cross-linking with a separate catalyst; white to tan with colorless bondline	Liquid emulsion mixed with catalyst; cure at room temperature or at elevated temperature in hot press and radio-frequency press	High dry strength; improved resistance to moisture and elevated temperatures, particularly long-term performance in moist environment	Interior and exterior doors; moulding and architectural woodwork; cellulosic overlays
Elastomeric contact	Viscous liquid, typically neoprene or styrene-butadiene elastomers in organic solvent or water emulsion; tan to yellow	Liquid applied directly to both surfaces, partially dried after spreading and before pressing; roller-pressing at room temperature produces instant bonding	Strength develops immediately upon pressing, increases slowly over a period of weeks; dry strengths much lower than those of conventional wood adhesives; low resistance to water and damp atmospheres; adhesive film readily yields under static load	On-the-job bonding of decorative tops to kitchen counters; factory lamination of wood, paper, metal, and plastic sheet materials
Elastomeric mastic (construction adhesive)	Putty like consistency, synthetic or natural elastomers in organic solvent or latex emulsions; tan, yellow, gray	Mastic extruded in bead to framing members by caulking gun or like pressure equipment; nailing required to hold materials in place during setting and service	Strength develops slowly over several weeks; dry strength lower than conventional wood adhesives; resistant to water and moist atmospheres; tolerant of out door assembly conditions; gap-filling; nailing required to ensure structural integrity	Lumber to plywood in floor and wall systems; laminating gypsum board and rigid foam insulating; assembly of panel system in manufactured homes
Emulsion polymer/isocyanate	Liquid emulsion and separate isocyanate hardener; white with hardener; colorless bondline	Emulsion and hardener mixed by user; reactive on mixing with controllable pot-life and curing time; cured at room and elevated temperatures; radio-frequency curable; high pressure required	High dry and wet strength; very resistant to water and damp atmosphere; very resistant to prolonged and repeated wetting and drying; adheres to metals and plastics	Laminated beams for interior and exterior use; lamination of plywood to steel metals and plastics; doors and architectural materials

Table 9–3. Working and strength properties of adhesives, with typical uses—con.

Type	Form and color	Preparation and application	Strength properties	Typical uses
Epoxy	Liquid resin and hardener supplied as two parts; completely reactive leaving no free solvent; clear to amber; colorless bondline	Resin and hardener mixed by user; reactive with limited pot-life; cured at room or elevated temperatures; only low pressure required for bond development	High dry and wet strength to wood, metal, glass, and plastic; formulations for wood resist water and damp atmospheres; delaminate with repeated wetting and drying; gap-filling	Laminating veneer and lumber in cold-molded wood boat hulls; assembly of wood components in aircraft; lamination of architectural railings and posts; repair of laminated wood beams and architectural building components; laminating sports equipment; general purpose home and shop
Hot melt	Solid blocks, pellets, ribbons, rods, or films; solvent-free; white to tan; near colorless bondline	Solid form melted for spreading; bond formed on solidification; requires special application equipment for controlling melt and flow	Develops strength quickly on cooling; lower strength than conventional wood adhesives; moderate resistance to moisture; gap-filling with minimal penetration	Edge-banding of panels; plastic lamination; patching; film and paper overlays; furniture assembly; general purpose home and shop
Isocyanate	Liquid containing isomers and oligomers of methylene diphenyl diisocyanate; light brown liquid and clear bondline	Adhesive applied directly by spray; reactive with water; requires high temperature and high pressure for best bond development in flake boards	High dry and wet strength; very resistant to water and damp atmosphere; adheres to metals and plastics	Flakeboards; strand-wood products
Melamine and melamine-urea	Powder with blended catalyst; may be blended up to 40% with urea; white to tan; colorless bondline	Mixed with water; cured in hot press at 120°C to 150°C (250°F to 300°F); particularly suited for fast curing in high-frequency presses	High dry and wet strength; very resistant to water and damp atmospheres	Melamine-urea primary adhesive for durable bonds in hardwood plywood; end-jointing and edge-gluing of lumber; and scarf joining softwood plywood
Phenolic	Liquid, powder, and dry film; dark red bondline	Liquid blended with extenders and fillers by user; film inserted directly between laminates; powder applied directly to flakes in composites; all formulations cured in hot press at 120°C to 150°C (250°F to 300°F) up to 200°C (392°F) in flakeboards	High dry and wet strength; very resistant to water and damp atmospheres; more resistant than wood to high temperatures and chemical aging	Primary adhesive for exterior softwood plywood, flakeboard, and hardboard
Polyvinyl acetate emulsion	Liquid ready to use; often polymerized with other polymers; white to tan to yellow; colorless bondline	Liquid applied directly; pressed at room temperatures and in high-frequency press	High dry strength; low resistance to moisture and elevated temperatures; joints yield under continued stress	Furniture; flush doors; plastic laminates; panelized floor and wall systems in manufactured housing; general purpose in home and shop
Polyurethane	Low viscosity liquid to high viscosity mastic; supplied as one part; two-part systems completely reactive; color varies from clear to brown; colorless bondline	Adhesive applied directly to one surface, preferably to water-misted surface; reactive with moisture on surface and in air; cures at room temperature; high pressure required, but mastic required only pressure from nailing	High dry and wet strength; resistant to water and damp atmosphere; limited resistance to prolonged and repeated wetting and drying; gap-filling	General purpose home and shop; construction adhesive for panelized floor and wall systems; laminating plywood to metal and plastic sheet materials; specialty laminates; installation of gypsum board
Resorcinol and phenol-resorcinol	Liquid resin and powdered hardener supplied as two parts; phenol may be copolymerized with resorcinol; dark red bondline	Liquid mixed with powdered or liquid hardener; resorcinol adhesives cure at room temperatures; phenol-resorcinols cure at temperatures from 21°C to 66°C (70°F to 150°F)	High dry and wet strength; very resistant to moisture and damp atmospheres; more resistant than wood to high temperature and chemical aging.	Primary adhesives for laminated timbers and assembly joints that must withstand severe service conditions.
Urea	Powder and liquid forms; may be blended with melamine or other more durable resins; white to tan resin with colorless bondline	Powder mixed with water, hardener, filler, and extender by user; some formulations cure at room temperatures, others require hot pressing at 120°C (250°F); curable with high-frequency heating	High dry and wet strength; moderately durable under damp atmospheres; moderate to low resistance to temperatures in excess of 50°C (122°F)	Hardwood plywood; furniture; fiberboard; particleboard; underlayment; flush doors; furniture cores

must be cured at high temperatures and require expensive, heated presses. Some of these can be cured within minutes in expensive high frequency heated presses. Cold presses or clamps are satisfactory for room-temperature-curing adhesives, although the long curing time in production can be a constraint. Even after hot or cold pressing, adhesive bonds must remain undisturbed until most of the curing has occurred.

There are other important considerations, particularly in furniture and interior millwork, where appearance is all-important. Adhesive color, ability to absorb stains and finishes, and freedom from bleeding and staining are critical factors. The urea-formaldehyde and polyvinyl acetate adhesives used in the furniture industry are formulated to give a tan or colorless joint with good acceptance of stain.

Ease and simplicity of use can also be important factors. One-part adhesives, like liquid animal, polyvinyl acetate, hot-melt, and phenol-formaldehyde film, are the simplest to use because there is no chance for error in weighing and mixing components. Water-dispersed and film adhesives are easy to clean up, whereas films are the least messy. Two-, three-, or multiple-part adhesives require careful measuring and mixing of components. They often require special solvents for cleanup after bonding. Frequently, adhesives are toxic to the skin or give off toxic fumes. Formaldehyde hardener for resorcinol, phenol, melamine, and urea adhesives is an irritant to many people. Amine hardeners in some epoxy adhesives are strong skin sensitizers.

The cost of an adhesive and related application equipment must be balanced against comparable cost factors for substituted adhesives. In recent years, the cost of organic solvents and the cost of recovering volatiles to prevent air pollution have increased. Substituted water-based systems can be cheaper due to low cost of the solvent; however, grain raising of the wood and slower drying must be considered because of their effects on performance and overall cost.

Bonding Process

The bonding process involves a great number of factors that determine how successfully an adhesive bond will ultimately perform in service. The better these factors are understood and controlled, the fewer bonding problems will be encountered, along with their attendant expense. It is not necessary to be an adhesive expert to manufacture acceptable bonds, although more knowledge is always helpful. However, it is essential that the user follow the instructions of the adhesive supplier during the entire bonding process. The supplier has extensive technical knowledge of an adhesive's composition, working characteristics, and performance properties, which is reinforced by the experience of customers.

Moisture Content Control

After adhesive selection, the next most important factor contributing to trouble-free service of adhesive bonds is

control of wood moisture content before and during the bonding process. Moisture content strongly affects the final strength and durability of joints, development of surface checks in the wood, and dimensional stability of the bonded assembly. Large changes in the moisture content compared with that at the time of bonding will cause shrinking or swelling stresses that can seriously weaken both wood and joints and can cause warping, twisting, and surface irregularities. Wood should not be bonded at high moisture content, particularly high density hardwoods that have large coefficients of shrinkage, unless the in-service moisture content is also expected to be high. The wood should be dry enough so that even if moisture is added during bonding, the moisture content is at about the level expected for the assembly in service.

Determining the proper moisture content for bonding depends primarily on the amount of moisture that is contained in the wood and adhesive and whether or not the adhesive curing process involves heating. For example, if boards are bonded at room temperature, the final moisture content is controlled mainly by the moisture content of the wood. In a lumber laminate, the number of bondlines are so few that a waterborne adhesive adds only 1% to 2% to the total moisture content of the laminate. However, if several pieces of veneer are bonded at room temperature, the moisture added by the adhesive in many bondlines can significantly increase the moisture content of the wood well above the target in-service level. Thus, thickness of the laminates, number of laminates, density of the wood, water content of the adhesive, quantity of adhesive spread, and hot or cold pressing all have a cumulative effect on the moisture content of the wood. During hot pressing, a moderate amount of water evaporates from the laminate as it is removed from the press. However, to minimize plastic flow of the hot and moist wood and prevent steam blisters or blows, the total moisture content of the assembly should not exceed 10% during hot pressing. A lumber moisture content of 6% to 7%, assuming 1% to 2% will be added by aqueous adhesives, is satisfactory for cold pressing of furniture and interior millwork. Lumber being laminated for exterior use should contain 10% to 12% moisture before bonding. A moisture content of 3% to 5% in veneer at the time of hot pressing is satisfactory for hardwood plywood intended for furniture and interior millwork and for softwood plywood intended for construction and industrial uses.

Lumber that has been kiln dried to the approximate average moisture content intended for bonding may still be at different moisture content levels between boards and within individual boards. Large differences in the moisture content between adjacent boards bonded together result in considerable stress on the common joint as the boards equalize toward a common moisture content. Best results are achieved when differences are not greater than about 5% for lower density species and 2% for high density species.

The moisture content of wood in bonded products should be targeted to the EMC that the product will experience in

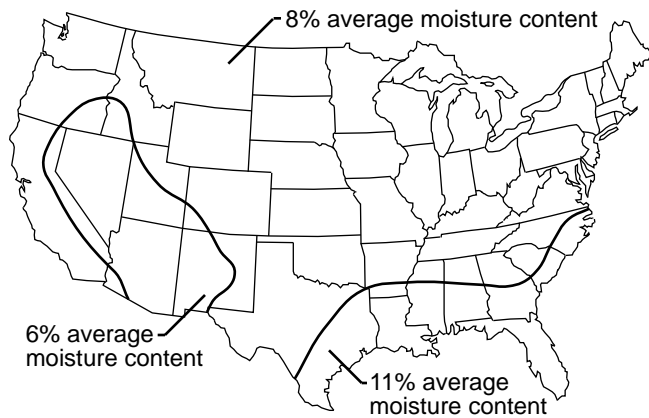


Figure 9–4. Average equilibrium moisture content for wood in building interiors in regions of the United States.

service. These conditions vary in the United States; regional average EMC values of wood in building interiors are shown in Figure 9–4. The average moisture content for most of the United States is 8%. The average increases to 11% along the Atlantic and Gulf coastal regions; in the arid southwest, the EMC is relatively low at 6%. The moisture content of wood exposed to outdoor air generally is higher and more variable and averages near 12% and ranges from 7% to 14% in most of the United States. During winter in the northern states, heating of indoor air that is normally dry lowers wood EMC to 4% to 5%. Furniture manufactured in the southeast at 11% EMC, then sold or moved to northern states where EMC drops to 4%, usually will experience some splitting, delamination of joints, or other noticeable appearance defects. Manufacturers of bonded wood products must be aware of these regional and seasonal variations, then condition the wood and bond it at moisture content levels that are consistent with regional service conditions.

Surface Preparation

The physical and chemical condition of wood and nonwood surfaces was described in a previous section where emphasis was placed on understanding the relationships between surface condition and adhesive bond performance. Wood surfaces are best prepared for maximum adhesive wetting, flow, and penetration by removing all materials that might interfere with bond formation to sound wood. Ideally, wood should be knife-planed within 24 h of adhesive spreading. However, other surfacing methods have been used successfully for certain types of bonded joints, including sawing for furniture and millwork, knife-cutting for veneer, and abrasive-planing for panels. All must produce smooth, flat, parallel surfaces, free from machining irregularities, such as burnishes, skips, and crushed, torn, and chipped grain. Properly planed flat surfaces help ensure that a layer of adhesive of uniform thickness can be uniformly spread over the adherend.

Adhesive Spreading

Regardless of method, the purpose in spreading adhesive is to distribute an adequate amount of adhesive of uniform thickness over the bonding area, so that under pressure, the adhesive will flow into a uniformly thin layer. Assuming that the spreader is capable of applying adhesive uniformly and that surfaces are smooth, flat, and parallel, then adhesive will flow ideally if uniform pressure is applied. The amount of adhesive needed will depend on the wood species, moisture content, type of adhesive, temperature and humidity of the air, assembly time, and whether adhesive will be applied to one or both surfaces. Adhesives can be spread by hand with brush, roller, or bead-extruder, but in manufacturing, adhesives are applied by machines, such as roll-spreader, extruder, curtain-coater, or spray. Instead of applying a uniform film, extruders apply continuous, uniformly spaced beads of discreet diameter and flow rate. When pressure is applied to both adherends, the adhesive is squeezed into a uniformly thin layer. An extruder of this type is used to apply adhesive to veneer in the manufacture of laminated veneer lumber (LVL) (Fig. 9–5). A pressurized extruder is used in the field to apply a single bead of elastomeric construction adhesive to joists for a plywood floor system (Fig. 9–6).

Assembly and Pressing

Control of consistency after the adhesive has been spread and until pressure is applied is a balancing act of a variety of factors. The relationships between adhesive consistency and bonding pressure as they affect formation of strong bonds are illustrated in Figure 9–7. Adhesive consistency strongly affects adhesive wetting, flow, and penetration, particularly the transfer of adhesive to an unspread wood surface, when pressure is applied to the assembly. Adhesive consistency depends upon type of adhesive, type of solvent, and proportion of solvent in the mixture, age of adhesive mixture, amount of adhesive spread, species of wood, moisture content of wood, temperature of wood, temperature and humidity of surrounding air, and the critically important evaporation and absorption of solvent during the assembly time. Assembly time is the time between spreading adhesive on wood surfaces and applying pressure to the assembly. When the adhesive-spread surfaces remain open before assembly (open assembly), then consistency is most affected by evaporative capacity of the surrounding air and absorbency of the wood's surface. When the assembly is closed and before applying pressure (closed assembly), consistency is most influenced by absorbency factors and least affected by evaporation. Cold-setting waterborne wood adhesives lose water by absorption and evaporation so that consistency steadily increases until they eventually set. Thermosetting waterborne adhesives also dry out, but despite water loss, they flow to some extent in the presence of heat, then harden with additional heating.

Pressure serves several useful purposes: it forces entrapped air from the joint; it brings adhesive into molecular contact with the wood surfaces; it forces adhesive to penetrate into the wood structure for more effective mechanical interlocking;

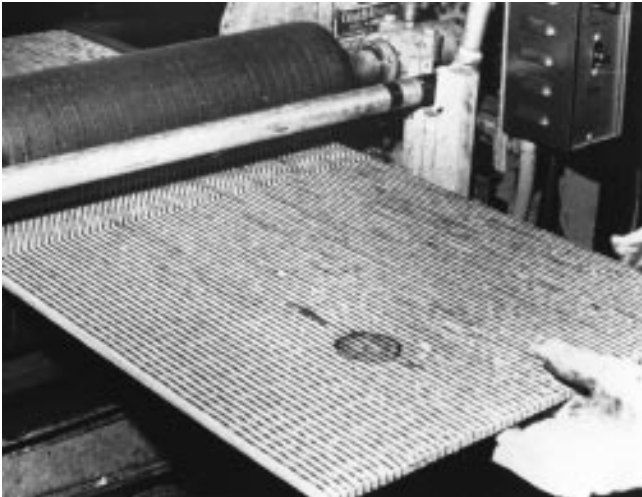


Figure 9-5. An extruder applies continuous and uniformly sized and spaced beads of adhesive to veneer for laminating into LVL.



Figure 9-6. A pressurized extruder applies a single bead of elastomeric construction adhesive to floor joists for assembly of a plywood floor system.

it squeezes the adhesive into a thin continuous film; and it holds the assembly in position while the adhesive cures. But if pressure is too high, the adhesive can overpenetrate porous woods and cause starved joints that are inferior in bond strength (Fig. 9-7). The strongest joints result when the consistency of the adhesive permits the use of moderately high pressures that are consistent with the recommended pressures for the density of the wood.

Low pressures near 700 kPa (100 lb/in²) are suitable for low density wood because the surfaces easily conform to each other, thus ensuring intimate contact between adhesive and

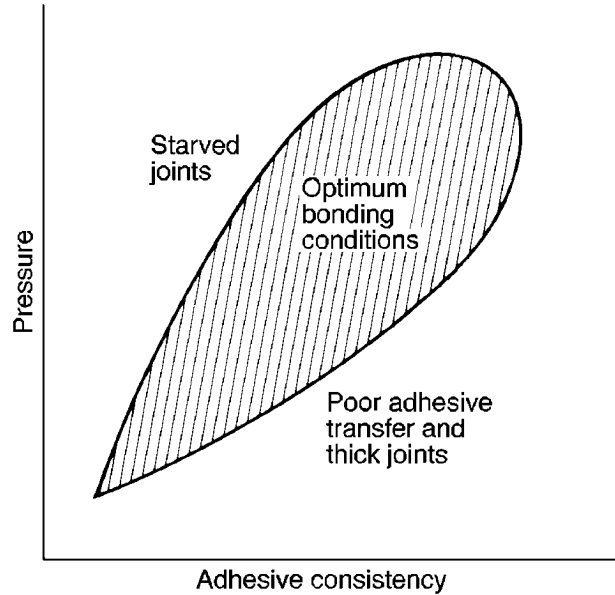


Figure 9-7. An illustration of the relationships between adhesive consistency and bonding pressure as they affect bond formation by a thermosetting adhesive.

wood. High pressures up to 1,700 kPa (247 lb/in²) are required for the highest density woods that are difficult to compress. Flat, well-planed surfaces of small area can be bonded satisfactorily at lower pressures; however, because high pressure tends to squeeze adhesive into the wood or out of the joint, adhesives of greater consistency are required for denser woods (Fig. 9-7). Greater consistency can be achieved with longer assembly time, which allows increased absorption of liquid solvent by the wood and evaporation into the air. Care is required, regardless of wood density, to ensure that the assembly time is not excessive, lest the adhesive dry out or even precure before pressure is applied. Predried or precured adhesive will result in inadequate transfer of adhesive to an opposite unspread surface, and the bondline will be thick and weak (Fig. 9-7).

Lumber joints should be kept under pressure until they have enough strength to withstand handling stresses that tend to separate the pieces of wood. When cold-pressing lumber under normal bonding conditions, this stage can be reached in as little as 15 min or as long as 24 h, depending on the temperature of the room and the wood, the curing characteristics of the adhesive, and the thickness, density, and absorptive characteristics of the wood. When hot pressing, the time under pressure varies with temperature of platens, thickness and species of wood, and adhesive formulation. In actual practice, hot-pressing times vary from 2 to 15 min and up to 30 min for very thick laminates. The time under pressure can be reduced to less than 3 min with high frequency heating. High frequency concentrates energy in the conductive bondline to rapidly cure the adhesive. It is commonly used for bonding lumber, forming end- and edge-grain joints, patching, scarfing, fingerjointing plywood, and in

manufacturing various panel products. Careful control of power and press time is essential to prevent formation of steam that could lead to steam blows and even arcing.

It has been observed that bondlines of structural adhesives that withstand the highest of stresses from mechanical loading and dimensional changes generally have bondline thicknesses within the range of 0.076 to 0.152 mm (0.003 to 0.006 in.). Below this range, the bondlines are too thin to effectively transfer stresses from one adherend to the other, particularly stresses from moisture-induced dimensional changes. Above this range, bond strength becomes progressively weaker as bondline thickness increases. Structural wood adhesives are brittle, so they fracture more in thicker bondlines than in thinner ones. These adhesives also contain solvents, and because solvent is lost while curing, the thicker adhesive film shrinks and fractures more than the thinner and may contain more voids from entrapped solvent gases. Thick bondlines result from inadequate pressure, either from low applied pressure or from rough, uneven, poorly mated surfaces. When uneven surfaces are joined, pressure will not be uniform along the bondline. As a result, the adhesive will be squeezed out from the areas of very high pressure, and the areas of little to no pressure will have very thick bondlines. Both starved and thick bondlines produce weak joints.

Post-Cure Conditioning

In the process of bonding edge-grain joints, the wood in the joint absorbs moisture from the adhesive, then swells. If the bonded assembly is surfaced before this excess moisture is evaporated or absorbed uniformly, more wood is removed along the swollen joint than elsewhere. Later, when the added moisture evaporates, the wood in the joint shrinks beneath the surface. These sunken bondlines become very conspicuous under a high-gloss finish. This is a particularly important consideration when using adhesives that contain relatively large amounts of water. Redistribution of moisture added by the adhesive can be accomplished by conditioning the bonded assembly for 24 h at 70°C (158°F), 4 days at 50°C (122°F), or at least 7 days at room temperature before surfacing. In each case, the relative humidity must be adjusted to prevent drying the wood below the target moisture content.

After bonding, plywood-type constructions should be conditioned to the average moisture content expected in service. The best conditioning is accomplished by controlling humidity on time schedules. If bonded products cured at room temperature are exposed to excessively low moisture content, warping, checking, and opening of joints will increase significantly. Softwood plywood is very dry after hot pressing, so panels may be sprayed with water and tightly stacked to allow moisture to diffuse uniformly. This practice restores some of the panel thickness lost by compression during hot pressing and apparently minimizes warping in service.

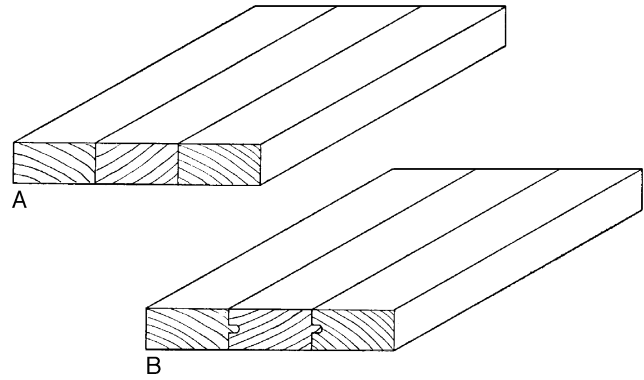


Figure 9-8. Edge-grain joints: A, plain; B, tongue-and-groove.

Bonded Joints

Edge-Grain Joints

Face-grain joints (wide surface of a board) are commonly seen in structural laminated lumber products, where adhesive bonds are stronger than the wood. Edge-grain joints (narrow surface of a board) (Fig. 9-8) can be almost as strong as the wood in shear parallel to the grain, tension across the grain, and cleavage. The tongue-and-groove joint (Fig. 9-8) and other shaped edge-grain joints have a theoretical strength advantage because of greater surface area than the straight, edge-grain joints, but they do not produce higher strength. The theoretical advantage is lost, wholly or partly, because the shaped sides of the two mating surfaces cannot be machined precisely enough to produce the perfect fit that will distribute pressure uniformly over the entire joint area. Because of poor contact, the effective bonding area and strength can actually be less in a shaped joint than on a flat surface. The advantage of the tongue-and-groove and other shaped joints is that the parts can be more quickly aligned in clamps or presses. A shallow-cut tongue-and-groove is just as useful in this respect as a deeper cut, and less wood is wasted.

End-Grain Joints

It is practically impossible to make end-grain butt joints (Fig. 9-9) sufficiently strong to meet the requirements of ordinary service with conventional bonding techniques. Even with special techniques, not more than about 25% of the tensile strength of the wood parallel-to-grain can be obtained in a butt joint. To approximate the tensile strength of clear solid wood, a scarf joint or fingerjoint must closely approach the parallel-to-grain direction of the edge-grain joint (Fig. 9-8). The surface area of this edge-grain joint should be at least 10 times greater than the cross-sectional area of the piece, because wood is approximately 10 times stronger in tension than in shear. In plywood scarfs and fingerjoints, a slope of 1 in 8 is typical for structural products. For non-structural, low-strength joints, these requirements need not be met.

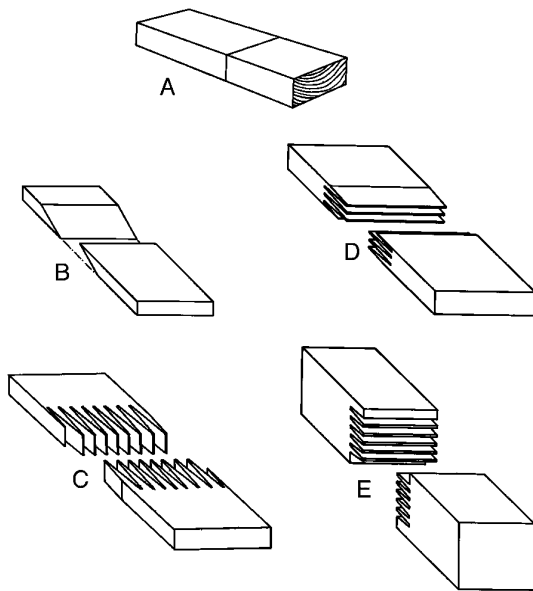


Figure 9-9. End-grain joints: A, butt; B, plain scarf; C, vertical structural fingerjoint; D, horizontal structural fingerjoint; E, nonstructural fingerjoint.

Fingerjoints can be cut with the profile showing either on the wide face (vertical joint) or on the edge (horizontal joint) (Fig. 9-9). There is greater area for designing shapes of fingers in the vertical joint, but a longer cutting head with more knives is needed. When the adhesive is cured by high frequency heating, the cure is more rapid with the vertical than with the horizontal joint. A nonstructural fingerjoint, with fingers much shorter than in the two structural fingerjoints, is shown in Figure 9-9.

A scarf joint is shown in Figure 9-9. Slopes of 1 in 12 or flatter produce the highest strength. This is also true in fingerjoints, but the tip thickness must be small and no greater than 0.8 mm (0.031 in.). A thickness of 0.4 to 0.8 mm (0.016 to 0.031 in.) is about the practical minimum for machined tips. Sharper tips can be created with dies, which are forced into the end grain of the board.

A well-manufactured end joint of either scarf, finger, or lap type can have up to 90% of the tensile strength of clear wood and exhibit behavior much like that of clear wood. However, test results indicate that the cycles-to-failure for a well-manufactured end joint are somewhat lower compared with the results of similar tests for clear wood.

End-to-Edge-Grain Joints

Plain end-to-edge-grain joints (Fig. 9-10) are difficult to design to carry appreciable loading. Furthermore, internal stresses develop in the members in service from unequal dimensional changes with moisture content changes. Such stresses can be great enough to cause failure. As a result, it is necessary to design these joints with interlocking

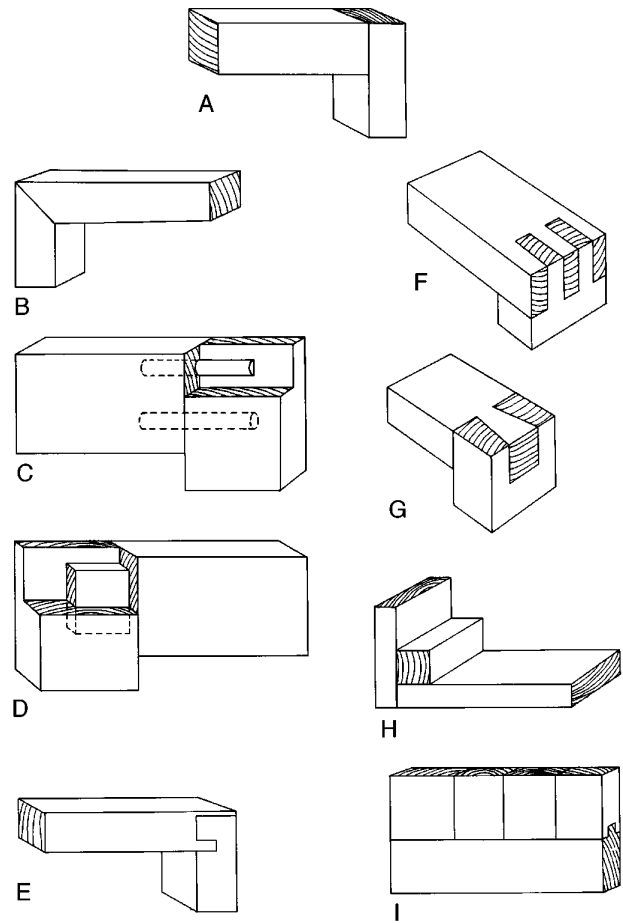


Figure 9-10. End-to-edge-grain joints: A, plain; B, miter; C, dowel; D, mortise and tenon; E, dado tongue and rabbet; F, slip or lock corner; G, dovetail; H, blocked; I, tongue-and-groove.

surfaces, for example, dowels, mortise and tenons, rabbets (Figs. 9-10), so that edge grain of the interlocking piece is bonded to the edge grain of the adjoining piece. The joint area is enlarged as well. All end-to-edge-grain joints should be protected from appreciable changes in moisture content in service.

Construction Joints

Elastomeric construction adhesives are commonly used in the light-frame construction industry for field assembly of panelized floor and wall systems. Structural panels are bonded to floor joists and wall studs with mastic adhesives that have the unique capability of bridging gaps up to 6.5 mm (0.25 in.) between rough and poorly fitting surfaces (Fig. 9-11). Without any premixing, the adhesive is extruded in a bead along framing members with a hand-held caulking gun or a pressurized dispenser similar to that shown in Figure 9-6. Nails or screws provide the only pressure for bonding, and they hold materials in position while the adhesive sets. Elastomerics are also uniquely tolerant of the



Figure 9–11. Gap-filling construction adhesive in field-assembled plywood floor system.

temperature and moisture content variations at field construction sites. Although they do not deliver the strength and durability of conventional structural adhesives, elastomeric are strong and flexible enough to give long-term performance under most conditions of installation and service.

Construction adhesives enable a nailed floor system to act to some degree as a composite assembly with increased stiffness. Greater stiffness permits joists to be longer and spaced more widely, with one layer of plywood subflooring replacing two. Floors are less bouncy with fewer squeaks and nail pops. However, structural design of the composite assembly is based only on the increased stiffness of nailed panel and framing materials. Structural credit for strength is not allowed for the adhesive in the engineering design.

Testing and Performance

An adhesive is expected to hold materials together and transfer design loads from one adherend to the other within a given service environment for the life of the structure. The purpose of testing performance is to ensure that adhesive bonds will not deteriorate before they can meet these expectations. A variety of methods are available to test bonding performance, particularly for bonded assemblies. Generally, these testing methods attempt to predict how bonded joints are likely to perform in a specific loading mode (shear, tensile, creep) in an assembly at specific temperature and moisture conditions for a specific time.

Most performance tests are short term. They are based on chemical, mechanical, and rheological laboratory tests of adhesive polymers and their adhesives and bonds. Intermediate-term tests of products that are conducted in pilot operations and field experiments are integrated with short-term laboratory tests in an effort to extrapolate these data into long-term performance. Long-term tests of bonded assemblies under actual environmental exposures are conducted, but these supporting data may not be available for 10 to

30 years. Therefore, heavy reliance must be placed on short-term tests to predict long-term performance. As the relationships between chemical structure and mechanical performance, particularly long-term performance, are better understood, the greater the reliance will be on short-term testing.

Analytic Chemical and Mechanical Testing of Polymers

The molecular structures of adhesive polymers are chemically characterized spectroscopically by nuclear magnetic resonance, either in the liquid or solid state. Molecular-size distributions of polymers are determined by gel permeation chromatography. Rates of chemical reaction are studied by differential scanning calorimetry. The rheological properties of curing and cured adhesives are characterized by dynamic mechanical analysis and torsional-braid analysis. Sophisticated fracture mechanics techniques are used to measure toughness of adhesive bonds as they fail in a cleavage mode. High magnification microscopes, including scanning electron microscope, transmission electron microscope, and atomic force microscope, enable scientists to visually analyze surfaces of adhesives and adherends before, during, and after fracture. Much can be learned from measurements of chemical, mechanical, and rheological properties of polymers and adhesives as they exist apart from adherends. Until such data can be correlated with performance, there is no substitute for testing performance in bonded assemblies prepared with specific adhesives and materials, and tested under specific loading modes, environmental conditions, and duration of loading. When adhesives are formulated through a blend of scientific analysis and art of formulation, they are tested for strength and durability in the laboratory and field, usually by industry- and government-accepted standard methods of test and product specifications.

Mechanical Testing of Bonded Assemblies

Responses of adhesive-bonded assemblies to mechanical loading are defined in terms of several commonly used modes of applying stress to joints. In all test modes, specific materials, conditions of materials and test, and testing procedures are completely specified to ensure repeatability to enable valid comparisons of data. Most test methods, specifications, and practices for adhesives and bonded assemblies are consensus standards published each year in the *Annual Book of ASTM Standards* by the American Society for Testing and Materials (ASTM). Several trade associations have their own specifications and performance standards that apply to their specific wood products. The Federal government also has specifications that are used by the General Services Administration to purchase products.

Four basic stressing modes—shear, tensile, cleavage, and peel—are commonly used to test bonded wood assemblies with variations of these to determine strength levels during impact, flexure, fatigue, and creep under long-term stress.

The following describes the basic stress modes in adhesive-bonded joints:

- Shear, resulting from forces applied parallel to the bondline
- Tensile, resulting from forces applied perpendicular to the bondline
- Cleavage, resulting from separation along a bondline by a wedge or other crack-opening type of force
- Peel, resulting from forces applied to a bondline that tend to progressively separate a flexible member from a rigid member or another flexible member

As the names imply, impact, fatigue, and creep are tests that have more to do with the rate at which basic modes and variations are applied. Impact loads are sudden, much faster relative to the controlled slow rates of shear or tensile stressing. Fatigue is the loss in strength from repeated loading and reflects deterioration of bonds from mechanical rather than environmental stresses, although the latter may be imposed during fatigue testing. Creep loads are statically applied but are of prolonged duration that can last from a few days to years, usually at extreme conditions of environmental exposure. The flexure test applies a bending force to a simple beam at midspan, perpendicular to the bondline. In a laminated beam, the test directs a large proportion of the shear forces to bondlines between the laminates.

The common measures used to estimate potential performance of bonded wood joints are strength, wood failure, and delamination. Best performance produces a bond strength that is greater than that of the wood, wood failure that is more than 75% over the bonded area, and delamination of the joint that is less than 5% for softwoods and 8% for hardwoods, under severe service conditions. These performance values reflect how wood adherend, adhesive bond, and environmental exposure have interacted in response to loading.

Bond strength is tested most commonly in shear parallel to the grain. Because most wood adhesives exceed the shear strength of wood in this direction, the maximum potential strength of the adhesive may not be realized, particularly for moderate to lower density species. Bonds in structural assemblies are expected to exceed the strength of the wood, so in traditional design of joints, adhesive strength has been ignored. Adhesives not as strong as wood simply have not been used in design because methods for determining allowable mechanical properties of adhesives for engineering design had not been developed. One such method now exists as a consensus standard—ASTM D5574–97 (ASTM 1997). Exceeding the strength of wood is an essential performance criterion; therefore, the amount of wood that fails in a joint is estimated as a percentage of the area of the bonded joint. This is an important indicator of bond strength, often more important than the measured shear strength of the bond. The higher the wood failure and the deeper the fracture into the grain of the wood, the stronger and more durable the bond, particularly with durable types of adhesives. If wood failure is shallow with only wood fibers remaining attached to the

adhesive film, then bond strength and probably durability is lacking in the bond. Thus, a consistently high level of wood failure, above 75% in some standards and above 85% in others, means that shear strength associated with these average wood failures are good estimates of the load-carrying capability of the joint. High levels of wood failure and shear strength in a wet and hot environment might indicate that the adhesive bond is as strong as the wood. If cycles of alternate drying were included with cycles of wet and hot conditions, then high wood failure would indicate even more durable bonds. High wood failure in shear tests of water-saturated bonds is also a strong indicator of bond durability, particularly with durable types of adhesives. Wood failure is considered a valid measure of bond strength only to solid wood, not to reconstituted products made of bonded wood particles.

High shear strength and wood failure in themselves are not sufficient indicators of the durability of a structural bond. Delamination is an indicator of how well the bonded joint withstands severe swelling and shrinking stresses in the presence of high moisture and heat. Delamination is the separation between laminates because of adhesive failure, either in the adhesive or at the interface between adhesive and adherend. If strength of adhesion is not as strong as the wood in resisting forces tending to separate laminates, then delamination occurs. If adhesion does resist delaminating forces, then the wood will fail adjacent to the bondline, but not within the adhesive. The stressing modes induced by stresses from moisture-related dimensional changes are combinations of tensile and shear forces with cleavage acting at joint edges. Delamination of adhesives in structural laminated wood products exposed to the cyclic delamination test in ASTM D2559–97 (ASTM 1997) cannot exceed 5% in softwoods and 8% in hardwoods.

Short- and Long-Term Performance

In the short term, the mechanical properties of wood, adhesives, and bonded products vary with the specific environmental exposure. In most cases, all properties decrease as the temperature and moisture levels increase. Strength and stiffness may return to their original levels if the yield points of the materials have not been exceeded while under load. The properties of rigid thermosetting adhesives like resorcinol-formaldehyde, phenol-formaldehyde, melamine-formaldehyde, and urea-formaldehyde change less than do wood properties under equivalent temperature and moisture changes. Therefore, evaluating short-term performance of products made with these adhesives is simply a matter of testing bonds at room temperature in dry and wet conditions. Thermoplastic adhesives like casein, polyvinyl acetate, and elastomers, whose properties change more rapidly than those of wood with changes in moisture and heat, are tested dry, dry after water soaking, and after prolonged exposure to high humidity environments. In addition, some specifications require testing of bonded structural and nonstructural products at elevated temperatures such as occur in roofs or enclosed shipping containers. A short-term dead-load test at elevated temperatures may also be required. Specifications for

adhesives for structural products like laminated beams and plywood require conformance to high minimum strength and wood failure values after several different water exposure tests. Adhesive bonds in laminated beams must also withstand severe cyclic moisture content and temperature changes, with only low levels of delamination allowable.

In the long term, wood, adhesives, and bonded products deteriorate at a rate determined by the levels of temperature, moisture, stress and, in some instances, by concentrations of certain chemicals and presence of microorganisms. Long-term performance is equated with the ability of a product to resist loss of a measured mechanical property over the time of exposure. A durable product is one that shows no greater loss of properties during its life in service than wood of the same species and quality.

Many adhesives in bonded products have decades of documented performance in many environments. Thus, it is possible to predict with a high degree of certainty the long-term performance of similar products. Well-designed and well-made joints with any of the commonly used woodworking adhesives will retain their strength indefinitely if the moisture content of the wood does not exceed approximately 15% and if the temperature remains within the range of human comfort. However, some adhesives deteriorate when exposed either intermittently or continuously to temperatures greater than 38°C (100°F) for long periods. Low temperatures seem to have no significant effect on strength of bonded joints.

Products made with phenol-formaldehyde, resorcinol-formaldehyde, and phenol-resorcinol-formaldehyde adhesives have proven to be more durable than wood when exposed to warm and humid environments, water, alternate wetting and drying, and even temperatures sufficiently high to char wood. These adhesives are entirely adequate for use in products that are exposed indefinitely to the weather (Fig. 9–12).

Products well-made with melamine-formaldehyde, melamine-urea-formaldehyde, and urea-formaldehyde resin adhesives have proven to be less durable than wood. Melamine-formaldehyde is only slightly less durable than phenol-formaldehyde or resorcinol-formaldehyde, but it is still considered acceptable for structural products. Although considered less durable, melamine-urea-formaldehyde is also accepted in structural products at a melamine-to-urea ratio of 60:40. Urea-formaldehyde resin is susceptible to deterioration by heat and moisture (Fig. 9–12).

Products bonded with polyvinyl acetate and protein-based adhesives will not withstand prolonged exposure to water or repeated high–low moisture content cycling in bonds of high density woods. However, if they are properly formulated, these adhesives are durable in a normal interior environment.

Some isocyanate, epoxy, polyurethane, and cross-linked polyvinyl acetate adhesives are durable enough to use on lower density species even under exterior conditions, but exterior exposure must be limited for most of these. Some elastomer-based adhesives may be durable enough for limited exposure to moisture with lower density species in

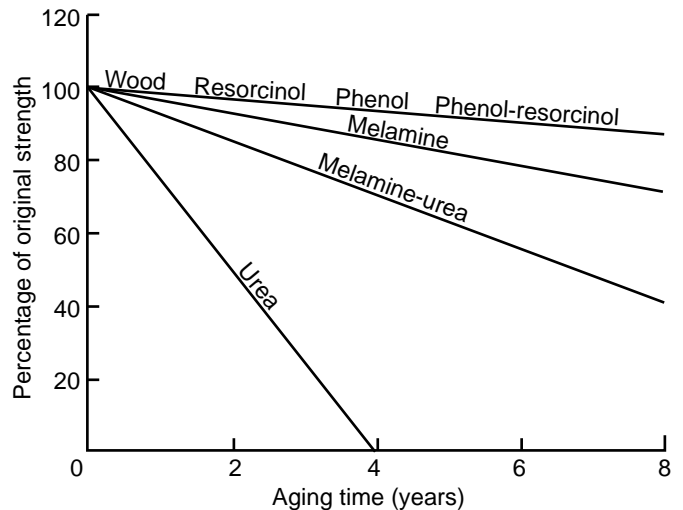


Figure 9–12. Relative rates of deterioration of bond strength of small specimens exposed directly to weather.

nonstructural applications or in structural applications when used in conjunction with approved nailing schedules. Polyurethane adhesives that chemically cure and still remain flexible are among the most durable construction adhesives.

New adhesives do not have a history of long-term performance in service environments, so accelerated laboratory exposures that include cycles of heat, moisture, and stress are used to estimate long-term performance. However, laboratory exposures cannot duplicate the actual conditions of a service environment. Estimates of long-term performance can be obtained by exposing specimens outdoors for up to 30 years. Outdoor exposures may be intensified by facing specimens south at an angle perpendicular to the noonday sun and by establishing exposure sites in regions with the most extreme of service environments, for example, southern coastal and arid southwestern regions. Only four long-term laboratory aging methods have been standardized, and none specifies minimum performance levels. Therefore, performance of any new adhesive or bonded product must be compared with the performance of established adhesives or products tested in the same laboratory exposure.

Product Quality Assurance

After the short- and long-term performance of a product has been established, then maintenance of the manufacturing process to ensure that the product will be made and perform at that level is the major concern of a quality-assurance program that consists of three parts:

1. Establishing limits on bonding process factors that will ensure acceptable joints and product.
2. Monitoring the production processes and quality of bond in joints and product.
3. Detecting unacceptable joints and product, determining the cause, and correcting the problem.

The structural panel, laminated-beam, particleboard, millwork, and other industrial trade associations have established quality-assurance programs that effectively monitor the joint and product performance at the time of manufacture for compliance with voluntary product standards. Usually, product performance is evaluated immediately after manufacture by subjecting specimens from the product to a series of swell-shrink cycles. The treatments are more rigorous for products intended for exterior exposure. For example, exterior softwood plywood is subjected to two boil-dry cycles, while interior plywood is subjected to a single soak-dry cycle at room temperature. After exposure, the specimens are examined for delamination or evaluated for percentage wood failure. The test results are compared with the minimum requirement in the trade association's standards. Lengthy experience and correlations between exterior performance and accelerated laboratory tests have shown that products with at least the minimum values will probably perform satisfactorily in service. If the product meets the requirement, it is certified by the association as meeting the standard for satisfactory performance.

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