

Wood: Adhesives

Wood adhesives are polymeric materials that are capable of interacting physically or chemically, or both, with the surface of wood in such a manner that stresses are transferred between bonded members, hopefully without rupture of the adhesive or detachment of the adhesive from the wood. Adhesives and the physicochemical phenomenon of adhesion play an important role in more than 70% of all wood-based materials in use today (Marra 1984). This includes not only bonded wood products but paper products, paints, and finishes. By far, the largest amount of adhesive is used to manufacture building materials such as plywood and other laminated veneer products, particleboard, oriented strandboard, fiberboard, laminated beams and timbers, edge- and end-jointed products, windows and frames, architectural doors, and fiberglass insulation. Adhesives are used in lesser 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 furniture, overlays, floor coverings, countertops, ceiling and wall tiles, trim, and accessories.

The bonding of wood with adhesives is known to date back at least to the Pharaohs, and in all likelihood dates even further back in history (Keimel 1994). For example, the Egyptians used adhesives derived from animal sources to laminate wood for producing bows and furniture and for attaching decorative wood veneers. In addition, they are known to have used gum arabic, eggs, balsams, and resins from trees as sources of adhesives. Up to World War II the dominant adhesives for bonding wood were made from natural sources (Lambuth 1989). Natural adhesives that have been used by the forest products industry include adhesives derived from starch, soybeans, animal waste and by-products of the meat processing adhesives derived from starch, soybeans, animal waste and by-products of the meat processing and tanning industries, and casein from skim milk. Of these, protein-based adhesives (soy, blood, and casein) were most commonly used. However, adhesives derived from natural sources were limited to dry interior applications.

During the past 50–60 years, the use of adhesives in the production of bonded-wood products has increased dramatically. For example, in 1997, approximately 1.6×10^9 of adhesive resin solids were used in North America (United States, Canada, and Mexico) to bond nearly $57 \times 10^6 \text{ m}^3$ of glued wood products (Sellers 1998). This amount does not include adhesives used for the production of nearly US \$30 million of furniture and other secondary products. The increased use of adhesives after World War II is largely due to the availability of low-cost, highly durable synthetic adhesives that could be produced from petrochemicals

no longer needed to support the war effort (Lambuth 1989). Many of these adhesives, unlike their natural counterparts, could be used in exterior applications.

Highly durable synthetic adhesives allow efficient and economical utilization of diverse and changing wood resources. Adhesives allow the manufacture of useful products from residues and waste wood; the manufacture of stronger, more efficient structures by removing or minimizing natural defects; the re-assembly of smaller forms of wood such as veneer, flakes, and fibers into efficiently engineered shapes and products; and the manufacture of a variety of new composites by blending wood with nonwood materials such as plastics and cement. Large bonded panels, such as plywood and oriented strandboard, provide superior structural integrity and consume roughly 50% less wood than lumber sheathing. Fingerjointing provides usable lengths of lumber from otherwise unusable short pieces, and wood I joists place high-strength wood where it is needed and eliminates wood where it is not needed. In the future, the bonding of wood with adhesives will continue to be a major factor not only for the efficient utilization of forests as a source of raw materials but also for the efficient manufacture of wood products and the recycling of waste wood. Efficiency in converting trees and waste wood to useful products will help to ensure the continual conservation of forest resources.

1. Classification of Wood Adhesives

Wood adhesives are broadly classed as either synthetic or natural (Table 1). Synthetic adhesives consist of either prepolymers (oligomers) or polymers that are synthesized from petrochemically derived raw materials. Adhesives must be applied in liquid form to disperse over and wet the surface of wood. Adhesive prepolymers can be applied directly if they are liquids or can be applied as solutions, usually water solutions. Adhesive prepolymers cure by further reaction of the oligomers to form polymers *in situ*. Often the curing reactions are facilitated by the addition of a cross-linking agent or catalyst and by the application of heat. Synthetic polymers, when used as adhesives, are melted, dissolved in a solvent, or emulsified in a solvent prior to application. The solvent is usually water. After application, polymer-based adhesives set by solidification of the melted polymer by cooling or by removal of the solvent via either evaporation or adsorption, or both.

Synthetic adhesives are further classified by the nature of the polymer after it has set or cured. Thermoplastic resins are polymers that soften when exposed to heat then solidify on cooling to room temperature. These polymers are generally soluble as well. The major wood adhesive in this category is PVAc (see Table 1 for definition of abbreviations).

Table 1

Classification and estimated North American consumption of wood adhesives.

Class	Resin type	Estimated 1997 consumption (10 ³ t) ^a	Typical adhesive system
Synthetic Thermosetting	Amino	980	Urea-formaldehyde (UF) Melamine-formaldehyde (MF) Melamine-urea-formaldehyde (MUF)
	Phenolic	567	Phenol-formaldehyde (PF) Resorcinol-formaldehyde (RF) Phenol-resorcinol-formaldehyde (PRF)
	Isocyanate	50	Diphenylmethane-4,4'-diisocyanate (MDI)
	Epoxy	-	Bisphenol A-based epoxy resins
	Elastomeric	-	Styrene butadiene rubber (SBR)
Thermoplastic	Vinyl	47	Polyvinyl acetate (PVAc) Polyvinyl alcohol (PVA)
	Hot-melts	-	Ethylene vinyl acetate (EVA)
Natural	Protein	5	Casein Soybean Blood Animal

a Source: Sellers (1998).

Hot-melts are also considered thermoplastics. However, the term "hot-melt" often refers to a polymer of lower molecular weight and viscosity than most thermoplastics. EVA is the prime example of this type of adhesive used in wood bonding. Thermosetting resins form polymers that are cross-linked during cure. These polymers, upon cure, are insoluble and do not soften on heating. Examples of this category of adhesives include amino resins, phenolic resins, epoxy resins, and isocyanates.

Natural adhesives are generally dispersed in water prior to application and cure primarily by solvent removal, although some are formulated with the addition of cross-linking agents. The early wood composite products industry was founded on the use of this type of adhesive for plywood production.

2. Thermosetting Wood Adhesives

Table 1 illustrates the fact that thermosetting resins constitute the main type of adhesives presently used to bond wood. Amino resins, phenolic resins, and isocyanates are the three most important thermosetting adhesive systems used by the wood products industry. Epoxies and elastomers are used to a much lesser extent.

2.1 Phenolic-Formaldehyde Resin Adhesives

(a) Phenol-formaldehyde resin adhesives. PF resins

are the major adhesives used for bonding wood panels for use in exterior applications. For example, approximately 60% of the total US demand for PF resins comes from the forest products industry (White 1995). The PF adhesive resins are used primarily in the production of softwood plywood, oriented strandboard, and waferboard. The PF resins are formed by the reaction of phenol with formaldehyde. By varying the reaction time, reaction temperature, catalyst type, and the ratio of formaldehyde to phenol, a number of adhesive systems with different characteristics can be produced (Knop and Scheib 1979). Novolac resins are produced using an acid catalyst and an excess of phenol. Initially formaldehyde reacts with phenol to form hydroxymethyl derivatives preferentially at the aromatic ring carbon para to the phenolic hydroxyl. High-ortho novolac resins can be made under weak acid conditions (pH 4-6) using divalent metal salts. As the reaction proceeds, reactions also take place between the hydroxymethyl groups and the aromatic ring carbons of phenol or another hydroxymethyl group to form methylene linkages. In this manner, the polymeric structure of the resin is produced. Due to the excess of phenol in the reaction, novolac resins do not have active hydroxymethyl groups. As a consequence, novolac resins are fairly stable. These resins have a low molecular weight (approximately 200-8000Da) and linear structure. Novolac resins are cured by the addition of a second reactive compound, usually hexamethylenetetramine (HMTA). For this reason, novolac resins are often referred to

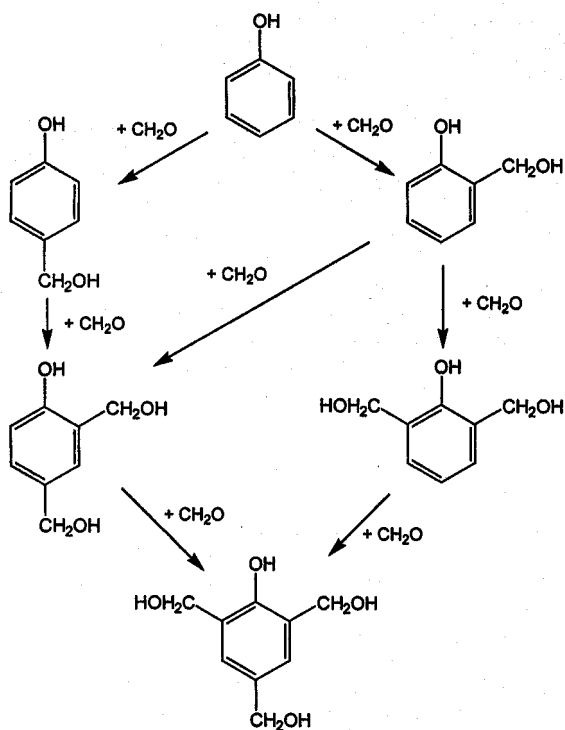


Figure 1
Formation of the hydroxymethyl derivatives of phenol.

as two-stage resins. The added HMTA facilitates cross-linking of the resin during cure. This curing process transforms the thermoplastic novolac resin into the thermoset form of the cured product.

Resole resins are produced with a base catalyst and an excess of formaldehyde. For resins used in the wood industry, sodium hydroxide is the most important catalyst, although other base catalysts such as sodium carbonate, alkaline oxides and hydroxides, and ammonia can also be used. Typical resole resins contain a molar ratio of phenol to formaldehyde to sodium hydroxide equal to approximately 1:2:0.5, with a resin solids content of about 35–50%. Resole resins are formed by heating the reactive ingredients in aqueous solution at about 80–100°C. Initially, mono-, di-, and trihydroxymethyl derivatives of phenol are formed (Fig. 1). Further reaction leads to condensation of the hydroxymethyl derivatives, giving methylene or ether linkages between phenol moieties (Fig. 2). Ether linkages form primarily under neutral or slightly acid conditions at temperatures up to about 130°C (Knop and Scheib 1979). Under alkaline conditions and above about 140°C, the methylene linkages predominate. Because these reactions are exothermic, the temperature of the reaction mixture must be carefully controlled. On reaching a target viscosity, the reaction is stopped by cooling. This gives

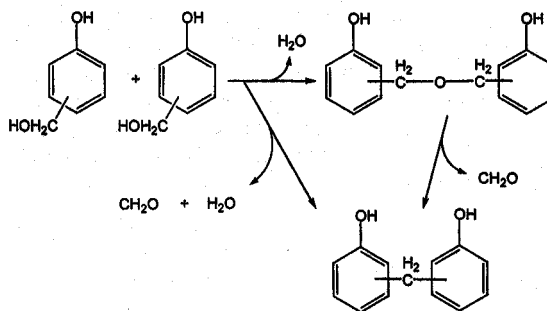


Figure 2
Condensation of the hydroxymethyl derivatives of phenol.

resins that are prepolymeric mixtures composed of mono- and oligomeric hydroxymethylphenols. Resole resins have a higher molecular weight than novolacs (200–30000 Da) and a highly branched structure. Because of the excess formaldehyde in the reaction mixture, resole resins have hydroxymethyl end groups that are not stable but continue to react even at room temperature.

When used as a wood adhesive, resole resins are generally aqueous solutions that are cured with heat and pressure. On heating, the resin mixture undergoes further reactions between hydroxymethyl groups to give a highly cross-linked, three-dimensional structure. While both resole and novolac resins can be used to bond wood, only resole resins have been used to any great extent. This is probably due to the fact that acids used in the production of novolac resins are corrosive to processing equipment and can degrade wood. Powdered PF resole resins are also produced, primarily by a spray drying process. These resins find application in waferboard production where good distribution on the large wafers is required and where limitations exist on the amount of water that can be present in the bond line during high temperature curing of the adhesive resin.

(b) *Phenol-resorcinol-formaldehyde and resorcinol-formaldehyde resin adhesives.* By incorporating resorcinol during the synthesis of PF resins or by replacing phenol with resorcinol altogether, phenolic resins can be made with significant decreases in cure time compared with PF resin adhesives. The chemistry associated with the formation and cure of PRF and RF resins is similar to that for PF resins. However, PRF and RF prepolymers are made at a low formaldehyde molar ratio and thus are essentially novolac resins. The prepolymers, which are stable, are cured by the addition of a hardener (e.g., paraformaldehyde or a formaldehyde solution). The PRF and RF resin adhesives are used in situations where

fast or room temperature curing is required (e.g., fingerjointed structures) or where the wooden assembly being bonded is too thick to allow sufficient heat for resin cure to reach the bond lines in the interior of the assembly (e.g., laminated timbers). The main disadvantage of these resins is the much higher cost of resorcinol compared with that of phenol.

2.2 Amino-Formaldehyde Resin Adhesives

(a) *Urea-formaldehyde resin adhesives.* Well over 10⁶t of UF resin are produced annually. More than 70% of this resin is used by the forest products industry (White 1995). The UF resin is used by the forest products industry in the production of particleboard (61%), medium-density fiberboard (27%), and hardwood plywood (5%), and it is used as a laminating adhesive (7%) for bonding furniture overlays to panels and for interior flush doors, for example. The UF resins are prime examples of the class of adhesives referred to as amino resins (Pizzi 1983, 1994, Pizzi and Mittal 1994) and comprise about 80% of the amino resins produced worldwide (Williams 1991). MF resins constitute the remainder of this class of resins, except for minor amounts of resins produced from other aldehydes or amino compounds (especially aniline), or both. The major use of UF resins by the forest products industry is due to a number of advantages, including low cost, ease of use under a wide variety of curing conditions, low cure temperatures, water solubility, resistance to microorganisms, hardness, excellent thermal properties, and lack of color of the cured resin. The major disadvantages associated with UF adhesives compared with PF or isocyanate adhesives is the lack of resistance to moist conditions, especially in combination with heat. These conditions lead to a reversal of the bond-forming reactions and the release of formaldehyde. For this reason, UF resins are usually limited to the manufacture of products for interior use only. However, even when used for interior purposes, the slow release of formaldehyde is a major concern that has come under close scrutiny by regulatory agencies in the USA and other countries (Meyer and Hermanns 1986). Industry has taken great strides since the 1980s to greatly reduce the amount of formaldehyde being released.

The synthesis of UF resin takes place in two stages. In the first stage, urea is hydroxymethylated by the addition of formaldehyde to the amino groups (Fig. 3). This reaction is in reality a series of reactions that leads to the formation of mono-, di-, and tri-hydroxymethylureas. Tetrahydroxymethylurea is apparently not produced, at least in any detectable quantity. The addition of formaldehyde to urea takes place across the entire pH range but is faster under acidic and basic conditions than under neutral conditions. The second stage of UF resin synthesis

consists of the condensation of the hydroxymethylureas to low molecular weight polymers. The rate at which these condensation reactions occur is very dependent on the pH and, for all practical purposes, occurs only at acidic pHs. The increase in the molecular weight of the UF resin under acidic conditions is thought to be a combination of reactions leading to the formation of:

(i) methylene bridges between amido nitrogens by reaction of hydroxymethyl and amino groups on reacting molecules (Fig. 4(a));

(ii) methylene ether linkages by the reaction of two hydroxymethyl groups (Fig. 4(b));

(iii) methylene linkages from methylene ether linkages by the splitting out of formaldehyde (Fig. 4(c)); and

(iv) methylene linkages by the reaction of hydroxymethyl groups splitting out water and formaldehyde (Fig. 4(d)).

The difference between the pH profiles of the two stages of UF resin synthesis is used as an advantage in the production of UF adhesive resins. In general, the commercial production of UF adhesive resins is carried out in two major steps. The first step consists of the formation of the hydroxymethylureas at a pH of about 8–9. This step is carried out under basic conditions to allow the hydroxymethylation reactions to proceed in the absence of reactions involving the condensation of the hydroxymethylureas. In the second step, the reaction mixture is made acidic (about pH 5) and the condensation reactions are carried out until a desired viscosity is reached. Then the reaction mixture is cooled and neutralized. Water is removed by vacuum distillation to give a resin with a desired solids content (typically 60–65%). Urea is often added in two, or sometimes more, steps. The initial addition of urea is made during the hydroxymethylation step, in which the formaldehyde-to-urea (F/U) ratio is typically large (about 1.6–2). Usually the second addition of urea is made during the condensation step. The second and any subsequent additions of urea lower the final F/U ratio to the desired level for the final resin.

These procedures for the synthesis of UF adhesive resin offer a wide range of conditions that make possible the synthesis of resins with important properties such as tack, gel time, and spreadability of the uncured resin. Formaldehyde emissions and the durability of the cured resin can be controlled and specifically tailored for the final end use of the resin. An acid-cure catalyst is usually added to the UF resin before its use as an adhesive. Ammonium chloride and ammonium sulfate are the most widely used catalysts for resins used by the forest products industry. A variety of other acids can be used as a catalyst including formic acid, boric acid, phosphoric acid, oxalic acid, and the acid salts of HMTA. Resin cure is conducted at a temperature of about 120°C and a pH < 5. The reactions that occur during the final cure

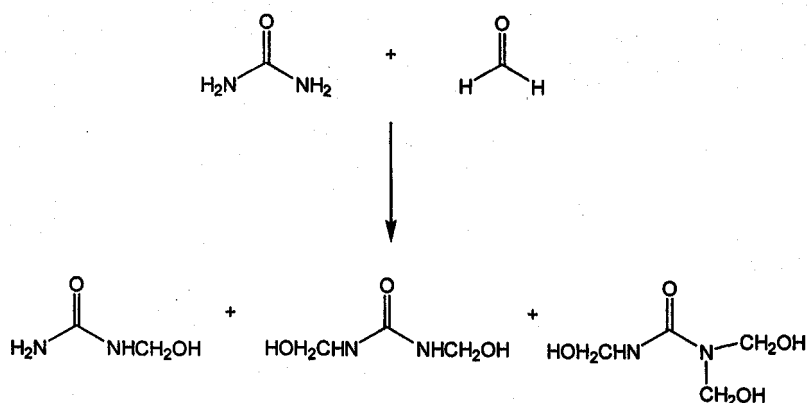


Figure 3

Addition of formaldehyde to urea to form mono-, di-, and trihydroxymethylureas.

of the resin are thought to be similar to those that occur during the acid condensation of the hydroxymethylureas. The traditional viewpoint is that these reactions lead to the formation of a cross-linked polymeric network for the cured resin. However, there is evidence that a colloidal phase also occurs during resin cure (Stuligross and Koutsky 1985). This evidence illustrates the lack of a full understanding of the physical and chemical processes leading to the cure of UF resin systems and the need for continued research. The reactions that occur during UF resin synthesis and cure are apparently reversible. In the forward direction, water is eliminated; therefore, the reverse reaction can be viewed as hydrolysis, which leads to the release of formaldehyde. Because most, if not all, of these reactions are catalyzed by acid, the use of an acid catalyst to hasten bond cure unfortunately also increases the rate of hydrolysis and formaldehyde liberation.

The reduction in formaldehyde emissions from products bonded with UF adhesive resins has been achieved by employing one or more of several technological methods. In general, these methods include:

- (i) changing the formulation of the UF adhesive resin (e.g., lowering the F/U ratio);
- (ii) adding formaldehyde-scavenging materials directly to the UF resin;
- (iii) separately adding formaldehyde-scavenging materials to the wood furnish;
- (iv) treating panels after manufacture either with a formaldehyde scavenger or by applying coatings or laminates; and
- (v) changing to an entirely different adhesive system.

The most widely used approach for reducing formaldehyde emission from bonded products has been decreasing the F/U ratio of the UF adhesive resin. Ratios of about 1.6 that were common in the 1970s and 1980s have now been reduced to values as low as 1.0 and in some cases even lower. Unfortunately, lowering the F/U ratio produces resins with less

tolerance for processing variations. These modifications that lower formaldehyde emissions have allowed UF resins to maintain their prominent position as a versatile adhesive system for bonding wood products.

(b) Melamine-urea-formaldehyde and melamine-formaldehyde adhesive resins. MUF and MF resins are more resistant to moist environments than are UF resins. However, melamine is much more expensive than urea. The MF and MUF resins are used for scarf jointing of plywood and end jointing of structural lumber that can be used in protected exterior exposure. In addition, these resins are used for bonding low- and high-pressure laminates and overlays. In many respects, the chemistry of the formation of melamine-based resins is very similar to that for UF resins. However, the addition of formaldehyde to the amino groups of melamine is faster and more complete than is the addition of formaldehyde to urea. Thus, complete hydroxymethylation of melamine occurs (Pizzi 1983), which as mentioned above, is not the case with urea. Another important difference is that the condensation reactions of the hydroxymethylated melamines occur not only under acid conditions but under neutral and slightly alkaline conditions as well (Pizzi 1994, Pizzi and Mittal 1994). In addition, products bonded with MF resins seem to be less susceptible to the release of formaldehyde than are products bonded with UF resin.

2.3 Isocyanate Resin Adhesives

Isocyanates are important industrial chemicals used in injection molding and for the production of poly-

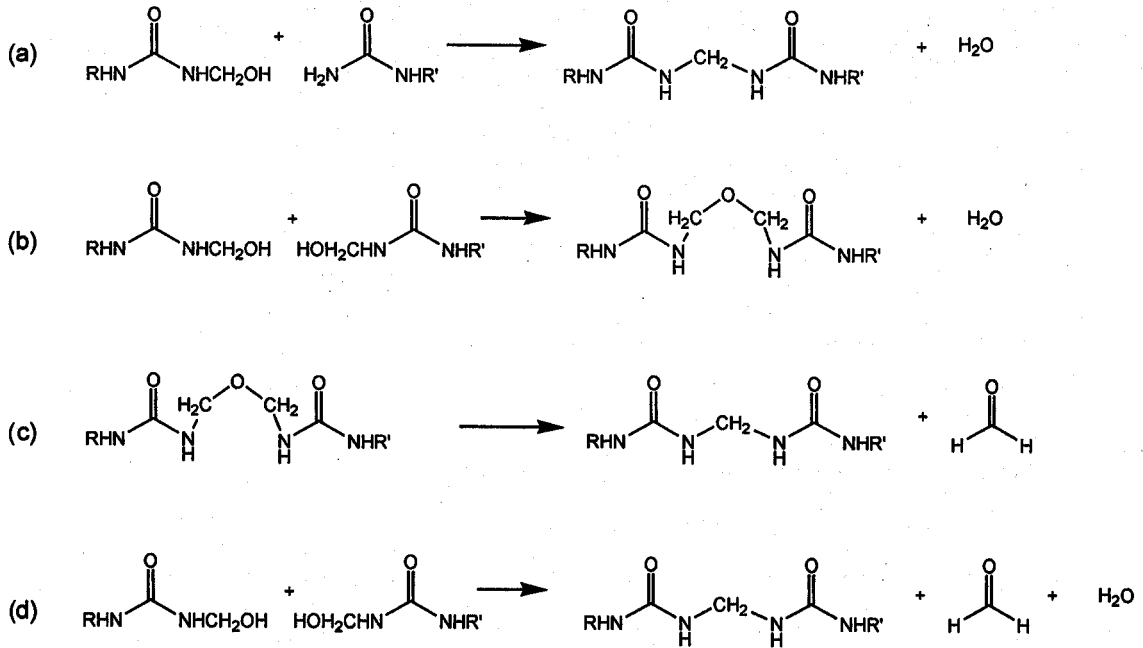


Figure 4
Condensation reactions of hydroxymethylureas.

urethane foams. All isocyanates of industrial importance contain two or more isocyanate groups ($-N = C=O$) per molecule. MDI has become an important adhesive in the wood products industry, especially for bonding oriented strandboard. Isocyanates are made by phosgenation of amines. The synthesis of MDI (Fig. 5) starts with the condensation of aniline with formaldehyde in acid solution. A complex mixture of isomeric diamines and oligomeric polyamines is formed. The 4,4'-diamine predominates. This complex mixture is phosgenated to give PMDI. PMDI, rather than a purified diisocyanate, is the material used by the wood products industry as an adhesive. At room temperature, PMDI is a clear brown liquid with a viscosity of about 0.5Pas and a low vapor pressure. It has an excellent shelf life as long as moisture is excluded. The adhesive properties of PMDI stem from the reactivity of the isocyanate groups. These groups react with compounds that have an active hydrogen, such as water, alcohols, and amines. Heating increases the rate of this reaction, and at high temperatures the reaction can be extremely rapid. In addition to reacting with the moisture in wood to form polyureas, it is theoretically possible that covalent bonds form between hydroxyl groups in the wood (e.g., on the cellulose) and the isocyanate. These covalent bonds, to the extent that they form, act to anchor the polyurea to the wood and help bridge the gap between pieces of

wood. As an adhesive, PMDI has several reported advantages:

(i) Because water is needed to form the polyurea that acts as the polymeric adhesive material, PMDI can be used with wood that has a higher moisture content than that usually employed with other adhesives. This eliminates part of the energy needed to dry the wood prior to bonding. It also means that the wooden materials are bonded closer to the moisture conditions at which they will be used. This eliminates a large portion of the stress that develops in the bonded material as it regains moisture after bonding, thereby imparting greater dimensional stability.

(ii) Because of the greater reactivity, PMDI can be cured at a lower temperature. This eliminates a portion of the energy required to form the bonded assembly.

(iii) Less PMDI is needed on a weight basis to form a bonded material with acceptable properties.

(iv) There are no formaldehyde emissions associated with the adhesive.

There are also some disadvantages associated with the use of PMDI as an adhesive:

(i) Isocyanate adhesives cost more than PF and UF resin adhesives.

(ii) PMDI is an excellent adhesive for metals as well as wood. Thus, MDI-bonded boards (e.g., oriented standard board) tend to adhere to the press platens. This problem has been overcome by the use of release

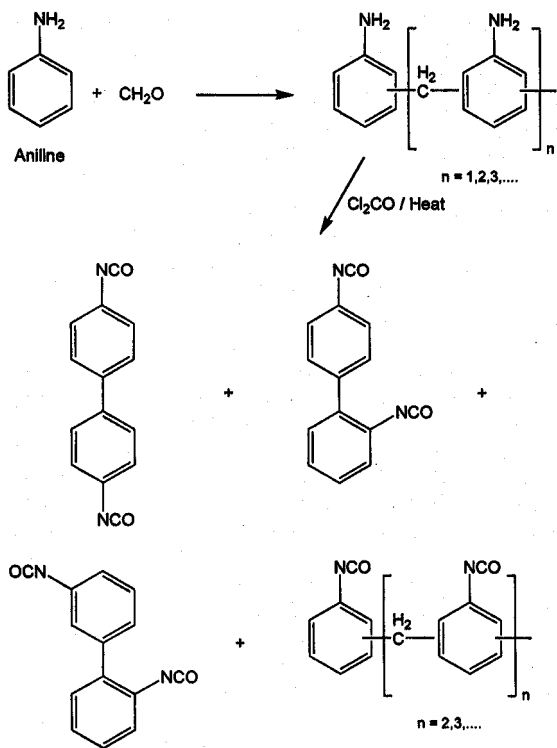


Figure 5
Synthesis of polymeric diphenylmethane diisocyanate (PMDI).

agents. A second approach has been the layering of materials during panel formation, with those layers that come into contact with the platens being bonded with a PF adhesive. Thus, the exterior of the panels is bonded with PF, but the interior of the panel is bonded with MDI.

(iii) Isocyanates, like other adhesive resins, are toxic chemicals. MDI is a respiratory irritant that produces asthma-like symptoms. Individuals can also become sensitized to isocyanates. Although MDI has a high vapor pressure, precautions should be taken to eliminate the inhalation of aerosols or dust particles coated with MDI.

Surprisingly, MDI can also be used in admixture with water. One method for doing this is to emulsify the MDI in water, giving an adhesive resin known as emulsified MDI (EMDI). It is thought that a thin film of polyurea is formed around each MDI droplet. Water does slowly permeate the polyurea barrier, so EMDI has a limited shelf life. A second method is to chemically block the isocyanate groups, such that the reactive isocyanate groups are reformed on heating. The advantage of using MDI in water is that it gives a resin system with a viscosity essentially that of water. Thus, the resin can be applied to wood chips with conventional equipment.

3. Thermoplastic Adhesives

Although not used in the same quantities as the thermosetting resins, thermoplastic adhesives, nevertheless, are extremely important for bonding wood (Table 1). The prime examples of this class of adhesives used in wood bonding are PVAc and EVA.

3.1 Polyvinyl Acetate

PVAc is most widely used as an emulsion of PVAc polymers in water. The emulsion is formed by polymerization in water of vinyl monomers, predominantly vinyl acetate, a process known as emulsion polymerization. The emulsion is white to off-white in color and is the familiar "white glue" used in many household projects. Because of its resistance to attack by microorganisms and its low cost, this adhesive has replaced natural adhesives made from hide and casein in, for example, the manufacture of furniture. This adhesive sets by diffusion of the water into the wood and coalescence of the polymers. Setting times are comparatively rapid at room temperature. The set resins are light in color and often transparent, resulting in a glue line that is practically invisible.

PVAc softens as its temperature is raised above room temperature, and it is less resistant to moisture and humidity than thermosetting resins. For this reason, PVAc adhesives are used in interior applications. In addition, PVAc tends to creep ("cold flow") under a sustained load. This limitation has been most serious when the adhesive is used to edge-glue lumber for solid stock, particularly high-density hardwoods. When such stock is exposed to low humidity, rapid moisture content changes through the end grain result in shrinkage stresses across the end of the bonded assembly. Often these stresses are of sufficient magnitude and duration to cause the adhesive to fail, resulting in open joints. Several modifications are used to enhance the resistance to moisture and to decrease creep of PVAc adhesive bonds. One such method is the addition of other types of vinyl monomer during polymerization to improve the properties. A second method is to add cross-linking agents that increase the rigidity of the polymer.

Because of the fact that PVAc is polymerized with minor amounts of vinyl alcohol, there are free hydroxyl groups on the polymer. Also, free hydroxyl groups can be formed by hydrolysis of the acetate groups. These hydroxyl groups offer sites for cross-linking. Cross-linking agents include strongly chelating metal salts such as chromium complexes. In addition, other adhesive resins such as UF, MF, and isocyanates have been used to advantage as chemical cross-linkers. Cross-linked PVAc's are more rigid, have better moisture and heat resistance, and have greater initial tack.

3.2 Ethylene Vinyl Acetate

In the woodworking industry, EVA copolymers and their blends with other resins and fillers are used as hot-melt adhesives. Petroleum-based waxes are used to reduce the melt viscosity. Rosin derivatives are used to increase tack. Hot-melts based on polyamide, polyester, and polyurethane are also used. For the hot-melt adhesives to wet the wood surface, they are applied in the molten state. The adhesive then rapidly sets upon cooling. Thus, hot-melts are suited for high-speed, continuous bonding operations. Typical applications include veneer splicing and edge veneering and banding.

4. Wood Adhesives Based on Natural Sources

Although natural adhesives were at one time the predominant adhesives used in the wood industry, since the mid-twentieth century they have been all but displaced by synthetic adhesives. However, synthetic adhesives are derived from petrochemical sources (Table 2). From time to time, various political and economic factors have caused the supply of petrochemicals to decrease dramatically producing a concomitant marked increase in price. This situation has led to continued interest in alternative, natural sources of wood adhesives or of starting materials for the production of wood adhesives (Lambuth 1989). In addition to the proteinaceous adhesives (i.e., animal, soy, casein, and blood adhesives) used in the past, several other natural materials have been and continue to be investigated as sources of wood adhesives. Carbohydrates, tannins, lignins, and "dissolved" whole wood and bark have been studied as total or partial replacement of the phenolic component in phenolic resin adhesives. Diisocyanate resin adhesives have been made from natural sources. And, the chemical bonding of wood has been studied.

4.1 Proteinaceous Adhesives

Protein-based adhesives can be derived from animal

and agricultural sources. These were widely used in the past as wood adhesives. Animal gelatin is obtained from waste and by-products of the meat-processing and tanning industries. The most common starting materials are hides, trimmings from the leather industry, sinews, and bones of cattle and other animals. The adhesive is sold in solid form. This is mixed with sufficient water to soften the adhesive, and the mixture is melted at a temperature under 66°C before application to the wood. Very clean conditions need to be maintained because this adhesive is very susceptible to bacterial attack.

Soybean, casein, and blood adhesives are globular proteins that are soluble in aqueous media. The proteins have a complex three-dimensional structure of highly coiled chains. The three-dimensional structure is dependent on the types of amino acid in the polypeptide chain and their sequence and the hydrogen bonding and disulfide cross-links between individual amino acid side groups. For the protein to function as an adhesive, the internal cross-links must be broken and the highly polar side groups on the amino acids made available for interaction with a polar adherend such as wood (Bye 1989). The disruption of the internal cross-links is accomplished by dissolving (dispersing) the protein, usually in alkaline media.

Bulk soybean flour, which is usually used as the source of wood adhesives, typically contains about 44–50% protein. The flour is formulated into wet-mixed adhesives usually using a combination of slaked lime, caustic soda, and sodium silicate. A number of formulations are possible, and a variety of additives are used to help improve properties. The sequence of adding and mixing of ingredients is often important to the successful utilization of the adhesive for bonding wood. Soy adhesives can be cured by either hot or cold pressing.

Casein, the main protein of milk, is precipitated from skim milk either by allowing the milk to sour, by acids, or by rennet. The adhesive is made by mixing casein and a basic component (e.g., hydrated lime or sodium hydroxide) in the proper proportions. Water is added at the time of use. By adjusting the proportions

Table 2

Source of raw materials for the production of the major synthetic wood adhesives.

Resin	Ingredient	Source
PF	Phenol	Petroleum
	Formaldehyde	Methanol derived from natural gas
UF	Urea	Natural gas
	Formaldehyde	Methanol derived from natural gas
Isocyanate	Aniline	Petroleum
	Formaldehyde	Methanol derived from natural gas
	Phosgene	Carbon dioxide and chlorine
PVAc	Vinyl acetate	Made from acetylene and acetic acid derived from petroleum

of lime or sodium hydroxide, adhesives with differing properties and pot life can be obtained.

Blood-based adhesives are made from spray-dried animal blood. As with the other protein adhesives, blood adhesive is formulated by redissolving the blood in water and dispersing with an alkaline ingredient, such as caustic soda or hydrated lime. Thermosetting resins (usually phenolic) are sometimes incorporated to increase the durability of the adhesive. Hot-press blood adhesives are probably the most durable of the proteinaceous adhesives but are not recommended for exterior applications. Blood proteins have found one modern niche, as foaming agents in PF resins for the plywood industry. The foamed PF adhesive has a high consistency and can be extruded onto the wood veneers instead of being sprayed. This allows a 20–30% reduction in the amount of PF adhesive used in the bonding process.

The major disadvantages of the proteinaceous adhesives compared with the thermosetting adhesives are the following:

(i) They are subject to attack by microorganisms. However, preservative materials can be added that inhibit microbial degradation to some extent.

(ii) They are much less resistant to moisture. However, various cross-linking agents have been tried that increase water resistance to some extent.

4.2 Naturally Derived Phenolic Resin Adhesives

A number of natural phenolic-containing materials are available, including lignins and tannins. Many attempts with varying degrees of success have been made to use these materials either totally or partially for the production of wood adhesives (Pizzi 1994, Pizzi and Mittal 1994). With the exception of cellulose, lignin is the most abundant polymeric material in the plant world. It is a complex, irregular polymer composed of phenyl propane (C_9) units. Lignin is recovered mainly as a by-product of the pulping of wood for the production of paper, primarily by kraft pulping (an alkaline process) and to a lesser extent by sulfite pulping (an acid process). The substitution of lignin, particularly kraft lignin, for phenol in PF resins is the most studied use of lignin. This stems from the fact that lignin is phenolic in nature and, as such, is expected to undergo the same sorts of reactions that occur between formaldehyde and other phenolics. However, due to the fact that the aromatic ring of the lignin molecule is rather highly substituted and that any remaining sites can undergo reactions during the pulping process, there are few positions remaining for lignin to react with formaldehyde. For most industrial lignins, the number of reactive sites per phenylpropane unit is between 0.1 and 0.3. For reactive kraft lignins to be used in the production of adhesives, they need to

be modified in some manner (e.g., by hydroxymethylation, epoxidation, conversion to an isocyanate, and so forth). Because of this lack of reactivity, lignins have not been a successful source of wood adhesives. However, lignins are used successfully as an extender in PF resin adhesives (Sellers 1990).

Sequential extraction of the bark of most coniferous and deciduous trees with water followed by aqueous alkali yields two fractions of polyphenols. These are commonly referred to as condensed tannins and hydrolyzable tannins, respectively. Hydrolyzable tannins have been used successfully as partial replacements for phenol in PF resin adhesives. However, their lack of a macromolecular structure, their low reactivity toward formaldehyde, and their limited worldwide production have led to minimal interest in these tannins as adhesive precursors (Pizzi 1983). Condensed tannins, on the other hand, constitute more than 90% of the total world production of tannins and have generated considerable interest as precursors for adhesive production. Some of these compounds can be reacted with formaldehyde or phenolic-formaldehyde prepolymers to produce suitable thermosetting resins for use in exterior conditions or for producing cold-setting, waterproof adhesives. Commercial extracts of western hemlock, Douglas fir, and redwood in North America were used in a limited capacity as sources of wood adhesives from about 1955 through 1975. Acacia bark tannin (wattle) is currently used in South Africa and South America as a source of wood adhesives. The large quantities of pine bark residues produced at wood-processing plants in North America, Australia, and New Zealand sparked research (especially following the oil crisis of the 1970s) on the use of tannin from these barks as “captive” sources of wood adhesives. But to date there has been no major application of pine bark tannins as wood adhesives. This is due, in part, to the difference in reactivity of pine bark and wattle tannins. Pine bark tannin is more reactive toward formaldehyde than is wattle tannin. This limits the shelf life and assembly times of pine bark tannin adhesives. Condensed tannins and, importantly, even whole bark, can be “liquefied” in phenol with an acid catalyst. This process is referred to as phenolysis or phenolation because the phenol acts not only as the solvent but also as a reactant. The product can be used directly in the formulation of wood adhesives without having to first isolate the tannin (Santana et al. 1995, 1996). The chemistry of the reactions that take place between phenol and tannin has been studied using catechin as a model (Peng et al. 1996, 1997). The results of these studies show that the reactions are very complex. The results suggest that, in part, the pyran rings of the tannin are opened and phenol is appended to the tannin structure.

Simple carbohydrates have also been studied as potential replacements for the phenolic component in phenolic resins or as extenders for phenolic resin adhesives (Conner *et al.* 1989, Sellers and Bomball

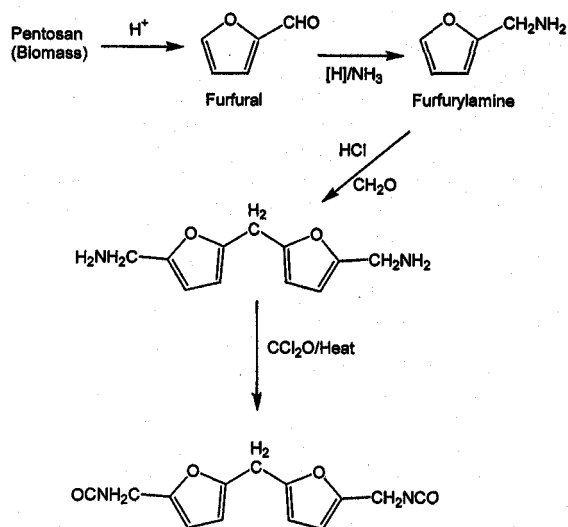


Figure 6
Synthesis of ethylidenebis(2,5-furandiylmethyl)ene)diisocyanate (EDFI) from the pentosans contained in biomass.

1990, Drury et al. 1991). However, they have not been used to any great extent commercially.

4.3 Difurfuryl Diisocyanate Adhesive

Furfural (Fig. 6) is readily obtained from pentosan-containing agricultural residues by an acid hydrolysis process. The primary commercial sources of pentosans (polysaccharides that yield pentoses upon hydrolysis) are corncobs and sugar cane bagasse. However, other pentosan-containing materials (e.g., hardwood residues and rice hulls) could be used. Furfural is converted to furfurylamine by reductive amination. Furfurylamine can be used as the starting material for the synthesis of difurfuryl diisocyanates. The mechanical properties of flakeboards bonded with difurfuryl diisocyanate (e.g., EDFI) were comparable with the properties that were obtained with MDI (Holfinger et al. 1993, Coppock et al. 1996). Thus, EDFI is an excellent adhesive that can be derived from renewable resources. A potential drawback is that the synthesis of this material might be expensive compared with the synthesis of other adhesives. There is a distinct advantage in using EDFI as an adhesive as opposed to the use of tannin or lignin. Tannin and lignin are complex materials that can differ in their exact chemical composition depending upon the methods used for their isolation and, indeed, upon the species of plant material from which they are isolated. Therefore, it is hard to be sure of the consistency of tannins and lignins from one batch to the next. On the other hand, EDFI, although ultimately obtained from

a renewable resource, is synthesized from a known compound (furfural). Therefore, its consistency from batch to batch should be the same. Indeed, this is one of the advantages of synthetic adhesives derived from petroleum sources.

5. Nonconventional Bonding of Wood

A variety of mechanisms have been advanced to explain the adhesion between an adhesive and a substrate (Kinlock 1987; see also Wood: Surface Properties and Adhesion). These mechanisms include mechanical interlocking-entanglement, specific adhesion (e.g., covalent bonds, hydrogen bonds, van der Waals bonds, and London forces), diffusion-molecular entanglement, and electrostatic interactions.

Mechanical interlocking-entanglement and specific adhesion have received the most emphasis as possible mechanisms for conventional wood bonding. Diffusion-molecular entanglement and electrostatic interactions are more controversial mechanisms when applied to wood bonding. With the possible exception of bonding with isocyanates (Wendler et al. 1996), the direct covalent bonding of wood has never been demonstrated.

Attempts to bring about covalent bonding as a mechanism for wood bonding has drawn the attention of many researchers (Zavarin 1984, Johns 1989) because covalent bonding would in theory provide a bond that is waterproof and is as strong as whole wood. These attempts have been termed "non-conventional bonding" (Zavarin 1984) or "chemical bonding" (Johns 1989). Nonconventional bonding of wood includes many different methods, most of which involve the activation of the wood surface in some way. All the methods involve attempts either to develop direct covalent bonds between wood surfaces, to employ bifunctional monomers for joining wood surfaces, or to attempt to covalently bridge between wood surfaces with polymers (Zavarin 1984). The most common methods for chemical bonding include the simultaneous application of some form of reactive chemistry plus heat to form the bonding system. The reactive chemistry can be either acidic, alkaline, or oxidative. Examples of these methods include bonding with spent sulfite liquor, furfuryl alcohol, and maleic anhydride after oxidative activation of the wood surfaces (Johns 1989); bonding of wood flakes with lignin after treatment with sodium hydroxide (Young et al. 1985); treating the wood surface with modifiers such as hydroxymethylated resorcinol (Vick et al. 1998); and attempts to form direct covalent bonds between wood surfaces after treatment of the surfaces with various oxidizing agents (Zavarin 1984). A variety of analytical methods, including x-ray photoelectron spectroscopy, diffuse reflectance Fourier

transform infrared spectroscopy, and nuclear magnetic resonance spectroscopy, have been used to investigate the effect of surface activation on the surface chemistry of the wood after treatment with acid, base, or an oxidizing agent (Gardner *et al.* 1991).

6. Wood Bonding

The bondability of wood is affected by both the surface properties of the wood (see *Wood: Surface Properties and Adhesion*) and the physical properties

Table 3

Categories of selected wood species according to ease of bonding.

US hardwoods	US softwoods	Imported woods	
<i>Bond easily^a</i>			
Alder	Fir	Balsa	Hura
Aspen	White	Cativo	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		
<i>Bond well^c</i>			
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
<i>Bond satisfactorily^e</i>			
Ash, white	Alaska cedar	Angelin	Meranti (lauan), dark red
Beech, American	Port Orford cedar	Azobe	Pau marfim
Birch	Pine, southern	Benge	Parana-pine
Sweet		Bubinga	Pine
Yellow		Karri	Caribbean
Cherry			Radiata
Hickory			Ramin
Pecan			
True			
Madrone			
Maple, hard			
Oak			
Red ^b			
White ^b			
<i>Bond with difficulty^f</i>			
Osage orange		Balata	Keruing
Persimmon		Balau	Lapacho
		Greenheart	Lignumvitae
		Kaneelhart	Rosewood
		Kapur	Teak

Source: Vick (1999).

a Bonds very easily with adhesives of a wide range of properties and under a wide range of bonding conditions. b Difficult to bond with PF adhesive. c Bonds well with a fairly wide range of adhesives under a moderately wide range of bonding conditions. d Wood from butt logs with high extractive content are difficult to bond. e Bonds satisfactorily with good-quality adhesives under well-controlled bonding conditions.

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

Table 4

Wood adhesives categorized according to their expected structural performance at varying levels of environmental exposure.

Structural integrity	Service environment	Adhesive type ^a
Structural	Fully exterior (withstands long-term water soaking and drying)	PF RF PRF Emulsion polymer/isocyanate MF
	Limited exterior (withstands short-term water soaking) Interior (withstands short-term high humidity)	MUF Isocyanate UF Casein Blood
Semistructural	Limited exterior	Cross-linked PVAc Polyurethane
Nonstructural	Interior	PVAc Animal Soybean Elastomeric construction Elastomeric contact Hot-melt Starch

Source: Vick (1999).

^a Assignment 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.

of the wood, particularly density, porosity, moisture content, and dimensional movement. Table 3 categorizes commonly used domestic and imported wood species according to their relative ease of bonding (Vick 1999). Density is a crude indicator of the bondability of a great variety of wood species. High-density woods are difficult to bond. Because of thicker cell walls and less lumen volume, adhesives do not penetrate easily, so important mechanical interlocking of the adhesive is limited to one to two cells deep. Much greater pressure is required to compress stronger, stiffer, high-density wood to bring contact between the wood surface and the adhesive. The severe stresses produced by high-density species as they change dimensions with changes in moisture content also contribute heavily to bonding difficulties.

Porosity varies greatly from species to species and affects the depth and direction that an adhesive flows into the wood. To maintain the highest joint strength, the adhesive must penetrate and mechanically interlock several cells deep into sound, undamaged cell structure. Porosity also varies with grain direction. Over-penetration of the adhesive can occur in certain directions, e.g., end grain, or is limited in other directions, e.g., across the grain. This can lead to difficulties in wood bonding. The amount of moisture in wood combined with water in the adhesive will influence the wetting, flow, penetration, and possibly even the cure of adhesives. In addition, dimensional changes that occur as the moisture content of wood changes can have broad-ranging and significant con-

sequences on the performance of bonded joints. For example, as wood in bonded assemblies swells and shrinks due to changes in the moisture content, stress develops that often can be great enough to rupture adhesive bonds or the wood.

As discussed previously, a broad array of adhesive types are available for bonding wood materials and wood to nonwood materials. These adhesives were classified earlier as to the chemical and physical nature of the adhesive resin. These adhesives can also be classified by their relative strength and durability according to levels of structural integrity (Table 4). In selecting an appropriate adhesive, the structural integrity of the adhesive bond under anticipated service loads in the presence of expected environmental exposure conditions is the prime consideration. The selection process must also consider the compatibility of the adhesive system with the physical and chemical properties of the surface of the wood adherend. The polar, aqueous adhesive must be capable of wetting the usually polar surface of wood. As the adhesive wets the surface, it must have flow properties that enable it to spread over the surfaces of variable roughness and to penetrate wood structures that differ in porosity, with respect to grain orientation at the bond line. The adhesive must make molecular contact with the lignocellulosic components of the wood and penetrate deeply enough to interlock mechanically into the cellular structure of the wood on cure. Typical applications for various wood adhesives are outlined in Table 5.

Table 5
Working and strength properties, with typical uses of wood adhesives.

Type	Form and color	Preparation and application	Strength properties	Typical uses
Natural origin Animal, protein	Solid and liquid; brown to white bond line	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 bond line	Mixed with cold water, lime, caustic soda, and other chemicals; applied at room temperature; pressed either at room temperature or 120°C and higher	High dry strength; moderate resistance to water and damp atmosphere and to microorganisms	Interior-type softwood plywood, sometimes in combination with soybean adhesive. Mostly replaced by phenolic resin
Casein, protein	Powder with added chemicals; white to tan bond line	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 bond line	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 resin. New fast-setting resorcinol- soybean adhesives for fingerjointing of lumber being developed
Lignocellulosic residues and extracts	Powder or liquid; may be blended with phenolic resin; dark-brown resin and bond line	Blended resin modified with extender and filler by user; adhesive cured in hot press 130–150°C similar to phenolic resin	Good dry strength; moderate to good wet strength; durability improved by blending with phenolic resin	Partial replacement for phenolic resin in composite and plywood panel products
Synthetic origin Cross-linkable PVAc resin emulsions	Liquid, similar to PVAc resin emulsions but includes a resin capable of cross-linking with a separate catalyst; white to tan resin and colorless bond line	Liquid resin 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; molding and architectural woodwork; cellulose overlays
Elastomeric contacts	Viscous liquid, typically neoprene or styrenebutadiene 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 procedures instant bonding	Strength develops immediately upon pressing, increases slowly over period of weeks; dry strengths much lower than those of conventional wood adhesives	On-the-job bonding of decorative tops to kitchen counters; factory lamination of wood, paper, metal, and plastic sheet materials; low resistance to water and damp atmospheres; adhesive film readily yields under static load

Table 5
(cont.)

Type	Form and color	Preparation and application	Strength properties	Typical uses
Elastomeric mastic (construction adhesives)	Putty-like consistency, synthetic or natural elastomers in organic solvent or latex emulsions; tan, yellow, gray	Mastic extruded in head 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 outdoor 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 resins	Liquid resin, emulsion and separate isocyanate hardener; white resin and brown hardener; colorless bond line	Resin 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
Epoxy resins	Liquid resin and hardener supplied as two parts; completely reactive leaving no free solvent; clear to amber; colorless bond line	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; delamination resistance to wood greatly improved with hydroxymethylated resorcinol coupling agent (Vick et al. 1998); gapfilling	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-melts	Solid blocks, pellets, ribbons, rods, or films; solvent-free; white to tan; near colorless bond line	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 resins	Liquid resin containing isomers and oligomers of methylene diphenyl diisocyanate; reactive with water; light brown resin and clear bond line	Resin applied directly by spray or coating by user; reactive with water, but requires high temperature and high pressure for best bond development in flakeboards; laminating resins curable at room temperature	High dry and wet strength; very resistant to water and damp atmosphere; adheres to metals and plastics	purpose home and shop Flakeboards; strandwood products; lamination of components in I joists

Table 5
(cont.)

Type	Form and color	Preparation and application	Strength properties	Typical uses
Melamine and melamine-urea resins	Powder with blended catalyst; may be blended up to 40% with urea; white to tan; colorless bond line	Mixed with water; cured in hot press at 120–150°C; particularly suited for fast curing in radio-frequency-heated presses	High dry and wet strength; very resistant to water and damp atmospheres	Melamine-urea primary adhesives for durable plywood, end-jointing, and edge-gluing of lumber; and scarf-jointing softwood plywood
Phenol resin	Liquid, powder, and dry film; dark red resin and black bond line	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 120–150°C, and up to 200°C 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
PVAc resin emulsions	Liquid ready to use; often polymerized with other polymers; white to tan to yellow; colorless bond line.	Liquid applied directly; pressed at room temperatures and in radio-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 housings; general-purpose home and shop
Polyurethane resins	Low viscosity liquid to high viscosity mastic; supplied as one part; reacts with moisture on adherends and air to cure; two-part systems completely reactive; color varies from clear to brown; colorless bond line	Resin applied directly to one surface, preferably to water-misted surface; reactive with moisture; 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 resins	Liquid resin and powder; hardener supplied as two parts; phenol resins may be blended with resorcinol resins; dark red resin and bond line	Resin mixed with powdered or liquid hardener; resorcinol adhesives cure at room temperatures; phenol-resorcinols cure at temperatures from 21 °C to 66°C	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 resin	Powder and liquid; may be blended with melamine or other more durable resins. White to tan resin with colorless bond line	Powder mixed with water, hardener, filler, and extender by user; some formulations cure at room temperatures, others require hot pressing at 120°C; curable with radio-frequency heating	High dry and wet strength; moderately durable under damp atmospheres; moderate to low resistance to temperature in excess of 50 °C	Hardwood plywood; furniture; fiberboard; particleboard; flush underlayment; flush doors; furniture cores

Source: Vick (1999).

7. Conclusion

Adhesive bonding of wood is not only key to the efficient utilization of wood, it has been a key factor in the development and growth of the forest products industry. As the world population increases, the demand for wood and wood products will increase. To meet this increased demand while protecting the fragile ecosystems in which wood grows, the utilization of wood harvested from those ecosystems must be maximized. Because of this, adhesives will continue to be important to both the consumer and manufacturer of wood and wood products well into the future. Because of the importance of adhesives to the utilization of wood, it is expected that improvements in adhesive systems will continue to be made. Future areas for the improvement of adhesive systems will concentrate on increased durability, faster cure, and cure in the presence of higher moisture contents within the wood being bonded. A wide variety of adhesive types are presently available. These types meet the needs of the consumer of wood products and the forest products industry very well. It is expected that these adhesive systems, or new adhesive systems based on the same basic types of chemistries, will continue to be the primary adhesive types used to bond wood.

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See also: Lumber: Laminated Veneer; Wood: Macroscopic Anatomy; Wood-Plastic Composites; Wood: Nonstructural Panels

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Encyclopedia of Materials : Science and Technology

ISBN: 0-08-0431526

pp. 9583–9599