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Gluing of Eastern Hardwoods: A Review

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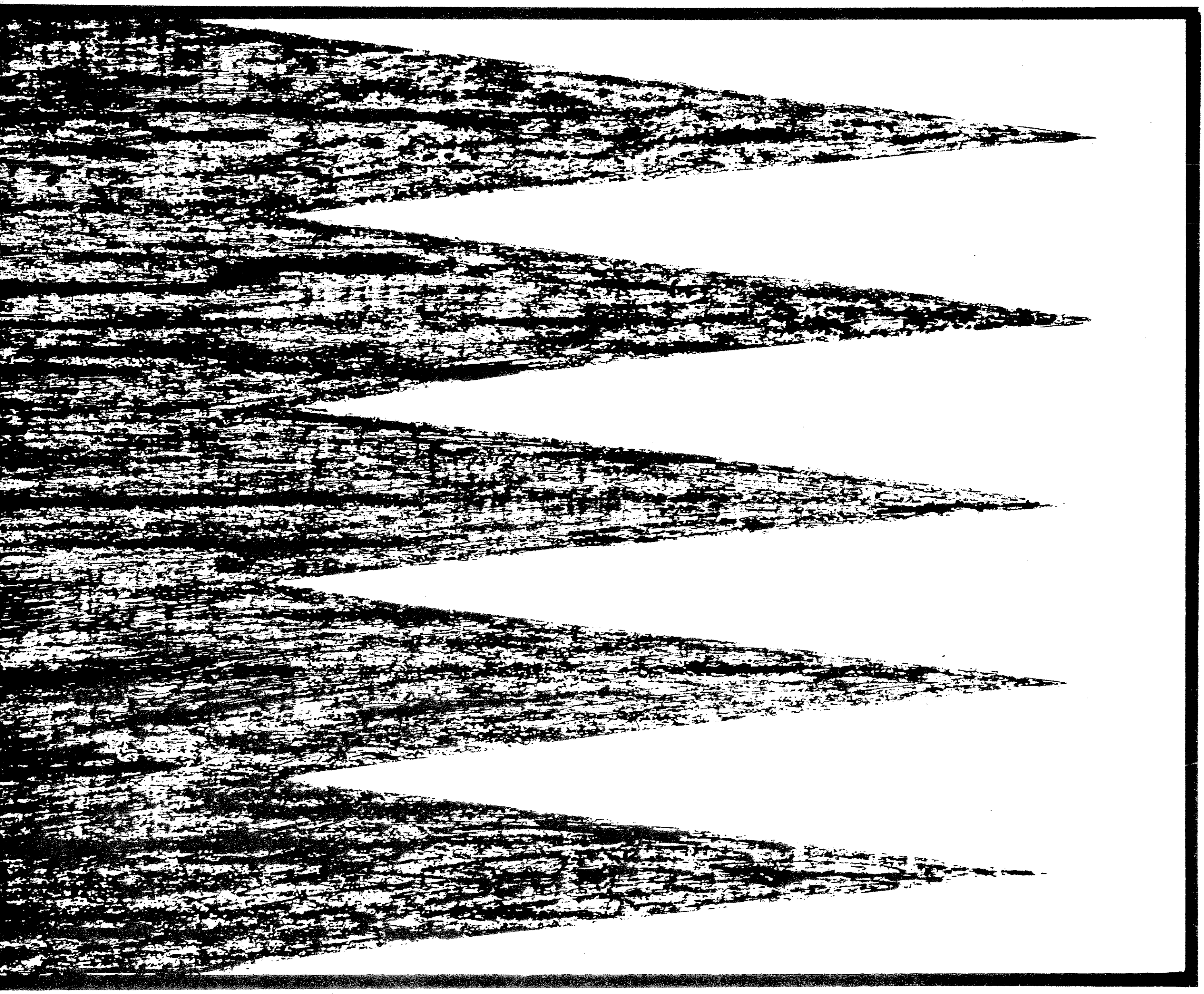

SUMMARY

Over a period of years, increasing demand for softwoods in the Eastern United States has led to an increase in the growth of hardwoods on cut-over softwood sites. Unfortunately these hardwood trees are often of a size and shape unsuitable for the production of high-grade lumber and veneer. They do, however, represent a viable, economic source of raw material for plywood, fiberboard, particleboard, and oriented strandboard (or flakeboards), all products that require the successful use of adhesives in their manufacture.

The current status of gluing eastern hardwoods is reviewed in this report, with emphasis on hardwoods growing on southern pine sites. The subjects covered include adhesives, wood and wood-surface properties and their interactions with the adhesive, and the quality of the bonds produced when these hardwoods are used in the manufacture of end joints, laminates, plywood, and other composite panels.

A variety of adhesives are available that equal or exceed the strength of the hardwoods being bonded. The choice of a particular adhesive is dictated in large measure by the adhesive price and the end-use criteria for the finished product.

In discussing the gluing of eastern hardwoods, the approach taken is that the fundamentals that determine the quality of an adhesive bond should remain the same whether the substrate is a softwood or a low-, medium-, or high-density hardwood. To illustrate the differences encountered in gluing the various hardwood species and the best approach for dealing with them in terms of bonding fundamentals, in this report we will concentrate on:

- The quality and character of the surface as affected by wood structure.
- Bond strength, dimensional change, porosity, and compaction of composites as affected by species' density.
- Ability of the resin to wet the surface and penetrate the fine structure of the cell wall.
- Gross penetration as affected by wood structure, resin viscosity, and resin flow.
- The interaction between pH of tannins, or other extractives, and the curing mechanism of resins.

Adhesives are available to provide the necessary structural integrity for plywoods, particleboards, flakeboards, and fiberboards with hardwood substrates; however, in many cases the adhesive cost may be considered excessive in terms of current commercial practice. Development opportunities lie in providing a family of adhesives that will provide exterior bonds at a competitive price over the whole range of southern hardwoods, including those at the high end of the density scale.

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INTRODUCTION

Hardwoods constitute about one-third of the United States timber resource and occupy slightly over half the Nation's commercial timberland. Occurring mainly in the East, they predominate over two-thirds of the eastern forest acreage. Although varying widely in many characteristics and often of high value in large, clear sizes, most hardwood trees tend to be small, crooked, and defective. Over much of the South they occupy sites on which pines could be grown more profitably (table 1). In both the South and the Northeast, stands of hardwoods, even on the better hardwood sites, contain much material that is of marginal value for traditional uses.

One of the better ways to make optimum use of this low-grade hardwood resource is in composite products, such as fiberboard, particleboard, and flakeboard, where product quality is not a direct function of stem quality. Another possibility is to use hardwoods for the production of structural plywood or glued-laminated materials, such as truck bedding or furniture parts.

Hardwoods have been glued routinely over a long period of time using a variety of adhesives ranging from the most primitive natural-based glues used at the time of Egyptian Pharaohs to the latest of the polymerics. In most past instances, the bonds formed were neither stressed to the capacity of the substrate nor used in applications where they were exposed to a hostile environment, such as alternate wetting and drying, prolonged exposure to high moisture, or a combination of high moisture and high temperature. There have been notable exceptions, e.g., the gluing of red and white oak for use in the construction of anti-magnetic minesweepers during and after World War II.

Recently there has been a renewed interest in the details of hardwood bonding due to the economics of the wood supply in the Southeastern and North Central United States. In both of these areas, low-grade or under-utilized hardwood species are attractively priced as furnish for structural, reconstituted flakeboard panels (waferboard and oriented strandboard). In the Southeast, the use of medium-density hardwoods in structural plywood and flakeboards not only provides a low-cost raw material, but the inclusion of these hardwoods in the logging operation reduces both the cost of southern pine delivered to the mill and subsequent site preparation costs for replanting to pine.

In both structural plywood and reconstituted wood panels, bonds are required that will develop the load-carrying capacity of the wood and retain a high percentage of the dry strength following prolonged exposure to heat, high moisture, and numerous cycles of wetting and drying. Under these circumstances, the gluing of hardwoods, especially those of higher density, is more of a challenge than when these same species are

Table 1.—*The hardwood resource on southern pine sites, ranked by percentage of total hardwood volume*[1]

Common name	Scientific name	Percent
Sweetgum	*Liquidambar styraciflua* L.	13.2
White oak	*Quercus alba* L.	12.3
Hickory	*Carya* spp.	8.5
Southern red oak	*Q. falcata* Michx. *var. falcata*	8.1
Post oak	*Q. stellata* Wangenh	7.0
Yellow-poplar	*Liriodendron tulipifera* L.	7.0
Black tupelo	*Nyssa sylvatica* Marsh.	5.5
Water oak	*Q. nigra* L.	4.7
Chestnut oak	*Q. prinus* L.	4.2
Black oak	*Q. velutina* Lam.	4.0
Scarlet oak	*Q. coccinea* Muenchh.	3.6
Red maple	*Acer rubrum* L.	3.6
Northern red oak	*Q. rubra* L.	2.4
Laurel oak	*Q. laurifolia* Michx.	1.4
American elm Winged elm	*Ulmus americana* L. *U. alata* Michx.	1.4
Cherrybark oak	*Q. falcata* Michx. var. *pagodifolia* Ell.	1.2
Green ash White ash	*Fraxinus pennsylvania* Marsh. *F. americana* L.	.9
Sweetbay	*Magnolia virginiana* L.	.6
Shumard oak	*Q. shumardii* Buckl.	.2
Hackberry	*Celtis* spp.	.1
Other hardwoods		10.1
Total		100.0

[1]Source: "The Wood and Bark of Hardwoods Growing on Southern Pine Sites—a Pictorial Atlas" *(99)*.

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used in glued assemblies put to service in a less severe environment. Add to these criteria the need to treat structural plywood and reconstituted wood panels to impart decay and fire resistance and the problem increases in difficulty. A substantial body of literature has evolved from the long-term and continuing interest in the gluing of hardwoods. It identifies some of the problems and opportunities associated with the adhesion and performance of glued hardwood products under various conditions. Although much of the literature describes results obtained with hardwoods from nonpine sites (table 2), the data are, for the most part, equally applicable to pine-site hardwoods.

By pointing out some of the general principles that determine bond quality, this report should provide a background that will help the reader solve problems encountered in gluing southeastern hardwoods. Included in the discussion is an overall concept of adhesion and adhesives, an overview of hardwood anatomy, and comments as to the interactions that must occur in the processing steps in order to form high-performance hardwood glue bonds. This report can easily serve as a companion volume to Agriculture Handbook Number 605, "Utilization of Hardwoods Growing on Southern Pine Sites," by Peter Koch, published by the U.S. Department of Agriculture, Forest Service, Washington, DC.

WOOD ADHESION AND ADHESIVES

The Nature of Wood Adhesion

When gluing two pieces of wood together, the basic objective of the resultant adhesion is to hold the two pieces of wood in a fixed position so that when under load to the point where the stress applied exceeds the strength of the wood, the failure occurs within the wood. To achieve this goal, it is necessary that both the molecular attraction between the adhesive and the wood surface (adhesion forces) and the molecular attraction by which the adhesive is united throughout its mass (cohesion forces) are greater than the strength of the wood.

The total adhesion of glue (adhesive) to any wood is the sum of the adhesive forces of varying magnitudes operating on the excised (cut) and unexcised (uncut) surfaces of the cell walls exposed during machining (*76, 148*). The exact nature of the adhesive forces involved in wood gluing remains moot. For the purposes of this discussion it is assumed that mechanical interlocking is a minor factor; the major contributors are Van der Waal's forces, hydrogen bonding, and covalent bonds (*96, 115*). These forces operate over very short distances, 2 to 3 angstroms (0.2 to 0.3 nm), hence it is essential that the adhesive be in intimate contact with the wood surface for adhesion to take place. Stated differently, it is necessary that the adhesive flow onto and wet the wood. Certain southern hardwoods have surface films of cellular protoplasmic residue or cellular waste infiltrates (tannins, oleoresins, etc.) that preclude wetting of the wood surface, and adhesion does not occur. It should be noted that once adhesion takes place, failure in joints loaded to the point of destruction is invariably a cohesive failure in either the adhesive or wood.

Table 2.—*Hardwood species common on nonpine sites*

Common name	Scientific name
Aspen, bigtooth	*Populus grandidentata* Michx.
Aspen, quaking	*P. tremuloides* Michx.
Basswood	*Tilia* spp.
Beech, American	*Fagus grandifolia* Ehrh.
Birch, river	*Betula nigra* L.
Birch, sweet	*B. lenta* L.
Birch, paper	*B. papyrifera* Marsh.
Birch, yellow	*B. alleghaniensis* Britton
Blackgum	*Nyssa sylvatica* Marsh.
Boxelder	*Acer negundo* L.
Butternut	*Juglans cinerea* L.
Cherry, black	*Prunus serotina* Ehrh.
Cottonwood, eastern	*Populus deltoides* Bartr. ex Marsh.
Elm, slippery	*Ulmus rubra* Muhl.
Elm, rock	*U. thomasii* Sarg.
Elm, cedar	*U. crassifolia* Nutt.
Hickory, mockernut	*Carya tomentosa* (Poir.) Nutt.
Hickory, shagbark	*C. ovata* (Mill.) K. Koch
Honeylocust	*Gleditsia triacanthos* L.
Maple, silver[1]	*A. saccharinum* L.
Maple, red[1]	*A. rubrum* L.
Maple, sugar	*A. saccharum* Marsh.
Oak, bur	*Q. macrocarpa* Michx.
Oak, blue	*Q. douglasii* Hook. & Arn.
Oak, overcup	*Q. lyrata* Walt.
Oak, pin	*Q. palustris* Muenchh.
Osage-orange	*Maclura pomifera* (Raf.) Schneid
Pecan	*C. illinoensis* (Wangenh.) K. Koch
Hickory, water	*C. aquatica* (Michx. f.) Nutt.
Persimmon, common	*Diospyros virginiana* L.
Poplar, aspen	*Populus* spp.
Sweetgum	*Liquidambar styraciflua* L.
Sycamore	*Platanus occidentalis* L.
Tupelo, water	*N. aquatica* L.
Walnut, black	*J. nigra* L.
Willow, black	*Salix nigra* Marsh.

[1]Soft maples.

Bond formation consists of the following steps:

- Spreading the adhesive evenly on the surface to be joined.
- Bringing the surfaces into intimate contact.
- Immobilizing the adhesive through evaporation/absorption/adsorption.
- Applying pressure to mate the surfaces and facilitate adhesive flow and wetting.
- Applying heat to induce flow, accelerate immobilization of the adhesive, and initiate or increase the rate of cure.
- Allowing wetting and penetration of the adhesive into the cell wall (required for a fully waterproof bond).

- Completion of the chemical-physical reactions that convert the polymer into a rigid solid.

If the requirements of each step can be met in terms of the adhesive operational parameters and the interaction of wood and adhesive at the interface, it is possible to form a hardwood glue bond that will have long-term structural integrity in exterior service. In the case of the high-density hardwoods, adhesive and processing costs to achieve this end may limit the procedure to specialty items.

Adhesives: Background

To be a satisfactory adhesive, a material must be capable of both wetting the wood substrate (polar attraction) and being converted into a rigid solid through either evaporation of the solvent or a chemical reaction that may require a catalyst and/or heat to complete. Many applications require that the cured adhesive retain its strength in the presence of moisture and elevated temperatures. When used in structural applications, the cured adhesive must equal or exceed the substrate in strength. Fortunately there are a number of materials that meet these requirements, and they are commercially available at a reasonable cost (tables 3 and 4).

In a generic sense, most of the modern wood adhesives listed in table 3 can be used in gluing southern hardwoods. To achieve bonds, it may be necessary to adjust the chemistry (molecular weight distribution, pH, etc.) of the basic polymer, tailor the adhesive mix, and alter process parameters. To make these adjustments on a commercial scale may require the assistance of an adhesive vendor, of which there are over 500 in the United States competing for the total adhesive market (*56*).

Adhesives: Development

Early wood adhesives were natural-product based, i.e., animal, casein, soybean, and starch glues (*114*). Although some natural adhesives, such as casein, formed a moderately water-resistant bond, a truly waterproof glue line was not available to the wood industry until the advent of various coal tar or petroleum-based synthetic resins in the mid-1930's. These versatile adhesives, known generically as urea-, melamine-, phenol-, and resorcinol-formaldehyde resins, dramatically increased the kinds and amounts of glued-up products that could be manufactured. Polyvinyl resin emulsions were a later addition to the synthetics, which in their copolymer forms are continually being upgraded in durability. Although polyvinyl resin emulsions lack the complete durability and rigidity of phenol and resorcinol resins even in their cross-linked aliphatic or other copolymer forms, their quick tack and rapid cure at room temperature have made them widely used as adhesives for panel and assembly gluing. During the early 1980's, isocyanate polymers found limited use in bonding waferboard and particleboard products. Various combinations of emulsion polymers with isocyanates and phenol have found increased use for specialty applications. Adhesive technology has advanced over the years from an empirical art to a sophisticated, semiquantitative science (*11*).

Adhesives: Types

Characteristics of the common resin-adhesives used to bond hardwoods are described briefly in table 3. More complete information follows with emphasis placed on the widely used petrochemical derived adhesives.

Urea-Formaldehyde Resin.—Urea-formaldehyde (UF) resins are amino-aldehyde products whose price is determined in large part by the agricultural urea consumption in the United States (*152*). The raw materials used in its production, urea and formaldehyde, contain no benzene or aromatic compounds. As a result these resins are low in cost when compared to most emulsion polymers and other synthetic thermosetting resins. Urea-formaldehyde resins are acid curing and heat accelerated. In final form they are generally regarded as highly cross-linked, rigid, crystalline-like polymers noted for their fast cure and high strength (*145*). Because of their versatility and low cost, they are widely used in the manufacture of either hardwood or softwood furnish particleboard.

Urea-formaldehyde resins will not withstand continuous cycles of wetting and drying and will begin to degrade at about 140 °F (60 °C) and 60-percent relative humidity. Wood moisture content of 15 to 20 percent accelerates UF resin degradation at temperatures lower than 140 °F (60 °C). Plywood and reconstituted wood panels made with UF resin are not used for roof decking or exterior siding as they lack the necessary long-term moisture and temperature resistance.

Phenol-Formaldehyde Resin.—Phenol-formaldehyde (PF) resin is derived from benzene, which in turn originates from the distillation of petroleum (*152*). These polymers are considered waterproof and are being increasingly used to bond structural hardwood products suitable for exterior purposes.

Two types of PF resins are produced "novolaks" and "resols" (*78*). Novolaks are more linear in structure than resols and require heat to cure plus hardener to improve cross linking. They do not lose their melt flow and soluble properties, even after prolonged heating, until a formaldehyde (cross-linker) addition has been made. They are manufactured under acid conditions using an excess of phenol, for example a 0.8-to-1 molar ratio of formaldehyde to phenol (F to P).[1] Due to the

[1]A mole used in this report is the amount of a substance that has a weight in grams numerically equal to the molecular weight of the substance. The molecular weight of phenol is 94.1 and formaldehyde is 30.

Table 3.—*Adhesives commonly used in gluing hardwoods*[1]

Adhesive resin	Characteristics	Typical applications	Mixed cost/lb[2]	Spread range[3]
			Dollars	
Urea-formaldehyde (UF)	Hot setting and cold setting; acid curing with heat and/or catalyst accelerated fast cure; cold-water resistant; colorless; may emit formaldehyde in use	HW flooring, Type II plywood (decorative), particleboard, and fiberboard; interior exposure	0.08	45–65 (PB 5-8%)[4]
Phenol-formaldehyde (PF)	Hot setting; normally cured above 200 °F (105 °C); usually highly alkaline for rapid cure; waterproof; dark in color	Structural plywood, truss components, OSB, and waferboard; exterior exposure	0.10 0.34 0.55	35–50 (plywood) (OSB 3.5–6%, liquid PF) (WB 2–3%, spray-dried PF)
Melamine/Urea (MF/UF)	Hot setting; heat and catalyst accelerate cure; warm-water resistant; colorless	Plywood (decorative), flat-bed stock, and end joints in laminating; interior and limited exterior exposure	0.30	45–65
Emulsion polymer/ isocyanates (EPI)	Cold or hot setting; two-component system; room-temperature curable; water and temperature resistant; neutral in color; nonformaldehyde emitting	Laminating wood-to-wood and wood-to-nonwood substances, mill work contact and pressure sensitive; interior and exterior exposure	0.45	25–30
Isocyanates (MDI)	Hot setting; water and heat accelerate cure, waterproof under severe conditions; neutral in color (press release agent tans wood surfaces).	Waferboard, OSB, and particle-board; interior and exterior exposure	0.70	(WB 2–4.5%, PB 4–5%)
Melamine-formaldehyde (MF)	Hot setting; heat and catalyst accelerate cure; water resistant; colorless; shipped in spray-dried form	Laminated beams (moderate use in U.S.), end joints in laminating truck decking, and Type I HW plywood (decorative); limited exterior exposure	0.40	45–65
Polyvinyl acetate and derivatives (PVAc)	Homopolymers (compounded or uncompounded): Cold setting; somewhat flexible when cured; poor water resistance; light in color; tendency to creep under load; gap filling; rapid tack	Assembly gluing, gluing face veneers to core stock, and edge banding; interior exposure	0.60	35–50
	Copolymers: Cold or hot (and Rf) setting; heat and catalyst accelerates cure; moderately water resistant (cross-linked); more rigid and gap filling	Edge and face stock, HW plywood, finger joints; interior and limited exterior exposure		
Phenol-resorcinol formaldehyde (PRF)	Room temperature and warm setting; heat and catalyst accelerate cure; waterproof under severe conditions; dark in color; particularly suited for difficult bonding conditions	Bridge and pier components, laminated beams, and truck decking; interior and exterior exposure	1.30	45–65
Resorcinol-formaldehyde (RF)	Cold or hot setting; cure accelerated by catalyst and heat; waterproof under severe conditions; dark in color; particularly suited for difficult bonding conditions.	Laminates, ship components, outdoor furniture, and fire-rated panels; extreme exterior service	1.45	45–65

[1]Abbreviations used in this table are hardwood (HW), oriented strandboard (OSB), particleboard (PB), and waferboard (WB).
[2]In terms of 1985 dollars
[3]Spreads are shown on a weight-per-square-area basis (lb/1000 ft^2 of joint area) merely for comparison purposes.
[4]PB 5–8% denotes 5 to 8 percent resin solids applied to board on a weight basis.

Table 4.—*Mix cost and spread range of adhesives commonly used to glue hardwoods*

Adhesive resin	Mix cost/kg[1]	Spread range [2]
	Dollars	
Urea-formaldehyde (UF)	0.17	219–317
Phenol-formaldehyde (PF)	0.22 (plywood type)	171–244
	0.74 (liquid, OSB)	
	1.21 (spray-dried, WB)	
Melamine/urea (MF/UF)	0.66	219–317
Emulsion polymer/isocyanate (EPI)	0.99	122–146
Isocyanates (MDI)	1.54 (OSB, WB)	....
Melamine-formaldehyde (MF)	0.88	219–317
Polyvinyl acetate (PVAc) and derivatives	1.32	171–244
Phenol/resorcinol (PRF)	2.86	219–317
Resorcinol-formaldehyde (RF)	3.19	219–317

[1]In terms of 1985 dollars.

[2]In g/m^2 of joint area. Multiply g/m^2 by a factor of 0.205 to convert to lb/1000 ft^2, single glue-line basis.

cured acidity, the higher cost, and the additional requirement of a cross-linking hardener to overcome the thermoplastic characteristic of novolaks, they are not often used as wood adhesives in the United States. Novolaks plus cross-linking agents, such as hexamethylenetetramine ("hexa") or paraformaldehyde ("para"), are used in blends with melamine-formaldehyde resin in Europe (*128*).

Resols are phenolic resins produced under alkaline conditions (pH greater than 7) using molar ratios of formaldehyde in excess of phenol (the reverse of novolak). A resol for wood gluing may have a 1.6-to-1 to 2.5-to-1 formaldehyde-phenol molar ratio. Resols prepared at low F-to-P ratios have a relatively linear structure, whereas resols prepared at high F-to-P ratios have a highly branched (cross-linked) form.[2] A typical plywood PF resin may be near an F-to-P mole ratio of 2 to 1, with resultant high heat-distortion temperatures, high modulus, high tensile strengths, excellent dimensional stability, low flammability, and good moisture resistance in the cured state due in part to greater cross-linking density. Unlike novolaks, resols are irreversibly hardened at higher temperatures without added cross linkers and classified as thermosetting. They are made in a very wide range of viscosity and molecular weight for specific end uses. Resol PF resin adhesives are the mainstay of structural plywood and waferboard/strandboard (flakeboard) panel manufacture. These phenolics and other resin adhesives have been used to bond dense hardwood plywood for custom orders since they became available during the 1935–45 era.

[2]Takahasi, K; Hsu, L. C. 1982. Molecular Weight Distribution Studies of Resole Type Phenol-Formaldehyde Resins. Unpublished presentation, CIC Conference, 31 May, Toronto, Ontario, Canada: On file at Reichhold Chemicals, Ltd., 50 Douglas Street, Port Moody, BC, Canada V3H 3L9.

In selecting PF adhesives suitable for bonding hardwoods, the literature recommends that the resin chosen have the following characteristics (*83, 115*):

- Relatively low alkali content, generally about one-third to not more than one-half molar (caustic to phenol) as compared to softwood plywood resins, which are typically one-half molar or higher.
- As much as 50 percent lower in average molecular weight than phenolic resins designed for softwood gluing.
- High in methylol group content. Alternatively, the resin may contain free-formaldehyde or require a matching catalyst that contains paraformaldehyde.
- The B-stage characteristic of reliquefying briefly under heat and pressure to allow transfer and flow on the glue lines of a plywood panel or at the interface of flake-to-flake bonds.
- Higher thermal softening points than many other conventionally prepared resins. This characteristic indicates a network that has more cross links after the final cure, leading to greater durability.
- Forty to 45 percent nonvolatile solids for plywood manufacture, 50- to 60-percent nonvolatile solids content for use in strandboard, and usually 100 percent solids (powder) for use in waferboard.

Melamine-Formaldehyde Resin.—Melamine-formaldehyde (MF) is also an amino-aldehyde product; however, in its spray-dried form, it is more costly to manufacture than a UF resin. As a result, MF resins in the United States are more expensive on a solids basis than either UF or most liquid PF resins, but they are comparable in cost to spray-dried phenolics. Although technology is available to make large quantities of MF resin as cheaply as PF resins, melamine lacks the durability to compete with phenolics on a large scale. As previously noted, blends of MF with cross-linked novolak PF (acid curing) are used to produce MF/PF formulations suitable for exterior exposures in Europe. Heat is required to set MF resin, and acid catalysts are often used to accelerate their cure. Blends of UF/MF are used by the hardwood plywood and laminating industries for products that require improved durability over that of UF and light-colored glue lines.

Resorcinol-Formaldehyde Resin.—Resorcinol-formaldehyde (RF) resin is also derived from benzene; however, the cost of resorcinol is about five times that of phenol. Resorcinol differs from phenol in that it reacts readily with formaldehyde under neutral conditions at ambient temperatures. Due to the high degree of reactivity, resorcinol resins are made deficient in formaldehyde. The balance of formaldehyde required for cure is added at the time of use. Because of this reactivity and ability to penetrate into the wood and cure completely at relatively low temperatures, resorcinols are capable of producing fully waterproof bonds under the most difficult gluing conditions. Because of the initial high cost of resorcinol, no volume wood-bonding market developed for the RF resins except for specialty lumber laminating. As a result they continue to be considerably higher in cost than phenolics.

To obtain some of the quality of a resorcinol resin at a lower cost, phenol-resorcinol-formaldehyde (PRF) resins have been developed. These resins are produced by combining phenol with formaldehyde under mildly alkaline conditions, followed by a resorcinol addition and completion of the synthesis. These PRF resins are highly durable and will usually show improved bonding capability when used with difficult-to-glue species, such as extremely hard hardwoods.

Polyvinyl Acetate and Derivatives.—Polyvinyl acetate (PVAc) is a thermoplastic polymer that has gained wide acceptance over the years as a raw material for the adhesives industry. Modified or unmodified, in solution or emulsion form, and as homopolymer or copolymer, it exhibits a versatility that makes it suitable for bonding a wide variety of substrates. In particular, it is capable of producing strong and durable bonds on hardwood and hardwood-derived products. Although PVAc adhesives are not generally recommended for joints that are under continuous load or subjected to high temperatures and/or high humidity, these adhesives can be formulated for improved performance under such conditions (e.g., aliphatics or copolymers containing phenolics).

Isocyanates.—Polymethylene polyphenyl isocyanate and methylene bisphenyl diisocyanate (MDI) have high bonding strength, are free of formaldehyde, and have the ability to cure at room or elevated temperatures (*31*). There have been problems with these isocyanates when used to bond hardwoods with low moisture content (less than 5 percent). Isocyanates have been used to bond composite boards using softwoods and hardwoods, but there have been some instances where the panels have stuck to the hot-press platens (*143, 156*). Normally release agents, surface paper overlays, or other wood-adhesive surface layers accompany the use of isocyanates. Certain health hazards in the form of physiological and inhalation responses or sensitization reactions are associated with the use of isocyanates (*31, 163*). High cost, sticking problems, and health hazard concerns have restricted isocyanate use in the United States in the past, but at least six particleboard and waferboard plants were overcoming these problems in 1986 (*59*).[3]

Emulsion Polymer/Isocyanate.—Emulsion polymer/isocyanate (EPI) adhesive systems, consisting of a water-based polymer emulsion and an isocyanate cross-linking resin, have shown promise for various specialized laminating industries utilizing a variety of eastern hardwoods (*4*). In these cases, administrative and ventilation controls seem to have solved the health hazard problems associated with the isocyanates.

Review

Operational wood bonds are the result of molecular attraction between the adhesive and the wood surface (forces of adhesion) as well as the molecular bonds within the adhesive mass (forces of cohesion).

Adhesion occurs only if the adhesive is in intimate contact with a receptive wood surface. Strong cohesive forces require a properly formulated and cured adhesive.

Until recently, the majority of hardwood glue bonds were used in nonstructural applications and/or in locations protected from the elements, with many adhesives suitable for these purposes. Development and refinements of synthetic resin adhesives, specifically the isocyanates, phenols, resorcinols, and phenol-resorcinol blends, have provided adhesive systems of sufficient strength and durability to bond hardwoods for severe service (indoors or outdoors).

Phenolics and phenol-resorcinol blends are recommended for use with high-density, low-pH hardwoods under severe service conditions indoors or outdoors. Less alkaline, lower molecular weight phenolics will form better bonds with hardwoods than the higher molecular weight, more alkaline phenolics commonly used with softwoods.

CHARACTERISTICS OF SOUTHERN HARDWOODS THAT AFFECT GLUING

The inherent nature of the wood substrate is a critical factor in the selection of a suitable adhesive and the manner in which it is applied and cured. The

[3]Lambuth, A. L. 1981. Lignin-Isocyanate Adhesives: Practical Implications. Unpublished presentation, Adhesive Symposium for Structural Materials, September 29—October 1, Washington State University, Pullman, WA: On file at Boise Cascade Corporation, P.O. Box 50, Boise, ID 83728.

general gluing characteristics of most United States hardwoods have been reported in earlier studies (*6, 76, 141*). Experience has shown that generalizing about the gluing characteristics of hardwoods is not always possible. Compared to the relatively homogeneous softwoods, hardwoods vary widely in density, anatomical structure, and chemical properties, resulting in marked differences in gluability.

Wood Structure

Comparison of Hardwood and Softwood Anatomy.—Figure 1 is a schematic drawing of a typical softwood (southern pine wood), and figures 2 and 3 are scanning electron micrographs of two types of hardwoods. Note the uniformity of the softwood as compared to the hardwood samples. For all practical purposes, softwood structure consists of a single cell type (tracheids); cells are interconnected by a series of openings known as "pits." These pits permit mass movement of air and liquids from one cell to another. Hardwood structure is more complicated, consisting of at least two basic cell types commonly referred to as fibers (fiber tracheids) and vessels (pores).

Fibers.—Hardwood fibers, which comprise about 45 percent of hardwood stemwood, are short (0.03 to 0.09 in, 0.8 to 2.2 mm), with thick walls (12×10^{-5} to 24×10^{-5} in, 3 to 6 μm), small lumens (radial diameters of 16×10^{-5} to 67×10^{-5} in, 4 to 17 μm), and closed ends. Typically, fibers have very small interconnecting pits (gaps) with a solid pit membrane (modified primary wall) that allows neither air nor liquids to penetrate across the grain of most hardwoods. There are no innerconnecting passages between hardwood fibers (end to end or side to side) or between hardwood fibers and horizontal hardwood ray cells as there are in softwoods. As a result, little or no mass movement of adhesive components takes place via hardwood fibers adjacent to the glue line. Penetration in the denser hardwoods is typically confined to one or two fibers (fig. 4). By way of contrast, in softwoods, where tracheids are up to 0.27 inches (7 mm) in length and >0.001 inches (25 μm) in diameter, considerable adhesive penetration occures (fig. 5).

Rays.—Horizontal tissue (ray cells) in hardwoods that grow among southern pines is composed of ray parenchyma. Some hardwoods have very large rays (fig. 6) that assist lateral mass movement of liquids in the radial direction (*27, 146*).

Vessels.—Vessel elements in longitudinal series comprise the segmented structure termed a vessel; when in transverse section, a pore is exposed. Vessels constitute about 20 percent of the stem volume in hardwoods. They are short (0.013 to 0.05 in, 0.30 to 1.30 mm), large-diameter (0.002 to 0.012 in, 50 to 300 μm), cells whose end walls have partially disappeared, forming essentially open, vertical tubes within the wood. When vessels are approximately the same diameter and scat-

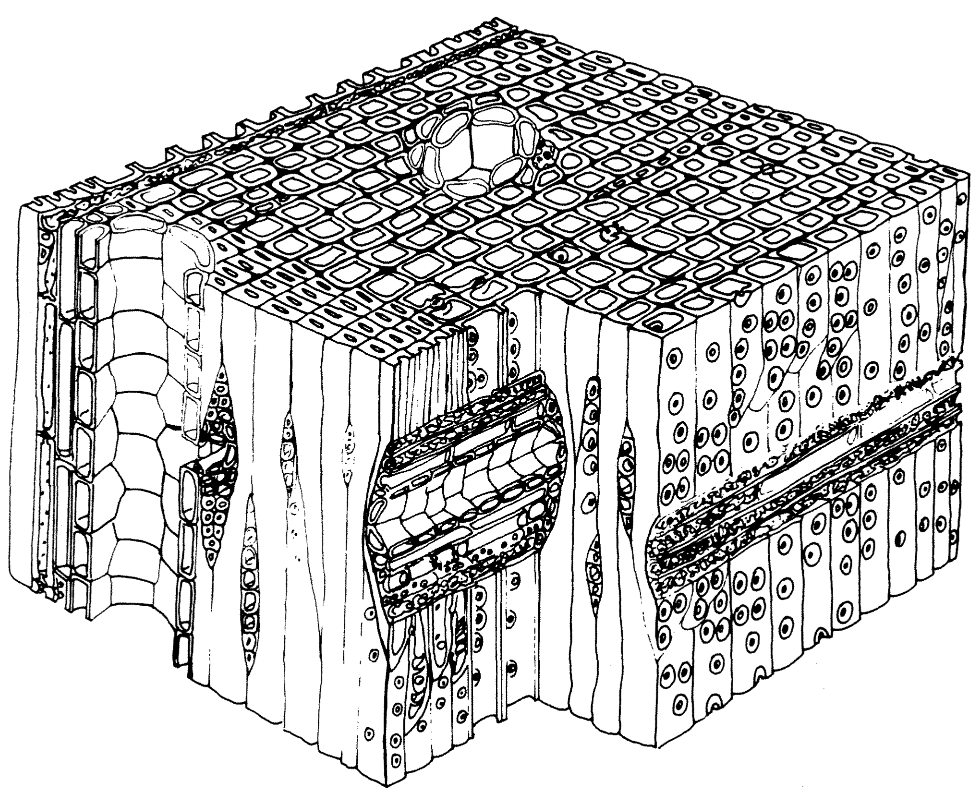

Figure 1.—*Schematic drawing of southern pine wood, a softwood.*

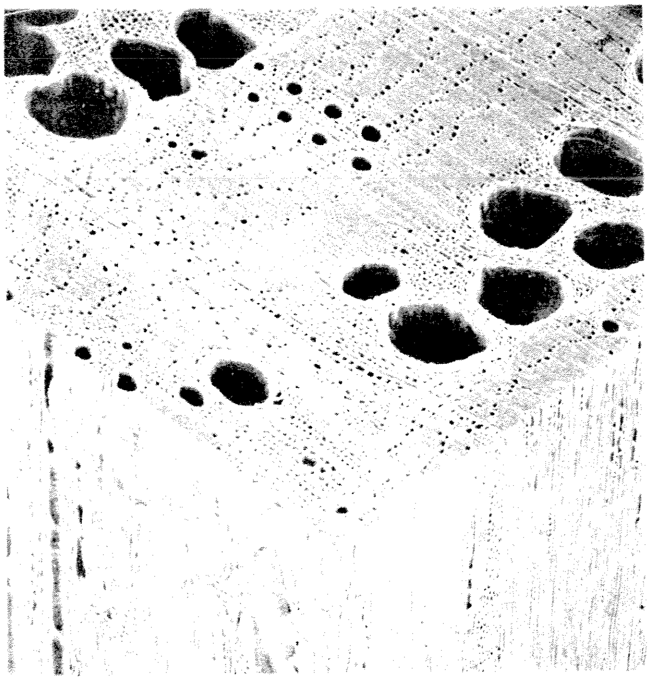

Figure 2.—*Scanning electron micrograph of red maple.*

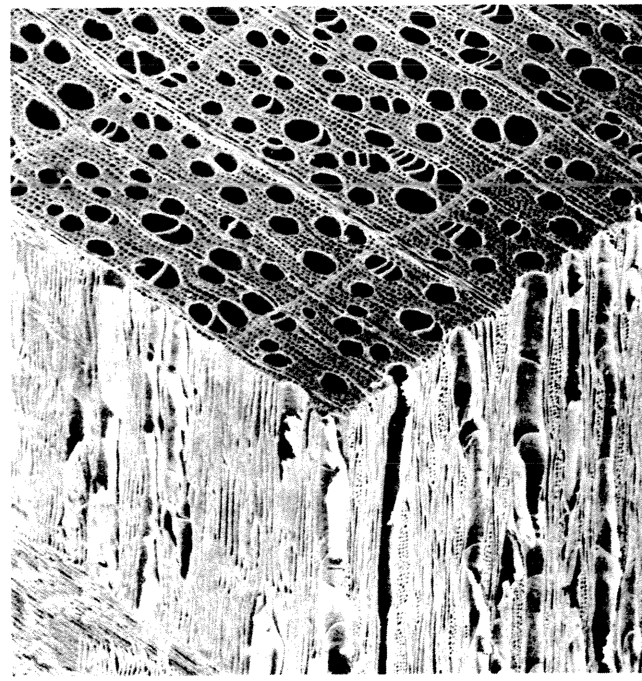

Figure 3.—*Scanning electron micrograph of northern red oak.*

Figure 4.—*Scanning electron micrograph of adhesive penetration in hardwood. Arrows point to glue lines (Courtesy Robert L. Krahmer, OSU, Corvallis, OR).*

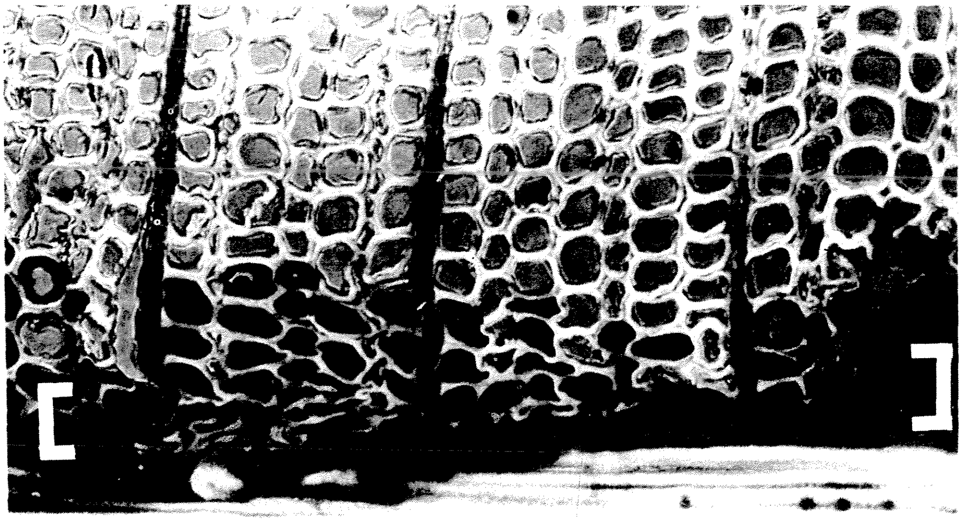

Figure 5.—*Scanning electron micrograph of adhesive penetration in softwood. Bracket defines glue line (Courtesy Robert L. Krahmer, OSU, Corvallis, OR).*

tered across the annual growth ring, the wood is called "diffuse porous." When large diameter vessels are concentrated in the early wood and smaller diameter vessels are in the latewood, the wood is called "ring porous." Because the vessel segments have no end walls, liquids can penetrate indefinitely from the end grain unless their progress is barred by tyloses (protoplasm growth), gum, or a vascular tracheid. This ease of penetration makes it difficult to prevent excessive penetration of the adhesive when gluing end joints.

Figure 6.—*Scanning electron micrograph of large rays in hardwood.*

Specific Gravity (Density)

Strength.—Wood is a matrix of cell wall and void volume (cell lumens). Regardless of species, the cell wall is composed of two major components, lignin and cellulose, approximately equal in density; hence density is a measure of the amount of cell wall present and a logical indicator of species' strength (*76, 110*). Although density is not a measure of the size, distribution, or interconnection of the openings within a species, it is a valid indicator of void volume for a given wood volume, i.e., high density, low porosity. Hardwoods exhibit a wide range in specific gravity (table 5), and this range has been shown to have a significant influence on bond performance (*109*). In an evaluation of the effect of pH, wettability, and specific gravity on the gluing properties of 22 hardwoods, including 4 Eastern United States hardwoods, specific gravity was the major factor influencing wood failure and shear strength with urea and resorcinol-phenol adhesives (*50*). Similar results were reported with six South Asian hardwoods with specific gravities ranging from 0.57 to 0.81 where PF, UF, and casein adhesives were used (*21*).

Dimensional Change.—Woods of high density shrink and swell to a greater extent than woods of low

Table 5.—*Comparison of specific gravity for various species of softwoods and hardwoods*[1]

Softwoods		Hardwoods	
Species	Specific gravity[2]	Species	Specific gravity[2]
Cedar, western red	0.32	....	....
Pine, eastern white	.35	....	....
Spruce, Engelmann	.35	....	....
Redwood (second growth)	.35	....	....
Pine, sugar	.36	....	....
....	....	Basswood, American	0.37
....	....	Aspen, quaking	.38
Fir, white	.39	Aspen, bigtooth	.39
Pine, ponderosa	.40	Cottonwood, eastern	.40
Redwood (old growth)	.40	....	....
Spruce, Sitka	.40	....	....
Spruce, white	.40	....	....
....	....	Yellow-poplar	.42
Hemlock, western	.45	....	....
Bald, cypress	.46	....	....
....	....	Maple, silver	.47
Douglas-fir (coast)	.48	Lauan, red	.48
....	....	Sycamore, American	.49
....	....	Tupelo, black	.50
....	....	Magnolia, southern	.50
....	....	Tupelo, water	.50
....	....	Elm, American	.50
....	....	Cherry, black	.50
Pine, loblolly	.51	....	....
Pine, shortleaf	.51	....	....
Larch, western	.52	Sweetgum	.52
....	....	Hackberry	.53
....	....	Maple, red	.54
....	....	Walnut, black	.55
....	....	Ash, green	.56
Pine, longleaf	.59	Oak, southern red	.59
....	....	Ash, white	.60
....	....	Oak, black	.61
....	....	Birch, yellow	.62
....	....	Maple, sugar	.63
....	....	Oak, northern red	.63
....	....	Oak, water	.63
....	....	Elm, rock	.63
....	....	Beech, American	.64
....	....	Birch, sweet	.65
....	....	Hickory, pecan	.66
....	....	Oak, chestnut	.66
....	....	Oak, post	.67
....	....	Oak, white	.68
....	....	Hickory, shagbark	.72
....	....	Hickory, pignut	.75

[1]Source: "Wood handbook: Wood as an engineering material" (*44*).
[2]Based on weight when ovendry and volume at 12-percent moisture content.

density in response to changes in moisture content (fig. 7). Due to shorter fiber length, lower lignin (a natural wood binder) and higher hemicellulose contents, hardwoods will shrink and swell to a greater extent than a softwood of similar density. This relationship affects bond performance in that the greater the dimensional changes that take place when the wood is placed in service, the greater the stress imposed on the glue lines.

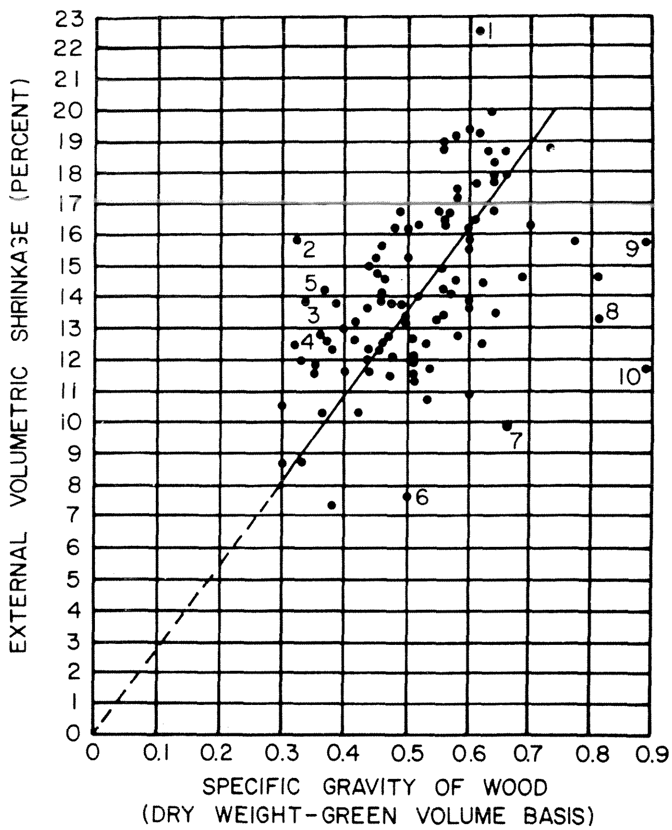

Figure 7.—*Average external volumetric shrinkage of 2- by 2- by 6-inch specimens for each of 106 different species of hardwoods from the green to ovendry condition (106).*

Moisture Content

Effect on Adhesive.—Moisture content of the substrate at the time of gluing is an important factor (*147*) in producing bonds that will perform well in service. Most adhesives will not form satisfactory bonds at high wood moisture content (>25 percent). Wood should be at least air dried (*62, 161*); for most gluing operations, lumber is kiln-dried to 7 to 16 percent. Historically, flakes, particles, and veneer have been dried in specially designed drier ovens to relatively low moisture levels (<10 percent) prior to gluing. Fiber in wet-process hardboard is dried during the hot-press cycle.

Shrinkage.—Large differences in the moisture content of wood that is to be glued together will result in considerable dimensional stress on glue joints and may cause delamination and warping of the product in service (*44*). These stresses are intensified in the case of the higher density woods (*149*). Ideally, wood should be dried to a moisture content slightly below that desired in the finished product to allow for the adsorption of moisture from cold-setting adhesives (*161*). For furniture and other interior items, a moisture content of 5 to 7 percent is generally satisfactory (*44, 62*). For lumber used in structural laminated timbers or exterior uses, a moisture content of 7 to 16 percent is specified (*3, 33*). The range in moisture content of various laminations assembled into a single member should not exceed 5 percent.

During 1986, several Southern structural plywood plants began using a high moisture content gluing concept. In such a program, veneers at 15- to 25-percent moisture content are bonded with the objective of ending up with panels out of the hot-press that are near the environmental moisture content for structural plywoods in use (8 to 12 percent). The economic benefits for reduced veneer drying time are matched by the quality benefits of improved dimensional stability for the panels in use, such as lack of warp (*129*).

Drying.—There are other factors involving wood drying that must be considered in gluing. Lumber that is to be glued should be free of drying-related defects, such as casehardening, warp, checks, and splits, in order to produce quality bonded products. Flakes and veneer should not be subjected to excessively high drying temperatures for long periods of time to avoid physical-chemical changes to the fresh cut surfaces, which can inhibit proper wetting of the surface to be glued.

Surfaces

Machining—Prior to a process in which boards, veneers, flakes, or particles are joined together with an adhesive, surfaces are created by sawing, peeling, planing, flaking, chipping, or sanding; these processes are referred to collectively as "machining." Poor machining practices result in rough surfaces, increased surface area, and damage to surface fibers. Surfaces resulting from poor machining practices will restrict adhesive movement and increase the amount of adhesive needed for spreading and good wetting. The damaged surface fibers forms a weak boundary layer resulting in low-strength joints with shallow wood failure. In difficult-to-bond species, such as the dense hardwoods, a tight, smooth surface that is not burnished is essential to achieving a high performance bond. This objective requires that knives and saws are properly sharpened and maintained, saw blades have the proper number of teeth, and that through-put is controlled on the basis of quality as well as volume.

Permeability.—The capacity of wood to allow passage of fluids under pressure is termed permeability. An important step in bonding is the removal of water from the glue line so as to produce a viscous, high-solids film before heat and pressure are applied (*83*). Otherwise the application of pressure causes migration of the adhesive to areas of minimum contact resulting in low overall bond strength. A direct relationship exists between the porosity of a wood and the rate at which it absorbs water from the glue line. Hardwoods of high density and low porosity require an increase in assembly time (elapsed time between spreading the adhesive and applying pressure) to immobilize the glue.

In a similar vein, porosity of the substrate affects the pressure time required with an adhesive that cures through migration and evaporation of its solvent. A comparision between a ring porous wood (red oak) and a diffuse porous wood (sugar maple) to determine the rate of strength development of a cold-setting aliphatic resin showed that the red oak required twice the clamping time of the sugar maple to develop 50 percent of the strength (*100*).

Chemistry.—During the process of bond formation, the adhesive and wood surface interact as "chemical reagents," in a manner that differs among species and adhesives. All eastern hardwood species are acidic (pH 3.5 to pH 6); oak heartwood is on the lower end of the pH range due to its high tannin content (*15, 54, 112, 122, 134*). A highly alkaline, phenolic plywood resin may precipitate when applied to a low pH hardwood. Since phenolic cures are slowed as the resin approaches pH 7, the same glue line would be under-cured out of the hot press and perform poorly in an adverse environment. Some hardwood species have a high acid buffering action that will result in increased gel times when using urea resins. Buffering capacity refers to the amount of alkali or acid required to adjust or maintain the pH of wood to a given level, such as 4.5 pH. Red oak is more acidic and more highly buffered than aspen; however, Douglas fir is acidic but not highly buffered. All these factors affect phenolic bonding, with oak being the most difficult to glue successfully.

Extractives.—The chemistry of extractives from Eastern United States hardwoods has been reviewed extensively (*121*), and the total extractive content has been compiled for the principal hardwoods growing on southern pine sites (*71*). These references do not specifically address the effect extractives (pH and polarity) have on gluing; however, relatively poor bonds have been reported in particleboard made from old, extractive-rich oak using an alkaline PF resin (*120*). The older oaks were shown to have a higher extractive content with a lower pH value and higher buffering capacity. Either water or sodium carbonate extraction removed these materials; sodium carbonate was more effective. It was concluded that the acidity of the extractives had a detrimental effect on bonding.

A recent study on the influence of extractives on the bonding properties of white and southern red oak veneer showed that bond quality was improved by neutralizing acidic extractives on the substrate surface with 1 percent sodium hydroxide (*81*). In another study using white oak veneer, ferric sulphate applied to the veneer surface improved the glue bond (i.e., higher wood failure) (*35*). However, neither of these techniques produced wood failures of over 40 percent (generally, the higher the wood failure the better the glue bond).

Extractives in the Southeast Asian species, kapur (*Dryobalanops* spp.), are sufficiently acidic to decrease glue-line pH from 11 to 9.5 immediately after spreading with a typical fast-curing softwood plywood phenolic adhesive (*107*). This reduction in pH is sufficient to cause phenolic solids to precipitate, require a significant increase in press time, and reduce cross linking and the ultimate bond strength. Similar effects can be expected when highly alkaline, highly advanced phenolics are used to bond tannin-rich southern hardwoods.

Wood pH.—The pH of wood is determined by the amount and kind of extractives in the wood. The pH of wood has a greater effect on bonding with a cold-setting urea resin than with a heat-cured phenol-resorcinol resin when used to glue hardwoods having specific gravities similar to those found in the Eastern United States (*50*).

Significant variations found in the pH of various species can be attributed to analytical technique, the season the tree was felled, pH of the soil, storage time and conditions, height on the stem where the sample was taken, and moisture of the sample (*67, 122*). The acidity of wood from several species was found to increase during storage under damp conditions (*112*). Marked increases in acidity observed with an increase in temperature were attributed to the hydrolysis of the acetyl groups of the hemicellulose to form acetic acid. Hardwoods (oak and birch) have been shown to liberate acid at a higher rate than two softwoods (Douglas-fir and Parana pine). When making comparisons between or within species, these factors are important in arriving at process changes to improve bond quality.

Bonding problems will occur if wood pH is ignored when introducing new species into a processing line. Increased hardener over that typically used for pine-type ureas was required to obtain optimum internal bonds in particleboard of beech, birch, alder, and elm due to the inherently higher pH's and higher buffering capacities of these species (*72, 73, 74, 75*). Experienced adhesive suppliers typically adjust acid catalysts in UF resins to achieve desirable cure times and bond qualities for the species used (*151*).

Age of Wood Surface.—It is well documented that adhesion in wood gluing is dependent to a measurable extent on the age of the wood surface (*30, 96*). The wood surface is constantly changing both physically and chemically from the time the wood is machined until the adhesive is applied (*137*). The gluability of wood surfaces degrades with age. This change is due to contamination and the chemical changes induced by exposure to heat, light, and oxygen that reduce the number of available bonding sites on the wood surface. The effect of age is generally more apparent in species rich in resins or extractive content, which can change upon exposure to the elements or migrate to the surfaces. In any difficult gluing situation, i.e., dense hardwoods, improved bonds will be attained if the surfaces are freshly machined prior to gluing.

Review

Adhesion is a surface phenomenon, hence the physical and chemical conditions of the surface are important parameters in bonding. Hardwoods with their heterogeneous structure will have inherently rough microscopic surfaces (*98*). They also tend to have a more variable chemical makeup than the more commonly bonded softwoods.

The stronger (more dense) the wood, the greater the care that must be taken to achieve glue line strength equal to, or greater than, the strength of the substrate. Greater density—reflected as substrate strength, increased dimensional instability, and reduced permeability—is the primary cause of the difficulties experienced in gluing high-density hardwoods (those with specific gravity >0.52). Acidity and polarity of extractives are secondary factors in gluing certain hardwood species.

Lower density, tannin-free hardwoods can be bonded with the same ease and expectations of good bond performance as with softwood species. The higher density, extractive-rich hardwoods will be more difficult to glue, particularly if the bonds are required to withstand high moisture, high temperature, or alternate wetting and drying.

TEST METHODS FOR GLUED PRODUCTS

Although a number of principles for wood gluing have evolved that provide guidance in the selection of adhesive and processing parameters to meet end-use requirements, accelerated proof testing is necessary to predict bond performance in service and as a diagnostic tool to make adhesive and process adjustments.

The American Society for Testing and Materials (ASTM) provides standards for evaluating adhesives. The Canadian Standards Association (CSA) in their Standards For Wood Adhesives (*13*) provides an excellent review of test procedures for evaluating commonly used adhesives. Since the opportunity for expanding the use of glued hardwood products lies in producing bonds that will maintain their durability when in service, tests that determine long-term moisture resistance are of particular interest.

In-service and accelerated-aging test techniques are employed to determine adhesive resistance to moisture (*13, 51*). Caster (*18*), Dinwoodie (*37*), Landrock (*84*), and Sellers (*128*) recently made detailed reviews of testing and evaluation procedures for adhesives and bonded products (fig. 8). Exposure to various temperatures, water, and moisture are used to accelerate the aging of certain glued products for strength degradation (table 6).

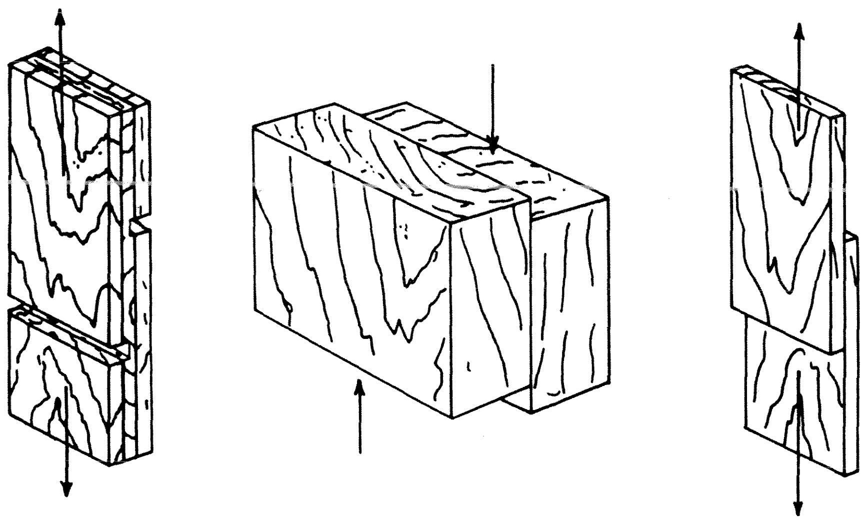

Figure 8.—*Common adhesive wood joint test specimens used to evaluate glue bonds. Arrows depict direction of force.*

Table 6.—*Relative performance of birch plywood glued with synthetic adhesive resins and shear tested after various weather-exposure and accelerated tests (9)*[1]

Test treatment	Phenolic			Melamine			Urea		
	Strength		WF[2]	Strength		WF	Strength		WF
	psi	*MPa*	*%*	*psi*	*MPa*	*%*	*psi*	*MPa*	*%*
Cold, soak (2 years)	400	2.75	98	400	2.75	98	400	2.75	98
Weather exposure (2 years)	360	2.48	92	350	2.41	85	0	0	0
Weather exposure (6 years)	416	2.86	80	250	1.72	50	0	0	0
Boil test (4 hours)	395	2.72	98	395	2.72	98	0	0	0
Boil test (24 hours)	380	2.62	98	380	2.62	98	0	0	0
Boil test (48 hours)	350	2.41	98	280	1.93	27	0	0	0

[1]The data is approximated to show magnitude of difference.
[2]WF refers to estimations of percentage wood failure on the sheared glue-line area.

Many comparisons have been made between accelerated test results and end-use performance. Caster (*17*) subjects laminated wood glued with nine adhesives to automatic boil tests and correlates these results with results observed after 11 years of exterior exposure. Venkateswaran (*144*) provides data on the relationship between accelerated tests of 16 wood adhesives in birch plywood and the values obtained after 15 years of outdoor exposure. The long-term performance of the adhesives melamine, urea, polyvinyl acetate, resorcinol, and phenol-resorcinol on laminated oak and beech is well documented (*43, 63, 123, 124, 142*). In general, accelerated tests do a reasonable job of predicting adhesive wood bond performance in exterior exposure. They specifically eliminate bonds that are certain to fail in service.

PANEL PRODUCTS

Plywood

Decorative Plywood.

Volume and Species.—In 1981, the total production of hardwood plywood (mostly decorative plywood) in the United States was 1.27 billion square feet (118 million m^2) surface measure (*12*). Of that amount, approximately 91 percent was from veneer species native to the Eastern United States: birch, oak, walnut, gum, and maple. Other domestic and imported hardwoods, mainly Philippine mahogany ("lauan"—Shorea, Parashorea, and Pentacme species), made up the remainder of the face material. Core veneer consisted of a variety of lower value domestic and imported hardwood species plus a significant amount of softwood.

Types.—The various types of decorative hardwood plywood (*2*), including those with a board type core (fig. 9), have waterproof bonds (Technical and Type I), moisture resistant bonds (Type II), and dry bonds (Type III). Moisture resistant Type II plywood comprised 72 percent of the hardwood plywood produced in 1981. Board-core plywood, which includes lumber, particleboard, or fiberboard as cores, made up the second highest volume, 22 percent, followed by Type III and Type I plywood with 5 and 1 percent, respectively. The disproportionate volume produced as Type II and board-core plywood reflects consumption by the furniture, cabinet, and paneling industries, which are the major markets, reported by the Census Bureau for hardwood plywood. Although United States hardwood plywood production has remained relatively static since 1960, recent trends indicate that board-core hardwood plywood is capturing an increasing share of the hardwood plywood market. This trend is attributed to homogeneous properties, good dimensional stability, availability, and cost advantages of composite wood materials.

Construction and industrial plywood specifications (U.S. Product Standard PS 1-83), which generally govern panels produced primarily from softwoods, allow some low- and medium-density hardwoods to be utilized. A few southern pine plywood mills currently use sweetgum and yellow-poplar as their major hardwoods (*128*). These same species are glued into furniture blanks and other market products using typical southern pine plywood manufacturing techniques (*116*).

Structural Plywood.—In 1985, about one-third of the structural plywood plants in the southern region of the United States used medium-density hardwood veneer (5 to 30 percent by volume) in their products. While there are definite opportunities for the inclusion of dense hardwood veneers in structural plywood panels, the processing and gluing of these species with phenolic adhesives are more difficult than it is with softwoods or most medium-density hardwoods. Given sufficient economic incentive in terms of wood supply, there is every reason to believe that adhesives and procedures can be developed that will allow the use of dense hardwoods in the manufacture of structural plywood panels.

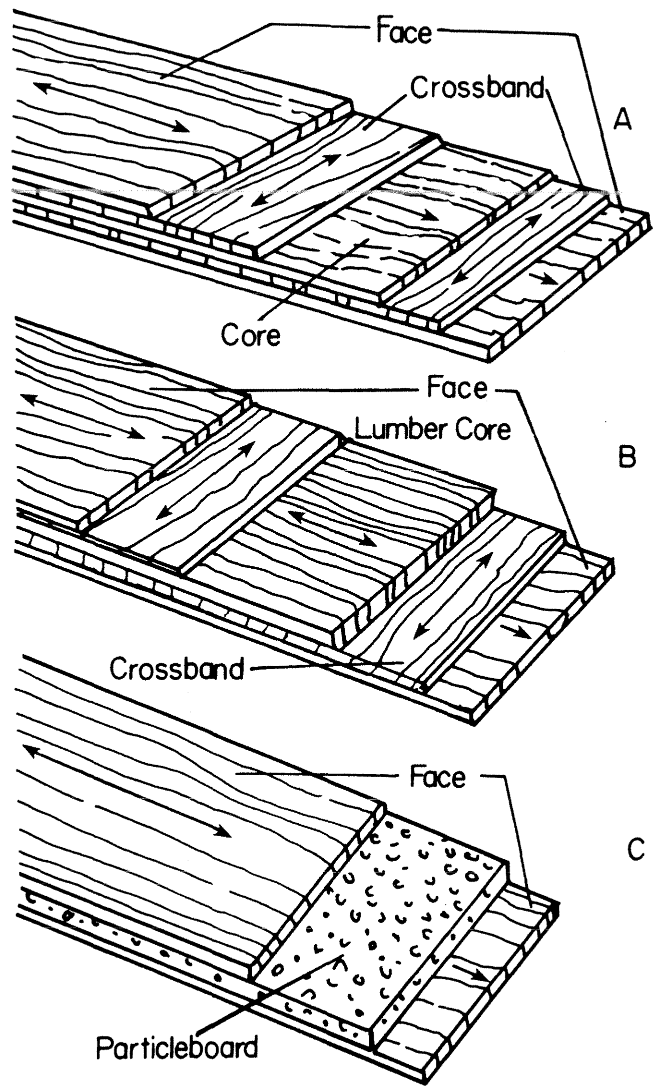

Figure 9.—*Hardwood plywood construction illustrating: A, total veneer; B, lumber core; and C, particleboard core. Arrows depict grain of wood.*

Veneer Edgebanding and Specialty Products.—Veneer edgebanding is common in the furniture and cabinet industries due to the increased utilization of composite and veneer core plywood where edge camouflaging is required. The major species utilized are those that are typical of hardwood plywood face plies. A fast growing edgebanding material is vinyl that has the appearance of wood. It is faster and less expensive to apply than veneer edgeband and is expected to continue to increase its share of the edgebanding market.

Hundreds of specialty products are made from both laminated and cross-laminated hardwood veneers.

These products may be recreational, household, or used in construction, and they often include edge-banding.

Processing.

Veneer Peeling.—The yield and surface quality of hardwood veneers depends on how well processing variables are adjusted for the species being cut. A wealth of data are available relating processing characteristics of eastern hardwood species to veneer quality. Suggested conditioning temperatures and veneer cutting procedures for most hardwood species in the United States are available in the literature (*41, 85, 86, 88, 89, 90, 92*). For example, temperatures that result in the best cutting of hardwood species are roughly related to the density of the wood (*42*). Although species such as yellow-poplar and cottonwood can be peeled at ambient temperatures most of the year in the South, heating prior to peeling is typically used with all hardwood species.

Proper heat conditioning is essential for producing smooth, uniform veneer surfaces and becomes increasingly important with high-density species to attain intimate veneer surface contact for bonding and for potential adhesive conservation (*83, 127, 128*). Where there is poor veneer-to-veneer surface contact due to surface irregularities, there is no adhesion with the non-gap-filling adhesives currently used in gluing veneer. Factors that affect veneer smoothness, such as lathe checks on the loose side, also have an effect on exterior performance and wood failure attained in accelerated-aging tests.

Loose veneer peels decrease prepress time; smooth, tight peels may require longer prepress time to yield solid panels. Even though faster prepressing is possible with rough veneer, the limited contact and nonuniform pressure distribution produced limit its use (*10, 82*).

Computerization of veneer lathes and improved auxiliary equipment, such as the power back-up roll, have increased veneer recovery and veneer quality (*132, 165*). Improved hardwood veneer yield (sweetgum and yellow-poplar) have been noted in softwood plywood plants using these lathe developments (*111, 116*).

Veneer Drying.—General drying characteristics and suggested drying temperatures for eastern hardwoods are available in the literature (*57, 68, 86, 89, 90*). In hardwood drying, excessive temperature results in thermo-chemical modifications of the wood surface (*83*). High temperatures, low humidity, and long heat exposure all promote deterioration of wood surface bonding sites and reduce adhesion with any resin adhesive. Shear strength and wood failure percentages are adversely affected by high dryer temperatures (*22*). The American Plywood Association (APA) reviewed southern pine plywood mill processing variables with drying sweetgum, yellow-poplar, and oak.[4]

[4]American Plywood Association. 1982. Processing Tips—Hardwoods. Unpublished member report: On file, American Plywood Association, P.O. Box 11700, Tacoma, WA 98411.

Although sweetgum generally dries faster than southern pine, a 5- to 10-percent reduction in drying time, accompanied by lower drying temperatures, is required when drying sweet-gum to prevent surface damage. Oaks must also be dried at lower temperatures and need approximately 40 percent longer drying times than southern pine (*28, 29*). Yellow-poplar is normally dried with sweetgum in southern structural plywood mills even though very dry yellow-poplar veneer often results.

Obviously the drying of hardwoods must be given special attention when integrated into southern pine plywood mills. The type of drying equipment used may determine the species utilized and vice versa. Roller restraint dryers typically found in southern pine plywood mills may allow sweetgum and other species with a high tendency to warp and buckle to pass through a short variable-section chest-type dryer, but may present problems in long, in-line dryers found in a few older mills. Dryers equipped with dual-end-feed mesh restraints are the most popular among decorative hardwood veneer producers. Some industrial success has been achieved using flat, ventilated press platens to dry veneer (*128*). Flatter veneer sheets and higher drying rates have been shown with platen dryers using temperatures up to 275 °F (191 °C) and pressures of about 50 pounds per square inch (345 kPa) (*87, 91*).

Panel Assembly.—Plywood construction requires the assembly of veneers into panels prior to bonding. Assembly time is the term used for the elapsed time from the application of the adhesive to the dry veneer until the layed-up panel is under pressure and the adhesive cure is initiated. Assembly time is very important in gluing veneers because during this time the adhesive film wets the veneers and the fluid glue lines increase in viscosity (thicken) due to solvent loss. Both of these factors are important to hot-press curing of resin adhesives. Depending on the density and porosity of hardwoods being bonded, assembly time and spread may be adjusted to optimize bonding. Tables 3 and 4 show some recommended spreads for various adhesives. Dense hardwoods often require longer assembly times because adhesive solvent loss is slow.

Press Parameters.—Hot pressing is the major means of adhesive cure in hardwood plywood. All PF and most UF adhesives used to bond plywood are hot-pressed at temperatures between 250 and 330 °F (121 and 166 °C), the exact temperature depending on the adhesive used. Plywood panels are assembled in batches. The number of hot-press panels in a batch consists of the number it takes to load the openings in a hot press; a structural plywood plant typically has 20 to 50 openings, and a traditional hardwood plywood plant typically has 10 openings.

Most PF adhesives require veneers of relatively low moisture content (3 to 7 percent) to prevent panel blisters (blows) at the higher temperature of 300 °F (149 °C) typically used for curing phenolics. As previously mentioned, certain structural plywood plants (including those that glue some hardwoods) have begun gluing high moisture content (>15 percent) veneers to achieve an 8- to 12-percent panel moisture content when coming out of the hot press (*129*). This procedure requires a faster cross-linking modification to the PF adhesives in use.

Adhesives.—Decorative hardwood plywood in the United States is to a large extent bonded with adhesives containing UF resins in combination with proper proteinaeous extenders and lignocellulosic fillers. A typical proteinaeous extender is soft wheat flour; a typical lignocellulosic filler is pecan shell flour. Such wide usage reflects the relatively low cost of urea adhesives as well as their ability to satisfy the Type II bond requirements for interior service. In 1981, an estimated 80 million pounds (36.2 Mkg) of UF resin solids were used for domestic hardwood plywood production (*58*). Other adhesives used in hardwood veneer gluing are relatively low in volume and vary with the type of panel exposure and uses. Melamine-formaldehyde resins or melamine-fortified ureas are used largely to meet the relatively small market for Type I (exterior) decorative hardwood plywood. When catalyzed, some copolymers of PVAc having cross-link capabilities and containing phenolic resin exhibit exterior-type nonstructural bonds for hardwood panel products. A small but increasing number of mills are using modified PVAc adhesives for Types II and III plywood because of the availability of faster, more durable cold-setting (or hot-setting) formulations and the absence of free formaldehyde.

Phenolic resins in combination with quality lignocellulosic fillers and proteinaeous extenders are used almost exclusively in the manufacture of structural plywood, whether the panel is made of softwood veneers or from a combination of hardwoods and softwoods. Structural plywood production (per U.S. Product Standard PS 1-83) consumes over 410 million pounds (186 Mkg) of PF resin solids annually (*126*). The adhesive accounts for approximately 9 percent of the variable costs of structural plywood manufacture (*135*).

Specialty items made from hardwood veneer, which include numerous products ranging from tennis racket frames to heels for women's shoes, are bonded with ureas, PVAc, and resorcinol for the most part. Hot melts, such as polyamides and ethylene-vinyl acetate, are the most widely used adhesives for veneer edgebanding (*138*). Other uses of hot melts are for bonding case goods (drawers and boxes), cabinet assembly, and surface lamination in the furniture industry.

Flakeboard, Strandboard, and Waferboard

Background.—Waferboard and strandboard are mat-formed wood particleboards of specified particle geometry (wafer or strand flakes), particle orientation (e.g., oriented strandboard or OSB), and binder type (e.g., PF for exterior bond). These parameters result in particleboards (flakeboards) with most structural properties being equivalent to those of exterior plywood and distinctly superior to conventional particleboard. The manufacture of structural composite panels is one of the fastest growing segments of the wood-using industry. Since roundwood is required as the starting material to produce the necessary particle geometry for this type of board, it represents a large potential market for low-grade hardwoods.

Processing.—Waferboard and OSB differ in particle geometry, the type and amount of resin used, and the degree to which the particles are aligned during mat formation. Figure 10 shows a schematic of the two processes.

Flake Geometry.—In Canada the term wafer refers to a wood particle having a length of at least 1.18 inches (30 mm) along the grain direction and a predetermined thickness (*14*). The width of the wafers vary but are normally made as wide as they are long. Each wafer is essentially flat and has the grain of the wood within the plane of the wafer. There are no specifications as to particle geometry in the United States standards for structural-use boards. Instead, there are performance requirements for the finished boards, and manufactur-

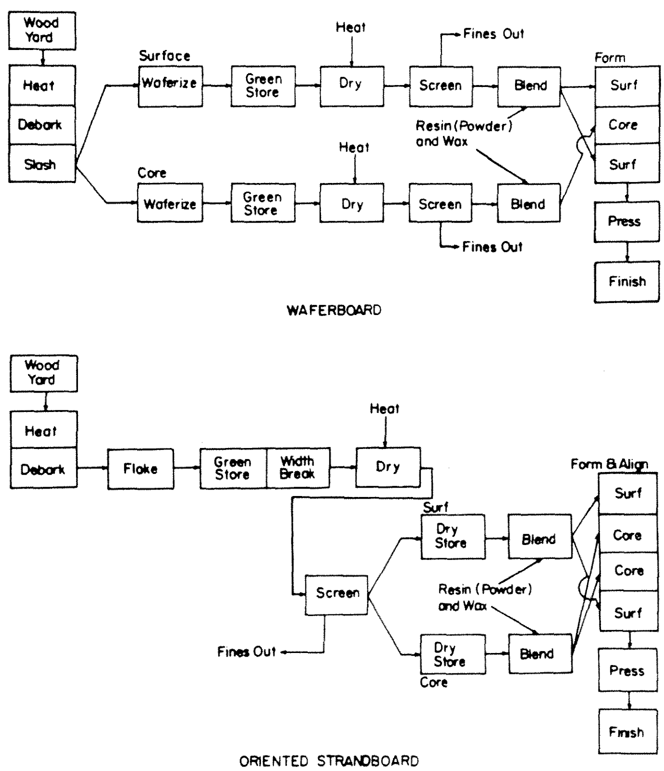

Figure 10.—*Schematic diagrams of a waferboard and an oriented strandboard process (19) (Courtesy Forest Products Research Society, Madison, WI).*

ing parameters have been developed to meet these standards. Wafers or flakes for waferboard should be approximately 2 square inches (51 square mm) in surface area and a minimum of 0.015 inch (0.4 mm) thick (*93*).

For OSB, wide flakes are broken into strands. In the United States, OSB flakes are about 1.5 to 2.5 inches (38 to 63 mm) long, 0.25 to 1 inch (6 to 25 mm) wide, and 0.015 to 0.030 inch (0.4 to 0.8 mm) thick depending on the product desired and process used.

The ability to use aspen, low-grade maple, and white birch has given waferboard and OSB mills located near these wood sources in Canada and the Northeast and North Central United States a delivered-price advantage in the central and eastern metropolitan markets compared to plywood from western mills. The cheaper small diameter trees and ease of gluing these species also provide incentives for the manufacture of flakeboard.

Only one OSB mill (Martco) was using southern hardwoods in 1985 (*55*), but several companies have subsequently announced new mill construction in the South with the intention of using medium-density hardwood furnish, such as yellow-poplar and sweetgum (*133, 150*). While Martco has used over 25 hardwood species in its furnish, sweetgum and red oak initially comprised 60 percent of the furnish. A current survey indicates that the Martco furnish is composed of 50 percent low- and medium-density hardwoods, 25 percent southern pine, and the balance dense hardwoods.

Flake Preparation.—For flake-type panels, and wood is cut to a specified length from which wafer-like flakes are produced. Other types of wood particles of indeterminate size and shape, such as those prepared by sawing, planing, hammermilling, or grinding wood, are excluded.

A study of the effect of flaking on the physical properties of flakeboard panels of southern red oak, sweetgum, and mockernut hickory showed that the higher density species (oak and hickory) generally had a larger percentage of loss in properties than the lower density species (sweetgum) after accelerated-aging tests (*118*). Part of the problem stems from the fact that flaker equipment tends to produce a high percentage of strands (long, narrow-type flakes) and fines (minute particles) when flaking oaks (*119*). The resultant strands are subject to easy disintegration along the rays or between the rings (*94*). Hickory tends to yield wide flakes that roll into tight cylindrical bodies when they are processed (*119*).

Flake Drying.—The furnish for structural-use reconstituted wood panels is dried to a controlled moisture content that ranges from 3 to 5.5 percent and 6.5 to 8 percent for core and face flakes, respectively, depending on the panel type being produced, the manufacturing process selected, or the resin binder used. For example, the wider wafers in waferboards require that this type of board be hot pressed at a mat moisture content below 7.5 percent because the wide wafers seal the surfaces, prevent venting of vapor during pressing, and result in panel blisters (blows) and delamination when the press is opened (*94*). The powdered phenolic, and more recently MDI, used in waferboard manufacture requires a moisture content sufficiently high (>5.5 percent) to contribute to the flow required for the adhesive to "wet" the wood surface without overpentration and to provide plasticity to consoldiate the mat.

Other factors that determine the preferred flake moisture content out of the dryer are the amount of water added when spraying a liquid phenolic and the target out-of-press panel moisture content. The out-of-press moisture contents for these panel types have usually been 1 to 4 percent. During 1987, attempts were being made to adjust the manufacturing process and the resins (i.e., by faster cross linking) to achieve out-of-press panel moisture contents of 6 to 9 percent, approximating the in-service conditions of these panels.

Blending.—After screening and drying, the furnish of structural-use reconstituted wood board is fed into a blender. The flakes tumble in air suspension and are sprayed with 3.5 to 6 percent liquid phenolic resin solids, about 2 to 3 percent powdered phenolic resin solids, or 2 to 4.5 percent MDI based on the dry weight of the flakes. Often 1 to 2 percent wax is added to the furnish as well. In the case of powdered resin, the wax helps distribute the resin solids uniformly; however, the principal reason for wax addition is to slow down the initial absorption of moisture by the panels in service. Wax does not reduce the total moisture absorption or control dimensional stability over time. As a result, a number of panel manufacturers no longer use a wax addition to their board.

Mat Formation.—After the furnish has been blended with resin (and usually wax), it is formed into a thick mat that is flat pressed to produce a board. For waferboard the direction of the grain in the wood particles lies predominately in the plane of the board. Oriented strandboard and oriented waferboard (OWB) differ from waferboard in that up to 60 percent of the furnish is laid as a core and 40 percent or more of the furnish is laid equally as face and back, with the long axis of the particles perpendicular to the core.

For OSB, the longer and wider flakes are separated as face (and back) material. The forming heads machine-orient and lay the face flakes first, then the core, and the back flakes last on a transfer belt or caul plate. Panel thickness is determined by caul speed. The mats for these boards are thick and loosely formed, with an approximate 8-to-1 ratio of mat thickness to pressed panel thickness. In recent years most waferboard plants in the United States began orienting wafers. The purpose of oriented wafers or strands is to realize increased structural properties in the long dimension of the panel, thus expanding markets for the product.

For all species, there must be a certain compaction in the flakeboard mat. That amount is expressed by the compaction ratio, defined as the ratio of panel density (or specific gravity) to wood density (or specific gravity). It has been shown that compaction ratios of 1.1 to 1.3 are necessary for hardwood flakeboard to meet required bond and panel strength and durability criteria (*64*).

Boards of low-density species are about 0.67 in specific gravity or 45 pounds per cubic foot (721 kg/m^3) in density at 8-percent moisture content (*94*). Since dense species, such as hickories, have a specific gravity of about 0.72, compaction ratios suitable to make a board weighing less than 50 pounds per cubic foot (801 kg/m^3) at 8-percent moisture content are difficult to attain unless they are mixed with lower density species. However, one study using northern red oak (specific gravity of 0.63) concluded that it is possible to manufacture a high-performance, durable, structural particleboard (flakeboard) from high-density species at an overall panel density equal to or less than the density of the raw material (*66*).

Press Parameters.—Mats for structual-use boards are hot pressed at temperatures of 360 to 420 °F (182 to 215 °C). The pressure in the hot press usually consists of multiple stages: very high initially to reach compaction ratios and density requirements (700 to 900 psi, 4.8 to 6.2 MPa), lowered to 350 to 450 pounds per square inch (2.4 to 3.1 MPa), and decompressed the last 30 to 60 seconds of the cycle. The press time is determined by the thickness of the panel, resin type, and mat moisture content. Press times may be 3 to 3.5 minutes for 1/4-inch (6.5-mm) panels, 5 to 6 minutes for 7/16-inch (11-mm) panels, and 7 minutes for 5/8-inch (15.5-mm) panels. Typically the minimum for press time under pressure is 20 seconds per 0.04 inch (1 mm) of board thickness.

Flake Bonding.—The quality of the bond between flakes is the critical component in meeting the long-term structural performance and integrity standards required of OSB and waferboard. Since adhesive costs represent approximately 20 percent of the variable manufacturing costs of these products (*135*), the economic health of the industry depends on both the delivered cost and effective application and cure of the adhesive.

Adhesives.—The historic adhesive of choice for bonding OSB and waferboard is PF resin. Since adhesive choice is driven by cost per board and process compatability, any thermosetting adhesive that is competitively priced and not inferior to PF resin in resistance to heat, attack by fungi and micro-organisms, hydrolysis, and creep is a potential binder for structural composites (*14*).

Phenol-formaldehyde resins are used in powdered or liquid form, may be resol or novolak type, and can be used alone or in conjunction with one another. The use of novolaks requires the addition of a cross-linking agent for thermosetting. Liquid phenolic resins formulated for structural boards may contain from 0- to 15-percent urea addition for various technical and commerical reasons. Powdered phenolics and isocyanates are used in the manufacture of waferboard and OWB while liquid phenolics are generally used in the manufacture of oriented strandboard.

In 1986, about 200 million pounds (90.7 Mkg) of PF adhesive resin solids (liquid and spray-dried forms) and about 10 million pounds (4.5 Mkg) of MDI (100 percent reactive) resin solids were consumed by the growing United States flakeboard industry. Driven by the size of the market and the opportunities to improve board properties and reduce costs, there have been a number of resin combinations considered as phenol replacements.

Isocyanate systems are used alone as binders or in conjunction with spray-dried phenolic resin (*65*). One study showed a substantial improvement in internal bond strength of all white oak and southern red oak panels with the application of isocyanate/phenolic resin rather than the use of phenolic alone (*65*). In addition to the handling problems referred to in the earlier discussion of isocyanates, there are unanswered questions as to the creep resistance of structural boards manufactured with this type adhesive (*163*). In 1987, Louisiana Pacific Corporation utilized isocyanates to bond aspen in four waferboard plants (with and without phenolic impregnated overlays). Other traditional particleboard plants used isocyanates to bond at least part of their production.[5]

In Canada, kraft lignin in combination with PF resin has shown some promise as a waferboard binder (*20, 38*). Usually such binders require slightly longer press times.

Work with a resorcinol-modified phenolic system resulted in little improvement in dimensional stability of southern hardwood flakeboard even though resorcinol resin adhesives have outstanding durability under severe test conditions (*65*). Resorcinols cost up to five times more than phenolics (*128*), which hinders their use in these products.

Particleboard

Conventional particleboard has no specified particle geometry and is used for interior application where surface smoothness and machinability are dominant requirements rather than construction applications

[5]Ellingson, G. Peter. 1985. (Letter to Terry Sellers, Jr., October 29): Located at Forest Products Laboratory, P. O. Drawer FP, Mississippi State, MS 39762.

where load carrying capacity and exterior durability are necessary criteria. The largest consumers of adhesives for wood bonding are the particleboard and medium-density fiberboard industries, which used over 800 million pounds (363 Mkg) of UF resin solids in the peak production year of 1978 (*152*). A variety of eastern hardwoods are bonded into particleboard and fiberboard products using UF resins, but the vast majority of the raw material is softwood.

Hardboard and Medium-Density Fiberboard

Hardwoods are used as the furnish in the manufacture of both hardboard [density approximately 60 pounds per cubic foot (960 kg/m^3)] and medium-density fiberboard [density approximately 40 pounds per cubic foot (640 kg/m^3)]. A mixture of southern hardwoods, including dense red oak, has been found to work well in wet-process hardboard using a phenolic binder. The process parameters of fiber preparation and wet pressing, both at high temperatures, eliminate the species variation that cause bonding problems in flake-based structural panels. Medium-density fiberboard is also manufactured from hardwood fiber using the medium-density hardwoods and phenolic resins to produce an exterior siding product. The volume of PF resin solids consumed for this product is about 60 million pounds per year (27 Mkg/annum) (*93*). In 1985, at least two medium-density fiberboard plants in the United States were using PF as a binder.

Review

Of particular promise in the gluing of eastern hardwoods is the use of low-grade hardwood flakes in the manufacture of structural composites. Ideally they would enter the process regardless of species. Unfortunately these woods vary widely in density, structure, and surface chemistry. To some extent these differences can be accommodated by a process change and by manipulating the adhesive. Certain of the hardwoods require processes and/or limitations in board properties that cannot be accommodated at this time.

Because hardwoods have differing surface chemistry, such as pH and extractives, bonding problems occur when they are used in random mixtures for flakeboards. A suggested solution to this problem is to treat the furnish using inexpensive chemicals that will cause the particle surfaces to become uniformly compatible with the chemistry of the resin binder system (*94*).

LAMINATES, INCLUDING EDGE GLUING

Surfaces

By the nature of tree growth with respect to growth direction (fig. 11) and because rectangular boards are cut from round trees, lumber has varying grain patterns (fig. 12). If the growth rings are at right angles to the wide faces of the board, the board is strictly quarter-sawn and the wide faces radially oriented. If they are parallel to the faces of the board, the board is flat-sawn and the wide faces tangentially oriented. If in between, the board is bastard sawn. When lumber is purchased for gluing, the grain pattern is seldom specified by the purchaser, except for some specialized products. Edge gluing refers to the gluing of the narrow side dimensions of a wide board. The grain direction of the glued edges (sides) may be radial, tangential, or of

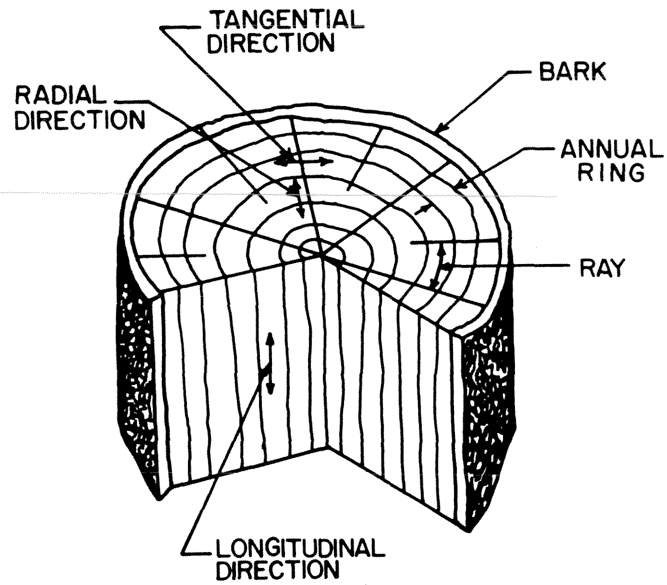

Figure 11.—*Section cut from the stem of a tree (149) (Courtesy Delta Communications, Inc., Chicago, IL).*

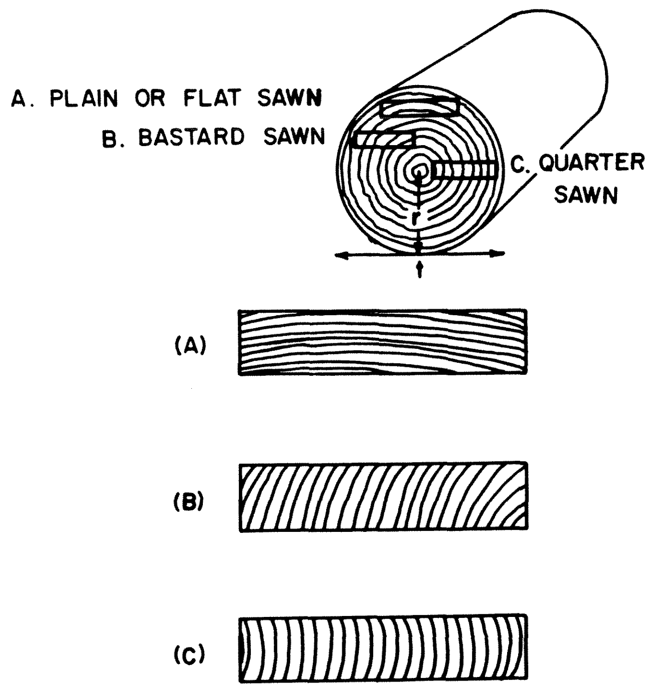

Figure 12.—*Three sawn-lumber grain patterns.*

varying degrees in between (fig. 13). When gluing side-grain to side-grain, the strength of a glue joint seems to be affected very little whether a tangential face is glued to another tangential, a radial is glued to another radial, or a radial is glued to a tangential (*155*). However, for critical structural joints, and/or for use under severe service conditions, it is undesirable to combine flat-grained (tangential) and edge-grained (radial) material because of the effects of the stresses that result from the 2-to-1 shrinkage differential between the two grain orientations (*7, 131*). In typical dry interior use, the moisture changes are normally too small to require segregation of grain (*77*).

Face gluing, or laminating, refers to the gluing of the wide dimension of rectangular boards or the wide dimension of a series of edge-glued stripes. Again, the grain direction for the face-glued product may be radial, tangential, or some varying degree between radial and tangential (*77*). Structural timber components are manufactured by laminating the wide faces of mainly tangential oriented boards (*23, 33*). It is particularly important that the outer face laminates in bending members be tangential because of the high stresses to which they are subjected.

Often edge and face gluing occur in the same product. In a solid lumber-core door, for instance, the core is edge-glued lumber, with banding or railing, and face veneers or other materials are glued (laminated) on the surface of the core (fig. 14).

Machining

For the edge or face joint to be the strongest part of the assembly, the basic strength of the adhesive must be greater than that of the wood species used. Most industrial rigid adhesives have strength values greater than that of wood loaded (stressed) in shear parallel or tension perpendicular to the grain. Fox example, the stronger hardwood species (hickory, oak, and maple) have across-the-grain tensile strength in the order of 2,000 pounds per square inch (13.8 MPa). Common wood adhesives show inherent cohesive strength of at least this magnitude (*130, 148*).

Apparent adhesive failure has been observed in glued hardwood components as evidenced by lack of wood failure and low strength in destructive tests designed to develop stress along the glue joints. Microscopic examination has shown that wood damage near the surface of the glue line is an underlying cause of the apparent failures in adhesion and that cohesive failure of the wood substrate due to surface damage was the root cause of the joint failure (*62, 130*). Failure often occurs between the damaged layer of wood cells and the glue line. This damaged layer is made up of mashed, torn, frayed, and matted wood fibers that lack the full structural properties of undamaged wood. At least a 30-percent reduction in tensile across-the-grain strength can be expected with such bonds (*130*). Damaged wood surfaces will also prevent normal adhesive penetration into the wood. Although gross adhesive penetration into the wood surface in itself is not a significant factor in determining strength of the glue joint (*130*), the lack of adhesive penetration is an indication of lack of intimate contact between the adhesive and the adherend.

Damage to the wood surface can result during preparation of the component parts prior to gluing. Jointing, planing, and sawing will provide acceptable surfaces for gluing if sharp tools are used, and the machinery is in excellent condition.

Sanding can produce good glue line surfaces pro-

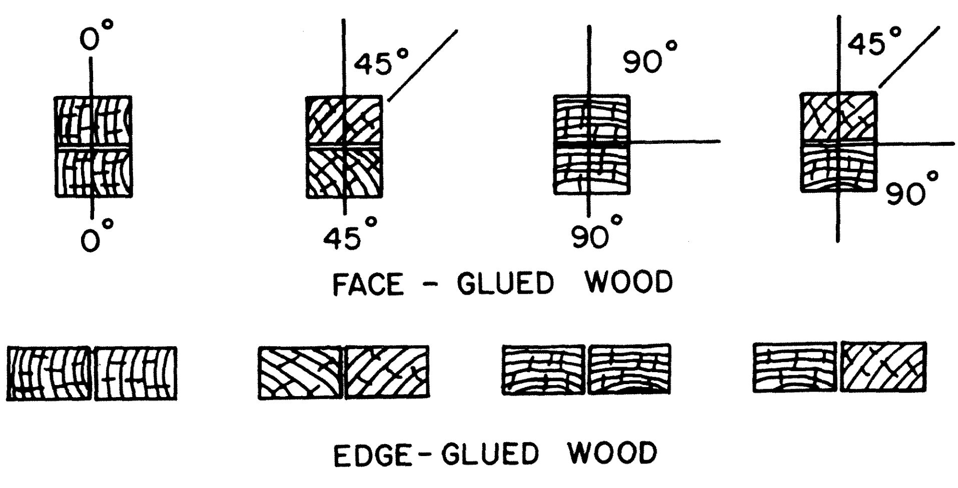

Figure 13.—*Typical types of face- and edge-glued panels by end-grain slope.*

vided the job is done carefully and fine grit sizes are used (*44, 62, 130, 158, 159*). Abrasive planing has been used successfully to prepare gluing surfaces for oak furniture parts (*158*). The Gamble Brothers' Louisville, Kentucky, plant reported extensive use of abrasive planing for edge and face gluing of oak, maple, and yellow-poplar (*159*). They concluded that finer grit sanding provided adequate and improved bonding, more than adequate for general woodwork. Even with the 20-percent reduced shear strength values developed using abrasive-planed surfaces, the bonds exceed the modulus of rupture (MOR) values of standard particleboards used for core and panel stock.

Press Parameters

When thermosetting adhesives are used in edge and end gluing or in laminating structural timbers, heat is often applied to accelerate glue-line cure and to reduce the time under pressure (*77, 125, 153*). Heated platens or bars, high-frequency electric fields, or heated chambers are common methods of increasing glue-line temperatures.

The fundamentals of high-frequency gluing have been well documented (*5, 16, 24, 25, 40, 46, 47, 95, 97, 104, 125, 142, 153*). Wood adhesives rated from easiest to most difficult to use with high frequency are: ureas, melamine-ureas, thermosetting vinyl-acetates, melamines, resorcinols, phenol-resorcinols, and phenolics (*26, 36, 95, 125, 142, 154*).

High-frequency edge gluing is not difficult with medium- or low-density hardwoods, such as poplar or soft maple. However, when this method is applied to edge gluing of denser species, such as birch, beech, or hard maple, processing methods and/or adhesive formulation modifications are often required to produce adequate glue lines (*36, 113*). Process changes may include a longer assembly time to thicken the adhesive before pressure and heat are applied. Adhesive alterations may include formulation changes that provide a more viscous (thicker) adhesive to prevent starved glue lines (excessive migration of the adhesive) when side pressure and heat are applied (*26, 113*).

The dielectric property of an adhesive is a very important property for high-frequency gluing. High-frequency burning within the glue line will reduce glue-line strength and performance. There are some indications that the occurrence of high-frequency burns is related to the type of wood being glued. Machining or anatomical features can cause irregularities on the wood surfaces within the joint, resulting in dielectric stress and burns (*164*). Miller and George (*103*) indicated that the tendency of an adhesive to burn was related to the rate at which moisture escapes from the glue line during the heating period. The more rapidly the moisture leaves the glue line, the greater the tendency of the wood to burn. (*103*).

Adhesives

A species is considered to be satisfactorily bonded when the strength of side-grain to side-grain joints is approximately equal to the strength of the wood (*44*). This criterion is considered reasonable by most standards when used for the conventional rigid-setting wood adhesives, such as UF, MF, PF, or RF (*44*).

To date, UF has been the most cost effective adhesive for radio-frequency edge gluing of hardwoods. However, adhesives such as thermosetting cross-linked vinyl acetates are competing with UF for high-frequency cured edge/face glued flat-bed stock, joints for truck and railcar oak flooring, and for the gluing of hardwood plywood because of improved production efficiencies and the absence of free formaldehyde. In 1987, over 8 million pounds (3.6 Mkg) of cross-linked vinyl acetate resin solids were used for gluing edge/face flat bed stock.

Review

Hardwoods are used extensively in edge and face glued products, particularly in furniture and other household or office products. There are a wide variety of adhesives, both natural and synthetic, suitable for bonding these products. Laminating adhesives are most often applied by roll or extruder coaters (*8*).

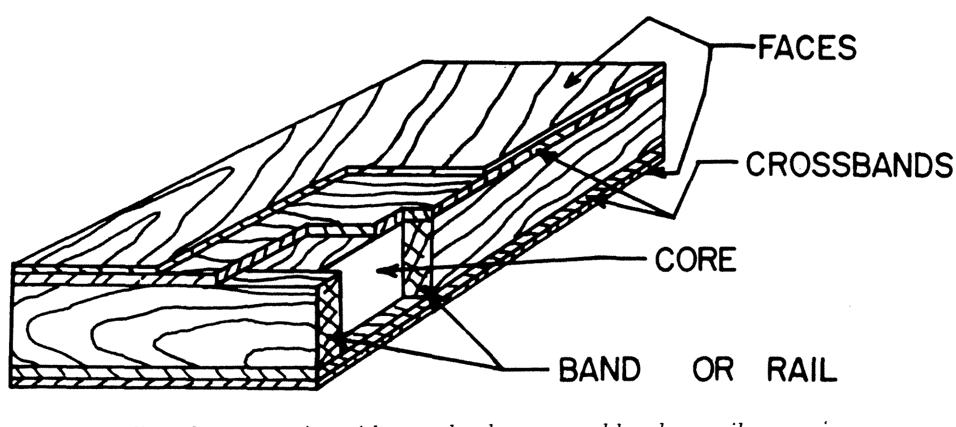

Figure 14.—*Five-ply construction with sawn lumber core and bands or rails.*

END GLUING

End Joints

End-grain to end-grain joints (fig. 15) are important elements in the manufacture of structural components such as laminated beams and load bearing furniture parts. They are also used for nonstructural applications in the manufacture of molding and paneling where the joint strength required is limited to that needed to hold the parts in place during handling and machining, and a tight, neat appearance is the main criterion for acceptance. The design of end joints using hardwoods has been investigated and discussed by numerous authors (*39, 44, 45, 69, 108, 136*). In general, there are three types of glued end-grain to end-grain joints: butt joints, scarf joints, and finger joints (fig. 15).

It is practically impossible to make butt joints (fig. 15, A) sufficiently strong or permanent to meet load carrying service requirements with present water-based adhesives and techniques (*44, 125*). Even with the best technique, no more than 25 percent of the tensile strength of the wood parallel with the grain can be developed (*44*). Yet this simplest of end joints remains in use for some limited, load-bearing applications (*160*).

To approximate the tensile strength of various hardwood species, one must use a scarf, finger, or any other type of end joint that mates side-grain surfaces with enough glue-line area to resist internal and external forces (fig. 15, B-E). Because wood is approximately 10 times stronger in tension than in shear, side-grain surfaces should be at least 10 times as large as the cross-sectional area of the piece in order to realize maximum strength (*44, 125*).

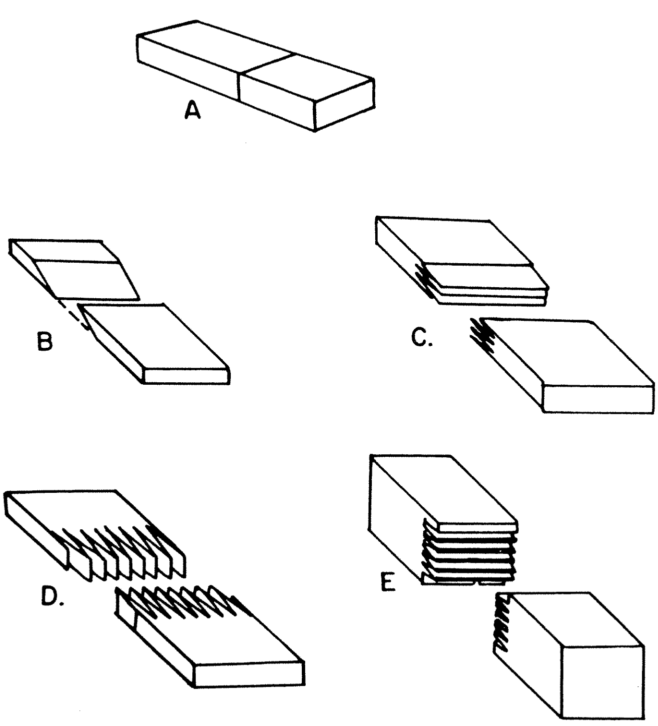

Figure 15.—*End-grain to end-grain joints: A, end butt; B, plain scarf; C, horizontal structural finger joint; D, vertical structural finger joint; E, nonstructural finger joint (44).*

In timber laminating, finger joints are the preferred method for developing end joints that are capable of approaching the tensile strength of wood in commercial operations. The four primary variables in the design of a finger joint are pitch, length, slope, and width of fingertips. Experiments conducted to determine the optimum finger joint geometry of end-grain to edge-grain finger joints normally used in furniture manufacture showed that a finger length-to-pitch ratio of 2.87 to 1 produced significantly stronger joints than lower or higher ratios. Strength values in these tests indicated finger joints can be used as replacements for mortise-and-tenon or dowel joints. For maximum strength, the end-to-end joints must have a distinct glue-line thickness if they are to be stressed in static bending (*105*).

Finger joints formed with dense hardwoods using cold-setting adhesives require an extended assembly time to give viscous glues sufficient time to wet and flow before pressure is applied (*69*). Assembly times that are too short will result in starved joints. When radio frequency (Rf) curing is used, the wood temperature must be >60 °F (>15 °C), or the energy from the Rf unit will be diverted from curing the glue line to warming the wood (*117*).

Table 7 shows some of the factors affecting the bonding of finger joints as well as other end joints. These factors include wood properties, basic joint properties, and production considerations.

End-to-Edge Joints (Assembly Gluing)

Assembly gluing involves side-grain to end-grain joints, as in dowel joints, mortise-and-tenon joints, dovetail joints, and miter joints (fig. 16). In the case of dowel joints, it is important to use dowels of high-shear strength hardwoods, such as maple or birch.

Assembly gluing of furniture primarily entails side-grain to end-grain bonding. The stresses to which these joints are subjected are not usually as great as in edge- and face-glued products. Therefore, polyvinyl acetates, hot melts, or other thermoplastic products are often used because of their quick set time (*61, 101, 157, 162*). Factors to consider in selecting adhesives of this type include setting time, assembly time tolerance, viscosity, sandability, heat and moisture resistance, solvent resistance, and gap filling capability (*48, 60, 102*).

The impetus behind the introduction of these new adhesives for furniture assembly has been two-fold: more efficient production methods and the 1982 target date to meet full compliance with stringent EPA, OSHA, and energy conservation laws restricting the use of solvent-based adhesives (*70*). Excellent reviews of these adhesive systems can be found in papers by Subramanian (*138*) and Pizzi (*115*).

Assembly

Assembly gluing with hardwoods is not appreciably different from edge or face gluing when similar adhesives are used. In many end joints there is a tendency to wipe away the adhesive from the glue line during assembly as the two parts are put together, particularly with mortise-and-tenon and dowel joints (*115*). Removal of the adhesive by wiping reduces the opportunity for a good glue bond. This wiping action does not occur in finger jointing where the tapered surfaces prevent wiping, indicating the importance of joint design, joint fit, and joint surface properties in assembly gluing.

Curing Pressure

Pressure is applied to end joints during assembly to force close contact of the mating surfaces to attain a thin, continuous, and uniform glue line. Pressure is often required to hold the glued members in position until the adhesive sets enough for handling.[6]

The pressure required for end jointing varies with type of joint. After the assembly of some finger-jointed stock, the glue line is often cured with little end or surface pressure (*139*). In other applications, however, considerable pressure is required. The pressure applied to adhesive bonded end joints should be closely correlated to the mechanical properties of the hardwood members. Higher pressures are needed to bond denser hardwoods.[6]

[6]Rabiej, R. 1983. Criteria for Glue Pressure Applied During the Process of Wood Gluing. Unpublished report. On file with the Department of Forestry and Natural Resources, Wood Research Laboratory, Purdue University, West Lafayette, In 47906.

Table 7.—*Factors affecting the strength of finger-jointed sawn timber (52)*

Properties	Factors
Wood properties	Anatomy of the wood species
	Specific gravity
	Summerwood percentage
	Knots (size, type, number and shape)
	Slope of grain
	Size of annual rings (rings per inch)
	Tension wood
	Juvenile wood
	Moisture content
	Drying checks
	Crook and twist
	Resin content
Joint properties	Type of joint
	Geometry and dimensions of the joint
	Cutting direction of the joint
Production properties	Size of sawn timber
	Drying and conditioning
	Sorting
	Crosscutting
	Cutting of fingers
	Adhesive type
	Adhesive application
	Pressing (lateral pressure)
	Application of heat to joint
	Crosscutting of the finger-jointed sawn timber
	Storage
	Dressing
	Quality control at the mill

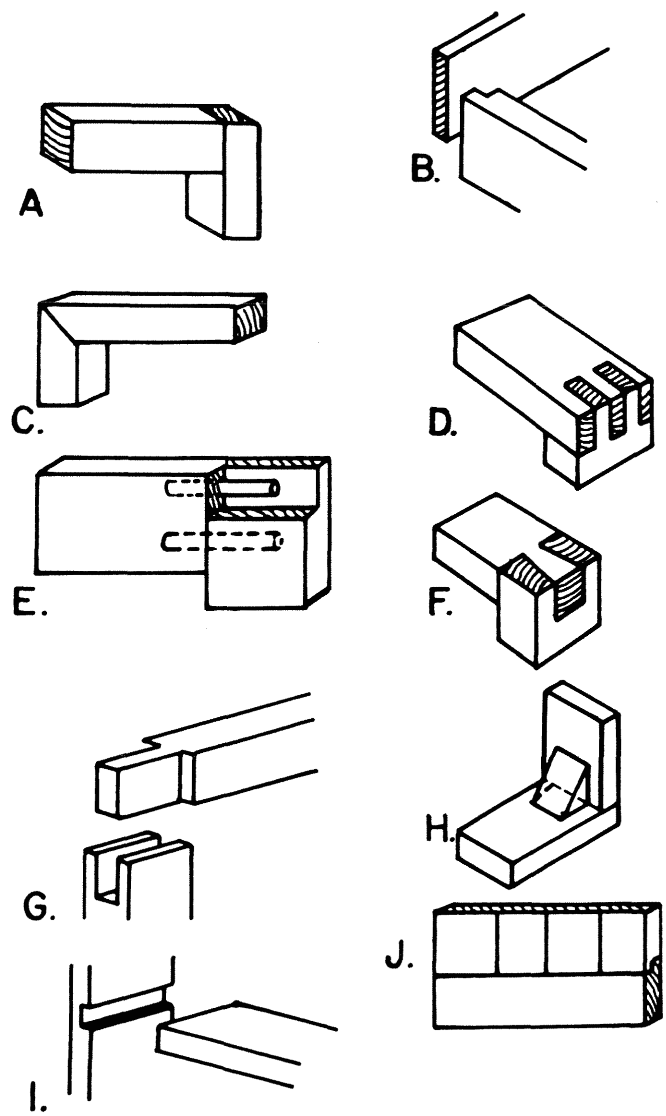

Figure 16.—*End-grain to side-grain joints: A, plain; B, rabbet; C, miter; D, slip or lock corner; E, dowels; F, dovetail; G, mortise and tenon; H, corner block; I, dado; J, tongue and groove (44).*

Adhesives

Adhesives commonly used for high strength (structural) end-joint applications are UF, MF, RF, PRF, melamine-urea-formaldehyde, and cross-linked (copolymer) polyvinyl acetates. Resorcinols and phenol-resorcinols have been and still are recommended for gluing dense hardwoods or any species of treated lumber because their solvent systems and low molecular weights enhance penetration and bonding of these woods (*1, 32, 34, 49, 53, 79, 80, 140*).

Many types of adhesives are used in furniture assembly. Recently the trend has been away from the amino resins (urea and melamine) toward a multiplicity of specialty resins. Rapid-bond water-based PVAc emulsions are now prominent among adhesives used for assembly and edge/face gluing. It has been estimated that 25 million pounds per year (11.3 Mkg/annum) of PVAc resin solids are used by the furniture industry, with 20 percent of this volume being of a cross-linked type for high-frequency curing and higher moisture durability. Approximately 21 million pounds per year (9.80 Mkg/annum) of hot melt resin solids (polyamide and ethylene-vinyl acetate copolymers) are used by the furniture industry for cabinet assembly adhesives, low and high pressure lamination, edge veneering, and case goods (drawers and boxes). Other specialty adhesives include contact cements, acrylics, epoxy adhesives, high-speed thermosetting emulsion, and emulsion polymer/isocyanate (*4, 102, 138*).

Review

In general, all joints function to accurately position individual parts with respect to each other and to hold the parts in place against internal and external forces. By providing enough glue-line area to resist the internal and external forces involved and/or by designing the joint so that the wood carries the load, the adhesive simply holds the parts in place. There are many adhesives suitable for bonding hardwood end joints.

OUTLOOK FOR GLUING EASTERN HARDWOODS

Domestic production of interior-bonded hardwood plywood is not anticipated to change significantly in the years to come. Imported hardwood and high-density vinyl overlays on composite board materials will continue to capture a greater share of the present domestic hardwood plywood production. Because board-core hardwood plywood is cheaper to produce than all-veneer plywood, overall production is expected to increase.

Use of urea adhesives for decorative hardwood plywood will continue in the foreseeable future, unless further impacted by Federal environmental guidelines on formaldehyde emission. Modified PVAc adhesives will gain wider acceptance due to their faster cure rate, more durable formulations, and the fact that they contain very little, if any, formaldehyde. Hot melts currently used for edge banding will have increased competition from PVAc as faster and cheaper processes are sought.

The use of hardwood veneer in southern softwood plywood plants will become more widely accepted as southern pine log costs rise and increase the pressures to utilize the vast volumes of available hardwoods. Softwood plywood mills will continue to seek markets in the furniture and cabinet industries where phenolic bonded hardwood panels will supplement their present sheathing production. Improving phenolic adhesive technology for dense hardwood bonding will increase the potential of these species for exterior veneered products.

Parallel laminating of hardwood veneer appears to have significant potential for structural materials. A wide range of industries, including pallet manufacturers, furniture plants, producers of railroad ties and trusses, telephone pole crossarm manufacturers, and specialty product producers, have shown interest in using laminated veneer components. Several furniture manufacturers are using laminated hardwood veneers as bed rails and structural components for chairs. The adhesives relied on for bonding these hardwood products will be PF, PRF, and EPI types.

Domestic use of hardwoods for furniture and other assemblies will continue to be strong, although furniture and furniture component imports are increasing. Adhesive types will continue to be varied and center around those that lead to quick tack, fast setting, and improved production efficiencies.

The greatest potential need for gluing eastern hardwoods lies in flake-to-flake bonded products. Medium-density hardwoods using PF and MDI adhesives are receiving the greatest initial attention. The more difficult-to-bond, dense hardwoods (oaks and hickories) will require additional research for improved adhesive systems.

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The current status of gluing eastern hardwoods is reviewed in this report, with emphasis on hardwoods growing on southern pine sites. The subjects covered include adhesives, wood and wood-surface properties and their interactions with the adhesive, and the quality of the bonds produced when these hardwoods are used in the manufacture of end joints, laminates, plywood and other composite panels.

Keywords: adhesives, bonding, composites, hardwoods, resins.

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