Wood bonding in the furniture industry and the effect of changing wood supply

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Abstract: *Wood is a complex and heterogeneous material, exhibiting variation in its structure and properties at all size scales. For furniture manufacturing, both macro- and microscopic variations in wood structure affect its bondability with various adhesives and the longevity of those bonds. For example, the relative proportion of earlywood and latewood affect mechanical and rheological properties of wood and dimensional stability and is an important macroscopic feature. Especially in some hardwoods, microscopic characteristics such as vessel size and their distribution influence minimum thickness of the veneer or adhesive formulation to minimize bleed through. At a larger size scale, the presence of juvenile wood or reaction wood in a piece of core stock affect mechanical and physical properties of the wood, thus potentially changing the expected efficacy of bonding and durability of these bonds. The substitution of plantation-grown wood for old-growth wood complicates the performance of these bonds by decreasing uniformity of wood properties. In summary, variations in chemical composition and micro- and macroscopic wood structure play important roles in bonding wood. Understanding these factors is the first step toward achieving good service life for furniture and structural wood applications.*

Introduction

The widespread availability, favorable economics, and aesthetic appeal of wood have led to many uses in our homes and in businesses of bonded wood products from lumber, veneers, flakes, fibers, and particles. Different product types and assembly conditions necessitate many types of wood-bonding adhesives. The fact that an adhesive for structural uses needs very different properties than one for furniture assembly makes it difficult to draw general conclusions about essential adhesive properties. However, two aspects are desired for all wood adhesives: the bond should be stronger than the wood, and the bond should adjust to dimensional changes of wood as humidity and temperature change. A better understanding of wood structure, adhesive properties, and adhesive interaction with wood can help manufactures make better wood products, including furniture.

Wood is an unusual substrate in many respects. For a structural material, wood can shrink and swell repeatedly with changes in moisture content while losing only a small portion of its intrinsic structural integrity. Wood is porous, so adhesives and bonding conditions need to be controlled to obtain sufficient but not excessive penetration. Material properties can vary widely between the many wood species and even within a species, depending upon the quality of the material and the way in which it was processed. Even material properties of pieces of wood from the same tree can vary greatly depending on the relative amounts of juvenile, reaction, and mature wood present. The small joint sizes used in furniture can make these bonds very sensitive to changes in material properties of the wood used and its moisture level. Given that most of the questions about bonding problems or bond failures that we receive at the Forest Products Laboratory are related to furniture, we felt that more detailed knowledge about wood and wood bonds would be helpful to the furniture industry. Thus, this paper discusses wood structure, adhesives, adhesive–wood interactions, and wood availability issues.

Wood Anatomy and Properties

Wood is a biological composite having coordinated domains of various component cells in distinct sizes, shapes, and configurations. One can describe wood at a variety of scales, from single chemical bonds all the way to functioning of wood in a living tree. For this paper, we consider wood structure at two interrelated levels: (1) cells and cell assemblages that define the microscopic structure of wood and (2) larger scales of analysis that are evident to the unaided eye. Both scales of analysis are critical for understanding bond durability in wood–adhesive interactions

Cell walls and cell types in wood

Cells in wood are composed of two domains, the cell wall and the cell lumen (pl. lumina) (Figure 1B,C). The cell wall is the actual substance of wood, and the lumen is the air space internal to the cell wall. This air space or void volume is critically important in wood properties because it affects physical properties such as density

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and adhesive interactions with the wood. The lumen of a cell is as much a part of the cell as is the cell wall itself.

Although all cells in all wood species have both cell walls and lumina, not all cells in wood are the same; characteristic cells are found in hardwoods (wood from broadleaved trees such as maple and beech) and characteristic cells are found in softwoods (wood from cone-bearing trees such as pine, fir, and cedar). The relative proportions of cells in each wood species combine to define its wood structure and consequently its properties.

Softwoods contain two main kinds of cells: tracheids and parenchyma cells. Tracheids are long, thin cells that make up over 90% of the volume of most softwoods. They are oriented along the grain of the wood and vary in wall thickness, cell length, and other microscopic features but are otherwise similar across all softwoods. In the tree they function in long-distance water transport in sapwood and mechanical strength, which makes them the critical cell type in softwood–adhesive interactions. Tracheids have either thin or thick walls, depending on their position in the growth ring (see below). Parenchyma cells are roughly brick-shaped cells that play only a small role in either mechanical strength of wood or interaction with wood adhesives. The resin in the resin canals can cause surface appearance and bonding problems.

Hardwoods contain three main cell types: parenchyma cells (virtually identical to those in softwoods and less important to wood bonding than other cell types), vessel elements, and fibers. Vessel elements are the defining cell type of hardwoods, are specialized for long-distance water transport, and are oriented along the grain of the wood. They are barrel-shaped, large-lumined, and thin-walled, with little mechanical strength. Fibers, also oriented along the grain of the wood, are thick-walled, long spindly cells, much like tracheids in their overall shape but narrower and shorter; they are specialized for providing mechanical strength. Knowing the functions of these cell types in the living tree will prove relevant to understanding wood–adhesive interactions in the context of wood permeability and bond strength.

Gross wood structure

Although the component cells of softwoods and hardwoods differ in some respects, the overall organization of cells in both kinds of wood is similar. Specifically, wood has two cell systems: an axial system and a radial system. The axial system is the sum of all the cells running along the grain of the wood; indeed, the grain of the wood is the axial system, and it functions largely in water transport and in providing mechanical strength to the tree. The radial system runs at a 90-degree angle to the axial system, from the center of the tree out toward the bark, and functions primarily to provide living cells with necessary chemicals, including water.

The axial system, however, is critically important, and is further subdivided into functional units that are important to the tree, to the wood user, and to adhesive interactions. As most people know, trees in the temperate world lay down a certain amount of wood each growing season—a growth ring or growth increment. That growth increment is, at least in some species, clearly divided into two different domains, earlywood and latewood (Figure 1D,E). The earlywood is the first-formed wood of the growth increment and when distinct from latewood is characterized by generally thinner cell walls and larger lumina. This results in the earlywood having lower density and higher permeability. Conversely, the latewood is generally characterized by cells with thicker cell walls and narrower lumina. In addition to wall thickness, hardwoods can show appreciable variation in the proportions of cell types (vessels and fibers) in each domain of the growth ring. An important macroscopic property of wood that is derived from growth rings and growth rate is the number of rings per centimeter, which is a measurement of how quickly the tree grew. In the case of softwoods and many hardwoods, slower growth generally indicates higher density and more desirable wood properties. For ring-porous hardwoods such as oak, elm, and ash, slower growth actually results in lower density and generally less desirable wood properties because of relatively fewer fiber cells and more vessel elements.

The two systems give rise to three planes of section, or three directions of observation, in wood. They are the transverse, radial, and tangential (Fig. 1A) planes. Radial and tangential are also used to describe directions of dimensional change across a board. Tangential change is change in the direction along the growth rings, across the board, and radial change is at 90 degrees to tangential change.

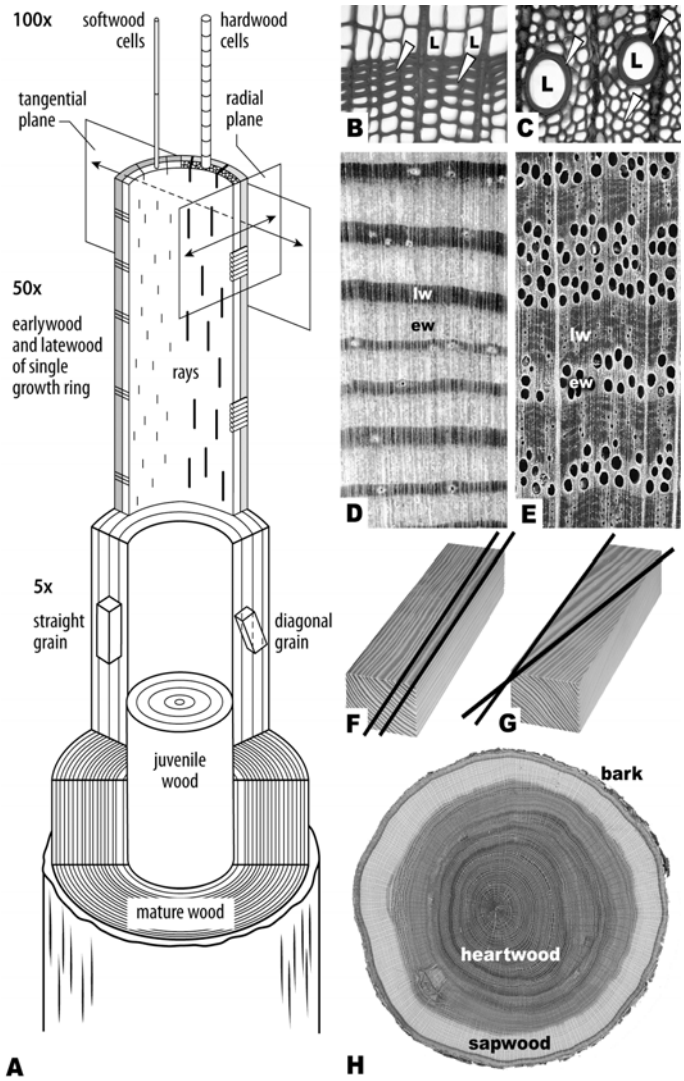


Fig. 1. *A, cut-away illustration of a tree at various magnifications intended to correspond roughly with the images at right; top, a softwood cell and several hardwood cells illustrated to give a sense of scale between the two; one tier lower, a single growth ring of a softwood (left) and a hardwood (right) and an indication of the radial and tangential planes; next tier illustrates many growth rings together and how one might produce a straight-grained rather than a diagonal-grained board; lowest tier illustrates the relative position of juvenile and mature wood in the tree. B and C, light microscopic views of the lumina (L) and cell walls (arrowheads) of a softwood (B) and a hardwood (C). D and E, hand-lens views of growth rings, each composed of earlywood (ew) and latewood (lw) in a softwood (D) and a hardwood (E); F, a straight-grained board; note that the line along the edge of the board is parallel to the line along the grain of the board. G, a diagonal-grained board; note that the two lines are markedly not parallel; this board has a slope of about 1 in 7. H, gross anatomy of a tree trunk, showing bark, sapwood, and heartwood.*

Zones in the tree

If we step away from the microscopic structure of wood and instead think about the standing or freshly cut tree (e.g., Fig 1A), we can consider several large-scale features. Specifically, the typically dark-colored, extractive-rich heartwood is distinct from the light-colored sapwood (Figure 1H). The heartwood represents the older wood in the tree and often is the wood of commercial importance for most furniture applications because it is the color-bearing wood. The sapwood, found directly beneath the bark, is conversely the younger wood of the tree, lacks the color of the heartwood, and is sometimes removed during wood processing. However, some species have mainly sapwood. Historically, when people were harvesting mature, naturally grown trees, heartwood and sapwood were the only distinctions of importance to make in lumber.

Now, as we harvest ever-increasing volumes of fast-grown plantation material, the difference between juvenile and normal wood is another distinction of concern.

Juvenile wood is the collection of the first 5 to 20+ growth rings, depending on species, found at the center of the tree. This means that some of the heartwood is in fact juvenile wood. Juvenile wood is structurally and chemically different from mature wood and as such it has different physical and mechanical properties. For example, Kretschmann (1997) concluded that shear strength parallel to the grain of solid wood decreased as the percentage of juvenile wood in the shear specimen increased in loblolly pine. For the most part, compared with normal wood, juvenile wood has undesirable traits and is best avoided, if possible. In many ways like juvenile wood, reaction wood (wood that is formed by leaning trees) also has chemical and structural differences compared with normal wood and behaves differently, as well. Juvenile wood is discussed below in some detail with regard to moisture relations in wood and how it affects the properties of an adhesive–wood bond, but much of what is said applies to reaction wood, as well.

Moisture relations in wood

Wood is fairly unique as a material, in that it undergoes dramatic changes in dimension with changes in moisture content (MC) of the board. The MC is defined as the weight of water in a board as a percentage of the dry weight of the board. Moisture in wood can either be chemically/physically adsorbed into the cell walls (bound water) or be liquid water in the lumina of the cells (free water). When a board has adsorbed all the water that can be physically bound, it is said to be at fiber saturation point (FSP), and any additional water will be held as free water. Between the FSP and the oven-dry state is where the gain or loss of water causes dimensional change in wood. Environmental conditions of temperature and relative humidity determine the MC of wood. The MC under a given set of conditions is referred to as the equilibrium moisture content (EMC), at which point the moisture taken up by the wood is equal to the moisture lost.

In the case of normal wood, changes in MC between 0 percent and FSP give rise to radial and tangential strain; generally, tangential strain is roughly twice the radial strain, and strain in the longitudinal direction is negligible. In juvenile wood, however, longitudinal strain can approach that of radial strain, resulting in massive changes in board length and influencing stress on bonded joints.

Wood Adhesives

Adhesive interaction with wood

This complex nature of wood makes it likely that adhesive interactions with wood will be complex. In addition, the wide variety of adhesives used in wood bonding and the different joint types further increase complexity. Both wood and adhesive play important roles in controlling the bond formation process and ultimate performance of the assembly.

A key issue in wood bonding is proper control of penetration so that it is sufficient to develop a good adhesive–wood interaction but not so excessive that it leads to an adhesive-starved joint. Penetration into wood can involve either flowing into the lumina and cracks or migrating into the cell wall. To aid in distinguishing these two fundamentally different processes in this paper, the former will be referred to as penetration and the latter as diffusion. Penetration into lumina is controlled by grain angle, density, wood species, and wood surface preparation. Grain angle is very important: In bonding to the edge or face of wood pieces, adhesive penetration is limited if the surface is exactly parallel to the grain. However, being exactly parallel to grain is unlikely (see Figure 1G, for an extreme example); thus, adhesive can flow into many open lumina, leading to deeper penetration than when parallel to grain. This flow into lumina away from the surface can provide stronger bonds through mechanical interlocks, but it also removes adhesive from the bondline. If too much adhesive flows into the wood, over-penetration occurs and insufficient adhesive remains at the bondline (i.e., a "starved bond"). Excessive flow into lumina can be a large problem for butt, scarf, and finger joints. Excessive flow can cause bleed-through on veneers, especially if they have large vessel elements (Christiansen and Knaebe 2004). The ability of the adhesive to penetrate into wood is species dependent and is generally greater for earlywood than for latewood, especially in softwoods and for vessel elements in hardwoods. For example, adhesives more readily penetrate into a pine board, such as loblolly pine (*Pinus taeda*), than they do into a hard maple board, such as sugar maple (*Acer saccharum*), because of the larger median cell lumina of the earlywood cells in pine. Penetration of heartwood is generally more difficult than it is for sapwood because heartwood can have aspirated pits and higher extractives, decreasing its porosity. Many adhesive studies are done on sapwood; thus, bonding of a wood species can be more difficult than the literature indicates if the wood surface is heartwood.

For penetration to take place, the adhesive needs to wet (intimately cover) the wood surface. Thus, freshly prepared surfaces from mechanical planing or hand sanding are better for bonding because the adhesive better wets the surface (River et al. 1991). On the other hand, abrasive planing often crushes surface cells, with poor bond strength resulting from a mechanically weak boundary layer. Some wood species, such as teak (*Tectonia grandis*), are hard to bond because they have oily extractives that limit the ability of the

adhesive to come into contact with the wood and therefore provide a chemically weak boundary layer. Solvent-wiping the surfaces of oily wood improves bond strength. In contrast, a wood without such oils, such as Afrormosia (*Afrormosia elata*, known by some as "poor man's teak") is more easily bonded. Thus, correct identification and understanding of the wood to be bonded can reduce bonding problems.

Adhesive properties also greatly influence their interaction with wood. Key factors include the ability of the adhesive to wet the surface and penetrate/diffuse into the wood. Although most wood adhesives are water-borne and wet surfaces poorly, the few that are not, such as polymeric diphenylmethane diisocyanate and epoxies, can wet wood surfaces well, especially those that are not freshly prepared. As for ability to penetrate/diffuse into the wood, most adhesives will fill cell lumina at and near the surface, creating a mechanical interlock. Additionally some actually penetrate into cell walls, creating micro-sized mechanical interlocks; those that penetrate may also alter the cell walls' swelling capacity and modify their mechanical strength.

Another important factor is their ability to fill gaps between the surfaces. Those adhesives that are cured by moisture, including isocyanates and polyurethanes, generally prefer tight fitting joints because the curing process generates gas bubbles that can weaken the joint of thicker adhesive bondlines. The formaldehyde-type adhesives using phenol, resorcinol, urea, melamine, and combinations of these chemicals can tolerate somewhat thicker bondlines. Poly(vinyl acetates) are generally used in tight bondlines because shrinkage is an issue in thicker bondlines. For gap-filling ability and lower clamping pressures, epoxies are preferred.

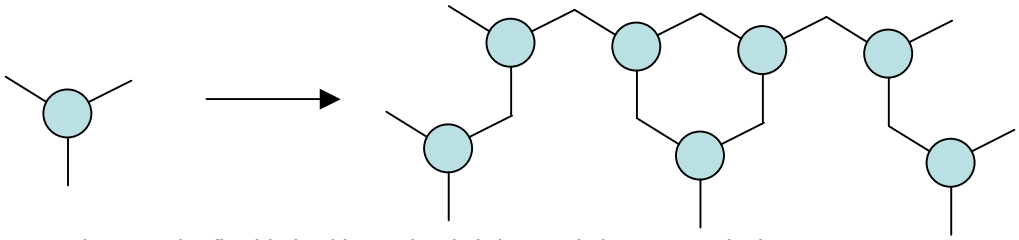
Wood adhesives also exhibit a variety of means of setting, including polymerization and loss of water solvent. Some that polymerize, such as epoxies and phenol-resorcinol-formaldehydes, cure (polymerize) at ambient temperatures, whereas most others require heat or moisture. Moisture-cured adhesives need to have sufficiently wet wood to cure within a reasonable time. In addition to setting by polymerization, most wood adhesives are water borne and set by the wood absorbing water. Those adhesives that set by water removal may cure more slowly when bonding heartwood than sapwood because the former absorbs water more slowly than the latter. Bonding conditions are greatly influenced by type of product being produced. For example, plywood bonding generally requires a different adhesive than does oriented strandboard production because of adhesive application conditions and the amount of compression that the wood experiences for bringing the surfaces together during bonding. For furniture, many phenolics are undesirable because of their dark color and slow setting speed. The traditional poly(vinyl acetate), or white glue, is often being replaced by moisture-cured isocyanates because the latter have better durability. The selection of adhesive depends upon wood substrate, type of joint, bonding conditions, and use conditions for the bonded product.

Bond durability

Wood products are expected to have a long lifespan—over 100 years is fairly typical of wood products, whether used in buildings or furniture. Thus, adhesives need to very "durable." As noted by Kamke (2006), we use the term durability but often do not define service conditions and service life. Service life is generally easier to define—that of inexpensive furniture and cabinets is usually measured in tens of years, while that of structural elements and fine furniture is measured in hundreds of years.

Service conditions involve both applied loads and internal forces as generated by changes in temperature and wood MC. For a beam, bookcase shelf, or vertical member, the load applied to the wood product can generally be calculated and the bonded product tested for its performance. This allows the manufacturer to determine the suitability of the wood product for its load-bearing ability. On the other hand, internal forces generated by the setting process of the adhesive and moisture level changes are harder to quantify, making it more difficult to know the true service life. The shrinking of wood as it dries and the expansion as it picks up moisture are well known, and overall dimensional changes can be measured. For wood to swell and shrink means that much of the water absorption by the cell wall goes into making the cell walls increase in thickness by expanding outward from the lumen during swelling and the opposite during drying. However, even knowing the expansion of the bulk wood, converting the swelling data into actual internal forces on the bondline is difficult. How much of the dimensional change is mitigated by stress relaxation in the wood and how uniform is this stress given that earlywood should have different expansion and contraction values than latewood? How are the forces distributed given the anisotropic nature of wood? How much of the stress is distributed through the adhesive? How much internal force originally exists in the bondline from normal volume shrinkage of the adhesive during the setting process, from loss of the solvent, or the polymerization process? Changes in wood MC while in service are difficult to prevent, but the best practice to maintain the wood during bonding at a moisture content near the average level the product will experience during use.

(A) In-situ polymerized – rigid, multifunctional oligomers that highly crosslink, but can diffuse into cell walls.



(B) Pre-polymerized – flexible backbone that lightly crosslinks or extends during setting.

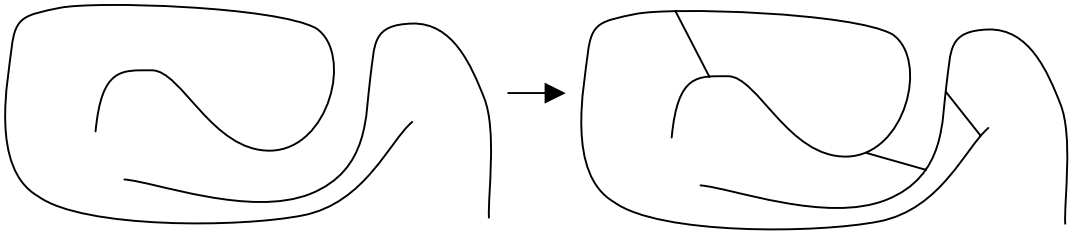


***Fig. 2**. Wood adhesives can generally be classified as either (A) those that are in-situ polymerized where the applied adhesive consists of small molecules that polymerize to form large molecules during the adhesive setting process or (B) those that are pre-polymerized and are often crosslinked during the adhesive setting process.*

Although these questions may not be readily answered, we can better understand the performance of wood bonds if we understand how two general classes of adhesives deal with internal forces (Figure 2). One class, which represents the largest volume of wood adhesives, includes those that are formed from *in situ* polymerization. These adhesives are made of rigid monomers that are often highly crosslinked, yielding an even more rigid cured adhesive, and include the formaldehyde-cured adhesives made from phenol, resorcinol, urea, and melamine, and epoxy adhesives. If the adhesives are rigid, how do they cope with dimensional changes of wood as moisture level changes, especially in exterior exposure? Many of these adhesives are made from chemicals that are known to stabilize the wood by making it more rigid and reducing dimensional change with changing moisture levels. Thus, the difference in dimensional changes between the bulk wood and the bondline is spread through the wood in the interphase region. The other class of wood adhesives is the pre-polymerized adhesives. These generally have a flexible backbone that is often crosslinked during the curing process and include poly(vinyl acetate), polyurethane, emulsion-polymerized isocyanate, and protein. These materials usually have the ability to adjust to dimensional changes of wood by spreading the strain through the adhesive layer. Thus, general comparison of adhesive mechanisms should include evaluation of the polymer morphology, its physical properties, and its mode of interaction with wood.

In the manufacture of panel products, most adhesives are of the *in situ* polymerization class. However, for furniture manufacture, both classes of adhesives are used. The bonds generally are strong enough to give wood failure, although most poly(vinyl acetate) or white glue is not crosslinked, so under high moisture conditions the adhesive softens as the swelling stresses increase, leading to bond failure.

Changes in Wood Supply

In the past 100 years, wood characteristics within species for many American woods have changed as we have moved from cutting old-growth trees to harvesting younger material. Wood quality within a species is governed by factors such as growth rate of the tree (rings per centimeter in a board), overall health and vigor of the tree as affected by silvicultural practices, and final age of the tree when it is cut. Directly related to these are factors such as presence of knots, completion of heartwood formation, proportion of juvenile wood, and greatest width of possible boards cut from the tree. The quality of boards cut from a single tree primarily depends on the proportions of juvenile, reaction, and mature wood. With these changes in tree and board characteristics come changes in the cost of material; as demand exceeds the ready supply of material of a given quality, price increases, often encouraging bold entrepreneurs to explore the use of alternative species.

When attempting to shift to a new species, people are generally seeking an identical wood that is, for the moment, available at a competitive price. Of course, "identical" means different things to different people; some may want the white color of high-quality sugar maple and care little about its strength, whereas others may be seeking only inexpensive, strong secondary wood for hidden parts of a large piece of furniture. Thus, if one's requirements are well defined, a cheap and plentiful alternative may be found by matching the relevant wood properties of the commonly used material with the alternatives available.

This means that a wood user must specify the exact characteristics of interest (e.g., correct scientific name, density, rings per centimeter, number and size of knots), particularly when grading standards are not available or not uniformly enforced (as with many tropical hardwoods). For example, a furniture maker might specify teak, thinking of good, old-growth Burmese *Tectona grandis* (Wood Identification 2007). Their supplier, however, may deliver a load of so-called Brazilian teak (cumaru) *Dipteryx odorata*, which, apart from being nothing like genuine teak in its wood properties, is also an endangered species. Or the supplier may provide Costa Rican teak, which, although it is in fact botanically the correct species (being plantation material), has growth rings of 20 to 26 mm, not at all what the furniture maker had in mind when the order was placed. Thus, to manage the changing wood resource, furniture makers must accurately and precisely specify their needs in contracts with wood suppliers.

Also of critical importance to the issue of wood quality and changing supply is the issue of moisture content in the product. With the relative increase in proportion of juvenile wood in many species, and the ever-decreasing diameter of trees being harvested, control of MC is even more important now than before, because the material itself is more likely to change unevenly with changes in MC. Also, targeting the MC of the wood at the time of processing to the expected MC at the site of end-use will minimize dimensional changes. Likewise, the correct adhesive must be chosen for the specific wood, at the correct MC, and on the correct type of joint for successful application. Targeting all these processes accurately and correctly will take best advantage of the properties of the raw material and will minimize the likelihood of product failure.

Relatively little work has been published on the effects of juvenile wood on mechanical properties of an adhesive–wood bond. The rising supply of wood with higher proportions of juvenile wood and this lack of published literature prompted researchers and the United States Forest Service's Forest Products Laboratory to conduct some basic experiments (Jakes et al. 2007). Using ponderosa pine (*Pinus ponderosa*), compression shear block specimens were constructed using two adherends and a phenol resorcinol formaldehyde resin. Three groups of shear block specimens were tested, one with two mature wood adherends (MM), one with two juvenile wood adherends (JJ), and one with one juvenile and one mature adherend (JM). Interestingly, despite juvenile wood's perceived inferiority to mature wood, the JJ group was significantly stronger than both the MM and JM groups. However, the JM group produced the weakest bonds. The resulting compression shear strengths were 11.3 ± 0.3, 9.1 ± 0.3, and 7.3 ± 0.5 for JJ, MM, and JM groups, respectively, where the uncertainties are 95% confidence intervals on the mean. An analysis of the corresponding load–displacement curves revealed that the JJ group had over twice the work to failure than did the MM and JM groups, and the overall bond stiffness was lower. This work suggests that during the loading of a compression shear block specimen, the more compliant JJ specimen is able to dissipate twice as much energy during loading than is the MM specimen, and the result is an overall stronger bond. However, if mature wood is bonded to juvenile wood, the opposite affect occurs, and a weaker bond results. This work demonstrates that juvenile wood, when present in adhesive–wood bonds, will affect bonding, but not necessarily negatively in all cases.

Conclusions

Understanding both the nature of wood and adhesive interactions with wood is important to making a wood product with an acceptable service life. Wood supplies are changing, with a greater proportion of earlywood or juvenile wood than in the past, which can have a variety of effects on end use. Furthermore, these changes can greatly affect the interaction and performance of adhesives with wood. Two main classes of adhesives, based upon their polymer chemistry and morphology, each respond differently to changes in wood moisture levels. The wood user, especially the furniture maker, needs to be cautious and informed in wood selection or may need to consider altering the design and adhesive used to accommodate these changes.

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