What Does Moisture-Related Durability of Wood Bonds Mean?

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ABSTRACT

The accelerated test methods that distinguish between acceptable and unacceptable wood adhesives generally involve subjecting the bonded assembly to abnormally rapid and extreme moisture exposure or cycling. In the United States and Canada, these tests for moisture durability have been established, but selection of the appropriate test methods for the different service classes (extent of water exposure) is still being discussed in some cases. For establishing these standards, a better understanding of the information provided by these tests about the bondline durability is important. Most studies involve different adhesives with the same wood species and evaluate bond efficacy using strength and percentage of wood failure. We studied different wood species, especially in durability testing, to provide crucial insight into the factors that contribute to a durable bond and demonstrate the utility of the percentage of wood failure. The bonding and bond durability of white oak, sugar maple, aspen, Sitka spruce, southern yellow pine, and ipê are covered. The data indicate that the wood properties greatly influence the internal or interfacial stress and thus the durability of the bonded assembly.

KEYWORDS

Wood swelling, bond durability, epoxy, ipê

INTRODUCTION

Often in wood adhesive research, emphasis is placed upon the adhesive's chemistry and properties with little importance placed upon the properties of the wood substrate. This is understandable because in most applications, the wood species is chosen first for its strength, decay resistance, appearance, or low cost, and then the adhesive is selected to fit the application. However, different species of wood often have distinctly different properties, one or more of which may affect bonding, and each of which is determined by the structure and chemistry of the wood. With the diversity of woods in the commercial marketplace, a better understanding of the interactions between adhesives and woods with different properties is critical for developing a more robust model for adhesive–wood interactions.

For wood-bond performance, the three most important aspects of wood are its interactions with the fluid phases of the adhesive, its dimensional stability, and its strength. First, given its cellular construction, it is not surprising that there is often considerable flow of the adhesive into the lumina of cells adjacent to the bondline. Kitazawa (1946) hypothesized that lumina filled with cured adhesives may create mechanical interlocks. However, too much adhesive flow into the wood can result in a starved bondline; this can be especially true with the large lumina of earlywood tracheids in softwoods and in the large earlywood vessel elements in ring-porous hardwoods. Bulk flow into the lumina is only the coarsest form of adhesive fluid movement in wood; a finer level of interaction often exists involving pits between cells, surface roughness on the S-3 or warty layers or both, microchannels hypothesized to exist within the cell walls, and solubility of the adhesive within the polymer domains of the specific components of the cell walls (Frihart 2006). Second, wood swells and shrinks dimensionally in response to changes in the amount of water in the wood (moisture content); the degree to which wood resists dimensional change (strain) as moisture content changes is referred to as a wood's dimensional stability. Strain in response to changes in moisture content is neither equal between wood species nor along the different axes of the wood (Simpson and TenWolde 1999) and can put high stresses on the interfaces between the wood and adhesive. Third, the intrinsic strength of wood varies greatly between species and the direction of the applied force. Under any conditions, a weaker wood species applies less force on the bondline before wood failure occurs, but considerable force can be applied to the bondline by a species with greater mechanical strength. Although the strength of the bond under ambient moisture conditions (representative of service conditions for the products) is important, the extreme test of the bond integrity is determined under wet conditions ($\geq$ FSP, fiber saturation point) or after wet/dry exposure cycles. Thus, moisture-related durability test methods play a crucial role in determining the acceptability of an adhesive for the selected wood species and application.

Most wood adhesive studies use only one or two wood species in testing bond strength and durability. Kitazawa (1946) researched in detail 22 wood species, including both softwoods and hardwoods and studied adhesive interactions of resorcinol-formaldehyde and urea-formaldehyde adhesives with these wood species. Parameters examined included glue line (thickness, defects, air pockets, crazing) and the wood interphase (total penetration, penetration into contiguous cells, ray penetration, percentage of filled surface pores), visual estimation of adhesion to the wood surfaces, and other aspects (Kitazawa 1946). This study was the only contribution we are aware of that considered a breadth of wood substrates and the adhesive interaction with the wood. However, this study did not address bondline properties with changes in moisture content.

We selected five species as wood substrates for our durability study: white oak (ring-porous hardwood), sugar maple (diffuse-porous hardwood), aspen (lower density, diffuse-porous hardwood), Sitka spruce (lower density, gradual-transition softwood), and southern yellow pine (higher density, abrupt-transition softwood). We evaluated these species using a single epoxy adhesive to minimize surface wetting problems, overpenetration, and large adhesive void issues, while still showing bondline failures under durability testing. For durability testing, both D 2559 wet/dry cycles and D 905 (wet and dry conditions) were used (ASTM 2007). We also studied the bonding of a tropical timber known internationally as ipê (*Tabebuia* spp.). Ipê is of interest because it is a high-density tropical hardwood able to withstand harsh service environments of exterior exposures. The combination of high density (and thus high intrinsic strength) and high concentrations of certain extractives makes ipê highly resistant to biological attack. However, these properties are also a severe challenge to bondline durability; thus, we examined the performance of five different ambient curing exterior adhesives using accelerated durability tests.

METHODS

For the epoxy bonding studies, we used FPL 1A, which involves first mixing 100 parts D.E.R. 331 epoxy resin (Dow Chemical Company, Midland, MI) with 12.5 parts of benzyl alcohol (Aldrich Chemical Company, Milwaukee, WI) and 2.50 parts of CAB-O-SIL® N70-TS hydrophobic fumed silica (Cabot Corporation, Boston, MA). After thoroughly mixing these materials, 11.10 parts of D.E.H. 24 hardener (Dow Chemical, Midland, MI) was well mixed in with epoxy. The five wood species used in these bonding studies were white oak (*Quercus* spp., white group), sugar maple (*Acer saccharum*), southern yellow pine (*Pinus* spp.), Sitka spruce (*Picea stichensis*), and aspen (*Populus tremuloides*). With the lumber purchased from several local distributors, sapwood was used for all species, except the white oak.

The method for wood selection has been discussed in detail as has the bonding and testing procedure for the ASTM D 2559 type tests (Christiansen 2005). For the ASTM D 905 test, all wood strips were conditioned at 27°C and 65% relative humidity until bonded. Specimens were prepared by laminating two strips of wood, 6.4 mm thick, 3 1.8 mm wide and 22.9 cm long. FPL 1A epoxy was spread at an approximate rate of 320 to 340 g/m^2 on both surfaces with a rubber-roll hand spreader. Adhesive spread rate was accurately controlled by automatic tare weighing the adhesive on the laminates as they were spread. Pressure for the epoxy was measured by squeeze out, generally about 10 psi. After removing material about 3 mm from all sides and ends, four block-shear specimens with a shear area of 25.4 mm by 25.4 mm were cut from each joint assembly to form shear blocks similar except for size differences as described in ASTM D-905-03 (ASTM 2007) and randomly assigned to either the ambient (~1 0% EMC, equilibrium moisture content), wet, or wet/ambient (re-equilibration to ~10% EMC) shear tests. Eight specimens for each wood species were subjected to a single vacuum pressure soak (VPS) of 85 kPa for 5 minutes and 517.6 kPa for one hour, and then tested for shear strength and wood failure while in the water-saturated condition. The saturation process procedure consists of submerging specimens in tap water at room temperature in a pressure vessel, maintaining a vacuum of 84.66 kPA for 30 minutes maintaining a pressure of 448 ± 35 kPa for 30 minutes, and submerging in water until tested.

The wet/ambient specimens were subjected to the VPS procedure and then were re-dried at 27°C and 65% relative humidity until their weight reached equilibrium, typically 3 to 5 days. Ambient and wet specimens were tested in a compression-loading shearing tool as described in ASTM Method D 905. Load was applied at a constant rate of 2.54 mm per minute until failure. The maximum load at failure was recorded, and then shear strength was computed for each specimen based on the nominal shear area. Wood failure was estimated to the nearest 5% on the sheared area, according to ASTM D 5266-99, Standard Practice for Estimating the Percentage of Wood Failure in Adhesive Bonded Joints (ASTM 2007). The wet-tested specimens were air-dried before estimating wood failure. Estimating is easier after drying because of greater color and light reflection contrast between the dry wood fiber and the adhesive.

With the ipê study, we investigated the effect five ambient curing exterior wood adhesives have on the shear strength of ipê during ambient (–10%EMC) and wet conditions using a modified ASTM D 905 compressive shear test. To investigate how ipê anatomy might relate to bond strength, we used fluorescence microscopy to analyze the cross-sectional bondline penetrability. The adhesives used were emulsion polymer isocyanate (EPI), epoxy (EPO), two types of polyurethanes — one fast (PUR1) and one slow (PUR2) reacting, and phenol-resorcinol formaldehyde (PRF). We made four assemblies (31.75 mm × 580.6 cm × 6.35

mm.) for each adhesive, totaling 20 assemblies. Each assembly provided four block-shear specimens. Two specimens from each assembly were tested in compressive shear under 10% EMC. Two other specimens from each assembly were tested in compressive shear directly after a 30-minute vacuum/30-minute-pressure-soak (VPS) cycle. The total number of block-shear specimens was 80 (5 adhesives x 4 assemblies x 4 specimens). Methods for testing were identical to that of the epoxy-bonding study described previously. We took measurements of the bondline area (width and length) before (10% EMC) and after (2 FSP) the VPS cycle. These measurements were taken with a Mitutoyo digital caliper to 0.01 mm. The fifth block-shear specimen was used for microscopy. After soaking the ipê bondline specimens for several days in water:ethanol (9:1 v/v), we microtomed the cross-sectional bondline to 50-micron thicknesses using a Spencer microtome (SN 3423) and viewed the sections with a Leitz Orthoplan photomicroscope equipped with a xenon lamp (emitting 200–800 nm) and Leitz H2 filter cube (exciting 390-490 nm). We selected two scales (6.3X and 40X) from each adhesive analyzed. Photos were taken using a Nikon Digital Sight DS-L1 (Nikon Instruments Inc., Melville, NY).

RESULTS AND DISCUSSIONS

Epoxy Bonded Wood

For our studies, we selected several hardwoods and softwoods to address differences in density and structure. Moisture-resistant bonds with white oak are often difficult to form because, as a ring-porous wood, the physical and mechanical properties of the earlywood and latewood are dramatically different. Moisture-resistant bonding of sugar maple is difficult because of its high density, high strength, and lack of dimensional stability (see Table A for shrinkage values).[8]

Table A. Properties of wood species used in these studies

Species	R shrink	T shrink	V shrink	SG	Shear II	MOE	Growth rings
White oak	4.4	8.8	12.7	0.68	13800	12300	Ring porous
Sugar maple	4.8	9.9	14.7	0.63	16100	12600	Diffuse porous
aspen	3.3	7.9	11.8	0.39	7400	9900	Diffuse porous
Sitka spruce	4.3	7.5	11.5	0.36	6700	9900	Gradual transition
SYP	4.8	7.4	12.3	0.51	9600	12300	Abrupt transition
Ipê	6.6	8	13.2	0.92[a]	14600	21600	Diffuse porous

Notations: R, T, and V shrink are green to oven-dry % shrinkage in the radial, tangential and volumetric modes, respectively; SG is specific gravity (oven-dry weight / volume at 12% moisture content), Shear II is shear strength parallel to grain in KPa; MOE is modulus of elasticity in MPa,. [a]Ipe specific gravity is oven-dry weight / green volume.

[8] As a note for laminated beams, volumetric value is probably more representative in that the pieces are not truly in the radial or tangential direction, while for bonding peeled veneer, tangential values are more appropriate. In addition, actual swelling data for the wood would be a better measure, but we used the shrinkage data upon drying as an approximation for the swelling forces due to its wide availability for many species.

Bonding of aspen is easier because it has lower strength, possesses modest dimensional stability, and its diffuse porous structure presents many open vessels for bonding surface. Like aspen, Sitka spruce often provides durable bonds because it has low strength, is low in swelling, and has fairly uniform structure. On the other hand, bonds with southern yellow pine can lack durability because of its relatively high specific gravity, dense latewood bands, higher swelling for a softwood, and higher strength.

Although epoxies are too expensive for most wood-bonding applications, they are used in repair of wood-to-wood bonds (e.g., wooden bridges, bolted timbers, airplanes, and boats) (Selbo and Bohannan 1968, Avent et al. 1976). Epoxies are used for these applications because they have good gap-filling properties and need low clamping pressures. We chose epoxies because with their low surface tension they form bonds easily, have limited pH sensitivity, use the same clamping pressure for the different species, are unlikely to form starved bonds due to overpenetration, and often produce moisture-sensitive wood bonds. These factors made it the choice for our study. We used FPL 1-A because it was a known reliable adhesive for critical wood bonding applications, such as aircraft bonding (Myal 1967).

One way to test durability is to examine the shear bond strength of both ambiently stored and re-equilibrated (after water soaking) specimens. We tested the shear strength of the bonded wood specimens not only using standard ambient and wet (water-soaked) conditions of the standard D 905 test but also after allowing the wet specimens to come back to the normal ambient condition. In Figure 1, it is clear that the bond strength varies by wood species and test conditions.

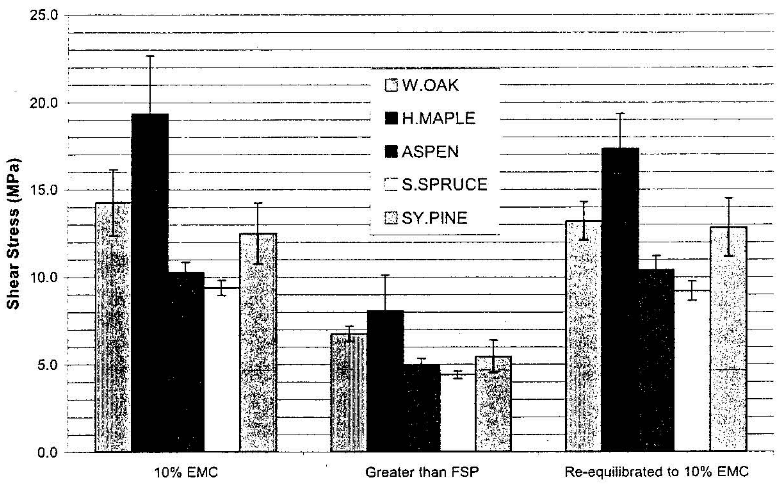

Figure 1. Strength determined using ASTM D 905 testing for different wood species with FPL 1A epoxy and tested for ambient (10% EMC), vacuum pressure soak (>FSP), and vacuum pressure soak followed by re-equilibration to 10% EMC (wet/ambient) specimens Under these test conditions, all specimens had sufficient strength to meet the D 2559 standard of 80% wood failure of the shear parallel to grain for that species. Only the white oak, Sitka spruce, and aspen meet the percent wood failure requirements The error bars are ± two standard deviations around the average value

The stronger wood species such as oak, maple, and pine (see shear parallel to grain in Table A) give higher bond strengths for the ambient specimens (shear strength in Figure 1), but the bond strengths for all species decline under the wet conditions, as expected based on the properties of wood itself (Green et al. 1999). However, all the strengths return within 90% of the original upon allowing the specimens to re-equilibrate back to 10% moisture content. A similar phenomenon was observed previously by Gillespie (1976), in which sugar maple and eastern white pine ASTM D-905 epoxy-bonded assemblies were subjected to substantial moisture extremes (i.e., 2% to $\geq$ FSP). Gillespie studied what effect shrink–swelland swell–shrink cycles had on the shear strength and wood failure. He found that for epoxy-bonded assemblies, the maple retains 87% of original strength upon going from 12% to 2% and back to 12% EMC, but only retains 50% of original strength in going from 12% to $\geq$ FSP and back to 12% EMC. More dramatically, he found that the epoxy-bonded pine retains full strength upon going from 12% to 2% EMC or ≥ FSP and re-equilibration back to 12% EMC.

Because wood strength decreases as its moisture content increases, the data in Figure 1 alone do not indicate whether the bond or the wood is responsible for these changes in shear strength. The shear strength data need to be combined with the percentage of wood failure to understand what is happening in these tests. The data in Figure 2 generally show a lower percentage of wood failure and therefore greater adhesive failure as the shear strength of the assembly increases. Thus, the epoxy forms reasonably strong bondlines, but when the wood is strong enough to exert high force upon the bond, the epoxy may fracture first. The percentage of wood failure decreases for all but the aspen and Sitka spruce in the wet specimens compared to the ambient specimens. Thus, even though the wood is weakening and putting less force on the bondline during the shear test, the bondline is failing first more often. The percentage of wood failure values for the wet/ambient recover to nearly those of the ambient specimens. Again, the previous study by Gillespie (1976) displayed a similar trend in wood failure results for maple and eastern white pine. Thus, the extra strain due to the differential swelling between the wood and adhesive causes an internal stress on the bond and greater failure within the bond. Those wood species with the greatest swelling have the largest decline in wood failure supporting the model of wood strain (Frihart 2007, Gillespie 1976) imposing an increased internal stress on the bondline. Once this internal stress is removed, the shear strength and percentage of wood failure return to close to their initial values.

Another test that shows the influence of swelling and shrinking forces is the ASTM D 2559 (Standard Specification for Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet Use) Exposure Conditions) delamination method. This test involves the swelling induced by vacuum and pressurized water soaks and shrinkage accelerated by oven drying of six-ply laminated wood blocks.

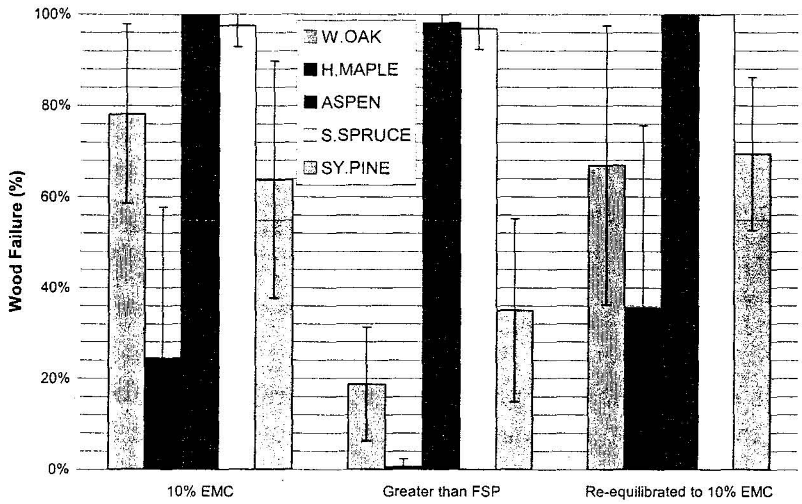

Figure 2. Percentage of wood failure for FPL 1A epoxy as determined using ASTM D 905 and ASTM D 5266 testing for different wood species and tested for ambient (10% EMC), vacuum pressure soak (>FSP), and vacuum pressure soak followed by re-equilibration to 10% EMC (wet/ambient) specimens. The error bars are ± two standard deviations around the average value.

The data in Table B showed less delamination for those wood species that had little loss in the percentage of wood failure in going from ambient to wet (Figure 2). With no externally applied load, the performance in this test is mainly dependent upon the swelling forces for rupture of the bond. The shrinking and swelling of the wood is one of the good predictors for bond durability. The use of hydroxymethylated resorcinol primer has been shown to greatly improve the durability of epoxy-bonded wood and the available data is in agreement with on this model (Christiansen 2005, Frihart 2007). Thus, these data also support the concept that the wood swelling strain imposed on the bondline can lead to failure of the bond via the interfacial stress.

Table B. Percentage of delamination determined using ASTM D 2559 testing for FPL 1A epoxy with different wood species. Only the Sitka spruce had sufficient durability to meet the standard requirements.

Wood species	Delamination (%)	
	Assembly 1	Assembly 2
White oak	83.1	83.9
Sugar maple	79.1	84.2
Aspen	10.5	13.9
Sitka spruce	0.0	0.0
Southern yellow pine	67.3	51.7

Ipê Bonding

To decrease the use of chemically treated wood, more naturally decay-resistant tropical species are being used in exterior applications for decorative trim and decking. Ipê (*Tabebuia* spp., lapacho group), a currently popular tropical hardwood of the family Bignoniaceae, is known to be very difficult to bond with wood adhesives. However, its high resistance to fungal and termite attack (Miller et al. 2003, Paes et al. 2002, Greenwood and Tainter 1993) makes this wood an attractive choice for exterior applications. With the desire to use ipê for posts and railings at the Forest Products Laboratory and the lack of literature about bonding of ipê, a study on a suitable exterior adhesive for ipê lamination was desirable. The data in Table A show the density of the ipê is much greater than commercial North American hardwood species, such as white oak and sugar maple. Density influences the penetration of vessel and fiber lumina by the adhesive, and density also influences the permeability of the cell wall, which is quite hindered with species of low void volume, as in the case for ipê. The high ipê density also leads to greater swelling and shrinkage of the wood. The vessels in ipê are filled with a yellow powdery material called “lapachol,” a naphthoquinone with antifungal properties (Velasquez et al. 2004, Grohs and Kunz 1998). This compound and other extractives from ipê may play a role in affecting bondability of the wood with some adhesives. However, it still is not known whether the presence of the ipê extractives hinder, help, or are unimportant to the performance of these adhesive bonds. Several studies of the bondability of various tropical woods with various adhesives exist. In some cases, extraction of tropical woods with solvents of varying polarity does increase bond strength (Moredo et al. 1990, Alamsyah et al. 2007). However, in other cases, extractive removal does not correlate well with bond strength (Chen 1970, Moredo et al. 1996). Clearly, there are mechanisms beyond wetability of the wood surface that are taking place, which likely include density, chemistry of the S-3/warty layer, and hygroscopicity (rate of water-vapor sorption, which is related to dimensional stability). For example, studies have shown that species characterized by high extractive content have a decreased hygroscopicity, particularly as indicated by low fiber-saturation points (Nearn 1955, Wangaard and Granados 1967). Species with low fiber-saturation points display low equilibrium moisture contents at high relative humidities. This is most likely caused by a bulking action of the extractives, thus lowering the moisture sorption and dimensional changes.

In this study, we tested the bond strength of block-shear specimens of ipê under ambient (10% EMC) and wet ($\geq$ 2 FSP) conditions. Figure 3 shows the results of the compressive shear test. In the ambient (10% EMC) condition, it is apparent that most adhesives performed well.

The EPI and PRF gave the highest average shear stresses of 21.9 and 20.6 MPa. The EPO, PUR1, and PUR2 gave very similar average shear stresses of 17.1, 17.2, and 18.4 MPa. After the VPS cycle, the compressive shear stress dropped considerably with all adhesives (averaging ~5 MPa), except the PRF adhesive, which gave an average shear stress of 14.2 MPa. This dramatic difference in wet-bond strength between the PRF and the other four adhesives displays why phenolic and resorcinolic adhesives still exist in today's market as the true standard for exterior bondline exposure. Under ambient conditions, almost all adhesives showed exceedingly poor wood failure results after the shear test, except for EPI and PRF with averages of 72% and 84%, respectively (Figure 4).

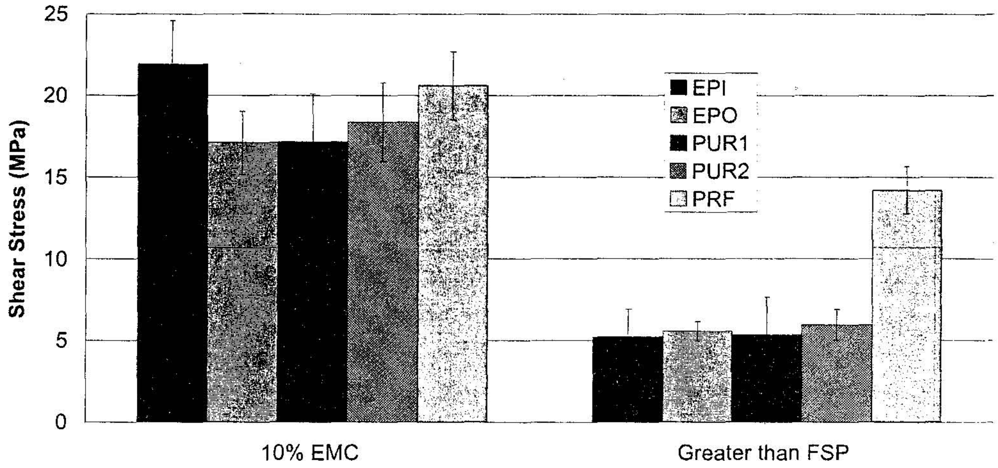

Figure 3. Strength determined using ASTM D 905 testing for ipê with five exterior adhesives and tested under ambient (10% EMC) and vacuum pressure soak (wet, > FSP) conditions. The error bars are ± two standard deviations around the average value.

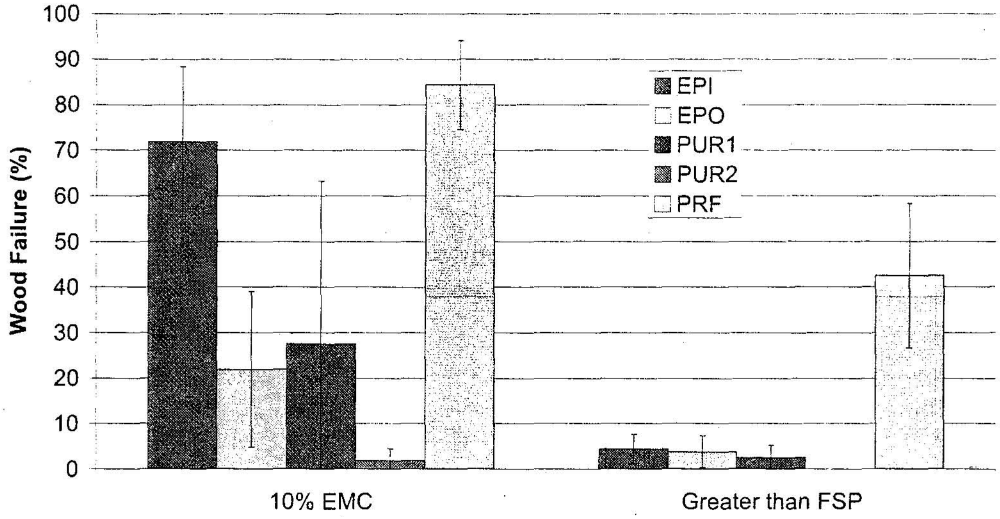

Figure 4. Percentage of wood failure for ipê bonded with five exterior adhesives as determined using ASTM D 905 and ASTM D 5266 tested under ambient (10% EMC) and vacuum pressure soak (wet, > FSP) conditions. The error bars are ± two standard deviations around the average value.

After VPS exposure, the wood failure results are again quite dramatic, showing that most adhesives gave average values of only 0%–5%whereas the PRF gave an average of 43%. The dimensional changes measured in the bondline area after the VPS cycle for all adhesives displayed an average change of only 2%. These collective results suggest that most adhesives used to bond ipê cannot withstand the swelling stresses induced at the bondline during the VPS cycle, even with very small final dimensional changes. However, PRF seems to have a way of stabilizing the bondline and the interphase region, thus maintaining a sufficient amount of bondline integrity to allow failure in the wood.

Using fluorescence and transmitted light microscopy, we analyzed cross-sections of several bondlines with all five adhesives. For simplicity, we selected two magnification scales (6.3X and 40X) from all adhesives analyzed and the 6.3X magnification images are shown in Figure 5.

From the microscopic images, it is seen that all adhesives have difficulty in penetrating the ipê anatomical structure. Most are able to fill the vessel lumina and voids between fibers fairly well. Vessel elements are not thought to contribute significantly to the overall strength of hardwood xylem. It is the fibers, with their thick secondary cell wall layer and more substantial length, that are thought to contribute most to the bondline integrity. In the wood failure analysis of ipê, we noted that when the wet PRF-bonded specimens failed, the failed surface typically displayed wood only a few cells deep (viewed in Environmental Scanning Electron Microscopic images). We hypothesize that PRF, being known as an adhesive with capabilities of permeating the cell wall, may diffuse into the first few fiber cells and act as stress diminisher for fractured surfaces.

Testing Moisture-Related Durability

The purpose of these accelerated tests is to predict real performance and bond failure in exterior exposure. The D 2559 is considered to be a minimum requirement for most structural bonding processes. It does allow for 60% greater failure with hardwoods, most likely due to the greater swelling and shrinking of the more dense species. Does a single or a few cycles of high amplitude strain caused by rapid wetting and drying of the wood in the accelerated tests represent the slower wetting and drying in actual end use? The slow natural penetration of moisture deep into the wood and the stress relaxation modes of the wood could indicate that the rapid cycles may not be a good representation of actual end-use conditions. However, in general the literature shows a good relationship between those adhesives that hold up in exterior exposure and those that pass the accelerated durability tests (Caster 1980, Frihart 2008, Iwata and Inagaki 2006, Raknes 1997, Sugimoto et al. 2007). In addition, the tests recommend the use of the same wood species that is used in the end application, thus eliminating the effect of the structural, chemical, and swelling differences from giving an incorrect assessment.

What about products whose exposure are not exterior, but may nonetheless have limited or accidental exposure, such as occurs during construction? The regulations in the United States and Canada require structural adhesives to pass ASTM D 905 and 2559. These may fail some adhesives that would perform well in service (Avent 1976, Gillespie 1976, Raknes 1997), but because these adhesives are used for structural applications, the general consensus is to develop regulations that are conservative in nature.

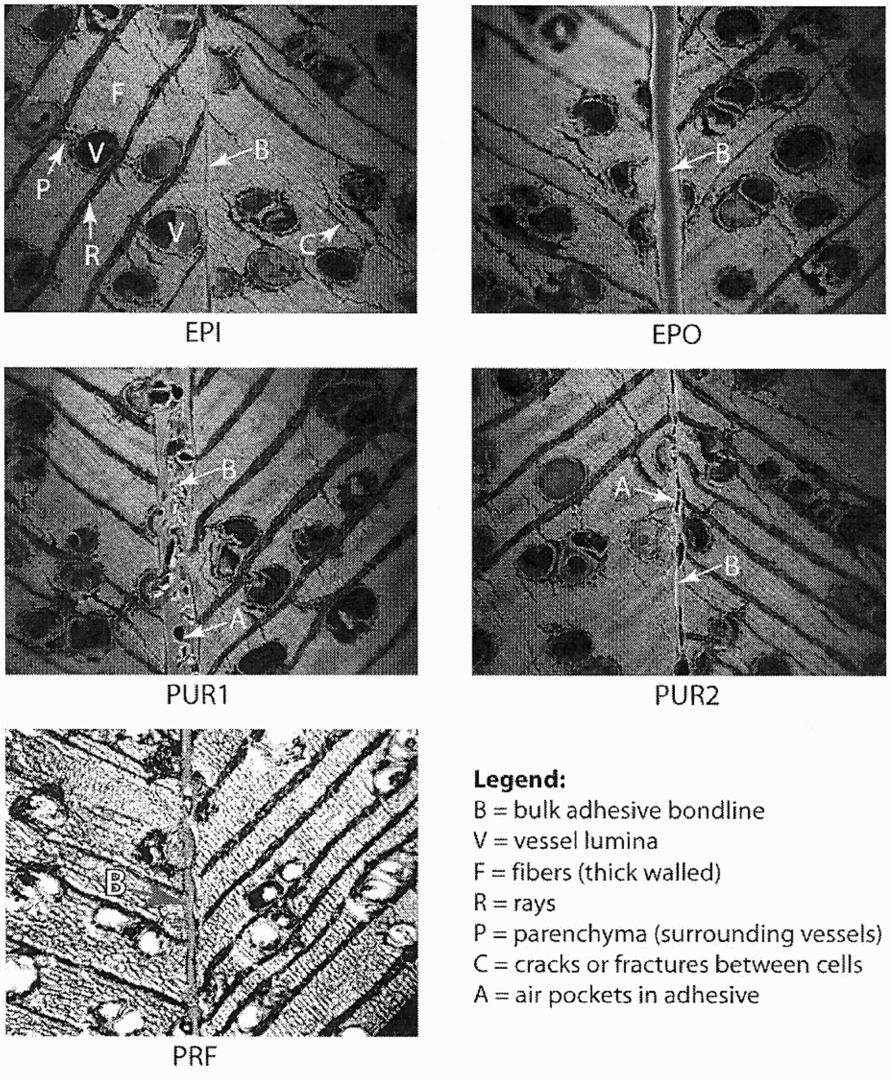

Figure 5. Fluorescence microscopy of the cross section of ipê bonded with five exterior adhesives. Images are the following: EPI (emulsion polymer isocyanate), EPO (epoxy), PUR1 (polyurethane, fast curing), PUR2 (polyurethane, slow curing), PRF (phenyl-resorcinol formaldehyde). Images are shown at 6.3X. The PRF images are transmitted light only because of non-fluorescence of this adhesive.

The other area of discussion is the importance of the percentage of wood failure (Frihart 2008). Reliance only upon strength can be deceiving because the observed decrease in wet strength compared to dry strength can be caused by lower strength of the wood or the adhesive bond. The wood failure data help to demonstrate where the failure takes place. More specifically, one can categorize wood failure to occur: catastrophically (i.e., instable), in moderate increments of growth with intermediate arrest points (stick/slip), or in continuous small increments (stable) (River 1994). Failure in the wood through continuous small increments indicates bond strength in excess of the intrinsic strength of the wood, whereas failure along the bondline could indicate an unstable failure of the adhesive itself or failure in the adhesive-wood interphase where a stick/slip fracture predominates. The data for the epoxy bond tests shown here are typical; specimens with loss of wood failure in the D 905 test fail to pass the D 2559 tests. Percentage of wood failure is therefore a valuable metric for evaluating bond performance.

CONCLUSIONS

Although the adhesive plays a vital role in wood-bond performance, the wood also plays a very important role. The density can give a good idea of the receptivity of the wood towards adhesive penetration, but other factors, such as hygroscopicity, extractives, pH of the wood, and properties of the cell wall can also play a role. Once a bond is formed, stronger wood species allow more force to be placed on the bondline under external loads, often resulting in higher bondline failure. For moisture-related durability, the degree of wood swelling under wet conditions affects the internal stress on the bondline area. These factors were used to evaluate the epoxy bond performance data for white oak, sugar maple, aspen, Sitka spruce, and southern yellow pine. The less dense and lower strength aspen and Sitka spruce formed more durable bonds in both the ASTM D 905 and 2559 type tests compared to the white oak, sugar maple, and southern yellow pine.

Ipê is an extremely difficult species to bond because of its high density and possibly its extractives content. We examined ipê using several exterior adhesives in ASTM D 905 tests and found that a PRF adhesive provided the most durable bonds. The fluorescence microscopy images provided evidence that all five adhesives failed to penetrate well the ipê void volume. However, our close evaluation of the 40X magnified images of transmitted light microscopic showed that PRF appears to penetrate the surface fibers better than the other adhesives.

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