

How wood adhesives work and where are the areas for improvement

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Abstract

Invoking normal adhesion theory, bonding of wood would seem to be easy in that the surface has plenty of roughness for mechanical interlocking with high enough surface energy, there is an abundance of hydroxyl groups on the wood for hydrogen bonding to the adhesives, and the aqueous solvent in the adhesive can readily soak into the wood. In fact most adhesives will form good to excellent bonds to wood as long as the bond is kept dry. However, because wood swells and shrinks with changes in ambient relative humidity, most bonded wood products must pass some type of moisture exposure test. Performance criteria eliminates many adhesives because the wood is swelling at the same time that the adhesive is being plasticized by the water, resulting in weak bondlines. Other adhesives can be too brittle to adjust to the dimensional changes of the wood leading to cracks that eventually cause macroscopic fractures. Thus, having enough moisture resistance for bonded assemblies continues to be a challenge. Other challenges include dealing with the variation and changes in the wood supply, addressing application and curing issues, dealing with lower formaldehyde emission standards, bonding new types of wood products and keeping wood competitive with non-wood products.

Introduction

Wood bonding has been used for centuries to make furniture and other useful household items. For nearly a century, wood bonding has been used to make plywood and glulam beams for wood structures. A number of researchers have proposed mechanisms to explain adhesive performance (Frihart 2012). Although about 30 billion pounds of adhesives are used annually to make a wide variety of wood products, a better understanding of adhesive performance and improved adhesives are still needed by industry, due to the steadily increasing requirements to be fulfilled, from technical, economical, as well as ecological standpoints. A brief discussion on adhesive performance is followed below by aspects that are not well understood. To find out more about the existing and future needs, information was collected from adhesive users and producers in North and South America and Europe. While this was not an exhaustive study, the opportunities for improved wood adhesives and their performance are substantial.

Standard bonding theories

The widely discussed theories of adhesion (strength of interaction between the adhesive and substrate surfaces, i.e. the interface) involve the following aspects (Schultz and Nardin 2002):

- Mechanical interlocking
- Chemical bonds
- Dispersive association
- Electrostatic attraction
- Diffusive entanglement

The use of these possible bonding mechanisms seems rather straight forward for bonding wood. After all, wood surfaces are very rough compared to most substrates providing for good mechanical interlocking. Cellulose and hemicelluloses polymers contain a lot of hydroxyls, and most adhesives have a many polar groups, enabling good polar and hydrogen bonds between the wood and the adhesive.

However, for these standard interface criteria to play a role, the adhesive must form intimate contact with the wood surface. This could be a problem since most wood adhesives are water borne and wood, being a non-homogeneous material, may swell differentially when exposed to moisture, creating some regions of poor contact. Intimate contact is not a problem with fresh smooth surfaces having a high polarity, but it is sometimes a problem with aged surfaces, especially if the wood has been exposed to high temperature drying or has undergone other treatment that reduces surface polarity (Christiansen 1990, 1991) or rough wood surfaces. The role of wetting the substrate may not be less significant in light of Paul's paper that explains how adhesives do not have an air interface in contrast to coatings, and thus the adhesive should spread well due to capillary flow alone (Paul 2006). Another factor is that smooth surfaces provide only a limited surface area for bonding, while a microscopically rougher surface provides a larger interfacial or contact area. This fine roughness not only provides a greater area, but also more opportunity for mechanical interlock. On the other hand, macroscopic roughness can prevent good surface contact. Given wood's porous structure, good adhesive wood interactions are expected.

Thus, it is generally expected that adhesives will form good interfacial interactions with wood. In fact, most adhesives form the desired strong bonds with wood that are greater than the cohesive strength of the wood. Attempting to break wood bonds usually leads to fracture of the wood. So why are there issues with wood bonding?

Wood surfaces and interphases

Looking at a wood anatomy book, we see nice pictures of wood with the cells on the surface cleaved cleanly to expose the lumens. The adhesive easily flows into these exposed lumens and over the wood surface. Thus, the bonding surface has a much greater surface area than exists for non-porous surfaces like plastics or metals. To understand the three dimensional structure of a bondline, Marra has divided it into nine distinct volumes (Marra 1992). Five of these volumes are easy to conceptualize. Two of the volumes are the wood substrate on either side of the bondline, see Figure 1. A third is the bulk adhesive, and two are the adhesive-wood interface. The other four are the less obvious wood interphases and adhesive interphases. Wood interphases are easy to see in the cross section by observing flow into lumens close to and in many cases deeper under the surface. Adhesive interphases are much smaller and harder to visualize. While

the bondline consists of all the places that contain the adhesive, the glueline refers to only the bulk adhesive and the adhesive interphase.

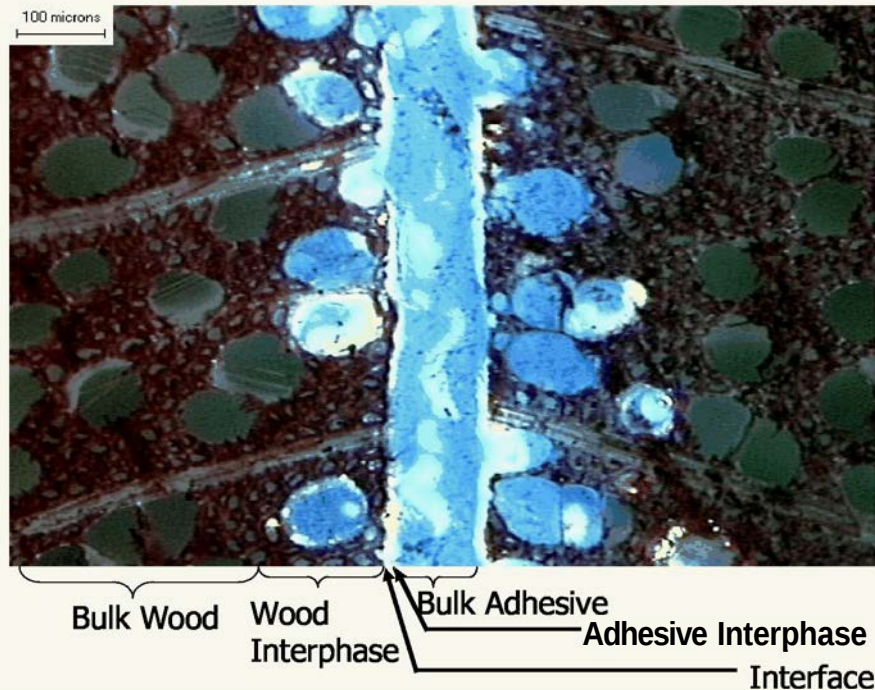


Figure 1. Cross-section of yellow poplar bonded with epoxy showing the different layers according to Marra (1992). The glueline between the wood surfaces is a combination of the adhesive interphase and the cohesive bulk adhesive layer.

A typical wood surface for bonding is more complicated than is often imagined from textbook images of wood cellular structure. Latewood cells of softwoods and fiber cells of hardwood are not cleaved through the cell, but are fractured in the middle lamella (ML) due to thick cell walls being stronger than the ML (River et al. 1991). The ML not only provides less surface area than the split open cells, but the ML surface is much higher in lignin, hence lower in polarity than within the cell walls. In reality these surfaces are very unevenly fractured by the planing, peeling, sawing or other methods of surface preparation. In Figure 2, it is clear that even a fresh surface prepared using sharp planer blades can be highly fragmented and structurally weak. In addition, many photographs in the literature show that many surface cells are crushed during surface preparation (Marra 1992, River et al. 1991). Thus, in addition to interfacial bonding, the adhesive must repair the damaged wood surface within the interphase.

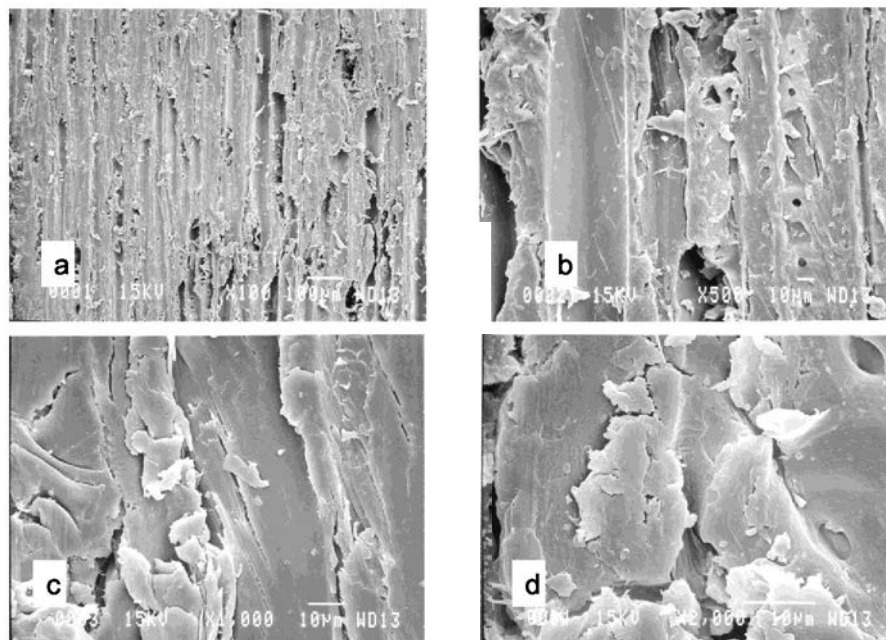


Figure 2. Scanning microscopy of fragmented surface and surface debris of yellow-poplar resulting from planing: (a) 100×; (b) 500×; (c) 1,000×; and (d) 2,000×

An important aspect of wood bonding that is not present for most other adhesive applications is the issue of penetration. There are two distinct types of penetration. The commonly observed flow into the cell lumens is a bulk process dependent upon viscosity and surface tension of the adhesive (Frihart 2006). This type of penetration provides a gross mechanical interlock, a thicker interphase as well as enlarging of the interfacial area. However, filler particles can possibly be too large to flow into lumens with the rest of the bulk adhesive. On the other hand, lower molecular weight components with proper solubility parameters can infiltrate wood cell walls to reduce their swelling with moisture, and provide micromechanical interlocks. Thus, it is important to understand what type of penetration is occurring. Although some penetration can enhance bond strength, too much penetration can leave too little adhesive between laminates resulting in a starved glueline between the wood surfaces.

Wood adhesive performance

Although adhesives need to meet many criteria, one of the most challenging is moisture-related durability. Given that wood swells and shrinks with changing moisture levels, bondlines need to withstand this dimensional change. The problem is that adhesives have a much lower dimensional change with moisture because they are generally cross-linked to avoid creep;

therefore, they expand and contract to a much lesser extent with changes in moisture than does the wood. This difference can cause a large interfacial strain between the wood and the adhesive layer, (glueline) and, consequently, large stress concentrations can occur at their interface. A main factor in the general design of a bonded assembly is to spread out stress as stress concentration leads to bond weakening and, eventually, rupture. Even though wood rapidly loses strength as it absorbs moisture, in many cases, the glueline between the wood surfaces becomes weaker at an even faster rate resulting in less wood failure under wet conditions than is observed under dry conditions.

The question then arises as to how to dissipate this strain differential to reduce bond failure. One way is to reduce wood swelling near the interface; this can be accomplished by the adhesive infiltrating and fortifying the cell wall when curing. The other is for the adhesive to have enough deformability that it can adjust to the swelling and shrinking of the wood. Given these two possible modes of strain relief, which one do adhesives use?

Our next step is to consider adhesives and their properties. Usually wood adhesives are considered as a single group with different chemistries, but the question is whether the differing chemistries operate by the same failure mechanisms. There are really two main groups of wood adhesives with different polymer morphology, interactions between the adhesive and the wood, and response to wood swelling and shrinking (Frihart 2009).

One group is the *in situ* polymerized adhesives which contain monomeric or low molecular weight oligomeric components that cure by chain extension and cross-linking after application, in addition to losing any solvent that may be present. These are rigid aromatic type molecules (in the case of phenolic resins, polymeric methylenediphenyl diisocyanate or epoxy resin), or rigid molecules (in case of urea-formaldehyde resins), or partly quasiaromatic triazinon rings (in the case of melamine-formaldehyde resins), always linked together by short carbon bridges. Thus, the polymers have limited ability to distort to accommodate dimensional changes of the wood. However, many of these adhesives have the ability to infiltrate and stabilize the surface cell walls, dispersing the strain at least partly into the wood cell layers. If they cannot stabilize the wood, then the high stress concentration can cause failure. This may occur in the bulk adhesive or more likely the adhesive interphase layer because this bounded layer is weaker due to an incompletely formed polymer network.

The second group of wood adhesives involves pre-polymerized adhesives and is mainly used in wood lamination. These contain polymers or high molecular weight oligomers that are often cross-linked or further polymerized during cure after application, in addition to losing any solvent that may be present. These adhesives have flexible backbones and the cross-linking can be adjusted to be light enough that the network has the ability to distort in small domains as the wood changes dimensionally. Thus, the strain is distributed in the adhesive to avoid a high stress concentration at the interface.

Given that the wood products will undergo changes in moisture content due to environmental changes, why not use mainly flexible adhesives? This leads to consideration of another important attribute of adhesives: the ability to resist creep under load, especially at elevated temperature and moisture. After all, nobody wants their bookcase shelves or their floor joists to sag with time or would desire their oriented strandboard to swell causing the floor covering or roofing to

become uneven. Consequently, the polymer chains need to be cross-linked to some extent to avoid creep under high temperature and moisture conditions which usually soften polymeric chains which are not tightly cross-linked. The *in situ* adhesives are generally rigid enough not to creep, while the pre-polymerized need some degree of flexibility to withstand wood swelling, but not to allow creep.

Although the discussion thus far has focused on the adhesive, one has to consider wood properties as well. Porosity of the wood surface has as much of an influence on the adhesive flow into the wood lumens as does the viscosity, size of molecules, and surface tension of the adhesive. Higher density and therefore lower porosity of some wood species can make it hard for the bondline to be stronger than the wood. Additionally higher density wood species not only have smaller void volumes providing fewer finger holds for the adhesive (as far as mechanical interlocking contributes to bond strength at all), but they also have greater dimension change with changes in moisture (Frihart et al. 2008). Not only is there considerable variation in properties between different wood species, but there can be considerable differences within a single species. Differences in porosity can be quite large, for example, between earlywood and latewood in a single growth ring especially in coniferous wood species.

However, the moisture content of the wood can be just as important as the wood porosity. Over-dried wood can be difficult to wet because it is harder for water to be absorbed in the tightly compacted polymer matrix of wood, and the surface is less polar due to migration of extractables to the surface and dehydration of some of the hemicellulose polymers (Christianson 1991). On the other hand, higher moisture content wood makes it harder to remove the water from the adhesive, slowing the cure rate of adhesives which cure by condensation (produces water) or form their bond strength just by physical solidification, but may accelerate those adhesives with moisture cure mechanisms. Bonding wetter wood introduces greater internal stresses when the wood goes from its swollen state to normal moisture content.

These moisture differences can be readily observed in making laminated wood products by observing resin penetration and the resistance of the bond to delamination. Moisture variations most likely effect bonding within oriented strandboard, particleboard, and fiberboard, but it is harder to relate the influence of moisture and wood variation to the performance of these products. An excess of moisture when bonding composites can overwhelm the process due to a high internal steam pressure that causes delamination when the pressing pressure is released.

Challenges in applying fundamental knowledge to adhesive strength

Most laboratory studies concentrate on using clear sapwood, but commercially available wood also contains heartwood, juvenile wood, compression or tension wood, knots, differences in the depth of lathe checks, compressed wood surface cells, large variations in grain angles, significant differences in wood moisture content, mixtures of wood species, and so forth. In addition, each plant has unique operating conditions; these include wood species, adhesive application conditions, and method of assembly of adhesively-coated wood pieces, including bonding temperatures, times and pressures, and post bonding handling. Within a specific plant, the ratio of wood species, wood moisture content, and plant temperature and humidity conditions continually vary, as can the types of products being made. Thus, adhesive robustness in order to overcome these variations is a very important factor in making a uniformly bonded wood

product, but sorting out the effect of all these variables is daunting. Even with these complications, fundamental studies are valuable for understanding how adhesives interact with wood when making laminated products, such as plywood, glulam, laminated veneer lumber, and cross-laminated timber.

On the other hand, the translation of this lamination knowledge to composites is difficult and becomes more tenuous as the wood particle size decreases in going from oriented strandboard, to particleboard and finally to fiberboard. In addition, most laminated bond tests are in the shear mode, but for composites, the tests often involve normal forces, which place more emphasis on the strength of the interphase. This would indicate that studying bond strength perpendicular to the bondline may be useful for understanding composite performance.

Hopefully, the development of more advanced tests and models will allow adhesive development to move beyond the traditional empirical process. With enough knowledge, the adhesive developer can use a more designed process of wood adhesive formulation and application. For this route, it is important to remember that macroscopic failure is the integral of microscopic failures. Thus, understanding the failures depends upon knowing the weak points of the bondline; once these are understood then the formulation can be modified to address specific deficiencies. This methodology has been applied to develop improved adhesives for other bonding applications.

The myriad of bonded wood products and their ability to perform in service for long periods of time show that wood adhesives work. However, this statement does not mean that there are not opportunities to make even better adhesive systems. To get a handle on many of these opportunities, I have had input from a variety of adhesive users, producers, and testers.

Application and curing issues

Even though adhesives used for wood bonding are generally the lowest cost among all adhesives, wood costs are in many cases even lower. Thus, knowledge of how to use these adhesives as efficiently as possible is very important. Given that the raw materials for wood adhesives are dominated by their use in other markets, such as farming and energy, price swings can be substantial. Market forces for commodity building products, furniture and cabinets limit the prices which may be charged for bonded products. With little room for producing the adhesives more economically, the emphasis has been for the adhesive users to apply as little as possible, while still making a product that meets performance standards. For laminated products this means having sufficient, but not excessive penetration. Analysis of cross-sections can visualize penetration, but we have no method to tell what optimum level of penetration is best for acceptable bond strength. For composites, a key for maximum performance is to have excellent distribution of the adhesive on the wood strands, particles, fiber etc. Only a few studies have been carried out to determine adhesive distribution and then to relate that distribution to performance (Plinke and Ben-Yacov 2010), but there is no general method available that can be used in a typical mill.

The effect of the variation in wood used in the process and its result on product performance is a widely shared concern. Great differences in porosity occur between different wood species and even within the same species as illustrated by the varying depths of penetration in Figure 3.

Consequently, the varying absorption of adhesive by the wood is going to lead to differences in the ability of the adhesive to bond two pieces of wood together. The ability to design adhesives so that they have consistent penetration despite differences in wood porosity would be beneficial. As the wood source varies, the composite manufacturer would like the adhesive to compensate for these day-to-day differences and make a uniform product. In the future, wood quality will continue to decrease as competition for wood resources increases and a greater percentage of wood comes from quickly grown, immature forests. Wood product manufacturers must rely on a robust adhesive to make up for these changes.

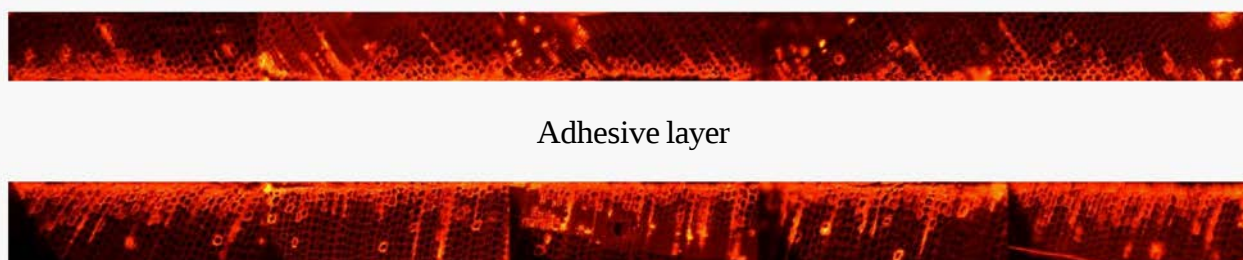


Figure 3. Tiled cross sections showing penetration of the sections above and below the glue line using a commercial phenol-formaldehyde adhesive with Southern yellow pine

Another process variation greatly impacting adhesive performance is the wood moisture content. Because the moisture content varies between trees and within a tree, it is not surprising that the moisture content of the wood supplied to the bonding process varies. Very dry wood is slow to wet due to both slow kinetic wetting of cell walls with a low free volume and thermodynamic wetting of walls containing dehydrated hemicelluloses (Christianson 1991). Overly wet wood also poorly absorbs aqueous adhesives, limits the infiltration of adhesives in the cell wall due to the high saturation level, and dilutes the adhesive. In addition, the condensation-cured adhesives, e.g. phenolics and amino resins, are slower to cure at high moisture content since the water produced in this reaction is less easily removed. In contrast, higher moisture can promote the cure of isocyanate-containing adhesives. In addition, there are seasonal variations, which effect bonding processes, such as humid summers and dry winters in the southeast United States, while in the northwest United States the opposite is true. This requires adhesive companies to alter their formulations, and therefore cure rates, based on the season. Robustness of an adhesive to wood moisture content is an important property for having consistent production of the bonded wood product. There is a strong desire by manufacturers to bond wood at higher moisture content levels to lower the cost of wood drying. However, this leads to greater product shrinkage and places greater internal stress on the bondlines as the product comes to its equilibrium moisture content.

Another area of interest for commercial bonding of wood products is having improved ease of application. The adhesive application process, whether this is by a roller/doctor blade, film coater, spray head, etc., the important aspect is evenness of distribution with no clogging of the applicator. Poor distribution due to inconsistent application requires higher adhesive usage in order to maintain product properties. Solving these issues depends not only upon the application

equipment but also the adhesive properties. For spray applications, a low viscosity improves distribution, while plywood manufacture requires a higher viscosity to reduce over-penetration. Another factor is the pot life or storage life of adhesives in that adhesives generally increase in viscosity with time due to pre-curing leading to variation in application efficiency and downtime to clean the application equipment. Many adhesives are multi-part; the mixing of components leads to additional process steps in the mills, and to an increased likelihood of ratio variation leading to differences in cure rates and properties. Stable single component adhesives are always desirable, but these are difficult to design, especially when a rapid cure rate is needed. This leads to the question, is there some economical way to provide an adhesive having a pressure- or temperature-induced mixing of the two reactants in a single component adhesive? In addition, increasing line speed is always important to bonded wood product manufactures. This is linked to the desire for adhesives which cure more quickly, but which still have the same pot life and shelf stability; a very hard balance of properties to accomplish. In addition, fast curing adhesives can be a problem when production problems slow line speeds. Curing and mechanical densification profiles of the adhesive then must be aligned to the changed press conditions, and less usage of ready to use adhesive mix might challenge maximum pot life.

There are other issues that are more related to specific types of adhesives. For example, with phenolic adhesives, the color is dark and the high pH can lead to caustic burns in the composite face; both of these are related to the need of a high pH to solubilize the phenolics and to keep viscosity low. Two approaches have been published that make lower pH phenolic dispersions (Broline et al. 2002, Wescott and Frihart 2008), with the latter being the lower cost option and a more biobased adhesive by replacing 40-50% of the phenol with soy flour.

Another example of an adhesive specific issue is the use of isocyanates which may lead to problems with composites sticking to caul plates and having machinability, and with strength and cure rate problems due to the lower adhesive levels. These problems are generally solved, respectively, by the proper coating of the caul plates (although some of these coatings can be corrosive) and using suitable release agents; besides these issues, there are still some isocyanate emission issues during the press process remaining. As discussed later, amino adhesives also have some product emissions issues.

More or less for all markets around the world board quality standards require adhesives to meet consistent, specific levels of formaldehyde emission; however, these limits can be different in various regions. Consequently, a plant not only must make products with different thicknesses, densities and strengths, but also to meet differing emission requirements.

The adhesive must do more than provide strength to the final product. In some applications, tack is an important property for handling purposes prior to curing. This need occurs in the transfer between sections when using a caulless line in the manufacture of composites and in the transfer of the plywood between presses prior to final cure. Adhesives of higher solids are desired in the composite production to reduce internal steam pressure and the risk of board delamination when the press pressure is removed; lower viscosity usually enables better distribution of the adhesive on the wood surface unless overpenetration due to too small droplets might threaten performance.

Additional factors have been mentioned by adhesive users. Emulsion polymer isocyanates and polyurethanes are more flexible, while the phenolics are brittle; might a combination provide benefits by combining the best attributes of both systems? There has been a desire especially in Europe for lower density boards. Can an adhesive compensate for a lower strength being provided by the less dense aggregation of the wood fraction? With the impact of reduced formaldehyde emission regulations, can a new catalyst be developed, which could allow for higher reactivity as well as higher degree of cure to compensate for the lower formaldehyde loading? Some adhesive suppliers are concerned about the reluctance of the market to look at alternative adhesive technology. On the other hand, adhesive users are concerned about other problems being generated by changes in the adhesive type used; these include such as issues as splice line discoloration, a “bleed through” type of discoloration, and delamination with time. With the growing interest in greater durability of wood products, adhesives able to bond thermally-modified wood, acetylated wood, and other modified woods are necessary.

Environmental

The biggest current environmental issue is that of formaldehyde emissions. Over the years the acceptable formaldehyde emissions levels have continued to drop, reaching at this point the CARB Phase 2 in the US and partly in Europe, F**** in Japan, and further discussions recently started in Europe for lower limits but not yet finalized. Proposals for emissions levels are down to the level of formaldehyde naturally present in wood, like “no added formaldehyde”. For producers, the tests and acceptable levels for these various standards are different, requiring additional testing, and varying product development efforts. Manufacturers supply adhesives allowing users to meet all these emission standards (it is important to note that the emission levels are based upon the bonded product, not only the adhesives themselves), but the lower the emission limit the more these formulations are usually less robust and are more expensive than prior formulations. In the US, the CARB Phase 2 standards are nearly universal, while in Europe only a quarter of the products may need to meet the CARB standards. The two main formulation approaches are ultra-low formaldehyde emitting (ULEF) urea-formaldehyde (UF) and no added formaldehyde (NAF) adhesives. The need of adhesive users due to economic restraints is to have no extra costs, no loss in press capacity, and the same “easy-to-use” systems with these new adhesives, but this is difficult to achieve given the good properties of a standard UF adhesive. Many comments were made about the desire for better NAF and ULEF-UF solutions. ULEF-UF solutions seem to involve low formaldehyde to urea ratios and use of scavengers, but I am not aware of any UF products that actually prevent the reverse reaction that generates the free formaldehyde out of the UF polymer due to hydrolysis.

Formaldehyde emissions are not the only volatile organic compounds being emitted by adhesives and bonded wood products. While none of these are currently major issues, this may not be true forever. There are various regulations of chemicals (VOC) being partly implemented in Europe, and also being applied to bonded wood products.

In addition to regulations on formaldehyde emissions, there are also guidelines, which may prohibit the use of urea-formaldehyde adhesives for green buildings. These changes have had a considerable effect on the types of adhesives that are used, and unfortunately some replacement adhesives have had other effects on product performance, including wood discoloration. As the wood industry works to promote the green aspect of wood especially in building standards, it is

important that the adhesives are a positive component of the sustainability aspects. This has led to interest in more biobased adhesives with the main sources being soy flour, tannin and lignin (Frihart 2010). All have shown promise with the soy more widely used in recent years, while the tannin is used only in some specific regions. The emphasis has been mainly in the panel market as biobased products have had less success in the more demanding structural market. Still biobased materials are only a tiny fraction of the overall adhesive market. Another approach to reduced fossil fuel use in bonded wood product manufacturing is to use inherent components of wood as its own adhesive or as a component of the adhesive. The former approach has been used in high density fiberboard products for many years. Very interesting recent work has been done on wood welding including the more promising rotational welding (Frihart 2010). Linear vibrational welding works, but current products do not demonstrate good water resistance. A limited amount of work has also been done on carbohydrate-based adhesives. Adhesive manufacturers desire to offer more bio-based adhesives, but economics and in-plant viability need to be further addressed.

Another environmental area is the reduction of energy used in wood bonding. This includes the use of lower bonding temperatures, higher solids adhesives, and reduced drying of the wood prior to bonding. Implementation of these improvements could also reduce the emissions generated by the treating wood at higher temperatures.

The use of recycled wood products is an issue that could also increase the life cycle assessment value of bonded wood products. Little information is available on the use of in-plant and external recycling of wood products for making new wood products. Especially European particleboard plants show great variability from zero to majority of recycled wood as raw material basis. High effort in collecting recycled wood base material as well as high effort in cleaning counteracts partly the economic advantage. Recycled material is most likely to end up in particleboard.

Multifunctional performance

One recent invention is the camera phone. The camera does not improve the phone function, nor *visa-versa*, but the combination of features brings value to the customer. A desire has been expressed for adhesives that also impart some other benefit, such as decay resistance. Studies have examined the impact of treated wood with improved decay, water absorption or fire resistance on the curing of typical adhesives (Lorenz 2006). In addition, there has been examination of retention of bond strength for wood products after post treatment for improved resistance. The desire of some adhesive users is to have an adhesive that also provides these resistance properties. Incorporation of some type of resistance properties means that an adhesive user would not need to investigate the compatibility of the adhesive with the chemicals that provide resistance and more importantly, the adhesive user would optimize only a single application/distribution process. Obviously, combination of attributes may make the production of the adhesive more difficult, but it would provide a unique adhesive. An even bigger problem with this concept is that the amount of treatment chemical is often equal or greater to the amount of the adhesive used. This amount of an additive would certainly prevent the cure of most adhesives.

Wood, wood products and competition

In addition as most everyone in the wood business knows, wood resources are changing. The lack of availability of old growth leads to the use of smaller and plantation grown trees with increasing levels of juvenile wood and earlywood; increased earlywood to latewood ratios and fewer growth rings lead to lower wood strength. This weaker wood can lead to products that have good wood failure, but fail to meet bond strength and product performance criteria. Given the difficulty of controlling all the parameters, adhesive users are looking for more robust adhesives to compensate for variations in the wood supply, including both typical supply variations, but also longer term in change of available wood types.

New wood products continue to be developed, but at a slow pace. One growing application is cross-laminated timber (CLT), also known as solid wood panel in Europe, that is being used to construct taller than three story wooden structures. CLT uses side-by-side boards bonded in a cross-ply construction to produce solid wall members. The great rigidity and strength of the CLT allows for engineering and building of multi-story wooden structures. In addition, to allowing good factory controlled construction, CLT also allows fast on-site assembly and good vibration damping during earthquakes. The testing criteria for these types of products are more developed in Europe where they are covered in EN 13353.

Even for existing products, new and revised tests are being examined so that the bonded products meet the performance expected by other standards organizations. The ASTM D-14 Adhesive Committee has been working on tests for more severe exterior exposure of laminated beams and high temperature creep resistance as experienced during fires. Some of the new tests have led to the changes in the adhesives used in certain applications, such as adhesives that were unable to meet the fire tests for finger-jointed studs.

A continuing problem for wood products is the challenge of losing market share to non-wood materials. Steel and aluminum studs as building members replacing wooden ones, plastic and fiberglass windows replacing wood windows, and molded plastic replacing wood trim are some examples. In some cases, the non-wood industries are better organized in lobbying to have their products being classified as being greener than wood products due to their higher recycling rates for some non-wood products, such as steel and aluminum. Thus, in certain rating systems the percent recycle content is considered to be more important than true life cycle assessment (LCA) values. Recycling of wood products does occur to some extent, so adhesives which allow for more recycling could be an advantage. It must be a priority of the wood products industry to ensure green building standards place greater emphasis on the LCA values.

In some cases, the advantage for non-wood products can be their uniformity and consistency, limited moisture uptake, and lower maintenance requirements. This brings new emphasis to the need to make adhesives that have added environmental resistance properties and the development of adhesives that bond well to modified wood as discussed above.

Conclusions

Wood adhesives have for decades made bonded wood products that provide good end use performance. However, the world is not static and the demand for adhesives that bring new or

improved attributes is increasing. This makes providing competitive adhesives an ongoing effort for the adhesive companies. Some of the needs for improved adhesives have been discussed in this paper.

A real benefit to the adhesive companies can be the development of improved models for adhesive performance so that the adhesives may be developed by a design process rather than reliance upon empirical testing. A basic model on moisture-related durability was discussed, but further refinements are needed to make it more a predictive type of model.

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Literature Cited

B. Broline, R. Adams, and R. Schmidt. 2002. Phenol-Formaldehyde Resin Emulsions as Wood Adhesives. In: *Proceedings 36th International Wood Composites Materials Symposium*, Pullman, WA, April 9-11, 2002, Washington State University, Pullman, WA. pp. 23-29,

Christiansen, A. W. 1990. How over-drying wood reduces its bonding to phenol-formaldehyde adhesives: A critical review of the literature, Part I: Physical responses. *Wood and Fiber Sci.* 22(4):441-459

Christiansen, A.W. 1991. How over-drying wood reduces its bonding to phenol-formaldehyde adhesives: A critical review of the literature, Part II. Chemical reactions. *Wood and Fiber Sci.* 23(1):69-84.

Frihart, C.R. 2006. Wood structure and adhesive strength. In *Characterization of the Cellulosic Cell Wall-The Proceedings of the SWST International Workshop on the Assessment and Impact of the Cellulosic Cell Wall*, Colorado, Aug. 25-27, 2003, D. D. Stokke and L. H. Groom, Ed., Blackwell Publishing Ltd., Oxford, UK, pp. 241-253.

Frihart, C. R. 2009. Adhesive Groups and How They Relate to the Durability of Bonded Wood, *J. of Adhesion Sci. and Tech.*, 23:601-617.

Frihart, C. R. 2010. Biobased Adhesives And Non-Conventional Bonding, in *Sustainable Development in The Forest Products Industry*, R. M. Rowell, F. Calderia, J. K. Rowell, Ed., Universidade Fernando Pessoa, Porto, Portugal, pp.98-112.

Frihart, C. R., 2012 Wood Adhesion & Adhesives, in *Handbook of Wood Chemistry and Wood Composites*, 2nd Ed. R. M. Rowell, Ed., CRC Press, Boca Raton, FL, pp. 255-318.

Frihart, C. R., D. J. Yelle, and A. C. Wiedenhoef, 2008. What Does Moisture-Related Durability of Wood Bonds Mean? In: *Enhancing Bondline Performance - Final Conference of COST E34 Bonding of Timber*; May 6-7, Sopron, Hungary, C. Csiha, Ed. University of West Hungary, Sopron, Hungary, pp. 89-101. ISBN: 978-963-9364-97-4.

Lorenz, L. F. and C. R. Frihart, 2006 Adhesive bonding of wood treated with ACQ and copper azole preservatives, *Forest Prod. J.* 56(9):90-93.

Marra, A. A. 1992. *Technology of Wood Bonding: Principles in Practice*. New York: Van Nostrand Reinhold, pp. 37-45.

Paul, C. 2006. Wet-Out: The Red Herring of Adhesion Science. **In:** Proceedings of the Annual Meeting of The Adhesion Society, Feb. 19-22, Jacksonville, Florida; The Adhesion Society, Blacksburg, Virginia. pp. 358-360.

Plinke, B. and Ben-Yacov, D. 2010. Spatially resolved monitoring of adhesive application. *Adhesion, Adhesives & Sealants*, 7(4):25-29

River, B.H., C.B. Vick, and R.H. Gillespie. 1991. Wood as an adherend. In: *Treatise on Adhesion and Adhesives*, Vol. 7. J.D. Minford, Ed. Marcel Dekker, NY. p. 1-230.

Schultz, J. and Nardin, M. 2002. Theories and mechanisms of adhesion, in *Handbook of Adhesive Technology*, 2nd ed., Pizzi, A. and Mittal, K.L., Eds., Marcel Dekker, New York, chap.3.

Wescott, J. M., and C. R. Frihart. 2008. Water-resistant vegetable protein adhesive dispersion, U.S. Patent 7,345,136, March 18



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