

Introduction to Special Issue

Wood Adhesives: Past, Present, and Future

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Adhesives have played and will continue to play an important role in the efficient utilization of wood resources. Early Egyptians used adhesives to attach rare veneers to wood furniture. Today, adhesives play a vital role in allowing almost all types and sizes of wood to be converted to functional products. For centuries, wood was bonded using biobased adhesives. In the 20th century, synthetic adhesives gradually took over because they were typically more effective and cost less. Refinement of these adhesives led to a great expansion in the bonded wood products industry by growing existing markets and allowing development of new bonded products. The 20th century also saw an increased understanding of wood adhesive chemistry and product performance knowledge. These trends continue in the 21st century along with the potential for more biobased adhesives. The increased use of engineered wood products will continue along with more utilization of other wood and plant resources, such as bamboo, for the production of bonded products.

Past

Most wood adhesives and bonded wood products—and the processes for making them—have been developed in the past century and have allowed for a great increase in wood utilization. The first Wood Adhesives conference was held in 1960, and in 1970 the conferences started meeting on a 5-year basis and in 2009 on a 4-year basis to bring interchange of knowledge and ideas among industry, university, and other researchers, starting mainly with those in the United States but with a growing international representation. The conference proceedings—available from the Forest Products Society—provide access to information that is often not published elsewhere.

Natural product adhesives

As early humans moved from a nomadic to settled existence, they needed structures and furniture in those structures that were more permanent. Many of these were made using mechanical connectors, but humans were also looking for adhesives from plants and animals. Some, such as blood, pitch, gums, and rubber latexes, could be used as adhesives and sealants with no processing. Others, such as casein from milk, soybean proteins, and collagen adhesives, needed more processing.

Animal glues from collagen, blood glues, and casein glues from milk have been used for a very long time; fish glues originated in the 1800s and soy glues in the 1900s. The first wood glues needed limited strength because they were used for interior applications, such as furniture. The desire to use wood more efficiently was an impetus for adhesive development in the 19th and 20th centuries. Two major early developments were the use of casein for glulam production and soy adhesives for interior plywood. Despite some success with biobased adhesives, they were replaced by synthetic adhesives starting in the 1930s, mainly due to economics, water resistance, and ease of use.

Tannins have been used for many years as a wood adhesive in locations where they are readily available and where phenolics are more limited in supply and are more costly. Despite much research showing that lignin can be used to make plywood that meets performance standards, it apparently has not been used much in commercial manufacturing of wood products. Carbohydrates are not used in wood bonding because of their water and thermal sensitivity.

Synthetic adhesives

Phenol-formaldehyde (PF) was one of the original synthetic polymers, and its application to wood bonding in the 1930s allowed for the development of durable exterior plywood. The gradual increase in use of synthetic adhesives became more rapid after World War II, when the large petroleum infrastructure built to support the war effort led companies to look for new outlets for fossil-based products. PF allowed for the development of exterior plywood, and the similar resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF) allowed for the development of more durable glulam and other structural wood products. Urea-formaldehyde (UF), being a low-cost, effective adhesive, has led to the expansion of existing interior products and the development of new panel

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products. Melamine-formaldehyde (MF) adhesives, being more water resistant but more expensive than UF, has been used to improve UF adhesives or used by itself as an exterior adhesive, especially outside North America.

After World War II was a prime period for the development and growth of many other synthetic polymers. Some found use as very successful wood adhesives. The main ones were poly(vinyl acetate) (PVAc), isocyanates, and polyurethane (PU). Others were aliphatic resins, epoxies, and construction adhesives. A main advantage of these adhesives has been that they can be formulated to have a wide range of properties, depending on the types and ratio of monomers. An important advantage of synthetics over natural products has been the ability to formulate the polymer backbone rather than trying to use what nature has provided.

Wood products

An important aspect of adhesives is that they allow scarce wood resources to be used more efficiently. Early on, adhesives were used mainly for furniture. As time progressed, prior applications continued to grow, while new products were developed that led to even more adhesive use. These new products not only led to more efficient wood utilization but also provided properties that were not available from solid wood products. Adhesives allowed for efficient conversion of logs into plywood for wall sheathing and roof decking and into glulam for long unsupported spans.

For furniture construction, joints were assembled using dowels or nails, or by carefully constructed designs such as dovetail joints. However, adhesives were needed to apply veneer to a surface. For many applications, the main force on the bond was related to the expansion and contraction of wood. As stronger adhesives were developed, they allowed greater load-carrying capacity. Major driving forces in bonded wood product development and utilization included the first and second World Wars with the need for military planes, boats, and shipping containers. The housing boom following World War II added to the growth in demand for bonded wood products.

To make these products, it was important to understand wood properties and preparation of the wood surfaces for bonding. The porosity and degree of swelling/shrinking influenced how wood products were made. For example, manufacturers learned that plywood requires symmetry of its layers to minimize warping, and glulam products require freshly prepared surfaces for durable bonds. Other knowledge emphasized that bonded wood products should be made with wood close to the final use humidity conditions to minimize excessive internal strain on the bondline. All the standard product designs and manufacturing processes had to be developed through basic science and experience.

Wood adhesion

Most adhesives were found to bond wood well enough to give wood failure under dry conditions. However, how long this adhesive bond lasted was an important issue, especially with changing wood moisture conditions. The development of qualification tests and adhesives that pass these tests were important for moving from solid wood products to bonded wood products having market acceptance. For structural

products, building codes were developed for solid wood; thus, bonded products needed to meet or exceed these requirements, including resistance to delamination, creep, and fire. Additional tests were developed to measure these performance criteria.

For many decades, new tests were being developed as many new products were being developed, especially panel products. For these, there was no solid wood equivalent, and without proper adhesive, there was no product. Better adhesives led to improved production methods, which in turn led to a demand for even better adhesives. A large amount of research went into understanding adhesive chemistry and adhesion processes in order to meet the demand for improved performance.

Many types of polymers were developed that can bond wood, but no specific formulation worked for all wood species and all product types. For laminated products, the adhesives were of higher viscosity to avoid over penetration, while for most composites, a lower viscosity was needed to allow good application to the wood. A wood adhesive needed to be formulated to match the adhesive application method and wood porosity. Optimizing the formulation to have sufficient penetration into the wood, but not excessive for the different wood species, has been a challenge that the adhesive industry has generally met.

Present

Wood adhesives have been widely used for structural and nonstructural uses for years without major problems. The emphasis has shifted from developing new adhesive types and new products to the refinement and expanded uses of existing ones. The International Conferences on Wood Adhesives, now held every 4 years, continue to be the main forum for researchers around the world on adhesives and bonded wood products. The proceedings and the articles published in this special issue of the *Forest Products Journal* emphasize the science of wood adhesives as presented at the 2013 International Conference on Wood Adhesives.

Natural product adhesives

Many of the natural adhesives have become too expensive or are too variable to be widely used in the wood adhesive market. Because of their good performance in the manufacturing environment and end-use durability, synthetic adhesives have replaced most of the protein ones. In recent years, there has been a revival of soy adhesives to replace UF because of the desire for no-added-formaldehyde adhesives and the availability of a viable co-reactant for the soy. A very large quantity of low-cost soy flour is not used for human food and is available for wood adhesive needs.

Tannin continues to be used in certain countries where it is available and where phenol-based resins are more costly. Lignin continues to be discussed as a replacement for phenol, but the higher cost for purified lignin and its low reactivity have been major issues. One major change is the availability of a new lower cost lignin source from partial acidification of black liquor. This has an economic advantage in that the lignin is removed to aid in adding pulp capacity to pulp mills without adding very expensive recovery boiler capacity.

Synthetic adhesives

As in the general polymer industry, the emphasis has switched from developing new polymer systems to modifying and combining polymer types. A main exception is one based on a bio-based monomer, lactic acid, but this polymer is not useful for wood bonding. Although there are not entirely new classes of wood adhesives, there continues to be refinement of existing formulations to meet process and wood supply changes.

It is often considered that there are just a few types of adhesives on the market because we talk about UF, MF, PF, RF, PVAc, and others. However, many of these are used in combinations, such as MF-fortified UF and PF added to PVAc. In addition, a PF for exterior plywood has quite different properties from that used in oriented strandboard (OSB). The applications are further divided because for OSB, a face resin used in the outside layers is quite different from one used in the core layer, especially in cure rate. The adhesives are further divided into specific formulations, because different plants have different wood furnish, equipment, and process conditions, and time of year can influence wood properties and cure rates needed for the adhesive. As one industry person put it, we make specialty adhesives for commodity prices. For simplicity, I will not go into all of these distinctions, but just discuss general types of adhesives.

The two main classes are the amino and phenolic resins. The amino resins are the largest group, with the main product being UF, a very low cost adhesive. UF adhesives are very effective for interior products such as particleboard, fiberboard, and decorative plywood, with their major drawback being the generation of formaldehyde under higher heat and humidity conditions. The more costly MF is much more water resistant, allowing it to be used in structural applications, and it does not emit formaldehyde. Melamine can be copolymerized with urea and formaldehyde or MF can be added to UF adhesives to improve their water resistance.

PF, RF, and PRF have been considered to be the wood adhesive gold standards for environmental resistance, in that they do not lose much strength when exposed to water or heat. However, PFs generally require a higher cure temperature than other wood adhesives, and phenolics are dark colored and more expensive than UF. They continue to be the main adhesives in the structural products in North America, but MF and PU adhesives are more prevalent in Europe. PF adhesives have been used for a long time in OSB, but polymeric diphenyl dimethyl isocyanate (pMDI) has been replacing PFs because of its good cure rate even with wetter wood furnish.

The most versatile adhesives are those containing isocyanate groups, whether classified as isocyanate or polyurethane adhesive. Being moisture cured, they can bond wood with a higher moisture content (saving drying energy). pMDI is very useful for making composites, especially in the core layer, which is lower in temperature and higher in moisture content than are the face layers. Although pMDI is more expensive than many other wood adhesives, it has greater efficiency, allowing it to be used in smaller quantities. Products bonded with pMDI usually have good water resistance properties; in addition, pMDI is good for bonding to difficult surfaces, such as wheat straw with its waxy surface. Polyurethane producers are trying to use the

technology developed in Europe, expanding it to the North American market, but they face a limitation in structural products in meeting the wood failure requirements in US and Canadian standards. Another adhesive type, emulsion polymer isocyanate, was developed in Japan and has found niche markets that use its quick cure and good water resistance for making engineered wood products.

Another versatile class is the PVAc dispersions. The original PVAc, commonly known as white glue, has good adhesion properties but very poor water and heat resistance. Cross-linked versions, PVAcX, are made to overcome these limitations. This can be accomplished by the formulation of the emulsion or by incorporation of other polymers, such as phenolics. They can be used for laminating veneers onto panel products and to assemble furniture, windows, and doors.

Wood products

Composites that use binder resins constitute the greatest volume of bonded wood products. These products are held together by spots of adhesive rather than by a discrete layer of adhesive between wood surfaces. They involve the least expensive wood source and allow for great efficiency in wood utilization by using wood that is not very suitable for other wood products. However, there is now competition for this wood for fuel pellets. In many building applications, OSB has replaced plywood, and it is also used as the web for wood I-beams. Particleboard and fiberboard are used in cabinetry, furniture, and shelving.

Adhesive films are used in making a wide variety of wood products. Exterior and decorative plywoods are major products. Although the exterior plywood market has seen a decrease in housing due to replacement by OSB, the interior plywood market continues strong because plywood is used in cabinetry. Adhesive films are used in bonding veneer and other overlays to surfaces of panel products. Another main application is laminated beams, such as glulam, laminated veneer lumber, parallel strand lumber, and rim flanges for wood I-joists. A relatively new wood product is cross-laminated timber (CLT), which is cross layered, like plywood, but made of boards instead of veneer. CLT involves factory-made wall panels for easy on-site erection and is the product popular for wood buildings more than three stories. Another newer product for construction is structural insulated panels; these are also factory-made walls, but in this case the products are more similar to conventional walls with the insulation as part of the wall design by contributing to the strength of the product reducing the amount of wood used.

All the products that use wood adhesives are too numerous to mention, but the list now includes almost all wood products. A consistent factor is that the bond must be durable enough to withstand the dimensional changes in wood due to changes in moisture exposure and the designed external load. It is also expected that wood failure will occur prior to failure within the bonded portion.

Wood adhesion

For most adhesives, the chemistry of polymer formation is well understood. However, measuring mechanical properties continues to be difficult. Only a few of the polymers form a cured solid of sufficient integrity such that its strength properties can be measured independent of the

wood bond. In addition, the adhesive interaction with wood can alter the adhesive's cure chemistry, especially near the adhesive-wood interface. Thus, most tests for the adhesive are done as bonded assemblies, preferably with the wood species that is used for making the final product. This is because the porosity of a wood species affects how much of the adhesive soaks into the wood, and different wood species have different strengths, which influence how strong the bond is expected to be.

The cure process is an important aspect of most adhesive applications, including wood bonding. The adhesive must be a liquid for application to the wood surface but then needs to be rapidly converted to a solid for strength. Because most wood adhesives are aqueous, loss of water to wood is an important part of the cure. However, most adhesives generally polymerize and cross-link, and the rate of chemical reactions and of strength development are used to look at curing. The economic importance of a faster cure rate to increase output continues to be an area for optimization.

Adhesion to the wood is important for making a product that will meet the customer's expectation of good durability. Much has been learned, but our understanding is still incomplete. It is encouraging that one building constructed with glulam beams stood 75 years and still maintained full design capacity when recently tested after deconstruction. The great variety of bonded products on the market also demonstrates the knowledge available in designing and using adhesives. More continues to be learned about the details of adhesive-wood interaction through advancement of new analytical techniques and designing compounds that allow use of these techniques.

Future

Tremendous progress has been made on developing and effectively using adhesives over the past century, but many important challenges remain. Energy efficiency and economic optimization in making wood products continue to be drivers, as does the efficient use of renewable natural resources. Innovations such as CLT cannot only change building construction techniques, but also allow wood to be used for structures where it was not previously considered to be a suitable building material. Emphasis on life-cycle analysis and reuse of building materials will be of increasing importance. The International Wood Adhesive Conferences should continue to be the main forum for interchange of knowledge between industry and other researchers around the world.

Natural product adhesives

One big challenge is to develop an economically viable lignin isolation and formulation process that allows adhesive companies to use fuel-value lignin as a significant replacement for PF in adhesives. Although this may seem straightforward, the challenge of making viable adhesives consistently for a variety of customers has yet to be met. Although great progress has been made on tannin utilization, the availability and cost seem unlikely to make this more than a local specialty.

Of all the protein sources available in nature, soy flour seems to be the most likely future protein source for adhesives. Very large quantities of soy flour are available with a reasonable degree of consistency, at low cost and with little impact on human food supplies. Even without a co-

reactant, water-resistant wood bonds can be obtained by soy protein isolates, showing that the protein in the right conformation can produce good wood bonds. Although there are commercial products using soy flour and a co-reactant, more research is needed to make these economically viable at higher solids and for a greater range of products.

Carbohydrates are the most widely available organic polymer and are generally available in a relatively pure state at low cost. Starch adhesives have long been utilized in making paper-based products. However, converting carbohydrates into low-cost wood adhesives with good water and heat resistance has been an unmet challenge.

Nature has developed ways to use proteins for bonding most types of materials even in adverse conditions, such as under water. Biomimicry and bioinspiration may be viable routes for using various monomers for making low-cost wood adhesives.

Synthetic adhesives

Synthetic polymers will continue to dominate the market with the same types of polymers used today, although the division among the different polymer types may change. Because performance objectives are generally met, anything that reduces the cost to use polymers (less adhesive needed, lower bonding temperatures, or higher wood moisture levels) will be important for making more competitive wood products.

Amino resins are likely to remain dominant given the low cost of urea and formaldehyde. Given that some formaldehyde emission standards are set at the same levels that wood produces under the same test conditions, lowering the standards is less likely. With the change in formulation to make ultra-low-emitting UF adhesives by changing the urea-to-formaldehyde ratio and adding a scavenger, one remaining way to improve UF adhesives would be to prevent the reverse reaction that leads to formaldehyde generation. Melamine is likely to continue to play a role, but its high cost will limit its use.

Given the excellent performance of phenolics, they will continue to play a major role in structural products and exterior plywood, even though the higher curing temperatures and dark color are drawbacks. Many ways to reduce PF costs are already being used, but further reduction could be accomplished by reducing excessive penetration or lowering the cure temperature.

Isocyanate systems will probably continue to increase their market share because of their ability to bond wood with high moisture levels and a wide variety of biomass materials, such as wheat straw. Lowering pMDI costs would increase their market share. With polyurethane adhesives, addressing the low wood failure issue on wet shear tests is important for expanding their use in North American markets.

Wood products

Adhesives will continue to be a growing part of efficient utilization of forest resources. However, acquiring suitable wood resources will continue to be a challenge because of a diminished supply of high-quality wood and competition for wood from wood pellet and biorefinery industries. The challenges involve dealing with species that are not currently being used and with a greater mixture of species. More plantation wood could involve increased porosity and lower strength because of increased proportion of early-

wood. The wood may also have increased or more variable moisture content as a result of efforts to reduce drying costs.

Wood products volume should continue to increase especially if engineered wood products replace other building materials for multi-story buildings and if there are sufficient housing starts. One challenge could be in bonding wood to other materials if glulam or laminated veneer lumber start using layers of stronger polymers or composites for greater strength. There also might be markets for bonding to modified wood, such as acetylated wood or heat-treated wood.

Wood adhesion

Durability and how to test for it continue to be issues of interest for many applications. This could involve control of penetration and curing as wood porosity and/or moisture content changes. The more we understand about bond formation and failure at the microscopic level, the closer we come to designing the best bonding methods. This is also very important for bonding of wood to other materials and adhesion to modified wood.

References

The resources below are excellent sources of information on wood adhesives and wood products, and each provides a different perspective of the bonded wood products.

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