WOOD ADHESIVE INNOVATIONS AND APPLICATIONS IN NORTH AMERICA

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North America is a major producer and consumer of glued-wood products. This article presents an overview of adhesive types and applications. The data given are from 1998 and this information was presented at the XXI IUFRO World Congress in Kuala Lumpur, Malaysia, in August 2000.

In 1998 in North America (excluding Central America), more than 1.78 million metric tons (t) of adhesive resin solids (Table 1) were consumed to bond about 58 million m^3 of primary glued-wood and related products (Table 2). This resin solids volume does not include the adhesives in furniture and other secondary products (worth more than $30 billion ($U.S.). The following are calculated resin solids values for wood products in North America: 1370 kt for the United States (77%), 374 kt for Canada (20%), and 36 kt (2%) for Mexico. More than 59 percent was amino resins (urea-formaldehyde [UF], melamine-formaldehyde [MF], etc.), approximately 32 percent of the volume was phenol-formaldehyde (PF)-type resins (includes resorcinol-formaldehyde [RF] types), and the remaining 9 percent was divided among a variety of other synthetic binders such as polyvinyl acetate (PVAc), cross-linked vinyl (X-PVAc), soy-modified casein, and polymeric diphenyl methylene diisocyanate (PMDI). In addition, a vast and increasing volume of natural-based and synthetic binders are in paper products, overlays, and surface coating industries. Cement/gypsum-type binders are also being incorporated with wood fiber.

Table 1. Estimated 1998 Consumption of Major Wood-Based Adhesives in North America.

Polymer Type	North American Consumption	
	(kt)	(%)
Amino	1060	59.5
Phenolic	568	31.9
Isocyanate	90	5.1
Polyvinyl acetate	50	2.8
Resorcinol type	7	0.4
Soy-modified casein	5	0.3
Total	1780	100.0

Source: Society of Plastics Industries, industry sources, and other calculations.

With increasing oil prices, and increased production capacities of raw materials and resin adhesive products for the expanding wood composites industries, resin prices will likely continue to increase. Resin adhesives are a vital part of glued wood composites, varying from a relatively small portion up to 32 percent of the total manufacturing cost of the item being glued and marketed.

Capital investment for improved processing equipment and for increased capacity has fostered significant North American and worldwide development of new glued engineered wood-based panel and lumber products. The expanded array of glued-wood products has increased demand for a variety of wood adhesive resins and initiated adhesive systems with enhanced properties.

Adhesives From Renewable Resources

Lignin

Since 1981 in North America, lignin-modified PF resins have been utilized in selected mills to bond fiberboards, strandboards, and structural plywoods, principally for lower costs. Most of the lignin used as wood binder (about 6 kt in 1997) has been based on the methylolation of lignin *in-situ* during PF resin formulation, replacing 15 to 35 percent of the phenol. Some lignin is added directly into the composites as a binder and formaldehyde scavenger. Currently, lignosulphonates from two North American pulping process sources (Georgia-Pacific/Bellingham, Washington, and Tembec-/Temiscaming, Quebec) have been the primary

WHEN CONSIDERING LOWER-COST EXTENDED ADHESIVES, MANY COMPOSITE PRODUCERS MAINTAIN THE VIEWPOINT THAT SUPERIOR PERFORMANCE (CURE RATES, MOISTURE TOLERANCE, ETC.) AND QUALITY ARE MORE IMPORTANT THAN MINOR COST SAVINGS.

types in PF resin substitutions. When considering lower-cost extended adhesives, many composite producers maintain the viewpoint that superior performance (cure rates, moisture tolerance, etc.) and quality are more important than minor cost savings. While industry continues to utilize small quantities of lignins in selected modified PF resins (up to 35% phenol replacement), research continues, principally in government agencies and universities, to find natural alternatives that are equally effective in replacing synthetic resin adhesives as wood binders. Since 1925, the Masonite wet process has relied heavily on natural lignin as a basic binder for their hardboards.

Table 2. Estimated 1998 Production of Wood-Based and Other Fiber-Based Composites in North America.

GLUED COMPOSITE TYPE	USA		CANADA		MEXICO	
	––––––(million m^{3}[a])––––––					
Structural Panels						
Plywood	15.730	(90)[b]	1.748	(13)	see hdw. ply.	
OSB/OWB	9.935	(36)	6.875	(20)	—	
Oriented Flake-Strand Lumber	0.051	(2)	—		—	
Parallel Veneer-Strand Lumber	0.200	(2)	0.030	(1)	—	
Hardwood Plywood	1.770	(75)[c]	0.200[c]	(15)	0.160	(25)
Particleboard	8.127	(51)	2.195	(16)	0.630	(9)
Agrifiber (Wheat Straw, etc.)	0.159	(3)	0.053	(3)	—	
Hardboard	1.903	(19)	0.057	(2)	—	
Medium Density Fiberboard (MDF)	2.480	(20)	0.898	(7)	0.036[c]	(1)
Insulation Board	1.454	(7)	0.100[c]	(3)	—	
Laminated Veneer Lumber (LVL)	1.161	(18)	0.056	(3)	—	
Wood I-Joist[d]	0.547	(29)	0.155	(14)	—	
Glulam	0.677	(33)	0.031	(9)	0.008	(1)
Inorganic Panels[e]	0.932	(8)	0.031	(1)	0.073	(3)
Fiber-Thermoplastic Composites	—		—		—	
Lumber End-Jointing[f]	—	(30)	—	(20)	—	
Total	45.126	(423)	12.429	(127)	0.907	(39)
Percent of Total North America	77%		21%		2%	

[a] The data in m^{3} do not account for density variation of products. Where 1998 data were unknown, carry-over data are included and dash (—) symbols indicate data unknown or do not exist in the format given.
[b] Values in parentheses represent the number of mills.
[c] Estimated.
[d] Approximately 1 square foot, 3/8-inch basis, (0.031 ft.^{3} or 0.00088 m^{3}) of structural panel (as web) produces each linear foot (0.3048 m) of wood I-joist; thus, 0.0029 m^{3} per linear m.
[e] Three cement/gypsum-type plants in Central America (0.150 million m^{3}) exist.
[f] Involves over 2 million m^{3} of mostly dry wood (<20% MC); excludes lumber finger jointing at 45 glulam plants and at approximately 1,000 molding plants.

Tannin

Tannin adhesives are not often utilized in North America, but continued interest in their worldwide applications exists. Bakelite AG (Germany) developed tannin-based adhesives for full exterior Marine Grade oriented strandboard (OSB). The resin solids of the Bakelite tannin adhesive technology were 90 percent tannin, applied at 13 percent binder solids, ovendry strand fiber weight, and at 24 percent moisture content (MC) re-sinated strands. Commercial applications of tannin-based adhesives (radiata pine bark extracts) for particleboard (PB) in Chile have been in existence since 1994. The Chile tannin adhesive contains 90 percent radiata pine bark tannin, 5 percent isocyanate, and 5 percent urea. Tannin extracts, depending on the extraction process and raw material, may contain substantial carbohydrate components, and it is not uncommon to see applications of tannin-based adhesives being applied at 10 to 15 percent binder solids, based on the ovendry weight of the panel fiber. The CanFibre Group (Kafus subsidiary) is conducting research on the application of high pressure and temperature to consolidate bark particles into a board by activating the bark's inherent phenolic compounds as the sole binder.

Caseins

Caseins, perhaps the first structural adhesives, are still available for special bonding purposes, but the volume (all imported into the United States) is small (4 to 5 kt per year) and mostly is modified with soy flour. Casein is very useful in bonding door skins to framing lumber (stiles). Most often door skins are treated with linseed oil to enhance the surface quality, thus improving the depth and strength of the door-skin/stile bondlines.

Soy

Soy products have a history as soybean glues and as soy-modified casein adhesives, but renewed interest exists in soy flour and soy protein isolates in binders for wood-based and agrifiber-based composites, including those made of recycled newsprint fiber. Extensive research is ongoing to define the soy products that can be incorporated in the following products: phenol-resorcinol-formaldehyde (PRF) co-polymers for finger-jointing; PF-adhesive foam promoters in plywood manufacture (replacing soluble animal blood); PF and PMDI resin blends in OSB; and peroxidase biocatalysts. Soy can also be used as part of a wheat/soy blend for plywood extenders and as an additive in wax emulsions.

Animal Blood

In North America, soluble animal blood is now rare as an adhesive, but it has become an indispensable ingredient of PF adhesives applied by foam application for bonding industrial and construction plywood. In 1999, 11 North American mills and 1 European plywood mill were applying foam glues. New technology now allows such foam adhesives to be recycled. Blood is also added to special UF and/or MF adhesive formulations for high-value furniture production (piano sound boards and high-grade veneer units).

Pyrolysis Oils

Transformation of wood with phenol to produce a pyrolysis oil results in a wide mixture of compounds that have shown promise as a raw material for modified-PF resin and modified epoxy resin. Up to 50 percent of the primary binder has been substituted with the liquified wood components. The concept seems to have merit, if the supply, and economic and government policies, can justify the need, and the environmental issues can be clearly defined.

Use of Adhesives in Wood Composites

Structural Plywood and Laminated Veneer Lumber

During 1998 in North America, PF resins in formulated adhesives were the almost exclusive synthetic resin for bonding mostly softwood veneer (e.g., southern pine and Douglas-fir) into industrial and construction plywood (103 mills) and laminated veneer lumber (LVL) (21 mills). The volume (18.695 million m^3) of these two industries represented 36 percent of total North American composites, consuming 273 kt of PF resin solids (Table 3) (322 kt minus 49 kt UF). Based on the type of construction, PF adhesive mixtures for construction plywood (252 kt PF resin solids) may equal 3 percent of the weight of the wood with 65 to 75 percent of the adhesive mixtures being PF resin solids (~2% of the ovendry wood weight).

LVL PRODUCTION IN NORTH AMERICA HAS GROWN CONSIDERABLY (EXCEEDING 1 MILLION M^3 PER YEAR) FOR SPECIALIZED LUMBER, I-JOIST FLANGES, HEADERS, AND GLUED-LAMINATED TIMBERS (ARCHES AND BEAMS) (GLULAM).

LVL production in North America has grown considerably (exceeding 1 million m^3 per year) for specialized lumber, I-joist flanges, headers, and glued-laminated timbers (arches and beams) (glulam). LVL is now produced with continuous press lines as well as with batch platen presses. The PF adhesive (21 kt PF resin solids) for LVL is similar to those in structural PF-bonded plywood, but LVL has many more bondlines on average compared to plywood, and

Table 3. North American Wood Composites and Adhesive Resin Solids Requirements.

Industry Category	Wood Composites		Resin Solids
	Percent	Quantity	Requirements
	%	(million m^3)	(kt)
Plywood, LVL	35	20.825	322[a]
Oriented Strand Products	29	16.861	311
Particleboard	19	10.952	723
Medium-Density Fiberboard	6	3.414	225
Other	11	6.410	199
Total	100	58.462	1780

[a] Includes decorative plywood binders (49 kt).

both utilize PF adhesives containing important filler-extender additions to enhance binder performance.

OSB and Strand Composite Lumber

During 1998 in North America, OSB comprised about 49 percent of the market share of industrial and construction (structural) panels (Table 2). Total oriented strand products represented 29 percent of all wood composite products (Table 3) and market share is growing yearly. Adhesives for bonding oriented strand products (56 OSB mills and 2 strand lumber mills) were approximately 82 percent PF (256 kt resin solids) and 18 percent PMDI (55 kt resin solids). Some systems, applying two-component PF resins and/or additives based on resorcinol or other compounds such as guanidine carbonate, react faster than conventional PF resins. Some of these systems reportedly have cure speed comparable to PMDI. PMDI resins have been applied primarily as core resins because of surface press sticking problems. When the entire OSB panel is bonded with PMDI, a PF overlay is usually added to the panel surfaces as a barrier or a release agent is added to the PMDI to prevent press sticking. Continuous press systems, now a consistent feature in PB/medium density fiberboard (MDF) plants, are being incorporated into OSB (two plants in North America) and other structural engineered wood component manufacturing. Some of these continuous presses have steam or microwave preheaters to increase press throughput.

One principal adhesive advancement made possible by isocyanate adhesives relates to gluing higher (>6%) MC strand wood at relatively fast speeds (4 s/mm when steam injection is part of the process). This area continues to be an important topic of research and involves more reactive resins (some with added cross-linking agents) with a faster cure in the presence of higher moisture and/or with basic resin reactivity in the presence of water.

In North America, other structural composite lumber products include veneer-overlaid strand lumber, veneer-based parallel strand lumber (three plants), and oriented strand lumber (two plants), as well as other product classifications. In some of these applications, combinations of PF resin and wax in a one-component adhesive system have been developed. In North America, the binder may equal 1.8 to 3 percent of the weight of the wood for commodity OSB and up to 6 percent for specialty (higher durability) OSB.

Particleboard and Fiberboard

During 1998 in North America, 104 mills manufactured PB (10.952 million m^3) and dry-process MDF (3.414 million m^3), bonded principally with UF resins. In 1998, PB and MDF represented more than 25 percent of total North American wood composites (Table 3) and have continued to increase in demand. Development continues on melamine-urea-phenol-formaldehyde (MUPF) resins for upgrades of PB and MDF, and opportunities to manufacture lower density boards at higher resin solids for these wood composites exist.

During 1998, 21 mills manufactured hardboard (1.960 million m^3) and 10 mills manufactured low-density insulation board (1.554 million m^3). Hardboard is typically bonded with PF resins or lignin-modified PF resins. Four mills manufactured specialized products such as flat and molded door skins bonded with PF or lignin-modified-PF resins. Door skins and other hardboards are typically post-treated with linseed oil, either as a surface enhancer for post gluing to other substrates or as a tempering agent. Insulation boards have a variety of binders.

Decorative Plywood and Hardwood Lumber

The manufacture of decorative plywood and glued hardwood lumber involves primarily UF, MF, and UF/MF blended resins, or PVAc emulsion and X-PVAc emulsion adhesive systems. A limited amount of PF and RF resin is also utilized. The resins are provided mostly in liquid form (emulsions for vinyl products), but some resin supplies are available in spray-dry form. Most often, a filler-extender and accelerator-hardener catalyst are part of the applied adhesive system. In 1998, these composite products represented about 3.6 percent of total North American glued wood products. The principal adhesive resin for manufacture of hardwood and decorative plywood continued to be UF resin (48.7 kt) but PVAc adhesives (50 kt, mainly assembly glues) have had some successful applications. When bondline upgrades are required, MF resins are added to the UF resins, particularly for edge gluing of hardwood lumber products.

Typically, the vinyl acetate-based adhesives for gluing wood are in the form of emulsions (~ 50% nonvolatile solids). The vinyl acetate emulsion adhesives are compounded formulations with various ingredients such as polyvinyl alcohol, cross-linked phenolics or isocyanates (as thermosets), wood flours, clay (i.e., kaolin), and other plastic additives such as butyl phthalate or diisobutyl phthalate. Some cross-linking varieties contain and require an acid catalyst, such as alumi-num/chromium salts or para toluene sulfonic acid, to realize the total accelerated and durability potential of the bondlines. Extension (up to 25%) of vinyl acetate emulsions with soft wheat flour-water solutions at the mill site have been developed for hardwood flooring constructions, reducing the emulsion resin solids and glue costs.

Continuous ContiRoll press for OSB production.
Courtesy of G. Siempelkamp GmbH & Co., Krefeld, Germany.

Parquet and Laminate Flooring

Due mainly to health concerns (allergies) related to carpeting, wood floors are a growing market in North America as well as in Europe. Wood floor systems include solid wood strips, solid and glued 3-ply parquet, and "laminate" flooring strips. The laminate flooring (3% of the total 1999 flooring market) includes 3-ply and 5-ply hardwood veneer plywood that is cut into strips or blocks and a 4-layer composite.

Treated Wood

Resin research continues to identify mechanisms to bond treated wood and composites, particularly those containing fungicides, copper-chromium-arsenate (CCA), or borate compounds, and fire retardants. Moderately low-molecular-weight RF resins as primers appear to be helpful in bonding CCA-treated wood. One-part polyurethanes containing 20 percent PMDI polymers are now available to bond treated wood. These same adhesives offer opportunities to bond recycled treated wood, as well as high-extractive-content wood species, into useful products.

Overlays

In North America, overlays and finish coatings are applied to the major percentage (> 90%) of PB and MDF panels. This percentage is similar in Europe (75% of sales). Clearly, these types of panels are mainly driven by the overlay and other surface-enhancement end-use sectors. In North America during 1998, according to the Laminating Materials Association, more than 983 million m^2 of decorative overlays were produced.

The overlaying business is becoming very sophisticated, with rapid changes in materials and processing technology. MDF wrapped in vinyl and paper overlay has found a growing market in molded products. The MF and MUF resins continue to be the predominate polymers for "thermally fused" decorative products. Polyester woodgrain types are still available for specialty patterns but are decreasing in market share. A resorcinol- or phenolic-type adhesive best suits bonding high-density overlays for exterior applications. Worldwide consumption of phenolic film-faced plywood, which is plywood overlaid with PF-resin-impregnated kraft paper, was predicted to reach 2 million m^3 by the year 2000, requiring 357 million m^2 of overlay. Kraft paper overlays impregnated with liquid PF resins and bonded to plywood, LVL, and OSB siding products are greatly expanding the usage of overlays in the North American construction and transportation industries.

Fiber-Reinforced Plastic Applications

A relatively new development has been the application of carbon (mesophase pitch, polyacrylonitrile, and rayon) and aramid (a form of nylon) or high-performance polyethylene fibers embedded in a vinyl-ester thermoset resin matrix in glued-laminated wood beams. Aramid fiber improves the tension property of beams and carbon fiber improves the compression strength. The fiber-reinforced plastic composite replaces the tensile laminate layer, permitting a smaller but stronger beam in comparison with conventional wood glulam members. The fiber-reinforced plastic composite improves the strength-to-weight ratio and lowers the wood cost.

> SOME OF THE AGRIFIBER RAW MATERIALS BEING CONSIDERED ARE WHEAT STRAW, SOYBEAN STALKS, FESCUE STRAW, BLUE GRASS STRAW, SUGAR CANE STALKS (BAGASSE), COTTON STALKS, RICE STRAW, HEMP, KENAF, AND OTHER AGRICULTURAL RESIDUES.

Agrifiber Composites

During 1998 and 1999 in North America, six agrifiber, particle-type panel mills were reportedly in operation (wheat straw furnish primarily). Seven additional agrifiber PB/MDF mills were scheduled for start-up during 2000-2001, resulting in a total announced industry capacity of 1.564 million m^3. Agrifiber composites are sometimes described as being between MDF and PB in physical/mechanical characteristics. Some of the agrifiber raw materials being considered are wheat straw, soybean stalks, fescue straw (Canada), blue grass straw, sugar cane stalks (bagasse), cotton stalks, rice straw, hemp (Canada), kenaf, and other agricultural residues. Without fiber modification (e.g., mild chemical and steam pretreatment and fiber bundle refining) to improve buffering capacity and surface functionality, PMDI resin (up to 6% resin solids or higher, dry fiber weight basis) has been shown to be the preferred binder for most agrifiber boards. Therefore, the adhesive costs for these nonwood materials are often up to three times more expensive for a given volume than for comparable wood-based composites bonded with 6 to 12 percent UF resin solids, dry fiber weight basis. However, with pretreatment and refining of the agrifibers, the conventional formaldehyde-based resins reportedly work well as a binder.

Inorganic Binders

The first commercial inorganic binder products were available about 1914 in Europe, and today most production exists in Europe and Asia. North America has less than 20 plants, but awareness is increasing for exterior applications (siding and roofing products) as well as for interior products (insulation, wall partitions, etc.). The inorganic binders may be Portland cement, gypsum, or magnesium cement. Portland cement is the most moisture resistant. The cellulosic fiber (wood or agrifiber) content of these composites ranges from 10 to 30 percent by weight and up to 70 percent of the volume percentage.

Wood Adhesive Processes

Radio-Frequency Curing

In 1998 in North America, the production of finger-jointed lumber for studs exceeded 1 million m^3 per year (50 mills, excluding 45 glulam end-jointing plants and hundreds of secondary end-jointing operations). Some adhesives for these end-jointing operations are cured by radio-frequency (Rf) methods. Adhesives for bonding end-joint lumber include cross-linked PVAc, MF, UF/MF, and RF. For bonding glulam dry stock ($<$ 20% MC), Rf curing of an MUF resin combined with a resorcinol-based hardener offers expanded opportunities with no arcing.

Some new designs of microwave and Rf presses (with and without microwave wood preheaters) for LVL, strand lumber, veneer-strand products (Parallam®), and MDF have fostered new application developments in PF adhesive technology not possible in the past. When microwave preheaters are incorporated with continuous LVL process lines, the adhesive is altered to accommodate the higher temperature furnish at the adhesive application step.

Glulam bondlines are usually bonded with a PRF resin, as are wood I-joist joints. Both of these industries are expanding in production in North America. Some glulam is bonded with MF-based resins, which are well suited for high-frequency curing processes as well as for providing a light-colored bondline.

Programmable logic controller systems to meter-mix, monitor, and dispense single or plural component fluids to exacting specifications (not possible in the past) have made Rf units (and conventional systems) more productive and uniform in cure properties through reduced coverage variation.

Steam Injection

Steam injection accelerates the cure of PMDI and PF resins for PB, MDF (including door face materials), OSB, LVL, and end-jointing. Some of the current operations are continuous hot-press lines that incorporate steam injection to increase mat MC, to act as a preheater, and/or to serve as a cure accelerator in conjunction with conventional oil/steam-heated press platen processes. The wood raw materials in such presses are about 5 percent MC, and the cure rates can be 1 to 4 s/mm. The faster resin cure accelerates the line speed, and therefore production, and results in an increase in desirable board properties.

Disk Atomizers

New spinning disk/spray atomizers have revolutionized liquid resin technology in the OSB industry (80% of the industry in 1997), allowing lower resin solids application through better resin distribution of more viscous resins (1000 mPa•s versus 100 mPa•s). Other disks are available that allow applying wax or mixing of a catalyst and a resin on the disk surface.

Refiners, Meters, and Pumps

New wood refiners have been designed with resins added during the cycles, and new press platens, some with molded designs, have required incremental resin improvements to accommodate them. Better pumping and metering equipment allow buffered catalysts for UF resins and buffered UF resins with conventional catalysts. These adhesive systems, which prevent dry out at the press for MDF and PB, were not practical before. Buffered catalysts for UF-bonded hardwood plywood have been utilized for decades, but other applications of buffered systems have not previously been widespread in North America. These new systems are important for the typical multi-layer (face-core-face) MDF and PB of North America versus the homogeneous boards produced in other parts of the world.

Foam Extruders

North American interest in foam extrusion application of PF adhesives for construction plywood manufacturing is increasing (11% of the mills in 1998). The new generation of foam equipment for plywood manufacture has computerized equipment capabilities to define veneer MC and veneer temperature, which are synchronized with adhesive coating weight (glue spread). The foam adhesive technology has been explored for UF-bonded PB as well. These foam technologies depend on the addition of air and a small percentage of dried animal blood to help expand the foam mixture 5 to 15 times the volume of the liquid resin. Alternatives (soy-based) to soluble animal blood are being explored by adhesive companies. The foam systems have the potential to reduce adhesive usage, minimize trim loss, reduce cleanup labor, and limit waste materials.

Continuous Versus Batch Platen Presses

The forming lines of continuous presses can accommodate different resins in the core versus the face. They provide a consistent opportunity to preheat and inject humidity into the mat just before hot-press entry. By consistent mat preheating and interjecting of moisture, the panel cure cycle can be reduced (up to 20% reduction), thickness swell can be reduced (up to 50% reduction), and the MOE/MOR and IB of the OSB can be significantly changed (not necessarily higher values).

Tool Wear Factors

Adhesive formulations are being changed to reduce tool wear when machining glued wood products. These formulation changes involve a wide array of adhesive systems: vinyl acetate emulsions, UF/MF catalysts, phenolic extender/fillers, and waxes (which reduce tool wear). The tool wear mechanisms from machining glued wood products include high-temperature corrosions by nitridation, halogenation, and sulfidation, as well as oxidation.

Environmental Issues

Life-Cycle Durability

With decades of historical knowledge on synthetic wood adhesive resins in service, much is known about their durability under a variety of conditions (Table 4). However, life-cycle and durability concepts of glued wood composites in the expanding market applications is yet to be well defined for the general public. One attempt to help solve this communication problem is the Environmental Resource Guides of the American Institute of Architects. The members of the Canadian Particleboard Association (now part of the Composite Panel Association) have decided to evaluate if life-cycle analysis could provide a basis for grading the environmental attributes of PB and

Table 4. Durability of Wood Composite Adhesive Resins and Glues in Some Relative Order.

Synthetic Resin-Adhesives	Durability Remarks	
Resorcinol-formaldehyde (RF)	No question about durability if properly used.	
Phenol-formaldehyde (PF)	No question about durability if properly used.	
Polymeric methylene diphenyl diisocyanate (PMDI)	No question about durability if properly used	
Urea-formaldehyde (UF)	Will not stand cyclic treatment nor high temperature.	
Melamine-formaldehyde (MF)	Damaged by 48-hour boil.	
Blends of UF and RF	A blend of UF and RF containing 40% RF may exceed the durability of an MF in certain test criteria.	
Blend of MF and novolak PF (Europe)	Exceeds 72-hour boil.	
Blends of UF and RF or MF	Durability of these blends depends on the ratio of RF or MF.	
Blends of polyurethanes and isocyanates	Durability depends on ratio of urethane and isocyanates (finger joints)	
Cross-linked vinyl	Depends on degree and type of cross link.	
Polyvinyl acetate (PVAc)	Will not stand long-term load (creeps).	
	Destructive conditions	
Natural adhesives (glues)	Humidity (%)	Moisture content (%)
Blood albumin	97	27
Casein	90	22
Animal and vegetable	80	17

Source: Table compiled by T. Sellers, Jr., using references such as R.F. Blomquist and W.Z. Olson. 1955. Durability of fortified urea-resin glues in plywood joints. Forest Prod. J. 5(1):50-56; Forest Products Laboratory. 1963. The durability of water-resistant wood working glues. FPL Report No. 1530. Rev. USDA Forest Service, Madison, WI; and R.A.G. Knight. 1952. Adhesives for Wood, Chemical Publishing, NY. 242 pp.

MDF. These issues involve energy and material inputs and outputs, and are part of the little known "industrial ecology" discipline, which is a growing new approach by industrial corporations.

Life-cycle analysis, which includes recycling, is helping to show that the cost of a product over its life must be considered and not just initial production costs. Most often, life costs of more durable wood adhesives for wood composites are considerably lower than the life costs when using inferior adhesives (quantities or types) and inferior composite process technology. The costs of using inferior adhesives and technologies must include the high costs (dollars and customer confidence) of litigation as experienced recently in the United States with certain exterior-applied, adhesive-bonded wood composites.

VOC Emissions: Resins

Resin producers are constantly researching ways to identify and reduce emissions that do not require a substantial increase in manufacturing costs and do not affect product performance. Since the 1980s, formaldehyde emissions from uncovered UF-bonded PB/MDF in the United States have been reduced by more than 80 percent. Substantial improvement in the mole ratio chemistry of UF, MF, and PF resins has been the major factor in reducing formaldehyde emissions of these resins. But trade-offs exist between mole ratio adjustments and performance, often requiring other adjustments to insure resin cure and panel performance properties. Some of these adjustments include addition of neutral salts and melamine to UF resins; both these additions enhance the cure capability of low-fume resins. Scavenger solutions based on urea, lignosulphonates (polymeric polysulfonic acid salts), low mole ratio UF and MF resins, and mixtures of carbohydrates with urea for low-fume UF and MF resins have been developed. Other cross-linking agents or aldehydes than formaldehyde are available, such as amines and urea-ethyleneurea-glutaraldehyde, but they carry their own environmental consequences, and initial costs for gaining government environmental approval can be high. The successful reduction of resin emissions in wood composites has made formaldehyde emission largely a technical nonissue in many applications.

VOC Emissions: Panel Producers

Many panel producers have installed scrubbers, regenerative thermal oxidizers (RTOs), and other emission reduction equipment to meet requirement levels of state and federal agencies such as the U.S. Environmental Protection Agency (EPA). These systems capture/alter emissions from wood drying, resin application, resin-adhesive curing, and burning of resin-coated wood and other wood waste materials, but the efficacy of these systems relative to ozone is not yet proven. Both federal and state (province) governments have required all producers of glued wood products to substantially reduce their VOC emissions (formaldehyde, methanol, phenol, isocyanate or vinyl monomers, and ammonia). These chemicals are especially significant in relation to air emissions (ozone depletion) and human exposure. Manufacturing users of the resin-adhesives require no spills, recycling of wash-waste water, and compliance to the on-site mandates. Many wood finishes and laminates can form a nearly impermeable barrier to VOCs from wood composites and adhesives, but their application processes can be significant sources of VOCs.

Resin formulation at Mississippi State University.

Recycling

The emphasis on environmental issues includes recycling technologies. The trend toward recycling and elimination of wastes is getting stronger. These issues relate to raw materials for manufacturing as well as end-product wastes and ultimately to end-product recycling (furniture and homes). Adhesive companies are incorporating disciplines to identify and eliminate wastes as a foundation to reduce costs and to identify value-added product opportunities. Part of the business strategy is increased working partnerships between adhesive suppliers and wood products companies in solving mutually beneficial issues.

Construction site accumulation of wood composite and other trim wastes involves some costs for removal. A need exists to define waste disposal of glued wood products remaining on the site after construction. One solution suggested by the U.S. National Home Builders' Association has been to grind up such waste products on the site and distribute the mineral/organic material (which includes adhesives) as mulch for lawn grasses and shrubs. Research to verify environmental acceptance of this procedure is being fostered. One U.S. Federal criterion is that such on-site mulching material must make a contribution as a soil amendment and not be solely a "landfill" material.

Thermoplastic-Fiber Composites

New composites such as molded blends of virgin or recycled lignocellulosic fiber as filler and virgin or recycled thermoplastics as matrix polymers are increasing the variety of wood composites in the marketplace. The plastics are chosen for their relatively low melting points (< 204°C), which allow processing below the degradation temperature of wood, paper, or other lignocellulosic fibers (agrifibers). Recycled forms of these plastics are readily available. In the United States, recycling thermoplastic is growing in volume, but slowly (~ 5% of all thermoplastic was estimated to be recycled in 1998). The principal recycled plastics are polyethylene terephtalate (PET) (35%), high-density polyethylene (34%), polypropylene (16%), low-density polyethylene (9%), and others (6%) such as polystyrene and polyvinyl chloride. The lignocellulosic fiber can be recycled wood (e.g., pallets, etc.), virgin wood flours, recycled newspaper, or agrifibers (e.g., kenaf, etc.). Because the hydrophillic wood/pulp-based fibers are not chemically compatible with the hydrophobic plastic polymers just mentioned, maleated (maleic andydride treated) versions of the plastics (thermoplastic resin alloys) can be added as a coupling agent where desired for improved test properties. Stearic acid has been added to kraft pulp fibers to facilitate dispersion of the fibers into plastic matrices. This technology is advancing, providing a mechanism for coupling the nonpolar thermoplastics to polar wood fibers (virgin wood, waste paper, recycled wood, etc.) in order to create useful products such as window and door components, molded decorative items, automobile parts, pallets, and recreational equipment. The list of compatibilizers researched includes isocyanates, anhydrides (e.g., maleic), copolymers, organosilanes, organic acids (e.g., stearic), and peroxides.

> ADHESIVE COMPANIES ARE INCORPORATING DISCIPLINES TO IDENTIFY AND ELIMINATE WASTES AS A FOUNDATION TO REDUCE COSTS AND TO IDENTIFY VALUE-ADDED PRODUCT OPPORTUNITIES.

Summary

The key to success for adhesive companies in the increasingly global environment is designing strategies that gather and analyze adhesive information from throughout the world and applying the knowledge to achieve interactive technologies and expansion of market share. For the wood adhesive and wood composite industries to be successful in the future, progressive and appropriate long-term investment is necessary to take advantage of the more than six decades of enduring progress of synthetic adhesive technology and centuries of natural-base wood adhesive experience.

Life-cycle analysis is a major factor in that investment. Life-cycle analysis of resin-adhesives includes energy costs, long-term durability, environmental and recycling factors, and humanities and social science functions, and not just raw materials, end products, markets, and resin delivery to a wood composite manufacturer.

In terms of durability in structural applications, the cured adhesive must equal or exceed the substrate (wood) in strength. For all end-use applications, the cured adhesive and wood composite must be evaluated for four environmental degradation conditions: 1) heat energy (pyrolysis) for thermal-chemical degradation; 2) chemical energy (hydrolysis) for MC changes, atmospheric exposure, tool wear, and coatings and finishes compatibility; 3) physical energy for swelling and shrinkage stress responses; and 4) biological energy for bacteria and fungi degradation susceptibility. Regardless of chemistry, structural adhesives should have known and comparable test properties for in-service performance of adhesively bonded wood assemblies. These test properties include strength (tensile and bending), impact and fatigue propagation, and tri-environmental durability regimes (cyclical loads under elevated temperature and moisture), as well as biological responses under adverse conditions where applicable.

For the future, the following areas are opportunities: 1) cure on command: latency, fast cure at moderately elevated temperatures, and accelerator or cross-linker encapsulation; 2) combination adhesive technologies convergence where the benefits from each combine into one; 3) adhesive primers and surface treatments that are relatively inexpensive and subject to normal engineering applications; 4) environmentally benign adhesive systems, with data to prove it; and 5) life-cycle predictions with associated costs.

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