ADHESIVES

The American Society for Testing and Materials (ASTM) defines an adhesive as a substance capable of holding materials together by surface attachment (1). The mechanisms by which a liquid adhesive makes intimate contact with a surface, undergoing physical and chemical changes to bond surfaces together, is highly complex and understood only in part. Nonetheless, adhesives appropriately selected for compatibility with adherend and service conditions can be used to great advantage in building construction. Adhesives increase strength and stiffness of building components, uniformly transfer and distribute stresses, and combine dissimilar materials that could not be joined otherwise. Applications in building construction vary widely in structural capabilities, from huge glued-laminated beams that support roof loads to nonstructural applications where adhesives support only wall coverings and decorative trim. Within the last 45 years, age-old animal and vegetable adhesives have essentially been replaced by chemically synthesized adhesives that enable the user to bond practically all materials from microchips to jet aircraft. The construction industry is the largest user of adhesives, but by far the largest proportion is used to manufacture building materials such as plywood, particle board, gypsum board, hard board, doors, sandwich panels, glass-fiber insulation, and various factory-laminated products. The amount of adhesive used in the construction industry to assemble building materials at construction sites and in small shops is unknown, but it is this latter group of adhesives and their applications that this article addresses. Mechanisms of adhesive bonding and the nature of bonding surfaces and polymers that are common to most adhesive applications are also discussed.

MATERIALS IN ADHESIVES

Practically all adhesives used in building construction are made from organic polymers of either synthetic or natural origin. Polysaccharides and proteins are the natural polymers. Since early civilization, natural polymers derived from animal and plant materials have been used as adhesives. Animal, casein, blood, soybean, starch, dextrin, and cellulosic adhesives are still in use today, although they are being replaced by synthetic polymers. Natural rubber is the other natural polymer used in both latex and solvent systems, but here again, the natural material is being replaced by synthetically derived rubbers.

Natural rubber and synthetic rubbers are elastomers. An elastomer is a generic term meaning a macromolecular material that, at room temperature, is capable of recovering substantially in size and shape after removal of a deforming force (1). These are extremely useful materials and undoubtedly make up the largest class of adhesives used in building construction. Adhesives based on elastomers range from relatively low-strength pressure-sensitive tapes, to contact-bond and mastic adhesives, to tough structural metal-bonding adhesives made from nitrile rubber and phenolic resins.

Synthetic polymers constitute the largest group of adhesive products by far. These polymers can be chemically designed and formulated to perform an almost infinite variety of bonding functions. Synthetics can be broadly classified as thermoplastic and thermosetting polymers. Thermoplastic resins are long-chain polymers that do not undergo chemical change on heating. They soften and now with heat and harden again on cooling. They have limited resistances to heat, solvents, and long-term loading. Common thermoplastics are polyvinyls, acrylics, polystyrenes, and polyamides. Thermosetting resins make excellent structural adhesives because they undergo chemical change on addition of heat. They form cross-linked polymers that have high-strength properties, resist deterioration by most chemicals, and support high long-term loads without deforming. Resorcinolic, amino, and epoxy resins are examples of thermosetting adhesives.

An adhesive formulation is a mixture of several materials that are added in various ratios to a base material in order to impart the desired strength, durability, and adhesion properties. Solvents are used to disperse or dissolve base materials, to act as a vehicle for the fluid system, and to provide viscosity control. Fillers can be used to control adhesive penetration of porous surfaces, to serve as thixotropes to control flow and penetration, and just to thicken and reduce cost. Reinforcing agents improve mechanical properties such as toughness, impact resistance, and shrinkage. Extenders are fillerlike materials that usually have a small degree of adhesion capability, but are added to a system to improve certain working properties while cutting cost. Certain chemicals or base materials may be added to plasticize and tackify resins, whereas other types called fortifiers are added to improve resistance to moisture or heat. Catalysts are chemicals used to speed chemical setting of the base polymers. Acids, bases, salts, peroxides, and sulfur compounds are a few examples. Catalysts do not enter into the chemical reaction; they simply increase the rate of reaction. Other chemicals may be added, such as preservatives, acid scavengers, antioxidants, and wetting agents, all depending on the type of adhesive and the property needing improvement.
ADVANTAGES, LIMITATIONS, AND SAFETY

The function of an adhesive is to fasten members of an assembly together and to maintain the integrity of the assembly under the expected conditions of service. In building construction, adhesives fulfill this role in a great variety of applications, from structural bonds that are expected to contribute great strength and stiffness under severe service conditions for the life of the structure, to nonstructural applications where bonds only support the weight of decorative trim. Even though nails, screws, bolts, rivets, and clips are still the most common means of fastening building materials together, synthetic adhesives are making significant inroads. When adhesives are properly matched to the stresses and service environment of the application and are used in accordance with the manufacturer's instructions, they offer several distinct advantages that cannot be equaled by mechanical fasteners.

At the top of the list is the ability of adhesives to distribute stresses uniformly over the entire joint area, thereby avoiding concentration of stresses, which can lead to failures. Joint continuity allows transfer of stresses from one component to another so that all members share the load. If a rigid adhesive is used to laminate pieces of lumber into a beam or arch, the result is a structural member of greater strength and stiffness than the sum of its individual components, even when the lumber is laminated with mechanical fasteners.

The advantage of effective stress transfer can be used to design new or conventional composite building components of diverse shapes and sizes at lower costs. For example, adhesives have been used to laminate layers of plywood into structural shells for complex roof systems (Fig. 1). Conventional applications such as the widely used stressed-skin panel system enable the designer to use materials of smaller size, of lower grade, and in smaller numbers to reduce material and assembly costs, weight, and volume while increasing the strength and stiffness of the component (Fig. 2). The cost of structural beams can be lowered by more effectively locating laminates of higher quality and moduli in the outer tension and compression members, where stresses are higher, and using materials of lower quality and moduli in the core members, where stresses are lower.

Elastomeric adhesives are capable of yielding to and absorbing stresses under short-term dynamic loading. Such adhesives are used to assemble manufactured housing because they reduce excessive stress concentrations around windows, doors, and joints, where damage can occur when these units are transported over highways and lifted at construction sites.

Adhesives permit the bonding of a variety of materials that may be dissimilar in composition, thermal expansion, modulus, and thickness. Thin sheet materials may be bonded where other joining methods would cause distortion or otherwise be impossible or impractical. Examples include bonding aluminum or hardboard skins to honeycomb or foam cores in making various lightweight sandwich panels. Wall covering, floor covering, and countertop are examples of where adhesives can be used to avoid

![Figure 1. Adhesive bonding of roof planes allows creative solution to an architectural design problem. Courtesy of Forest Products Laboratory, USDA Forest Service.](image-url)
marring smooth surfaces by protruding fasteners, overlaps, and irregular contours. Fewer fasteners can also reduce or eliminate the marring of surfaces by nail popping in gypsum board and resilient-tile floor coverings. Fibers, particles, and thin films could not be joined at all without adhesives. Examples are aluminum foil, paper, vinyl and fiber sheet materials, glass-wool insulation, fiber glass mat composites, sandpaper, veneered surfaces, particle board, and many others. Adhesives between dissimilar metals can reduce corrosion caused by galvanic action. If an organic adhesive is used to bond copper tubing to steel supports, galvanic corrosion can be prevented. Heat-sensitive material can be joined with adhesive that would be distorted or destroyed by brazing or welding. Adhesives can also be a good barrier to moisture and chemicals. When two metals of dissimilar coefficients of thermal expansion are joined and separated by a flexible adhesive, less stress develops with temperature changes.

Finally, there are many very important high-value building materials that have been reconstituted from low-value materials with adhesives. Examples are hardboard, particle board, flake board, plywood, composite panels and lumber, and finger-jointed lumber, not to mention a host of paper products.

The advantages of adhesive bonding can be realized, but not without knowledge of and careful attention to every aspect of the bonding process. Here lies the greatest limitation to the use of adhesives. A great variety of performance properties and working characteristics are available in an assortment of adhesive products. Realizing the desired results in a particular bonding job, however, requires that an adhesive be selected on the basis of performance requirements relevant to the expected service environment. These include the adhesive’s strength and resistance to creep under static loading in the primary stress mode, its resistance to heat and moisture along with repeating stresses that accompany dimensional changes from heat and moisture, and its resistance to chemicals, microorganisms, and fire. Since the adhesive must properly wet, flow, penetrate, and solidify on a particular type of adherend, it must be chemically and physically compatible with the surface. Adhesives vary in working characteristics; these characteristics dictate how and under what conditions an adhesive must be applied and cured. Careful consideration must be given to preparing and maintaining clean surfaces; preparing and applying the adhesive; providing control over processing time, temperature, and relative humidity; and providing jigs, presses (sometimes with heat), and
other processing equipment. The cost of these provisions is also an important consideration. It is extremely important to have adequate inspection and quality control procedures to ensure that bonded joints, particularly structural joints, will perform as expected in service. The unfortunate result of failure in quality control is unexpected failure in service. Even if bonded joints are found inadequate before being put into service, they usually cannot be dismantled easily and repaired, so materials, time, and labor are lost. To avoid such unsatisfactory results, it is essential to have knowledge and control of the critical aspects of the bonding process. The responsibility for material specifications and workmanship must be clearly established and placed in the hands of qualified people.

Although toxicity is not a major problem with most adhesives used in building construction, adhesives nonetheless contain chemicals that can be toxic if exposed to sufficient concentrations for prolonged periods of time. For example, resorcinol and urea resins react with formaldehyde to form thermostet adhesives that are nontoxic in the cured state. However, free formaldehyde is released from powdered hardeners during mixing, application, and cure (particularly when curing with heat). Adequate ventilation must be provided to remove gases. Formaldehyde gases may react with proteins of the body to cause irritation, if not more serious inflammations of the mucous membranes of the eyes, nose, and throat. Allergic reactions may also occur. The safe working limit for formaldehyde is 0.02 ppm in the air.

Many construction adhesives contain organic solvents that have dangerously low flash points. Generally, however, unless these materials are confined within empty containers or nonventilated rooms, they do not reach dangerous concentration levels. Unfortunately, tragic explosions have occurred simply because of cigarette smoking where solvent-based adhesives were being used. Adhesive producers have made efforts to change formulations to include less flammable solvents.

Other adhesive components may be subject to hazardous polymerization. For example, isocyanate in polyurethane systems can polymerize on contact with strong alkalies, strong mineral acids, and water. It can also cause irritation to the eyes and skin on contact and respiratory and gastrointestinal irritation if inhaled or ingested.

Health and safety regulations require that toxic and hazardous chemical substances be identified and visibly labeled to warn of dangers. Instructions are provided on proper handling procedures, protective clothing and gear, procedures for dealing with spills and fire, as well as first-aid procedures. These instructions also provide material safety data sheets on new products as a partial fulfillment of the OSHA hazard communication standard and worker “right-to-know” laws.

### ADHESIVES USED IN BUILDING CONSTRUCTION

Resorcinol–formaldehyde (RF) and phenol–resorcinol–formaldehyde (PRF) resin adhesives have filled a great need in the building industry as wood-bonding adhesives for structural applications. Since commercialization in early World War II, when they were used to assemble wood aircraft and naval vessels, they have proven their exceptional strength and durability even under the most severe service conditions. They are capable of sustaining high long-term loading without creep. Their exceptional performance properties relative to other adhesives used to bond wood are shown in Table 1, and in the exterior exposure tests shown in Figure 3. Since resorcinolic-type adhesives can be cured at room temperature, they are well suited for shop, and in some instances on-site, laminating. For these reasons, RF and PRF resins have become the standards for structural adhesives, particularly for laminating beams and bonding stressed-skin panels (Fig. 2).

RF and PRF adhesives are marketed as two-component systems; that is, resin and hardener are separate and mixed just before use. In laminating plants, they are ap-

### Table 1. Estimated Relative Performance Capabilities of Room-temperature-curing Adhesives in Douglas Fir Lumber Joints

<table>
<thead>
<tr>
<th>Adhesive Type* (Number of Components)</th>
<th>Shear Strength (Compression)</th>
<th>Delamination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vacuum-pressure</td>
<td>1 mo, &gt; 80% Relative Humidity</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>Soak</td>
</tr>
<tr>
<td>Douglas fir lumber</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PRF (two-part)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Epoxy, slow cure* (primer plus two-part)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>EPI (two-part)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Polyurethane (two-part)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>UF (two-part)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PVAc, cross-linked (two-part)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Casein (two-part)</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>PVAc (one-part)</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

* Refs. 2-8.

* Adhesives represented are of the highest quality available.

1. very high; 2, high; 3, moderate; 4, low.

Epoxy adhesive specially formulated for bonding to wood.
plied by powered roller-spreaders or extruders. In the field, a brush or hand roller is adequate. Open and closed assembly times vary according to reactivity, air and wood temperature, humidity, moisture content of wood, and spread rate. Even though lumber is planed to clean and smooth the bonding surfaces, pressures of 690-1380 kPa ensure intimate contact between adhesive and wood. The time a laminate remains under pressure may vary from 4 to 16 h.

PRF adhesives with gap-filling capability are not available except on special request, although there is a need for them in the construction industry. Conventional PRF adhesives are too thin to bridge gaps between rough, uneven plywood and lumber surfaces. Therefore, large presses, clamps, or extensive nailing must be used to apply enough pressure to bring intimate contact between adhesive and wood. Certain thickening and reinforcing agents can be incorporated into a PRF resin to make an extrudable, nonsagging adhesive that will bridge gaps of 1.5 mm or more. Instead of driving nails 10-15 cm apart, they can be spaced 30-40 cm. Nails are needed only to hold the assembly together until the adhesive sets. Even with thickening ingredients, the strength, rigidity, and durability of the adhesive in thick bondlines still exceeds the strength of plywood (2).

RF resins are prepared by reacting 1.0 mol resorcinol with formaldehyde in a low enough molar ratio, approximately 0.55:0.65, to make a formaldehyde-deficient prepolymer. When the adhesive bond is to be made, more formaldehyde is added to the prepolymer to complete the thermosetting reaction. Resorcinol is so reactive that polymerization can be completed at room temperature. A lower-cost phenol–resorcinol copolymer resin can be prepared by reacting phenol with formaldehyde to form a resole and then reacting it with resorcinol or resorcinol–formaldehyde, all depending on the type of copolymer desired. Molar ratios, concentrations, catalysts, and reaction conditions can be varied to yield a great variety of adhesive products.

Isocyanates are highly reactive materials that cross-link with a variety of polyols to produce polyurethanes. These materials are highly polar and develop strong hydrogen bonds. They bond to an unusually wide variety of surfaces, such as wood, metal, plastic, glass, rubber, ceramics, and nylon. Polyurethanes have high cohesive strength and impact resistance, as well as excellent cryogenic properties. Their chemical structures can be controlled to produce a rigid film in thin bondlines or a highly flexible film in thick bondlines.

Polyurethane-type adhesives have certain properties that make them particularly suited to bonding wood assemblies: notably fast cure rates, gap-filling characteristics, and little or no pressure requirement during bonding (6). A one-part fast-curing system is capable of developing wood failure within 15 min. The bonds have high dry strength, and they are tough and flexible. A two-part system has been developed with improved heat and water-soak resistance. These were areas of weakness in polyurethane adhesives, along with their questionable ability to withstand long-term static loading at elevated temperatures. Their performance relative to several wood adhesives is shown in Table 1. Figure 3 shows the durability of two polyurethane adhesives during 16 years of exterior exposure.

The polyurethane reaction is also used to produce elastomeric construction adhesives. These are high-molecular-weight one-part systems with free isocyanate groups that react quickly on contact with the surface or moisture in the air.

One of the newest isocyanate-based adhesives is the highly versatile emulsion polymer–isocyanate (EPI) adhesive (8). It is capable of bonding to a wide variety of sur-
faces, and for more than 10 years it has been used in structural applications where skin materials such as plywood, aluminum, fiber glass-reinforced plastics, acrylic sheets, gypsum board, hardboard, particle board, impregnated paper, and vinyl film have been bonded to lumber framing. They have also been used in hollow-core and solid flush doors, lumber finger joints, and wood I-beams.

EPI is a two-component adhesive that requires mixing before use. The aqueous emulsion phase contains the base polymer. During mixing, the isocyanate phase is protected from reacting with the water contained in the emulsion phase, but as water evaporates and diffuses into the substrate, the protective mechanism deactivates and the two phases are brought into molecular contact for reaction.

EPI adhesive is perhaps the strongest and most durable wood adhesive that will chemically set at temperatures as low as 4°C. Once the two components are mixed, the pot life can be several hours. It can be spread with conventional hand or powered equipment. Assembly times are quite flexible, allowing 0–30min open time and 0-60 min closed time. Press times are relatively short: 1 h at 21°C with fast-setting system. The adhesive meets all requirements for structural laminated wood products intended for exterior applications. Its relative structural performance capabilities on wood are shown in Table 1.

Epoxy resin adhesives are more widely used than any other adhesive type, primarily because of their high strength, excellent adhesion to a variety of surfaces, cure at ambient conditions, resistance to moisture, heat, and creep, and low shrinkage on setting. They have penetrated more fields of manufacturing, and have been used to bond more diverse materials, than any other adhesive type, including bonds to metal, glass, ceramics, plastic, wood, concrete, and others. In the United States, they have not often been used for structural applications in building construction; they are used only for repairs to structural and facial members, filling cracks and voids, and laying stone and ceramic floor tiles.

Most current applications are semistructural in the sense that the adhesive is not expected to sustain a high level of stress for long periods of time. Epoxies are capable of shear strengths of 25–35 MPa, but for such bonds as concrete-to-concrete and concrete-to-metal (10), no more than 350 kPa sustained load is ever reached. New concrete does not bond well to old, but if the epoxy resin is used to interface the old and new concretes, then bonds develop that have greater mechanical strength than the concrete. This technique is commonly used to enlarge structures or to repair existing concrete structures as in conduct walls, buttresses, pillars, and the joining of precast structural elements. Fastening steel bolts and fasteners into concrete is commonplace, as is injecting epoxy adhesive to repair cracks in concrete structures. Steel sheets or plates may be bonded to concrete beams to strengthen the composite. Steel reinforcement wires and posttensioning tendons may be bonded to concrete. In these cases, the adhesive does not support design loads, but it must be strong and durable, with enough resistance to creep at elevated temperatures to enable the adhesive-bonded metal additions to reinforce the structure.

Most epoxy adhesives considered for structural bonding of wood do not perform satisfactorily where high strength and resistance to delamination must be maintained during water saturation or outdoor exposure. However, two epoxy formulations have performed extraordinarily well over 16 years of outdoor exposure. As indicated in Figure 3, they have resisted strength deterioration as well as solid wood (3). The relative strengths and durabilities of one of these epoxies has been rated in Table 1 along with other structural adhesives. Both epoxies bonded well because the wood surfaces were primed before bonding with a 2% aqueous solution of polyethyleneamine. Apparently, these two epoxies, and others in their normal formulations, do not wet and flow effectively enough to penetrate porous wood surfaces; however, the primer overcomes this problem.

The reactive epoxy group is a three-membered ring consisting of an oxygen atom attached to two connected carbon atoms. On curing, these rings are opened by catalysts to form cross-linking networks. Epoxies owe their high chemical adhesion to epoxide, hydroxyl, amine, and other polar groups in the molecule. The most common epoxies used in adhesives are derived from bisphenol A and epichlorohydrin, and they are cured with reactive hardeners containing primary and secondary amine groups. The aliphatic amines set at room temperature, but aromatic amines require elevated temperatures. Various other hardeners such as acid anhydride, tertiary amines, mercaptans, and others may be related with epoxides to produce adhesives of varying mechanical properties, durabilities, and working characteristics. Generally, epoxies can be formulated to create a great variety of mixtures so that once a surface is properly cleaned, subsequent wetting, spreading, and penetration should not be a problem in developing a bond.

Urea-formaldehyde(UF) resin adhesives are not used often in building construction, but they are used in shops to make built-in furniture and to laminate various wood assemblies. UF's develop very strong bonds to wood, and they have structural capability as long as the joints remain free from moisture, particularly at elevated temperatures (4,5). The weakness in urea resins is that they are subject to hydrolysis, and of course, heat and moisture accelerate that process (Table 1 and Fig. 3). The adhesive is brittle and has poor gap-filling capability, so good-fitting joints are essential.

UFs are available as room-temperature-setting adhesives. In ready-mix form, the spray-dried resin powder, solid acid-forming catalyst with buffer, and fillers are mixed with water just before use. The pot life of the mix is 6-8 h, although complete chemical setting requires several days.

UF resins are products of the condensation reaction of 1.5–2.0mol formaldehyde with 1.0 mol urea. The methyol uraes formed in the partial polymerization process are dispersed in water at high concentrations and can be converted to a powder by spray drying. When the soluble powder is mixed with the acid-forming catalyst at the time of use, the polymerization reaction is completed.

Within the last 25 years, great volumes of a variety of elastomeric adhesives have been used in the building industry to assemble materials at construction sites, in shops, and in manufactured housing plants. Even though
elastomeric flooring and contact adhesives were in use earlier, the introduction of mastic-type construction adhesives essentially revolutionized the industry by bringing in new adhesive products and ways of assembling building materials for both semistructural and decorative purposes (Figs. 4 and 5). The variety of elastomeric-based adhesives available is extraordinarily wide, ranging from the general-purpose to those designed for highly specialized applications. The base materials are the natural and synthetic rubbers, including latex, neoprene, styrene—butadiene, polyurethane, and reclaimed rubber. Other nonelastomeric polymers such as acrylic, poly(vinyl acetate), asphalt, and copolymers of vinyl acetate with acrylic or ethylene and hydrocarbon resins may also be used. Most of these same polymers are used to make construction sealants (11).

Mastic construction adhesives have a number of unique working characteristics that make them well suited for building construction. Perhaps most important is their ability to bridge gaps between rough and poorly fitting lumber and plywood surfaces with a minimum of pressure from nails. They have viscosities ranging from 150,000 to 400,000 mPa · s (=cP) and can be extruded from a cartridge with a caulking gun (Figs. 4 and 5) to give a bead that does not slump on a vertical surface and can bridge a 7-mm gap. Construction mastics also tolerate a wide range of temperatures and moisture conditions in the air and on bonding surfaces. Adequate bonds can be developed even on very dry, wet, or frozen lumber surfaces (Table 2).

Mastic construction adhesives are not strong enough to fail solid wood in shear, but in plywood-to-lumber constructions they are capable of failing plywood. As a class, mastics do not have a high degree of water resistance, but they can support more than 700 kPa in a water-saturated condition. Since mastics are made from elastomeric materials, they have the ability to yield under stress (Table 2). This can be a distinct advantage where adhesive-bonded assemblies undergo dimensional changes with changes in moisture or where assemblies are subjected to short-term dynamic loadings. Mastics are used extensively in construction of manufactured housing to ensure the units can be transported from factory to building site without incurring significant damage to the finish or structure. See Table 2 for performance capabilities of typical construction and panel adhesives.

The semistructural capability of mastic adhesives imparts strength and stiffness to bonded assemblies beyond that possible with nailed construction. This results in economy of materials. For example, when wood floor systems are nail-glued, the added stiffness and strength resulting from the composite T-beam action permits reductions in the thickness of plywood skins, depth of floor joists, grade of floor joists, and amount of nailing. Furthermore, the floors feel firm under foot, and floor squeaks and nail popping are eliminated (Fig. 4).

Mastic construction adhesives generally meet the highest performance requirements of any adhesive in the mas-
tic class. Therefore, it is necessary to compound these adhesives with higher levels of elastomer and resins than would be required for panel, wallboard, and floor-covering adhesives. A high-strength mastic might contain 30-50% neoprene or styrene—butadienerubber and up to 45% phenolic resin or resin blend. Fillers help to control mastic consistency and reduce cost. Aliphatic, aromatic, and chlorinated solvents are commonly used to dissolve or disperse the solids into a uniform mixture of the desired viscosity. Other additions might include antioxidants, preservatives, stabilizers, cure accelerators, acid scavengers, and solvent release agents.

Mastics are also compounded as panel and wallboard adhesives. They have lower strength, and moisture and creep resistance than construction and subfloor adhesives and should be used only in nonstructural applications where moisture would not be encountered (Table 2). These adhesives are applied from a cartridge with a caulking gun or from a can or pail with a spatula, a trowel, or pressure equipment. They are used to install sheet materials such as decorative wall paneling, gypsum board, plywood, and hardboard to existing walls, studs, or furring strips (Fig. 5). These are good general-purpose adhesives that can be used to install flooring, ceiling, and wall tiles, fixtures, and decorative trim. These adhesives reduce or eliminate mechanical fasteners and the marring effects of nail popping, hammer marks, or exposed nails.

Floor-covering adhesives are available for vinyl, vinyl asbestos, rubber, and asphalt tiles, vinyl rolled goods, and carpeting. Generally, these adhesives are water-resistant enough for interior and exterior use. They can be applied to dry concrete above and below grade as well as to plywood and particle board surfaces. Flooring materials usually are installed when the adhesive is wet or tacky, and as solvents evaporate, the adhesive sets.

Mastics for rubber, vinyl, and cork tiles are rubber-based with water vehicle or resin-based with alcohol. Rigid asphalt and vinyl-asbestos tiles are bonded with asphalt emulsion, asphalt cut backs, and rubber-based systems with water vehicle. The asphalts must be dried before placing tiles, but the rubber-based systems must be wet. Latex or other emulsion systems should not be used with wood parquet or strip flooring because the wood will absorb moisture from the adhesive and swell, causing the floor to buckle. Mastics are also specially formulated for commercial and residential carpeting with impregnated, laminated foam and jute backing. Vinyl foam backing must have a special emulsion adhesive. Mastic adhesives for ceramic tile flooring are solvent and latex types, which are similar to ceramic adhesives used for walls, except the floor adhesives dry faster. The same mastic-type adhesives used for ceramics can be used with natural and simulated brick and stone. Mastics are also used to install vinyl and rubber cove base. They have enough wet grab to resist curling of the rolled cove base.

Contact-bond adhesives are so named because they develop a permanent bond as soon as two adhesive-coated surfaces are brought into contact and pressed together. Once the contact has been made, the surfaces cannot be repositioned. Generally, one or more thin coats of adhesive are applied to both surfaces, allowed to air dry to a tack-free state, and then positioned and pressed together. Roll pressure ensures intimate contact between both surfaces. Setting takes place by loss of solvent through evaporation and diffusion.

Contact-bond adhesives are used in nonstructural applications, particularly where sheet materials are laminated to rigid and flat surfaces. Typical applications in building construction are for bonding high-density laminates to countertops in kitchens and bathrooms and double-laminating gypsum board or paneling to gypsum board. Most contact-bond adhesives are made from neoprene, although styrene—butadiene and natural rubbers are common. A typical neoprene contact is made by mill mixing neoprene with magnesium oxide, antioxidant, and zinc oxide, and then churn mixing with tertiary butyl-phenolic resin and an appropriate mixture of organic solvents to give 15–30% solids. Organic solvents in contacts are slowly being replaced by water systems because of dangers from toxic fumes and fire. Water-based contacts are slower-drying and lack the rapid bond strength development and high ultimate shear strength of the solvent-based contacts.

Poly(vinyl acetate) (PVAc) emulsion adhesives are known as white glues. They have gained wide acceptance among consumers and industrial users because they develop strong bonds quickly at room temperature, are ready to use and easy to apply, and generally require a minimum of skill to develop good bonds. In the building industry, the greatest volume of PVAc adhesive is used to construct manufactured housing. They provide temporary strength

<table>
<thead>
<tr>
<th>Adhesive Base</th>
<th>Shear Strength Wet, kPa</th>
<th>Wet, Redried, kPa</th>
<th>Wet, Lumber, Cured 21°C, kPa</th>
<th>Wet, Lumber, Cured 2°C, kPa</th>
<th>Strength Loss, 6-Mo. Cyclic Relative Humidity, %</th>
<th>Shear Deflection, 2 Wk Dead Load, 345 kPa, mm</th>
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</thead>
<tbody>
<tr>
<td>Neoprene</td>
<td>2282</td>
<td>800</td>
<td>724</td>
<td>972</td>
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<td>Neoprene</td>
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<td>1275</td>
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<td>Styrene—butadiene</td>
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<tr>
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<td>765</td>
<td>1406</td>
<td>1218</td>
<td>4</td>
<td>1.12</td>
</tr>
</tbody>
</table>

*Ref. 12.*
and stiffness to the structure, which helps prevent damage from racking, bending, and shearing stresses that develop while the units are transported over highways. Once the units are on permanent foundations, normal structural loads are carried by mechanical fasteners. PVAc is used in manufactured housing to bond particle board or plywood decking to floor joists, to bond interior paneling or gypsum board to wall studs, and to assemble parts of built-in cabinets. They are used for the same purposes, but to a lesser extent, for on-site building construction.

PVAc emulsions are prepared by the emulsion polymerization process wherein vinyl acetate monomer, alone or in combination with other vinyl monomers, is polymerized in water under precisely controlled temperature and pressure in the presence of suitable emulsifying agents. PVAc is a brittle solid at room temperature; it must have an external plasticizer to lower its glass-transition temperature so a flexible adhesive film can form. When vinyl acetate is copolymerized with ethylene, the latter acts as an internal plasticizer to lower the glass-transition temperature (13). PVAc formulations can be compounded to yield a wide variety of working and strength properties by including varying amounts of plasticizers, emulsion stabilizers, tackifiers, fillers, solvents, wetting agents, and fungicides.

Casein adhesives (4,5,14) develop good structural bonds to certain species of wood, particularly southern pine, Sitka spruce, and Douglas fir. They do not produce high wood failure on high-density hardwoods. However, at the present time, caseins are used in wood panel-to-frame constructions and in the manufacture of hollow- and solid-core flush doors. They have been used structurally in beams, rafters, trusses, box beams, and floor systems. Caseins are suitable for interior structural applications, but they do not have the resistance to moisture to withstand water soaking or exposure to prolonged high-humidity conditions where condensation can occur. For example, rafters laminated with casein should not be used in cow barns where high-humidity conditions, poor ventilation, and frequent condensation occur. As long as the user understands the moisture limitations of caseins in structural applications and follows the manufacturer’s instructions for their preparation and use, they make good structural adhesives for the job site. They can be used at lower temperatures than PVAc, UF, or PRF adhesives. The minimum temperature for casein is 2°C; however, at this temperature, the press time must be longer than at the optimum temperature of 18–24°C. Performance of casein adhesives relative to other adhesives on wood is indicated in Table 1 and Figure 3.

Casein is a proteinaceous material made by precipitation from skim milk under mildly acidic conditions. Its high molecular weight accounts for its colloidal properties and its value as an adhesive. When di- or polyvalent metal ions such as calcium hydroxide are added, the insoluble salt calcium caseinate is formed by cross-linking with the carboxylic acid groups of the different protein molecules. When the bond is formed with the monovalent sodium hydroxide, the adhesive has less water resistance (13). Formaldehyde may also be used for cross-linking amino groups to improve moisture resistance.

**BONDING MECHANISMS**

Adhesion is defined by the ASTM as the state in which two surfaces are held together by interfacial forces, which may consist of valence forces, interlocking action, or both (1). Valence forces are forces of attraction produced by the interactions of atoms, ions, and molecules that exist within and at the surfaces of both adhesive and adherend. These primary and secondary valence forces give rise to what is generally called specific adhesion. These forces are of the same type that produce cohesion of particles within an adhesive. Interlocking action, also called mechanical bonding, means surfaces are held together by adhesive that has penetrated a rough or porous surface structure and anchored itself during solidification. Both valence forces and interlocking action are essential to effective bonding, but the extent to which each occurs with different types of polymers and adherends is generally acknowledged to be uncertain. Bonding to porous surfaces such as wood, paper, and textiles was thought to be primarily mechanical, but now there is evidence supporting bonding by primary valence forces as well. On the other hand, bonding to hard metal surfaces was believed to involve only valence forces, but this is no longer the accepted view. Metal surfaces roughened by etching or made microscopically porous with a layer of oxide are capable of interlocking with adhesive to produce exceptionally strong bonds.

The three types of intermolecular attractive forces that are the most important in adhesive-bond formation are described here. These include dipole-dipole forces, which occur between polar molecules, London forces, which attract nonpolar molecules to each other, and the hydrogen bond, which is a special type of dipole-dipole force (13,15–
Such intermolecular attractive forces have been variously named, but here the generalized van der Waals forces, named after the scientist who postulated their existence in 1873, refers to both dipole-dipole and London forces (15).

Purely covalent bonds (15) are the strongest of chemical bonds. They form when atoms of nonmetals interact by sharing electrons to form a molecule. A purely covalent bond consists of a pair of electrons that are shared by two identical atoms, the simplest being the hydrogen molecule. When two atoms of different elements are joined by a covalent bond, the electron density of the bond is not symmetrically distributed around the two nuclei, which results in a difference in the ability of the two atoms to attract electrons. This causes the molecule to become polarized with a positive and a negative charge. Polarized covalent bonds in molecules give rise to intermolecular attractive forces called dipole-dipole forces (15), where positive and negative poles of molecules attract one another. In a polar molecular substance, the molecules are lined up in positive-negative-positive-negative sequence. The attractions between molecules are considered very important in interfacial adhesion, particularly where polar surfaces such as wood, paper, and glass combine with adhesives containing phenolic and aliphatic hydroxyls.

There are also intermolecular forces that attract nonpolar molecules to each other. These molecules have no permanent dipoles, or dipole-dipole forces, as do the polar molecules. Yet some molecular forces exist, and their existence was postulated by London in 1930. The so-called London forces (15) arise from the motion of electrons, and at any one instant of time, instantaneous dipoles are created by an instantaneous distortion of the electron cloud of a molecule. The instantaneous dipole of one molecule induces matching dipoles in neighboring molecules. These momentary, ever-changing, and synchronized dipoles produce the attractive forces. London forces are not very strong, but the strongest occur between large, complex molecules as in polymers that have large electron clouds that are easily distorted or polarized. Although London forces also exist among polar molecules, they are the only attractive forces existing between nonpolar molecules such as polyethylene, natural rubber, styrene-butadiene, and butyl rubbers (17).

A special type of dipole-dipole force is the hydrogen bond (15). Intermolecular attractions of certain hydrogen-containing compounds are unusually strong. They occur in compounds where hydrogen is covalently bonded to highly electronegative elements of small atomic size. The electronegative element exerts such a strong attraction on the bonding electrons that the hydrogen is left with a significant positive charge. The positively charged hydrogen and the unshared pair of electrons on the electronegative atom of another molecule attract each other to form the strong hydrogen bond. Hydrogen bonding accounts for high solubilities of some compounds containing oxygen and nitrogen in hydrogen-containing solvents such as water. Such forces of attraction between molecules are important in interfacial attraction of adhesive polymers to surfaces such as wood with its polar hydroxyl groups in cellulose.

### WETTING AND SETTING

Two solid surfaces normally will not bond to each other even if they have high surface energies, are polished and flat, and are forced together under high pressure. This is because the surfaces make intimate contact at only a few points; the number of points of contact becomes insignificant relative to the overall area of the joint. Intermolecular forces of attraction are effective only at distances of less than 4 nm. In order for two solid surfaces to be held together, a liquid adhesive must make intimate contact and spread freely over both surfaces. This is called wetting. Molecules of the adhesive must diffuse over or into the surface to make contact with the molecular structure of the surface where intermolecular forces of attraction become effective. As will be discussed later, adherends are quite different in terms of their attractive energies, surface roughness and chemistry, and bulk properties. Surfaces may appear to be smooth and flat, but on microscopic examination, numerous peaks, valleys, and crevices can be seen. Therefore, the liquid adhesive must wet, flow, and penetrate the valleys and crevices while displacing or absorbing air, water, and other impurities bound to the surface. Pressure is normally used to force the liquid to flow over the surfaces while forcing out gas occlusions and other blockages to complete wetting.

Wetting of a surface occurs readily when the contact angle between the edge of a drop of adhesive and the solid surface is low. The contact angle approaches zero when the surface has high attractive energy, the adhesive has an affinity for the substrate, and the surface tension of the adhesive is low. Over 180 years ago, Young described the contact angle of a sessile drop of liquid resting on the plane of a solid surface as it was affected by three surface tensions, as shown in Figure 6. His equation is

\[
\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos \theta
\]

where \(\gamma_{SV}\) is the surface tension at the interface of the liquid and vapor phase, \(\gamma_{SL}\) is the surface tension at the interface of the solid and liquid, \(\gamma_{LV}\) is the surface tension at the interface of the solid and vapor, and \(\theta\) is the contact angle (18). Young’s approach is still used in various thermodynamic and intermolecular considerations of adhesion to surfaces. It is to be noted that the contact angle is not considered a reliable measure of molecular attraction between solid and liquid; it is rather a relationship between

![Figure 6. Contact angle of a drop of liquid on a plane solid surface as influenced by three surface tensions.](image-url)
three phases of contact and gives information on relative strengths of attraction between solid and liquid, and liquid and vapor (19).

When the viscosity of a liquid film is increased, or it is solidified to the point where the film effectively resists shear and other forces tending to separate the surfaces, then the surfaces are effectively bonded. An adhesive film changes from the liquid to solid phase essentially by one of three mechanisms: (1) solvent permeation or evaporation from the film as in water-based adhesives, (2) polymerization of the liquid film as in resorcinolic resins, or (3) cooling of a hot film as in hot-melt adhesives. The mechanisms by which an adhesive joint is made strong or weak are extremely complex. In general, though, the adhesive joint must have sufficient deformability to reduce the buildup of stresses that occur during the solidification process and while the joint is in service (18).

**BONDING SURFACES AND THEIR PREPARATION**

The surfaces of building materials, particularly wood surfaces, are highly contaminated and replete with minute cracks and crevices. These surface conditions cause gas pockets and blockages that prevent complete wetting by an adhesive. They are also concentration points for stresses. Even though construction adhesives are capable of molecular bonding, the sources for interfacial blockage seem so numerous as to reduce seriously the opportunities for molecular bonding. One of the greatest contributions to joint strength can be made by preparing clean and smooth surfaces.

To be useful in building construction, adhesives must bond to several types of materials, including wood, metals, plastics, concrete, brick, glass, rubber, and ceramics. The surface and bulk properties of each material differ drastically, and these properties must be understood so their surfaces can be properly prepared for effective bonding.

Wood is the most complex bonding surface. It is heterogeneous and highly variable in terms of its surface chemistry and roughness as well as its bulk properties, including density, dimensional stability, porosity, and moisture content (20). These properties are sharply different not only from species to species, but from tree to tree within a species. Furthermore, when a piece of wood is cut from a tree, three surfaces distinctly different in porosity and dimensional stability are presented, depending on whether the cut was made radially, tangentially, or transversely to the grain. Each surface can have a profound influence on the effectiveness of adhesive bonds.

Chemically, wood is composed primarily of polysaccharides, lignin, and extractives (2). Cellulose, the principal polysaccharide, is a high molecular weight linear polymer that makes up about 50% of the cell walls by weight. Lignin is a large complex polymer that makes up 16-33% of the wood. Extractives are the various solvent-extractable compounds that make up 5-30% of the wood's weight. Cellulose makes wood a highly polar surface, but lignin is much less polar (20). Extractives vary in amount and chemical nature and can dramatically affect the bondability of wood. Nonpolar extractives such as terpenes and fatty acids may inhibit bonding, whereas others may be present in such quantities that they cannot be dissolved and dispersed by the adhesive (20). The wood's surface can be chemically modified further by accumulating extractives and debris, overheating, and burnishing, all of which affect the degree to which the surface can be wetted by an adhesive.

Wood contains moisture that it gains or loses with changes in ambient moisture. The amount of moisture affects the depth of adhesive penetration and curing time, particularly with aqueous adhesives. The proper amount, depending on the type of adhesive and whether it is cured with or without heat, is critical to the development of sound bonds.

Wood shrinks and swells with changes in moisture. If such changes occur while the adhesive is setting or after, severe stresses develop, which in some instances can lead to failure. Dense woods develop higher stresses in bondlines with moisture-induced dimensional changes, so denser woods require stronger adhesive bonds.

Wood surfaces must be free of irregularities for bonding, but they are simple to prepare. Cutting the wood to shape, drying, and surfacing just before bonding ensures dry, smooth, and clean surfaces.

Plastics are relatively homogeneous in physical structure and chemical composition. Plastics have no microstructure, voids, or molecular orientation, and their physical properties are essentially the same in all directions. Thermoplastics are not as strong and stiff as cross-linking thermsets.

Surfaces of plastics, particularly plastics from nonpolar monomers, have low energy. This makes adhesives more difficult to spread. When melted, however, they readily wet and flow. Preparation of high-energy plastics such as fiber glass laminates based on epoxy or polyester resins requires only that surfaces be dry, clean, and of solid integrity. This is usually accomplished with abrading and solvent cleaning. Low-energy surfaces such as fluorocarbons and polyolefins require etching in solvent or acid solutions to increase surface energies. Some plastics may be bonded with the same plastic material dissolved in a solvent so that little or no surface preparation is required.

Metals are crystalline structures of metallic elements held together by very strong atomic forces of attraction. When different metallic elements are mixed together in various proportions, alloys that have their own distinct physical and chemical properties are formed. Metals have no microstructure. They are very dense, but alloys are usually of lower density. Normally, adhesive bonds to metals fail cohesively because the metals are so strong relative to the adhesive.

Metals have very-high-energy surfaces, but careful and thorough surface preparations are absolutely necessary for bonds to develop optimum strength, particularly when the bonds will be exposed to severe service environments. Weak surface layers, organic contaminants, oxides, absorbed gases, and moisture, which reduce surface energy or prevent intimate contact with solid metal, must be completely removed before bonding. Specific cleaning procedures are usually required for each type of metal. Generally, physical and chemical altering of the surface increases
energy level. Chemical altering, not to be confused with chemical cleaning, means the chemical reacts with some component of the substrate, which results in metal loss or formation of an oxide. Surface preparation may include one or more procedures, such as solvent cleaning (liquid or vapor), alkaline cleaning, abrading, chemical treatment washing with water, drying, and perhaps priming with dilute solutions of an adhesive to prevent further contamination.

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See also Sealants

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