SOPRONI EGYETEM

FAIPARI MÉRNÖKI ÉS KREATÍVIPARI KAR

# AZ ALKALMAZOTT MŰVÉSZET LÉTMÓDJAI ÉS A KREATÍV IPAR KIHÍVÁSAI NAPJAINKBAN

Faipari Mérnöki és Kreatívipari Kar Tudományos Kiadványa

**Szerkesztette: Márfai Molnár László és Pásztory Zoltán**

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# Tartalom

## Műszaki szekció



## Foregin languages section

# Advancements in Sustainable Wood Furniture: A Comprehensive Review of Bonding Techniques and Adhesives

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**Abstract**
The population is increasing worldwide and it is reasonable the demand on furnishing to be provided by sustainable wood-based furniture. Adhesives are used at every stage in the furniture production with the purpose to bond the wood-based materials with themselves or other materilas. The different methods of wood bonding, the environment friendly adhesives used, the preparations of the adhesives, the sustainable technology related to wood and adhesive application, the wood surface and adhesive interactions, the physical and mechanical properties of adhesive bonded wood joints, the related standards, potential application areas and ultimately prospects are reported and discussed in this review.

Keywords: sustainable wood furniture, wood bonding, environment friendly adhesives, sustainable wood bonding

## 1. Introduction

Wood material, which has been used as a building material since ancient times, has never lost its importance. Especially the fact that wood comes from renewable resources, and it is biodegradable, and cannot be replaced or partially replaced by another material increases the importance of using it. Wood material, whith its important place in human life, has a large range of uses [1]. The decrease of world's forest areas, associated with a simultaneous rapid increase of the population resulted an increasing consumption of forest products per capita which made it necessary to make better use of forests. Especially with the presence of synthetic adhesives and their participation in production, it has directed to obtain wood-based boards that have typical woody characteristics but do not work like wood materials by evaluating forest residues, some plant stems and plant fibers. As a result, such as particleboard, fiberboard and plywood boards etc. wood-based boards were produced. These plates have been used in many indoor areas by subjecting to various processes [2] .

Today, the bonding process applied to wood material is an important factor in terms of increased popularity in the forestry-based industry and effective use of our timber sources. General uses of adhesives are in the manufacture of building materiels with the inclusion of solid wood, particleboard, oriented particleboard, plywood, structural composite materials, frames, windows, doors, and factory-laminated wood products. At the same time, adhesives are used in the assemblage of cabinets and furniture, production of processed wood products, and structures of commercial buildings and residences. Adhesion of wood material with adhesives; the wetting ability of the surface depends on many factors such as penetration, polymerization, reaction, porosity, pH, degree of moisture, chemical interactions, extractive substances, free surface energy, surface area and the wood surface (tangential, longitudinal and radial) that will contact the adhesive has been specified [3-5].

The bonding process that controls the adhesive's capability to holding two wood surfaces together includes both mechanical and chemical elements. Due to significance of adhesives bonding, many important study activities have been carried out over the last decade. E.g.the impact of diverse physical and chemical property of adhesive and attached was widely revisaled by Dunky and Niemz [6]. For the manufacture of big efficiency wood composites, a basic understand- ing of property of related materiels is necessary. Macroscopic studies are conducted to appraise the mechanic performance of adhesive bond in wood material (Figures 1A and B). This is significant to examine and appraise the formation of bond and relationship of other components to each other on a microscopic scale, based on the relationship between stress transfer and flow logic across the adhesive bond (Figure 1C and D). As stated by Marra [7], the primary components in the wood glue bond are glue, sticky wood and interphase in which both factors are mixing with every one (Figure 1C).

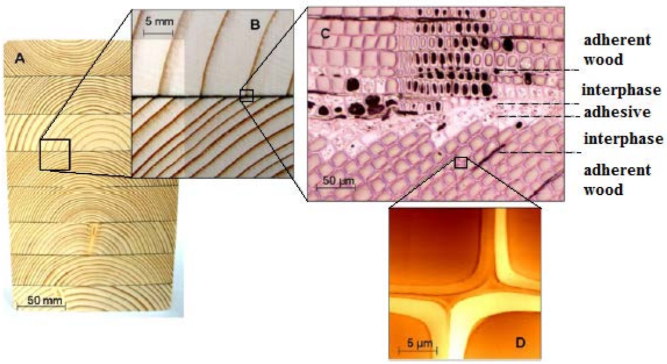


Figure 1: Adhesive bond scales. (A) and (B) Macroscopic measure (C) microscopic measure, (D) atomic strength microscope figure; wooden cell walls with specified binding sites. Reprinted with permissions from Elsevier[8]. Copyright, Elsevier, 2013.

The strongest, water-resistant bonds with most adhesives available on the market developed when the glue penetrates deeply into cell cavities and leaks into cell walls. The separation of the wood material from adhesive bonding and bond force are equivalent to the force of solid wood material, which is, even close to the best bonding standards. It is well-known that the attractive forces between wood molecules and the adhesive contributes greatly to the adhesion of wood. While covalent bonds forming, which is an important chemical bond among the wood materials and adhesive, may seem like appropriate in some adhesive materials, there is also proof that they promote to force the adhesive bonds. In addition, Van der Waal bonds, dipole-dipole strengths, and hydrogen bonding, which are intermolecular attractive forces, often occur and must be quite significant for adhesion forces, especially given the higher bonding region of the wood material with adhesive. On wood surfaces like teak, wood extractors can directly affect the adhesives connections, causing a chemically low limit impact and low adhesion force. To achieve the most efficient bonding strength, surface of the wood materials should be "wetted" with liquid adhesive, it should flow over the wood and penetrate to the wood. The adhesive molecules should be in direct contact with the wood molecules to ensure the best mechanic locking and interaction between the wood material and the adhesive.

Wooden surfaces may be appeared as well-formed and smooth, but microscopic inspections could also reveal for cracks, depressions, and peaks filled with the jagged fibers and other wrecks. It also said that the surface could have air pockets and clogs that may prevent the adhesive material from being completely wet and create stress concentrations when the adhesive materials harden. Moreover, the different properties of wood (such as extractants, grain angle and natural imperfections) are very much different and chemistry causes surface energies and roughness [9, 10]. Additionally, wetting or coating these diverse surfaces, adhesives must be in liquid forms and liquid could be sufficient to flux in microscopic crevices or capillary construction of wood materials. The compression treatment forces the liquid adhesive to flow over the surfaces and increases wetting by displacing air clogs and acting on the solid wood. The adhesive bond started to be formed when the adhesive hardens. However, it may take hours or even days to achive the full effects. The implemented adhesive material alterations from fluid to solid in one or more of stages (such as three): (a) solver bereavement from the adhesive by means of vaporization and diffusing in wood, (b) refrigeration of melted adhesive or (c) associated structures resistant to softening in cross-over chemical polymerization warming. Since water is a comprehensive carrier for many wood adhesives, hence water loss and chemical polymerizations usually happen at the same time [11]. In this study, it is aimed to make a comprehensive investigation considering the effect of wood adhesives on furniture products; thanks to the study, a review was made to include useful information in the literature to help the future studies.

## 2. Wood species used for Furniture Manufacturing

Wood material is of a great importance in the furniture industry. The raw materials used in this sector in many ways. Wood material, which forms the basis of these raw materials, is mainly due to the fact that it meets many requirements in human life too [12]. Wood is one of the highly used and preferred furniture manufacturing materiels because it is a renewable and peripherally friendly material [13, 14]. When we look around the world, widely used materials in furniture and cabinet manufacturing; there are diversified tree species called non tropical and tropical. Oak (*Querqus alba*), cherry (*Prunus serotina*), ash (*Fraxinus alba*), beech (*Fagus orientalis*) maple (*Acer rubrum*), pine (*Pinus strobus*) and black walnut (*Juglans nigra*) are the temperate species mostly used while ramine (*Gonystylusbancanu*s), teak tree (*Tektona grandis*), nhayot (*Sapotaceae*), balau (*Shorea ssp*.), chengal (*Neobalanocarpashemii*) are some of the examples for tropical tree types that are commonly used as raw materials for furniture production. One of the most widely used trees in furniture manufacture is the oak tree.  [15-17]. It is a heavy, hard, and open-grained deciduous tree class that grows widely in Canada, Europe, and the United States. The dimensional stability determinations of wood have low bending and shrinkage rate. Quartile reaped oak besides shows evident of ray spots enhancing the aesthetic charming [15] .

Pine is a softwood category types of trees which is grown up in diverse areas around the globe [12]. The wood is simple to work with and having a smooth texture, hence it gives good results to the products. In addition, it has some durability against pulling, distension, and bending. Pine tree is also mostly known as having a broad grain pattern and being light yellow appearances in color. The walnut tree is another densed hardwood species with a tight grain and durability. Due to its superior durability and brightness characteristics, it is also known as a tree type that is frequently preferred as floor coverings and cabinet making materials. It has two different types: white walnut and black walnut. Since walnut is an expensive types of tree, its timber is used as a junk wood and is not wasted. [16]. Cherry is also considered as hardwood with a reddish brown color appearances [18]-[16]. Cherry is resistant to bending and shrinkage. Therefore, it is used as a prominent raw materiel for the furniture productions.

Beech is a pale colored, heavy, hardwood types of trees. Since it has strict, wider, and thinner medullary rays, it is generally compared to maple appearances. Beech wood is extremely resistant to shock and stains as well. Even though it is a durable and hard wood type materials, but its strength level is not very good enough compared to some other hardwoods[16].

Maple is a medium to hard wood material possessing very light color. It has fine texture and smooth grain also popular for its resistance to impacts. In addition, it has high strength, can be dyed easy, and is more steady than several another types because due to its good smooth shape of grains [16]. The color of the ash tree ranges from creamy, light white to brown. Due to its shock resistance properties, high flexibility and strength to division, usually ash wood is used in the production of bent wood materials, baseball bats, device handles, and tennis rackets [16]-[17]. Ramin tree, also known as gonystylus, is also a hardwood types found in Southeast Asian countries, like Brunei, Malaysia, Philippines, Indonesia, Singapore and Papua New Guinea. Ramin is a slow-growing, medium-sized tree, which is usually grown in bog forests. It has bright white heartwood and yellow sapwood. Compared to other hardwoods, it is lighter and harder materials. It has a smooth grain and good texture too [15].Tropical hardwood trees like teak are indigenous to South and Southeast Asia. It has gradually spread to other subtropical and tropical areas in Australia, Africa, and Latin America as well. It offers strong, resilient wood that is resistant to decay and moisture and has many extractive elements. Additionally, teak is resistant to rotting, cracking, and warping. Teak has been used in furniture for ages because to its strength and longevity. Teak is water-repellent because to its increased oil content, making it resistant to pest incursions as well [19, 20]. Chengal is a tropical hardwood available in Southeast Asian countries. This wood is hard, strong, and resistant to damp. Chengal is widely used in fences, fish tank construction and another outer space uses [20]-[21]. Nyatoh is a reddy tropical hardwood grown in Southeast Asia, primarily in Philippines, Indonesia, and Malaysia. Nyatoh is simple to work with good polish and stain. It has a texture like the cherry tree. The wood of the Nyatoh tree is red or umber in color [20]-[21]-[22]. The balau tree is another tropical hard wood obtained from Southeast Asia regions. It is a highly intensive and tight-grained tree with rich tropic resin and oils. It has a good, and smooth tissue. The wood of balau is resistant to the moisture, rot, and mildew having superior strength. It has also better resistance to force and air conditions. For these reasons, it is a preferred type of wood used in heavy-duty furniture, shipbuilding, and heavy structures. [20].

Additionally, the afore types of solid wood, composite panels like medium density fiberboard (MDF) particleboard are extensively used like the substrate for fine veneers to produce cabinetry and modular type furniture units. The mechanical and physical properties of most of the mentioned wood, wood-based materiels have been widely researched and registered in the literary texts. As such materials are well-recognized, surface standard plays a significant act in their completion and bonding properties.

## 3. Moisture content of wood to be bonded

When the glue is cured in a hot press, moisture control is crucial because at temperatures about 100°C, surplus moisture within the material transforms into high pressure vapor [11].Several adhesives require certain moisture content to penetrate in wood. Also, polyurethanes and isocyanates are low perform and sensitive preferable at higher moisture contents only.

Table 3. Recommended wood moisture content values by the time of bonding [23].

| Area of use | The possible recourse | The wood to be installed retains moisture, % |
|---|---|---|
| **Outdoor** | | 12-19 |
| **Indoor** | In an unheated building | 12-16 |
| | In a heated building with a temperature between 12- 21$^{o}$C | 9-13 |
| | In a heated building with a temperature above 21$^{o}$C | 6-10 |

### 3.1. Effect of Dimensional Changes and Moisture Content on the adhesive bond

Water is a naturally occurring essential component in trees, and when the wood is harvested, the moisture level of the wood material affects the qualities of the wood and, therefore, the bonding strength of the adhesive. According to study findings, wood often absorbs 25% to 30% more moisture than its dry weight [11]. The wood reaches its fiber saturation point when it can no longer retain any more water. As it dries, wood below the fiber saturation threshold starts to harden and contract. If the moisture content is higher than the saturation level, the extra water fills the lumens, adding weight to the wood. As wood is used, it will expand and contract as it takes in and releases moisture from the environment. The typical moisture content of wood in an indoor environment is between 5% and 12% [11, 24].

When the moisture level in wood varies below the fibre saturation threshold, dimensional changes take place. Shrinkage and swelling are caused by moisture gain and loss, respectively. These dimensional changes are anisotropic, meaning they vary in the axial, radial, and tangential directions. Roughly 0.4 percent, 4 percent, and 8 percent, respectively, are the average shrinkage values. Volume loss is around 12%, however there are significant differences across species. These numbers are provided as a percentage of green dimensions and correspond to transformations from the green to oven-dry state. The cell wall structure is primarily responsible for the differential shrinking and swelling in various development orientations. The orientation of microfibrils in the layers of the secondary cell wall can be used to explain the differences between axial and the two lateral (radial and tangential) directions (bond strength also varies with these 3 directions; this needs to be mentioned), but the causes of the differences between radial and tangential directions are not well understood.

The three fundamental orientations in wood experience different dimensional changes as a result of shrinkage and swelling. Less than 1% of the longitudinal dimensions (along the grain direction) vary. The largest dimensional change is the tangential one, which typically ranges from 6 to 12 percent. The radial change is often only about half that of the tangential one [11].

When bonded assemblies are subject to shrinking and swelling, stresses appear in the bond line, which reduve its strength and may even cause the fail of the bond. The stresses are higher if differently shrinking /swelling surfaces are bonded together like tangential surface/radial surface, early wood/late wood, sapwood/heartwood. The highest stresses occur, when only one element of the bonded assembly changes its moisture content. Most problems in adhesive bonding of wood, derive from the dimensional changes due to moisture changes of bonded pieces [25]. Stresses due to moisture variation can be minimized by bonding the wooden parts with such a moisture content that can expected during the service of the bonded furniture [23], with coherent grain direction possibly of a radial section. The variation in size due to moisture content is different, depending from wood species also[11]. Moisture in the wood being related to the water of the adhesive material will widely affect the hardening, flux, wetting and penetration of waterborne wood adhesive materials. Generally, optimal adhesive penetration and adhesion can expect when the moisture content of the wood is thereamong 6% and 14%.

Formulations need to be used out of this MC this range. Water based adhesives tend to dry so quick if applied on a wood surface below 6% moisture content, that adhesion can not be achieved. The wood absorbs the water of the adhesive so rapidly that even under high pressure, the adhesive can not penetrate the wood tissue. The wood becomes so dry under 3% moisture content that it temporarily resists wetting. On the other hand, too, moist wood is also hard to bond with ordinary water-based adhesives.

### 3.2. Effect of wood Porosity and Density on the adhesive bond

Surface features are not the only factor controlling the adhesion in wood. The strength of the bond is strongly influenced by physical features of wood, especially like wood moisture content, strength and density of the wood, swelling-shrinkage, and porosity properties. The density of solid wood cell walls is around 1.500 $kg/m^3$ depending on different tree type. Also, the density factor changes widely among tree species within the types and among latewood and earlywood growth with respect to the volume of voids and thickness of the cell walls. High-density wood has small lumens and thick walls, while low-density wood has larger lumen and thin walls. Therefore, higher density wood includes more material per unit and can bear more load. Adherently bonded timber structures characteristically increase the wood density and durability by 700 to 800 $kg/m^3$ (12% moisture content). Under this level, adhesion material is usually simple, and the durability of the wood limits the assembly strength. Wood failures demonstrate the percentage of total fracture zone that is wood instead of the glue. High wood fracture is generally opt for, as the load design valuation can be depending common wood durability and will not decrease due to the quality of the bond line. [11].

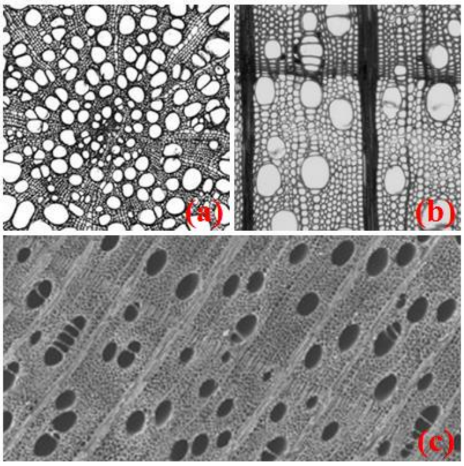


Figure 2: Cross sections of three dissimilar species of woods showing the openness of the cellular structure. Linden wood (a) falls under the category of "easily adhered", soft maple(b) "adheres well" and hard maple(c) "bonds satisfactorily" [26, 27].

*Easier glued wood has a larger lumen volume and low cell wall capacity for adhesive penetration. Compared to linden wood and hard maple, the lower density of linden wood weakens the wood and therefore less power can be applied to the bond line[11]. Adapted with permission from Elsevier.[26] [27] Copyright, Elsevier 2009 and 2020.*

High density wood is much more difficult to bond for various reasons. Due to their smaller diameter lumens and thicker cell walls, adhesive materials do not penetrate in the woods easily and restrict mechanic locking to fewer than two cells in depth. Harder, stronger, high-density wood materials require much more pressure to achieve more powerful bond between adhesive and wood surfaces. Higher concentrations of extractive substances that can inhibit the hardening of adhesives are widespread in high-density varieties, especially native importing tropic hardwoods and oaks. High density woods let high loads to be placed on the bond line because these timbers are strong. Finally, when comparing low-density woods to high-density woods, they tend to shrink and swell more with changes in moisture content. Density is useful for predicting links of many various tree species.

Table 4. Tree species and adhesion abilities

| **Low density** (Up to 545 kg / m3) [a] | **Medium density** (Between 555-745 kg / m3) [b] | **High density** (More than 755 kg / m3) [c] |
|---|---|---|
| Spruce | Larch | Acacia |
| Balsa | Yew | Teak |
| Fir | Birch (vine, fluffy, black, and yellow) | Hornbeam |
| Cottonwood | Chestnut | Iron wood |
| Juniper | Beech (Eastern, European) | Rosewood |
| Poplar | Elm | Pistachio wood |
| Magnolia | Pear | Iron birch |
| Willow | Oak | Buxus sempervirens |
| Aspen | Maple | |
| Bamboo | Hazelnut | |
| Alder (white and black) | Walnut | |
| Walnut (white, gray, and Manchu) | Sycamore | |
| Amur velvet | Mountain ash | |
| Linden | Persimmon | |
| Cedar | Apple | |
| Pine | Ash (ordinary and, Manchurian) | |

[a]It shows very easy adhesion with adhesives of various properties and under various bonding conditions.
[b]Moderate adhesion with various adhesives and under various bonding conditions.
[c]It shows difficult adhesion with various adhesives and under various bonding conditions.

## 4. Bonding of wood for furniture

Adhesives are playing a significant factor in the improving and efficient use of wood in the furniture and forestry product industiesy. The different adhesives are the most frequently used materials in wooden products. If we control dissimilar wood productions (like OSB, plywood, particle board, structural frame-windows, MDF, and wooden architectonic frames and doors) then glues are significant to protect their constructions. Furthermore, significant amount of adhesive is used in kitchen countertops, floor coverings, wall tiles, and ceiling. They are also used in non-structural practices, accessories, and car upholstery. Glues are also known to increase the stiffness and strength of composite panels. At the same time, the adherence of the glue depends on the wood material and the glue chain.

The bonding performance of the adhesive between wooden elements is considerably impressed by rating of penetration of the adhesive material in the porous network of leashed cells. In order to correlate with bonding performance, investigation on bonding performance has become prominent beside the microscopic inspection and related technics. Diversity in wood species, various adhesive application, curing processes, numerous adhesive chemistries, and formulations make the research comprehensive. After all, instauration bonding issues and planing recent adhesive systems and methods can be catalyzed by comprehending basics of adhesive penetration [28]. Interphase area is an irregular stratum like as shown in Figure 3. It is assumed that the geometry of the interface affects the bonding performance. Sticky parts subjected to load must be capable to transfer the tension from one component to another via interphase area. Constructive structure, volume, and shape of the interphase generally determines the size of the stress concentrations and having an important effect on the performance of bond [28].

### 4.1. Penetration of adhesives in wood

Much research has been conducted on the penetration of adhesives in wood. Adhesive penetration in wood can be divided into two categories: one is major and another one is cell wall penetration types. Major penetration is caused by inflow of fluid resin in porous structures of wood materials, usually refill the cell lumens. Gross penetration is hydrodynamic flux and capillary effect. Cell wall penetration consist of when the resin radiates in the cell wall or fluids in microcracks. In wood, minimum strength of hydrodynamic flux is a longitudinally way through lumens into long and thin tracheids of softwood or hardwood containers.

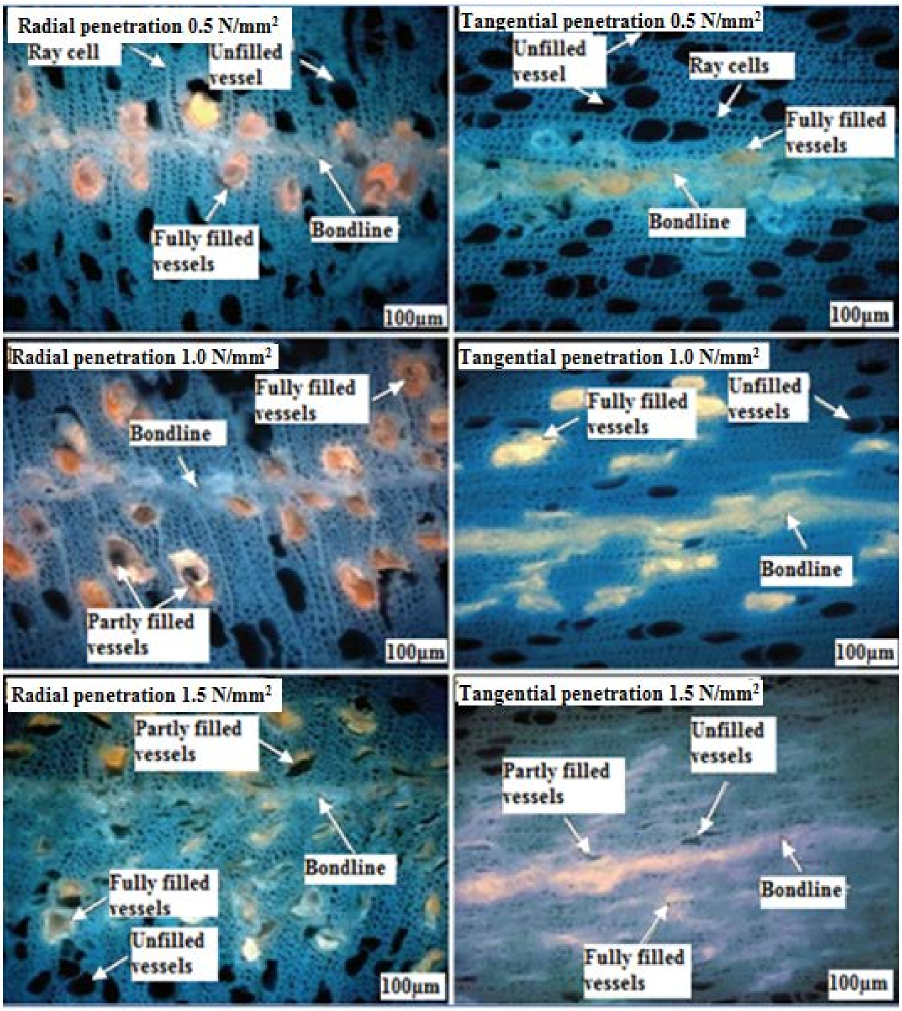


Figure 3: Sample of epi-fluorescence microphotograph in which UF resin penetrates into poplar wood applied during the press cycle under three different pressures: 1.5 N / $mm^2$ and, 0.5 N / $mm^2$, 1 N / $mm^2$ for tangential and radial penetration. Reprinted with permissions from BioRES[29]. Copyright, BioRES, 2016.

Type of cell commands the penetration of adhesives in hardwood, as the containers are attached end-to-end with perforated panels and there is no dimple wall appeared. Adhesive penetration affects the connection between link 4 and 7 in reference [7]. Totality possible adherence mechanisms are affected by penetration. The notion of mechanic interlocking is clearly attached to the penetration of adhesive stage beylow the outer wood surface. Also, associated bonding strength resulting from covalent bonding and the formation of subaltern chemical bonds is directly connected to the surface region of the cell wall and adhesive. In reference [7], a link-chain analogy for an adhesive bond was explained as shown in Figure 4 which is proposed and concluded that bond is merely as fine as the doughiest link in chain. Adhesive's penetration performs a vital act in this analogy. Junction1 is pristine adhesive grade that is not affected by the substrates. The links 2 and 3 symbolize the adhesive limit sheet that hardens below the effect of substrates, and which is also homogeneous. The junction 4 and 5 symbolizes the interface thereamong the substrates and limits layer and "adhesion" form mechanisms. This mechanism may be mechanic clamping, covalent bonding or secondary chemical bonds owing to electrostatic strengths. Link 6 and 7 symbolizes wood cells remodifying by wood surface preparation process or bonding period itself.

Proper penetration management is essential for successful wood bonding because it ensures that there is just the right amount of penetration to provide a satisfactory adhesive-wood interaction without creating an adhesive-starved junction. To penetrate wood, a substance may either migrate within the cell wall or flow into lumina and fractures. This study will use the terms penetration and diffusion to help readers differentiate between these two essentially distinct processes. Grain angle, density, wood species, and wood surface preparation all affect how much light penetrates into lumina. The grain angle is crucial: Adhesive penetration is restricted when bonding to the edge or face of wood pieces if the surface is precisely parallel to the grain. Although it is rare to be perfectly parallel to grain (see Figure 4 1G for an extreme example), adhesive may nevertheless flow into several open lumina, resulting in deeper penetration than when it is parallel to grain. Through mechanical interlocks, this movement into lumina distant from the surface may create stronger bindings, but it also removes adhesive from the bondline. A "starved bond" results from enough adhesive penetrating the wood and leaving inadequate adhesive at the bondline. For the joints in the butt, scarf, and fingers, excessive flow into lumina may be a serious issue. On veneers, excessive flow may result in bleed-through, particularly if those veneers include significant vascular features (Christiansen and Knaebe 2004). It depends on the species and is often easier for earlywood to enter wood than latewood, particularly in softwoods and for vessel components in hardwoods. For instance, due to the wider median cell lumina of the earlywood cells in pine, adhesives more easily penetrate a pine board, such as a loblolly pine (Pinus taeda), than they can a hard maple board, such as a sugar maple (Acer saccharum). Heartwood may contain aspirated pits and greater extractives, which reduce its porosity and make penetration into it more challenging than into sapwood. Numerous adhesive tests are conducted on sapwood; thus, if the wood surface is heartwood, bonding of a wood species may be more challenging than the literature suggests. The glue must moisten (intimately cover) the wood surface for penetration to occur. Because the adhesive better wets newly prepared surfaces via mechanical planing or manual sanding, they are better for bonding (River et al. 1991). However, since the boundary layer is mechanically weak, abrasive planing often smashes surface cells, resulting in weak bond strength. Some types of wood, like teak

(Tectonia grandis), are difficult to bind because their oily extractives prevent the 14 adhesives from making contact with the wood, creating a chemically weak boundary layer. Oily wood's surfaces may be cleaned with solvent to strengthen the connection. A wood lacking these oils, such Afrormosia (Afrormosia elata, also referred to as "poor man's teak"), is more readily bonded. Therefore, bonding issues may be decreased by correctly identifying and comprehending the wood that has to be bonded.

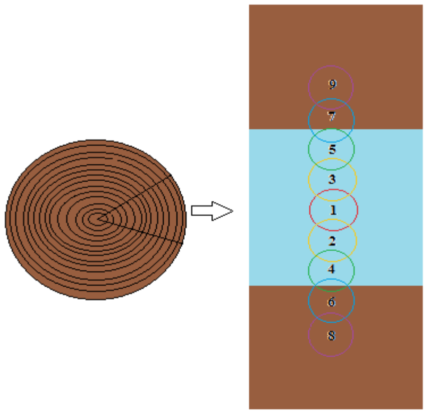


Figure 4: Link chain analogy for adhesive bond in wood

For instance, turning the peeling of coating consequences breakage that starts in radial-longitudinal layer. Cells in area may be poored and therefore rise the potency for bond rupture. Flaking-sanding, planning, and another mechanic surface arrangements techniques are also responsible for smaller breaks in wood cells. Lastly, links 8 and 9 reflects the unmixed wood. Agreeably, planed adhesive bond will have the sub-structural unity boundary found in junctions 8 and 9.

**4.2. Cohesion and adhesion during bond formation**

Adherence is the leaning of dissimilar grains or surfaces to bond the materials together. Internal forces thereamong molecules are liable for adherences like distributor bonding, chemical bonding, and widespread bonding. This inters molecular strengths can create accretive bonds and brought on exact resulting mechanical impacts. The word harmony means "sticking or staying together". The cohesive strength is called the leaning of likewise molecules to stick together. There are mutual attractions within them. The cohesive strength caused by structure and shape of the molecules makes the dispersion of orbiting electrons non-uniform when the molecules approach each other and creates electrical charm that can protect a microscopic construction like as water droplets. The chain link analogy for cohesion and adhesion is shown in Figure 5. The definition of adhesive and cohesion refers to the forces that hold the adhesive together with the substrate (adhesion) and with the adhesive (cohesion)[30].These strengths are further demonstrated as follow:

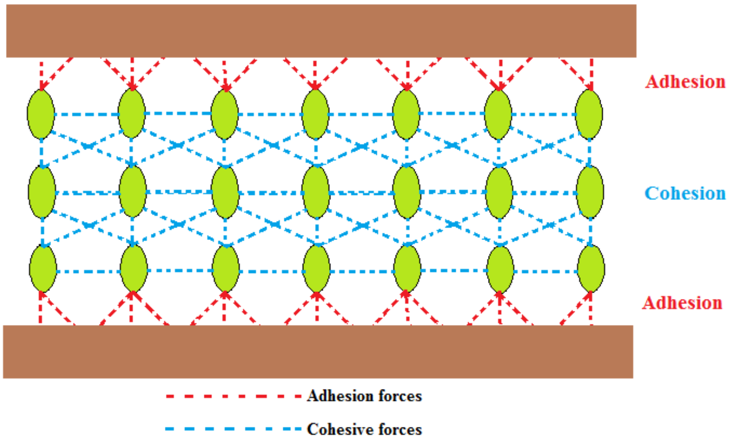


Figure 5: Chain links for cohesion and adhesion.

### 4.3. Wettability of the wood surface with adhesives

The sense of "wetting" is everytime misinterpretated, as there are severel statements for the definitions of wetting in the literature. There are few examples provided below:

- "Liquids that spread over a solid surface, the adhesion of these liquids to the solid can explain the wetting properties of the solid [31]."
- "Good wetting will help spreading and penetratations better, but not the same, good wetting is also generating zero contact angle [32]."
- "Wetting is when a liquid spreads over a solid surface and is firmly contacts with the solid surface [33]."
- "If molecules at the interfaces of liquid and solid are attracted more strongly by the solid than by the liquid, the liquid wets the surfaces and tends to creep outward across the surfaces. On an unwetted surface, the liquid molecules still attract each other [34, 35] .

"In reference [36], wetting is a commonly used term to describe what happens when a liquid comes into contact with a solid surface."

Since few events happen when this connection is made, it appears correct to suppose that the term soak is used as the most general meaning. Setting this notion in orderly, the period of wetting is used to contain the courses of penetration, spread, and adhesion. All of these situations certainly clarify the dissimilar kinds of soak. Adhesion arrangement as a sub-assembly of wetting is a conclusion of surface energy. This is only defined as the soak requirements prevailing pending "face to face contact" [37].

This phenomenon also could be explained using the surface energies approximation. While the word adherent refers to an interrace fact, in practice the two materiels are linked. The wetting fact is shown in Figure 6. "Penetration" refers to the wetting provisions when a fluid moves upward throughout the walls of a solid material and "spreading" refers to the soak provisions that happen when a fluid flows on a surface. This theory is clarifyed in Figure 6. As stated in reference [38], soak is clarifyed like a process that takes place when a fluid comes in contact with a solid surface. Generally, the third phase during adhesion is the air (gas phase) of the surrounding environment. Therefore, there are three stages: fluid, gas, and solid.

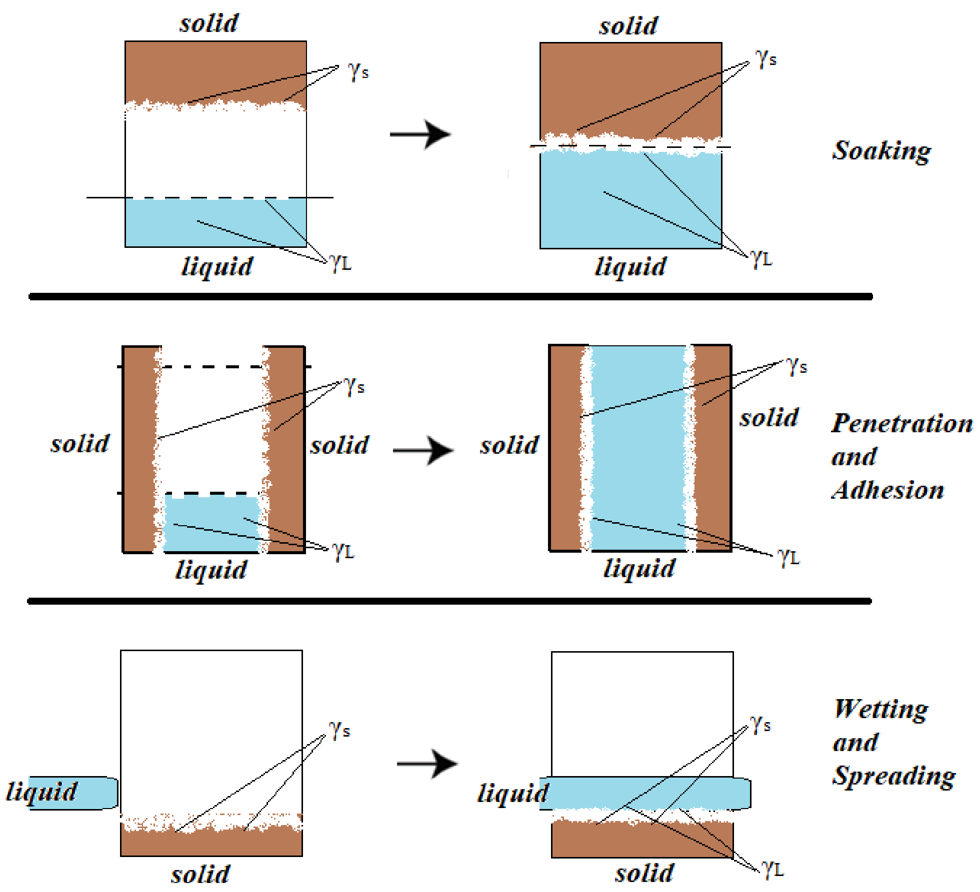


Figure 6: Explaining the wetting

### 4.4. Surface tension of the solid

The characteristics of a drop of fluid being in contact with a solid surface are an appropriate expression of wetting capability. Basic characteristics of the contact angle are described in Figure 7.

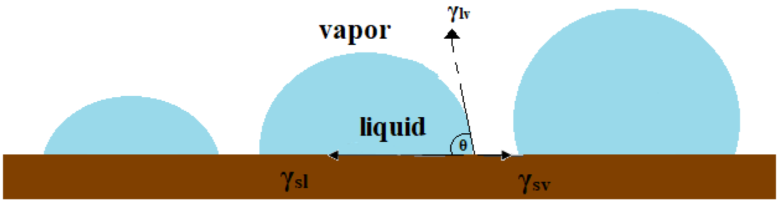


Figure 7: contact angle "θ" of a liquid on a solid surface (Seda, 2022)

Three kinds of surface tensions are supposed to be present:

- $\gamma_{lv}$, at the interface of vapor and liquid phase
- $\gamma_{sl}$, at the interface of liquid and solid phase
- $\gamma_{sv}$, at the interface of vapor and solid phase

The contact angle is inverse proportionate with the wetting capacity, while the cosine of "θ" is a visible direct measure. The surface tension of solid wood surfaces (also known as surface-free energy) affects its wettability and thus the adhesion of various adhesives. Increasing the surface tension of wood and/or at the same time decreasing the surface tension of the applied liquid are the ways to improve wetting and adhesion. Surface tension is not directly measurable, it is usually calculated from the Young Dupré equation, using the measured value of the contact angle (Zenkiewicz, 2007). Young (1805) stated that for a homogenous and ideally smooth surface, the contact angle of a wetting drop is described by the following equation:

$$cos\theta = \frac{\gamma sv - \gamma sl}{\gamma lv} \quad \text{Eq. 1}$$

Where $\gamma_{sv}$ is the surface tension at the solid-vapour interface, $\gamma_{sl}$ is the surface tension at the solid- liquid interface and $\gamma_{lv}$ is the surface tension at the liquid-vapour interface. The contact angle $\theta$ is formed between a drop of liquid (*a demi sphere*) placed on a solid surface and the tangential drawn to the drop in the point of intersection. Contact angles greater than 90° (high contact angle) generally mean that wetting of the surface is unfavourable, whilst contact angles smaller than 90° correspond to high wettability and it can be expected that the liquid will spread well.

As refered in reference [39], the "Dupre equation" is dedicated under,

$$W_{SL} = \gamma_{SV} + \gamma_{LV} - \gamma_{SL} \quad \textit{Eq. 2}$$

Combining and Eq. 1 it is possible to get the original Young-Dupre equation, one of the most beneficial equipments in empirical approximation of the state of the solid surface.

The Young's equation has more than one unknown, so different models were developed to offer a solution to calculate the surface tension of the solid: Fowkes theory, harmonic mean equation, Wendt Qwens model, the acid-base model, the equation of state model, - also referred single liquid or Neumann's model (Neumann et al. 1974), etc. The equation of state involves one single test liquid, the other theories involve at least two test liquids, a polar one and a dispersive one, the acid-base model involves at least three. Gindl et al. (2001) reported that the different methods result in different surface energy values. They found that tree methods offer relatively similar surface free energy values: the equation of state, the geometric mean and the acid base method. The literature shows that the harmonic mean and the geometric mean equations are often used to calculate the surface tension of a solid surface, for several different purposes [40].

## 5. Adhesives used for furniture bonding

### 5.1. Natural and synthetic adhesives

Adhesives are the most significant raw material after wood in the furniture industry. Specially, the adhesive usage increased significantly. After the World War II, the developments in adhesive types and bonding techniques have led to positive developments in the manufacture of particleboards, and plywood. The mechanical and physical features of these materials have been improved and utilization possibilities have also been arisen in various places of use. The vegetable and animal adhesives that were used in the early days were replaced gradually by synthetic resins later on. Glues of animal origin had week resistance against hot water and microorganisms which limited their usage. The development of the first synthetic resins made possible the introduction on the market of new boards for the furniture industry, like plywood boards etc. The development of new synthetic adhesives with improved qulity made possible these panels to be now used in dissimilar atmospheric cases, together with water, as well as in the production of molds for concrete pouring in direct contact with water, etc. It is widely used in many different areas [41]. Majority of "animal" origin adhesives can be only used in the furniture joints for inner use [42] because of their week resistance to water. Before 1930, glues used in the wood industry were of vegetable and animal origins and were classified as follows:

- Animal gelatin or glue - derived from bone, skin, and fish residuals.
- Blood - derived from crude with blood taken from abattoirs.
- Casein - obtained from the protein of animal milk.
- Soy - vegetable protein derived from soybeans and peanuts.
- Starch and vegetable glues - Derived from fruits, seeds or roots.

The first synthetic polymer-based wood adhesives were produced commercially in the 1930s. In the 20th century, wood bonding resins switched from natural adhesives to synthetic organic [35]polymers. Generally, having bigger water resistance than natural polymers started to be used for a wide range of applications. Synthetic polymers are tougher and stronger and more durable than the glues of natural origin. After 1930, adhesives that we commonly call synthetic resins developed rapidly. The most significant adhesive materials for wood are now produced by chemical syntheses. Based on their curing procedure the synthetic wood adhesives can be so called one component (1K) and two component (2K) adhesives .[43]. The 2K adhesives turn synthetic resin from fluid to solid supported by a so called hardener [44]. They are provided individually to be added to the resin before usage, or may be included in the resin as supplied (especially with spray-dried powder resins) [30, 45]. The 1K adhesives cure without any addition of a further chemical, because they are mixed in the can by production[46]. In order avoid the resin curing in the tinbox, the hardener is added in a so called "retarded" state[47]. After application on the surface these types of adhesives start to cure without the addition of any further chemical, just due to some circumstances. They may need energy or some extra heet, to force the retarded hardener to act. Or in case of isocyanate hardner, the moisture content of the environment speeds up the curing process. At the same time it is worth to emphasize that extra moisture may cause week adhesion or foaming of the PUR type adhesives.

The most frequent used synthetic adhesives for wood bonding can be classified as follows:

- Melamine-formaldehyde resin (MF)
- Urea-formaldehyde resin (UF)
- Polyvinyl acetate absorption (PVA, PVAC)
- Phenol - formaldehyde resin (PF)
- Silicone adhesives (polysiloxanes)
- Isocyanate
- Epoxy
- Contact adhesives
- Hot-melt adhesives
- Melamine-urea-formaldehyde
- Resorcin-formaldehyde
- Phenol-resorcin-formaldehyde
- Polyurethane
- Emulsion polymer isocyanate
- Starch
- Animal
- Poly (vinyl acetate)

Adhesives of the thermosetting type are dried out during the hot pressing and do not soften again when reheated. On the other hand, thermoplastics remain soft until they cooldown and when they are reheated, they soften again, but when they cool, they become harden [48, 49].

Table 1: Adhesives and application environments

| Structural and Semistructural | | |
|---|---|---|
| **Resistant to long-term water soaking and drying (completely outdoor) [11, 42, 50-55]** | **Resistant to short-term water soak (limited outdoor) [41, 51, 52, 56-58]** | **Short-term high humidity resistant (indoor) [41, 50, 57]** |
| Phenol- formaldehyde | Epoxy | Casein |
| Resorcin-formaldehyde | Melamine-urea-formaldehyde | Urea-formaldehyde |
| Phenol-resorcin-formaldehyde | Cross-linked soybean | |
| Emulsion polymer isocyanate | Polyurethane | |
| Isocyanate | Cross-linked poly (vinyl acetate) | |
| Melamine-formaldehyde | | |
| **Nonstructural** | | |
| **Indoor [11, 50, 51, 54, 59, 60]** | | |
| Hot melt adhesives | | |
| Elastomeric adhesion | | |
| Starch | | |
| Animal | | |
| Poly (vinyl acetate) | | |

## 5.2. Adhesive Selection

To many aspects must be paid attention when choosing an adhesive material for a wood bonding process. First of all, the adhesive should be applied with the appropriate technology, it is crucial the adhesive to spread well and to wet the wood surface, to penetrate into the wood, to harden and to achieve the expected strength for a sufficient period of time under different loads and different environmental conditions. There are two major factors of choice when designing an adhesive bond: the expected water resistance of the boneded assembly and the expected load bearing capability of the joint. Based on this later property generally three types of adhesives can be differentiated: structural adhesive, semi structural adhesives, and non-structural adhesives. A structural adhesive is a substance that fastens together elements to produce high modulus, high strength, and permanent bonds. It must be capable of transmitting structural stress without loss of structural integrity within design limits. Thus, it substantially contributes to the structural integrity of continuously stressed assemblies during their expected service lives under relatively severe service environments.

Non-structural adhesives are used for light loads or in more aesthetic applications. Both non-structural and semi-structural adhesives are much more cost-efficient alternatives to structural adhesives, but they are not suitable for all types of projects. Non-structural adhesives are often used as secondary fasteners in more long-term attachments rather than as a main adhesive. Semi-structural adhesives are ideal for less critical applications, though they still offer more strength and support than non-structural adhesives.

### 5.3. Classification of wood adhesives based upon their water resistance

The structural and non-structural adhesives are classified differently regarding thire resistance against water. The structural wood adhesives: according to European Norms are labelled with letter A regarding their water resistance from A1 to A5 whilst grouped in two cathegories Type I (thin) and Type II (thick) based on the thickness of the bondline they form, A5 being the most resistant to boiling and soaking in water. The water resistance non-structural adhesives is labelled with letter D in four cathegories, from D1 to D4, this lates being the most resistant to boiling and soaking in water. Table 2 displays the general forms, properties, preparation, and uses of many adhesive types, but there may be significant differences within each type. An adhesive manufacturer and supplier should review the material, all production processes, intended service environment and equipment before selecting a suitable adhesive.

### 5.4. Factors to be considered for furniture bonding

Regardless of the approximation to adhesive material choice, following factors are significant to consider.

**Strength -** At this point, the quantity of loading the adhesive materil has to bear is important, and this amount of load should be considered.

**Durability** - The type of environment (liquid water, humidity, heat, chemical, cold, loading grade, and exposed light) to which the bond (wood material and adhesive) will be exposed and the time of exposure will determine the durability.

**Timing** - Several timing options should be considered. The shelf life of the mixture depends on the duration elapsed before the glue material is implemented to wood. The open duration is the duration between the implementation of adhesive material and assembly of the parts. Closed duration meaning to the duration between assembling parts and implementing pressure. The clamping duration determines the set duration for clamping a finished part. The increase in temperature generally shortens the setting and setting duration. Emulsion polymer isocyanates harden quickly. After hot or cold pressing, days or weeks are required for the adhesives to be cured completely.

**Wettability** - The surface of the wood and the chemistry of the adhesive materials must match. It is very difficult for a water-based adhesive, free of surfactants and organic solvents, to spread on an oily surface and contain factors that would help making contact between the surface and the molecules.

**Consistence** - The viscosity or nature of the adhesive material should be coherent with the implemantation equipment such as curtain coater, brush, spray, extruder, and spatula. Besides, adhesive materials must be liquid and sufficient to penetrate the empty areas of the wood. Also, the adhesive should be small enough to pass through most of the connecting line causing the joint to open.

**Combinationing** - if catalyst, water, filler, hardener, diluent or any materials are necessary to be mixed with the resin according to the process needs, they must be available.

### 5.5. Main adhesives used in the furniture industry

Many adhesives such as PVAc, Polyurethane (PU), Epoxy (E), Polyvinylchloride (PVC) etc were used in furniture manufacturing. PVAc is the most used adhesive in furniture jointing, being a biodegradable polymer which has major advantages such as good mechanical and thermal properties, high functionalities, biodegradability, biocompatibility, and many applications[61].

Table 2: Color-form, properties and uses of various adhesives in furniture industry

| Species | Color and form | Adhesive properties | Species uses |
|---|---|---|---|
| Urea-formaldehyde [59] | It is found both in liquid and powder form and has a tan and white color. | UF resins have a thermosetting structure. A catalyst is needed to achieve a faster curing. Ammonium chloride (NH4Cl) or Ammonium sulphate is used as a hardening agent in hot pressing. It is resistant to water and humid environments. Viscosity is 200-300 (cps) depending on the purpose of use of the glue. Pressing pressure varies between 1.0-3.0 $MPa^2$ depending on the specific weight of the plate. The pressing time depends on the reaction of the catalyst used, the pressing temperature, and the plate thickness. | Used in hardwood plywood, medium density fiberboard and furniture. |
| Poly(vinyl acetate) | It is in a liquid form, from white to yellow | Liquid is applied directly. Pressing pressure and high frequency press is | It is widely used in the production of |

| | | | |
|---|---|---|---|
| emulsion [41, 45] | color; It has a colourless bond line. | performed at room temperature. It has poor resistance to moisture and high temperatures. | countertops, paneled surface-wall systems in residences, furniture and other similar industries. |
| Hot melt [51, 62] | From white to skin color. It has a colorless bond line and used is in liquid form. | It is applied to the surface in molten form. Adhesion occurs when it cools. Compared to traditional wood adhesives, it has lower strength and moderate resistance to humid environments. | It is used in the chassis and door applications, furniture assembly and edge banding of panels. |

### 5.5.1. Urea formaldehyde adhesives

Urea formaldehyde is a thermosetting material resulting from the chemical reaction between urea and formaldehyde under slightly acidic conditions. The rate of this reaction, and hence the curing time, is accelerated by heat; Once cured, further heating (within limits) has no effect on the material. It also has reasonable moisture resistance, and these two properties, combined with good adhesion to wood and wood-based materials, and low cost have made it widely used in the furniture industry for more than half a century[63].Urea formaldehyde (UF) glue is a low formaldehyde-containing glue. It is known for forming strong bonds. It is used in the application of wooden coatings to double or multi-layered panels, surfaces such as chipboard, MDF, by means of hot or high frequency presses. It is suitable for E1 class products due to its special formula. Its appearance is in the form of white powder. Amino resin is the most widely used type of glue class. The ureaformaldehyde reaction occurs in two stages. It is the first stage that is recyclable, has low resistance to hydrolysis caused by moisture and water, and is also the cause of formaldehyde emission.

The basic characteristics of urea-formaldehyde resins at the molecular level are listed as follows.

1 - High reactivity
2 - Solubility in water
3 - Hardness
4 - Incompatibility
5 - Colorless formation of cured polymers
6 - Easy adaptability to different curing conditions

Low resistance to weather conditions and water, and formaldehyde emission are the negative features of urea formaldehyde glues [64].

### 5.5.2. PVAC

**Pros and Cons of PVA Wood Glues[65]**

PVAs work well with wood because it's a porous material. This ensures good penetration that leads to a strong bond. In addition, it has no odor and is clear when it dries. For industrial-scale applications the PVA formulation can be tailored to provide the required open time, (the time after application for which the adhesive remains active,) and set time, (the time needed to form a bond.)

However, it also has some limitations. These are:

- Parts require clamping in position while the adhesive dries
- PVA retains a degree of flexibility and can break apart so should be considered a complement to other fasteners
- Not readily sanded and doesn't take stain well
- Doesn't necessarily seal a joint against moisture
- Water solubility limits use in wet or damp conditions
- Will soften in high temperatures (160°F (77°C) and higher.)

### 5.5.3. Hot melt adhesives

Chemical types of hot melt adhesive include polyolefins, polyamide, polyester, and polyurethane. Their serviceability must be balanced with ease of application. There are copolymer variants of each type, allowing a wide range of application and performance properties. Although nonreactive hot melt adhesives have been available for many decades and are widely used in many applications, they have certain performance limitations, such as poor heat resistance, water or solvent permeation, and creep. These limitations generally prevent their use in many critical or structural bonding applications. Unlike water-based adhesives that soak into the substrate, hot melt adhesives stay on the surface of the materials. Because of this, a bond line can be created, which may be aesthetically unappealing or may even affect the product or packaging itself. This bond line needs to be accounted for in the production process.

- Generally spoken, hot melt bonds may lose strength at elevated temperatures, this property needs to be cheked before making the choice of adhesive
- Some hot melt bonds may exhibit creep under stress and moderate temperatures, this property also needs to be cheked before making the choice of adhesive
- Some hot melt adhesive may be sensitive to moisture and chemicals, this property also needs to be cheked before making the choice of adhesive[65].

- Temperature affects the strength of the hot melts: in most cases, it’s the cooling and drying process that causes hot melt adhesives to become stiff and create a solid bond. Extreme heat applied to a solid bond can still decrease the solidity, stiffness, or “toughness” of the hot melt and lead to the substrates sliding apart as the adhesive’s hold gives out.

While different types of hot melt adhesive have different levels of temperature resistance, a good rule of thumb is that, as temps go up, the strength of a hot melt adhesive goes down as it loses its ability to hold two substrates together solidly. On the flip side, low temperatures do not usually have such an extremely adverse effect on the strength of adhesives. Typically, they will cause some simple stiffness rather than compromise their strength.

**Choosing the right hot-melt adhesive** for every use is critically important. It is most important to identify your adhesive needs in terms of performance rather than by polymer base. However, many users and suppliers use base polymers as labels for their hot melt adhesive type. The following list reviews general characteristics and applications for each polymer base[65].

#### 5.5.3.1. EVA (Ethylene Vinyl Acetate)

EVA is one of the original polymer bases used in standard in packaging and industrial hot melt adhesives. It still produces very competitive and very high performing packaging hot melt adhesives today. This base offers one of the widest ranges of performance across virtually every current application and is the best and/or main option for many applications. It works in both low application temperature and traditional application temperature hot melt adhesives.

#### 5.5.3.2. Polyethylene

These polymer bases work well for most case, carton and tray sealing applications. Polyethylene polymer-based adhesives provide low odor, light color, and often release easy from metal for easy clean up if it gets on your equipment. It is not ideal for difficult to bond substrates and is only used at traditional application temperatures.

#### 5.5.3.3. Metallocene

Metallocene polymers were introduced in the 90’s. Combining these polymer bases with other premium components offered much greater stability while heated for application and provided storage temperature strength under very cold and hot conditions. This disruptive jump in reducing char and breakdown from heat exposure while expanding heat and cold bond performance made them the fastest growing polymer base since then. There are many variants of premium no char performance hot melts today, some offerings marketed today may have some of this polymer in the adhesive but there are many variants with a wide range of price points, stability, and bond performance does not equivalent to the originally introduced products.

#### 5.5.3.4. Polyamides

These adhesives excel where for very high temperature resistance, oil and solvent resistance, or quick assembly strength is desired. This makes them an excellent choice for filter, wood, and other high performance assembly applications. These adhesives require high application temperatures typically around 400$^{o}$F and do not have as much stability under heat as the other types of adhesives[66].

#### 5.5.3.5. PUR hotmelts (HMPUR)

Used as a hot melt, PUR is applied to a porous surface like wood as a liquid. There, solidification forms the initial bond, after which the PUR adhesive starts to react with moisture. Some PUR hot melt adhesives have fast set times and can form strong initial bonds in as little as 15 seconds. Most PUR adhesives also require 24 hours before they are completely cured, and during this time their strength continues to increase from reactions with the moisture in the air. This means it is very important to expose the PUR adhesive to air once it is applied [66]. Disadvantages: **Fast Set Time Requires Fast Work.** Because PUR hot melt adhesive bonds quickly, it is imperative to get the application right the first time. Less “forgiving” than other types of adhesives, polyurethane hot melt gives a short window of time to apply the adhesive and make adjustments. Once that window is closed, the substrates aren’t going anywhere, so if the exact result wanted is not achieved by the first time, the whole process may need to be started over. **Other Disadvantages:** PUR equipment is considered very specialized and comes with an additional cost, and the maintenance on the production line must be adhered to **–** they are not very forgiving.

#### 5.5.3.6. APAO (Amorphous Poly Alpha Olefins)

Polyolefin Hot Melt adhesives are designed to be an LC (l*ower cost)* adhesive option for most Product Assembly applications. Polyolefin hot melts are often used as a lower cost replacement for Polyamide Hot Melt applications.

We expect the furniture to stay stable when we use it (for example we sit on a chair). Unfortunately, with the rise of quick manufacturing and the race towards lower prices, furniture has become less stable--literally. Materials used is one of main areas where furniture manufacturers have found a way to make furniture more affordable for everyone. Oftentimes, this comes at the cost of quality. A material costs less because it doesn't look as nice, or it won't last as long--always at the expense of the customer and the manufacturer's reputation. But this does not have to be the case. Furniture manufacturers can still use top of the line material at affordable prices. APAO hotmelts are one of the most essential adhesives in the furniture industry.

Amorphous Poly-Alpha-Olefin (APAO / APO) bulk hot melt is a non-crystalline adhesive that is soft, tacky, and flexible. APAO hot melts offer a long open time from 30 seconds to 4 minutes. Their low polarity makes them ideal for bonding polyolefin substrates like PP (polypropylene), PE (polyethylene) and PET (polyethylene terephthalate) along with non-woven materials.

APAO bulk hot melt offers a higher heat resistance and increased fuel, acid or chemical resistance compared to an EVA hot melt. APAO adhesives offer a better adhesion in low temperatures than a EVA. Many APAO hot melt adhesives are sprayable, which allow you to cover a large area without a problem, great for product assembly applications.

There are three main grades of APAO polymers available including butene-propylene copolymer, ethylene-propylene copolymers, and propylene homopolymers. These varying grades are what give APAOs their flexibility in various characteristics. Whether customers need to use a polyolefin neat or in a formulation, the low molecular weight, and amorphous properties are the key for customized solutions for each and every unique need, in any industry. In the furniture industry, APAO hot melt adhesives are best used in the following ways:

- **Mattress:** for purposes such as foam lamination, mattress ticking, upholstery layer attachment, pillow top attachment, and pocket coil assembly.
- **Panel Lamination**
- **Office Furniture**: for purposes such as foam binding, upholstery, nonstructural assembly, drawer liners, and case back.
- **Foam Bonding**

- **Woodworking**: for purposes similar to the office furniture manufacturing needs mentioned above.
- **Edge Banding:** vacuum deep draw laminating

Another benefit of APAO hot melts is that they often manage to provide a better adhesive at a better price. In order to improve the furniture industry customer margins, APAOs can boost productivity and last longer. Here are the specific ways that APAO hot melt helps companies accomplish both the productivity boost and the increased adhesive mileage:

- Quick and easy to use adhesive, which can significantly affect productivity.
- High thermal stability, which allows for less time-consuming precision during manufacturing.
- Versatile open time, which creates more leniency for the production process and employee's working hours.
- Less of the adhesive goes further, which allows manufacturers to use up to 30% less of the adhesive.
- Flexible uses, which means the APAOs can be used on their own or in combination with a formula.

There are only two alternatives to an APAO adhesive solution. The first is a waterbased system and the second is a traditional EVA or polyamide hot melt. However, neither of these systems hold-up when compared to APAO. The following lists the disadvantages of using the two other options, in comparison with APAO as a solution:

- **The waterbased system** involves significant labor because of the mixing involved during production, and because of the clean up that is required due to large amounts of waste. Some of the other drawbacks of using a waterbased system include the fact that the line speeds are slower and there is a much higher consumption of energy required. All in all, waterbased systems demand more labor and time, leading to a significant reduction in productivity when compared to APAO.
- **EVA or Polyamide Hot Melt** have some serious problems that APAO has addressed. Traditional EVA hot melt does not offer the strength or temperature resistance of APAO. While polyamide hot melt can offer temperature and strenght adavantages like APAO, they are often 5-10 times more expensive, have shorter shelf lives and can be hard on dispensing equipment.

For the furniture industry APAO products usually have a white appearance and, they all vary when it comes to open time (20 seconds or of 900 seconds), tensile strength (7,5 N/mm2 to 0,2 N/mm2), high initial tack, great cohesion, excellent thermal stability, etc.[67].

#### 5.5.3.7 Thermosetting wood adhesives

Unlike thermoplastics, thermosetting resins are plastic materials that change their properties with heat. Thermosets, when heated, undergo a chemical change and turn from a soluble and molten structure to an insoluble and insoluble structure as a result. Adhesives made with epoxy resins, polyesters, phenolic and amino resins from thermosets are among the important members of this group. A very strong bonding is obtained with adhesives in liquid, paste and powder form. The tensile strength of the adhesive is strong. Thermoset adhesives, which have high resistance to rupture and breakage, are used for bonding metals, ceramics, wood, glass, and similar structural materials. Thermosets provide hard and strong bonding. It is difficult for them to get away from where they are. They are resistant to cold, heat, humidity, atmospheric conditions and high temperatures[68]. However, thermoset adhesives are used at high temperatures such as 200C and above. In fact, thermosets change from a structure that melts and dissolves with temperature to an insoluble and insoluble structure. In general, they are cross-linked with heat and harden as curing. In addition to the temperature, they harden by cooking in a shorter time with the help of some catalysts and chemicals. As at high temperature, they are cooked (cured) with the help of catalyst at low temperature. Adhesives made with thermoset resins and thus thermosets in their cured state are insoluble in heat and insoluble in organic solvents[69]. Liquid thermoset adhesives can be prepared as one or two components. Liquid thermoset adhesives usually do not contain solvents. Even if present, the solvent is not reactive and is only added to the formulation to ensure the use of the adhesive[68]. The reaction of two polymer adhesives that can withstand high temperatures and thermoset adhesives with one or two components is very slow at room temperature. The adhesive is cured at high temperature in order to accelerate the hardening of the adhesive and to achieve adhesion in a short time[68].

Advantages of thermoset wood adhesives:

- More resistant to high temperatures
- Extremely flexible design
- Allows the production of thin or thick-walled parts
- High levels of dimensional stability
- More favorable initial investment costs

Disadvantages of thermoset wood adhesives:

- Not recyclable
- The surface is more difficult to paint
- Cannot be reshaped or corrected if they undergo shape deformation

**6. Pressure –** is applied to the joints, in order that the contact between the materials surfaces to glued together to be maintained. In general, many wood adhesives cannot fill the gaps well and therefore require high pressure. At the same time, the pressure supports the liquid state adhesive to penetrate the wood surface interface by pressing it into hollow parts of the wood. The measure of the pressure must be adjusted well, as too high pressure could cause most of the adhesive to flow out. During furniture production the bonding of different elements, according to their specificity, needs different pressure values. Generally bonding of veneers needs the lowest pressure (around 0,1-0,5 N/mm2).

Influence of pressure on the radial and tangential penetration of adhesive resin into poplar wood and on the shear strength of adhesive joints deals with the influence of specific pressure during the press process on the radial and tangential penetration of urea-formaldehyde (UF) adhesive into poplar, as well as on the shear strength of lap joints prepared at these different pressures. The average penetration depth (dap) and the size of the interphase region (I) increased with the increase of pressure from 0.5 to 1.0 N/mm2. Further increase in the pressure to 1.5 N/mm2 did not produce a significant change in dap or me. On the contrary, the area of filled lumens and rays (A) showed a steady decrease as the specific pressure increased. Such behavior influenced the filled interphase region (If), which also decreased with increased pressure. Tangential samples (radial penetration) obtained higher values of lap shear strength and showed less dependence on the specific pressure than the radial samples (tangential penetration). Higher shear strength based on radial penetration corresponded to the thicker interphase region of these samples. The highest shear strength for both directions of penetration was obtained for the specific pressure of 1.0 N/mm2.[29].

**7. Finishing and color specifications** - Within furniture and internal joinery applications where aesthetics is important, the color of the adhesive, ability to absorb stains and varnishes, and the absence of flowing and staining are very important elements. Adhesives used in the furniture industry are generally produced in tan or colorless form[70].

**8. Temperature** - Adhesives should work below dissimilar heat condition. The heat of the working environment can influence the speed of curing and the open assembly time of adhesive material. Some adhesives (especially the structural adhesives – which are not used in furniture bonding) require heat pressing, others dry/cure at room temperature too. If those adhesive whicht do not explicitly require heat pressing, are heat pressed, this reduces their dryin/curing time. Adhesives like emulsion polymer isocyanates, epoxy, polyurethanes and PVA and PVAC harden at room temperature[71].

**9. Comfort and simpleness of use-** One-component adhesive materials such as PVA, PVAC, one-component hot melt and polyurethane are the easiest to use as there is no probability of fault in mixing and weighing the ingredients. Water-based adhesives are easier to clean than others, but they require heated storage conditions. Generally, special solvents are required for cleaning after gluing. High water resistance generally means harder cleaning when the adhesive hardens.

**10. Environment and safety–** Plenty of adhesive materials cure with chemical reactions and for this reason in uncured state they are hazardous to some extent. Even water-based adhesive materials can have organic chemical components that vaporize, reasoning for health problems for consumers and workers. Often adhesive materials are deleterious to the skin or emit deleterious smokes. Formaldehyde emission is typical to urea-formaldehide (UF) adhesives. The consumption of UF adhesive is around 11 Mt per year worldwide, so high mostly because it's being widely used for panel production. [72]. The resin is used in smaller amount for furniture industry also, in the manufacture of an adhesive material for bonding plywood (5%), MDF (27%), particleboard (61%) and a laminating adhesive material for bonding (7%), e.g., furniture box products, overlaps of interior flush-mounted doors and panels [73]. The biggest deficit of UF adhesive materials is that they are formaldehyde emitters. The classification of formaldehyde as a 'carcinogenic agent for humans' reported by the International Agency for Research and Cancer (IARC) forces adhesive suppliers, panel manufacturers and research workers to enhance systems that reduce formaldehyde emissions to low steps such as those found in natural wood. [74].

The amine hardeners found in some epoxy adhesive materials are powerful skin sensitisers. According to State and Federal regulations in the USA and also in European Regulations, adhesive suppliers are required to decrease their air emissions [74]. Recently, especially the cost of recycling volatiles has increased in order to prevent air pollution and cost of the organic solvents.

**11. Cost -** Considering that adhesive materials are pricier than wood, the damage of adhesive material and the associated implementation apparatus and labour cost must be considered and noted. In the 20th century, synthetic adhesives were gradually replaced as they were generally more effective and cost less. When a group of adhesives with suitable performance capabilities for a particular bonded assembly has been determined, the user also must choose within that group an adhesive that can be mixed, applied, and cured with available equipment or consider the cost of purchasing equipment to meet specific working properties of another adhesive. Important working properties must be considered when making cost decisions. The cost of an adhesive and related application equipment must be balanced against comparable cost factors for substituted adhesives. In recent years, the cost of organic solvents and the cost of recovering volatiles to prevent air pollution have increased[45].

In wood manufacturing, each processing step affects the material utilization and the cost efficiency such as cutting, planning, sanding etc. [75, 76].

**12. Mechanical properties of adhesives used for furniture bonding**

The performance of the bonded assembly can be evaluated based on mechanical tests. Macroscopic pulling tests provide data for pulling strength of the bonded assemly, shear stress, or modulus of elasticity (MOE), while datas for an indentation modulus / curtailed modulus, creep parameters, stiffness and indentation work are derived from nano-indentation. Wood material, as a well-equipped product today; It is used to achieve many purposes at functional, environmental, and aesthetic levels. Most wood material products are exposed to loads for a long time. This situation causes a long-term mechanical deformation in the wood material and is called creep [114]. For a comparative study of the conclusions from all the dissimilar characterization techniques, modulus of elasticity (MOE) was considered the most logical because there is a clear relation of the performance with this parameter [77-81]. The MOE datas of hardened adhesive films, Nanoindentation (NI) on pulling tests or adhesive films and MOE datas determined by NI on adhesives tested in the bond line are collected in Figure 8. [77-81].

The diagram shows the MOE data of a few commondly used wood adhesive materials. The data are categoryed accordingly to the test process (macroscopic test on adhesive films, nano-indentation on film pieces) and the specified application area (wood-based panels or solid wood). Every point in the graph symbolizes the average MOE of the respective adhesive system. An evaluation of the data showed in Figure 8 displays a very large dissemination of

MOE data ranging from 0.1 to 15GPa. Even if when just adhesive materials of a special chemical subordinate group is thought, a large diversity of features continues, which is in the order of half the order for many adhesive materials, excluding for EP (epoxy) and PUR (polyurethane), where datas differ by nearly one and half.

The variations show that there is a high probability in the mechanical performance of wood adhesive materials, not only based on a specific adhesive ingroup, but also by adjusting their features with an ingroup of adhesives of the same chemical structure. During application, adhesive materials show a tendency to have much higher modulus values when planned to be used in wood-based panels, where adhesive systems are thought to be designed for solid wood bonding materials, even when similar chemical-based adhesives are considered. PUR and EP are commonly used adhesive in the wood industry.

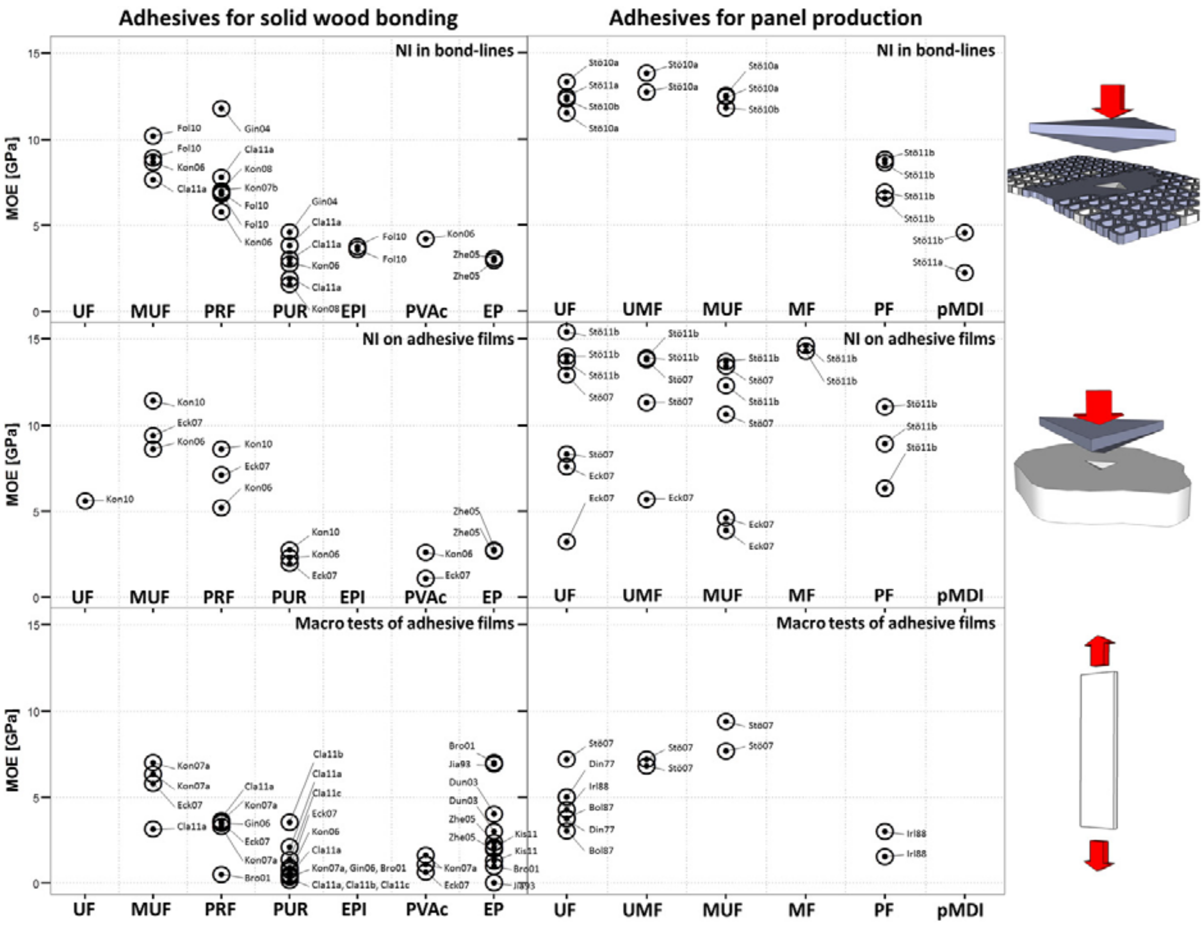


Figure 8: Elastic modulus of wood adhesives designed for panel production (right) and for solid wood bonding (left) measured by means of nano indentation inside bondlines (top), on adhesive films (middle)and by using macroscopic testing methods (bottom). Literature:Bol87 [82], Bro01 [83], Cla11a [80], Cla11b [84], Cla11c [85], Din77 [86], Eck07 [87], Fol10 [88], Gin04 [89], Gin06 [90], Irl88 [91], Jia93 [92], Kon06 [78], Kon07a [93], Kon07b [94], Kon08 [87], Kon10 [95], Stö07 [77], Stö10a [96], Stö10b [97], Stö11a [98], Stö11b [99], Zhe05 [81]. Reprinted with permissions from Elsevier[8]. Copyright, Elsevier, 2013.

During the processing stage, the valuations start in PUR gap, but also comparatively high modulus valuation up to 7 GPa are probable, a situation where the hardest MUF adhesive materials tested did not give information about the film[77]. Further analyzes can be obtained from the data without the bias of dissimilar test methods, taking into account the conclusions obtained from the tests performed with the help of only nano indicators. The reduced elastic modulus (Er) is plotted against the indentation hardness of adhesives in Figure 9. Elasticity modulus, which is an intrinsic material speciality depending on the bonding energies in the material, is relating to the yield strength of a materials according to Tabor's studies [100]. You can find the typical property ranges observed for the different adhesive categories in Figure 9. However, for the adhesive types seen there, the wide bandwidth of mechanical properties can only be seen between grades with the same chemical basis. The distribution is the largest among the class of amino resins coating a large hardness series from 0.15 to 1.5GPa. This is greater than the series of stiffness data from dissimilar phenolic adhesive materials. Net differences among the feutures of the adhesive kinds can be made from Figure 9, where amino-based adhesive materials offer the highest values of hardness and modulus in most cases pursued by phenolic-based adhesive materials. The features of epoxy groups, isocyanate-containing adhesive materials (eg PMDI) and PVA are below this wide gap of features of formaldehyde-based adhesive materials[77].

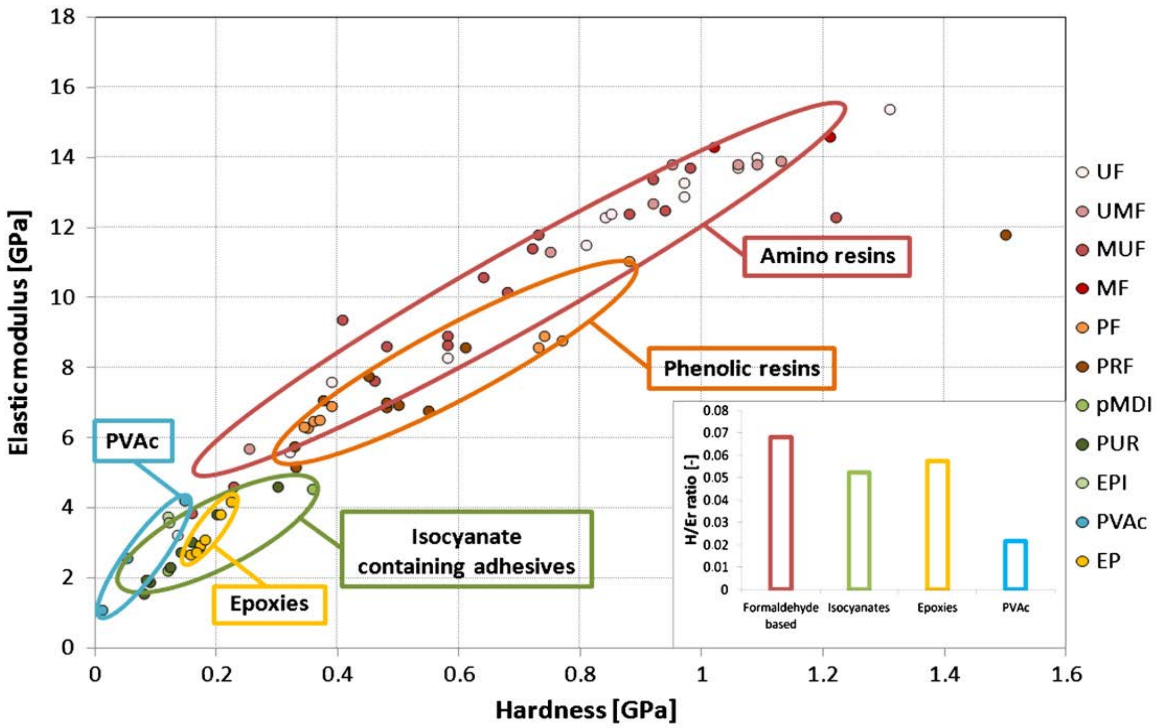


Figure 9: Elastic modulus used synonymously with the mechanical properties and reduced modulus Er of wood adhesives measured by nano-indentation. Reprinted with the permissions from Elsevier[8]. Copyright, Elsevier, 2013.

## 13. Bonding of auxiliary products to wood for furniture

In order to produce and repair furniture several auxiliary products are bonded with solid wood, or wood baesd panels. These are the products that can be used for purposes such as assembly and fixing during their production or repair process. The quality and properties of the auxiliary products directly affect the durability and service life of the products.

Properties and areas of use of adhesives used in wood bonding for furniture:

- Water based PVAC is used for fixing the assembly of door and window frames.
- Silicone is a high quality 100% silicone that can be used for sealing and filling applications in humid environments such as kitchens and bathrooms. Silicone is used to bond all common building materials with wood.
- PUR based adhesives are ideal for bonding wood, fabric, metal, leather, PVC, cardboard and many other plastic substrates.
- PUR foam is used on completely porous surfaces such as concrete, brick, and wood.
- Selected PUR's can be used in humid environments too.
- Mirror silicone is a neutral system, high performance silicone especially used in mirror bonding.
- Aquarium silicone is a single component silicone (acetate system) especially used in aquarium production.
- Bead glue PVC, and melamine is used for bonding edge bands[45].

## 14. Structural design of furniture products

Structural design of furniture is no different from architectural design and designs in other branches of industry. Therefore, it is possible to use the design methods used in these branches for furniture design too. The concepts of function, technology, economy, originality, and aesthetics are prioritized in furniture design. Considerations of esthetic design are shape, scale, proportion and rhythm, color, and texture. The elements of structural furniture design are functionality, safety, economy etc. foreseen in the evaluation phase for the selection of design methods. The factors can be considered as a combination of technology, originality, visuality (aesthetics), economy, and functionality in case of furniture products. The product put forward in the product design process should serve a specific purpose and should be functional because of a conscious selection of materials, technologies and design. Structural integrity of a furniture in most cases is secured by adhesive bonded fasteners like wood dowel pin, wooden bicuit dowel pin, etc. Structural desing must include the considerations of the best coice of jointing. The adhesive and the joint type together are responsible for the strength of the joint. The joints are considered on first place the weak points of a furniture, thus there are three types of tests: one specifically addressing the joint itself, the other ones addressing the furniture or its item (for example a drawer) in integrity, the third addressing the individual performance of the adhesive. These test are not explicitely addressing the adhesive bonding, but in case the bonded joint failes this leads back to an adhesion problem[35].

### 14.1. Furniture adhesives testing

Furnitures are considered non load bearing structures and have special adhesives and test standards specially developed to non load bearing adhesives. EN 205:2016 Adhesives. Wood adhesives for non-structural applications. Determination of tensile shear strength of lap joints describes testing of non-structural wood adhesives on first place for water resistance in three cathegories: D1, D2, D3 and D4, but in the same time by defining the D cathegory gives specification of the expected dry shear strength of the adhesive too. Generally, the dry tests suitable for non-structural adhesives decribed in other EN standards address the adhesion of bonded parts in pull off mode, perpendicular to the bondline, testing the force of adhesion of an adhesive, mostly suitable for comparative analysis of different adhesives.

**European standrads related to classification and testing of non structural wood adhesives** [101]

**ISO 26842-1**
Adhesives — Test methods for the evaluation and selection of adhesives for indoor wood products — Part 1: Resistance to delamination in non-severe environments
**ISO 26842-2**
Adhesives — Test methods for the evaluation and selection of adhesives for indoor wood products — Part 2: Resistance to delamination in severe environments
**EN 204:2016**
Classification of thermoplastic wood adhesives for non-structural applications
**EN 205:2016**
Adhesives. Wood adhesives for non-structural applications. Determination of tensile shear strength of lap joints
**EN 14256:2007**
Adhesives for non-structural wood applications. Test method and requirements for resistance to static load
**EN 14257:2019**
Adhesives. Wood adhesives. Determination of tensile strength of lap joints at elevated temperature (WATT '91)

**ISO 19210**
Adhesives — Wood adhesives for non-structural applications — Determination of tensile shear strength of lap joints
**EN 16556:2014**
Determination of the maximum open time for thermoplastic wood adhesives for non-structural applications
**EN 16556**
Determination of the maximum open time for thermoplastic wood adhesives for non-structural applications
**EN 12436**
Adhesives for load-bearing timber structures - Casein adhesives - Classification and performance requirements
**CEN/TS 927-8:2020**
Paints and varnishes - Coating materials and coating systems for exterior wood - Part 8: Determination of the adhesion on wood after water exposure by a double-X-cut test (2020.)
**EN 12765**
Classification of thermosetting wood adhesives for non- structural applications
**ISO 19209**
Adhesives — Classification of thermoplastic wood adhesives for non-structural applications
**EN 14292**
Adhesives - Wood adhesives - Determination of static load resistance with increasing temperature
**EN 17619:2021**
Classification of wood adhesives for non-structural timber products for exterior use
**EN 319**
Perpendicular Tensile Strength of Particleboards and Fiberboards
**EN 320**
Particleboards and fibreboards - Determination of resistance to axial withdrawal of screws
**EN 13446:2002**
Wood-based panels. Determination of withdrawal capacity of fasteners

### 14.2. Furniture and furniture item testing

Furniture test do not explicitely address the bonded joint, but when testing a furniture, may result that the adhesive bond used to be the weak point. The adhesive plays important role in providing strength to the joint (Kumar et al. 2015, Abdolzadeh et al. 2015). Polyvinyl acetate (PVAc) is a thermoplastic polymer which is widely used in the furniture industry. Several methods to improve the strength of adhesive joints have been investigated (Park et al. 2009, Aydemir 2015). The joints are generally recognized as being the weakest points within the furniture structure since the fitting profiles of the joints represent a discontinuity relative to a solid wood piece and may hinder the development of the full strength of the material (Tankut and Tankut 2011). Calculating the load bearing capacity and the strength of the joints is a complex problem depending on many factors. The most significant of these factors are the strength of the construction material, the method of loading, the strength of glue lines appearing in the joint, and the wood cross section as reduced by the joints profile (Eckelman 2003, Eckelman and Erdil 2000, Smardzewski and Papuga 2004). The strength of wood construction materials has been determined by many investigators and are satisfactory for practical purposes (Vassiliou and Barboutis 2008, Dai et al. 2008). There are also many data technical reports on the load bearing capacity and strength of furniture joints (Ho and Eckelman 1994, Zhang et al. 2005). The properties and types of glue lines in joints (and the factors influencing their mechanical properties (Bowyer et al. 2003, Veselovsky and Kestelman 2002) have also been widely studied. The mechanical properties and factors affecting the performance of the glue lines have been arranged into two groups: one of technological features like machining quality [35], moisture content of the wood and wettability of the surface with adhesives[102]. The second group is the one of strength characteristics: rigidity and load bearing capacity of joints, stresses in main directions of the glue lines, size of glued surfaces, anatomic surface of joined members (Eckelman 1990) etc.

**European standars related to furniture testing**[103]:

**EN 14749:2016 _** Domestic and kitchen storage units and worktops – Safety requirements and test methods
**EN 16121:2013 _** Non-domestic storage furniture – Requirements for safety, strength, durability and stability
**EN 14073-2:2004 _** Office furniture – Storage furniture – Part 2: Safety requirements
**EN 14073-3:2004 _** Office furniture – Storage furniture – Part 3: Test methods for the determination of stability and strength of the structure
**EN 14074:2004 _** Office furniture – Tables and desks and storage furniture – Test methods for the determination of strength and durability of moving parts
**EN 14727:2005 _** Laboratory furniture – Storage units for laboratories – Requirements and test methods
**EN 13150:2020 _** Workbenches for laboratories in educational institutions – Dimensions, safety and durability requirements and test methods
**EN 1023-1:1996 _** Office furniture Screens – Part 1: Dimensions
**EN 1023-2:2000 _** Office furniture – Screens – Part 2: Mechanical safety requirements
**EN 1023-3:2000 _** Office furniture – Screens – Part 3: Test methods
**EN 527-1:2011 _** Office furniture – Worktables and desks – Part 1: Dimensions
**EN 527-3:2003 _** Office furniture – Worktables and desks – Part 3: Methods of test for the determination of the stability and the mechanical strength of the structure
**EN 12521:2015 _** Furniture – Strength, durability, and safety – Requirements for domestic tables
**EN 15372:2016 _** Furniture –Strength, durability, and safety – Requirements for non-domestic tables

**EN 1729-1:2015 _** Furniture – Chairs and tables for educational institutions – Part 1: Functional dimensions
**EN 1729-2:2012+A1:2015 _** Furniture – Chairs and tables for educational institutions – Part 2: Safety requirements and test methods
**EN 581-1:2017 _** Outdoor furniture – Seating and tables for camping, domestic and contract use – Part 1: General safety requirements
**EN 581-2:2015 _** Outdoor furniture – Seating and tables for camping, domestic and contract use – Part 2: Mechanical safety requirements and test methods for seating
**EN 581-3:2017 _** Outdoor furniture – Seating and tables for camping, domestic and contract use – Part 3: Mechanical safety requirements and test methods for tables
**EN 12520:2015 _** Furniture – Strength, durability, and safety – Requirements for domestic seating
**EN 16139:2013 _** Furniture – Strength, durability, and safety – Requirements for non-domestic seating
**EN 14988:2017+A1:2020 _** Children's highchairs – Requirements and test methods
**EN 1335-1:2000 _** Office furniture – Office work chair – Part 1: Dimensions – Determination of dimensions
**EN 1335-2:2018 _** Office furniture – Office work chair – Part 2: Safety requirements
**EN 12727:2016 _** Furniture – Ranked seating – Test methods and requirements for strength and durability
**EN 1725:1998 _** Domestic furniture – Beds and mattresses – Safety requirements and test methods
**EN 716-1:2017 _** Furniture – Children's cots and folding cots for domestic use – Part 1: Safety requirements
**EN 716-2:2017 _** Furniture – Children's cots and folding cots for domestic use – Part 2: Test methods
**EN 13759:2012 _** Operating mechanisms for seating and sofa-beds – Test methods
**EN 747-1:2012+A1:2015 _** Furniture – Bunk beds and high beds – Part 1: Safety, strength and durability requirements
**EN 747-2:2012+A1:2015 _** Furniture – Bunk beds and high beds – Part 2: Test methods

### 14.2.1. Performance Testing

Performance testing is used to evaluate safety, durability, and the structural integrity of furniture. The combination of cycle and static tests used in performance testing simulate stresses that would be placed on furniture in a normal-use environment[104]. Standars are available to evaluate the static and dynamic load bearing capacity of the furniture. Population-based studies dealing with measuring the height and body weight of adult male populations were analyzed (body mass index categories: 25 kg/m$^2$ to < 30 kg/m$^2$ (overweight), > 30 kg/m$^2$ (obese), > 35 kg/m$^2$ (severely obese)). Based of the analysis of anthropometric parameters in Central Europe, researchers suggest that it is necessary to produce chairs with two weight categories for the common population (normal weight up to 110 kg) and a population with a higher weight[105].

### 14.2.2. Safety Testing

Safety testing is used to evaluate the product's mechanical and design safety in a normal-use environment. Safety standards are designed to test the collapsing behaviour of furnitures. For safety testing dynamic test were developed like for example dropping 56 kg on the seat over 100,000 times and impacting each seat with 102 kg, which is dropped from a height of six inches. Additionally, each seat and back is pushed with a lateral force between 113 and 136 kg simultaneously.

### 14.2.3. Flammability Testing

Flammability testing is used to evaluate the safety of a product to ensure that it does not ignite and pose risk to lives or property in its normal-use environment. Flammability testing has become a contentious issue as the concerns of flame retardant (FR) chemicals in products continue to rise. The requirements for flammability testing can range from the materials that make up the product, such as the foam, textiles, and laminate to the finished product. Lacquers and adhesives may act as ignition reducers, thus their flammability properties are also widely studied[106]. The flammability requirements can be influenced by the intended market in which the product will be sold.

### 14.2.4. Environmental attributes of adhesives for furniture

Environmental testing is used to evaluate the environmental, health, and sustainable attributes of a product and its manufacturers claims. The demand for chemical VOC (Volatile Organic Compounds) emission testing is increasing as product manufacturers, architects, designers, and end users are requesting chemical transparency. Furniture can widely be manufactured with different adhesives. Water based adhesives used for veneering and wood dowel jointing, usually do not contain VOC’s. Biodegradable and bio-based adhesives which have no toxic compounds and non-dangerous elements are promoted to be selected where the furniture is generally used in interior locations.

## 15. Developments in wood furniture adhesives due to nanotechnology

Nanoscience and nanotechnology, as of the point it has reached today, has proven its multi-disciplinary feature in practice at the sectoral level and has become one of the indispensables of the wood and furniture industry, as in other fields, in a short time. While nanotechnology enables lasers, microsensors, micromachines, optoelectronic elements and components to be produced and brought together in the industrial field, almost every product from the forestry industry to woodworking and furniture production machines, from chemicals to adhesives, from furniture textiles to wall paints is produced and perfected using nanotechnology made available for use[107].

With the developments in nano technology new properties can be achieved in case of adhesives too, by adding nanocompounds. The development and commercialization of nanoparticles has opened new possibilities for glue applications at the nanoscale. The development of adhesives with nanoparticle reinforcement is among the most researched topics in materials science and engineering today[108]. Studies have shown that polymer materials exhibit higher mechanical strength, higher heat, conductivity and improved electrical performance when combined with nanoparticles. The main nano-filling materials used in adhesive formulations are: silica, aluminum oxide, magnesium oxide, titanium dioxide, zirconium oxide, silver, copper and nickel[109]. In a study investigating the effect of silicon dioxide (SiO2) nanoparticles on starch-based wood glue, when compared to the control group that did not contain SiO2 nanoparticles, it was determined that glues containing 10% nanoparticles increased shear strength by 50.1% in dry state and 84.0% in wet state. It was also revealed that the water resistance increased by 20% [110]. The figure 10 shows the relationship between SiO2 nanoparticle content and tensile strength.

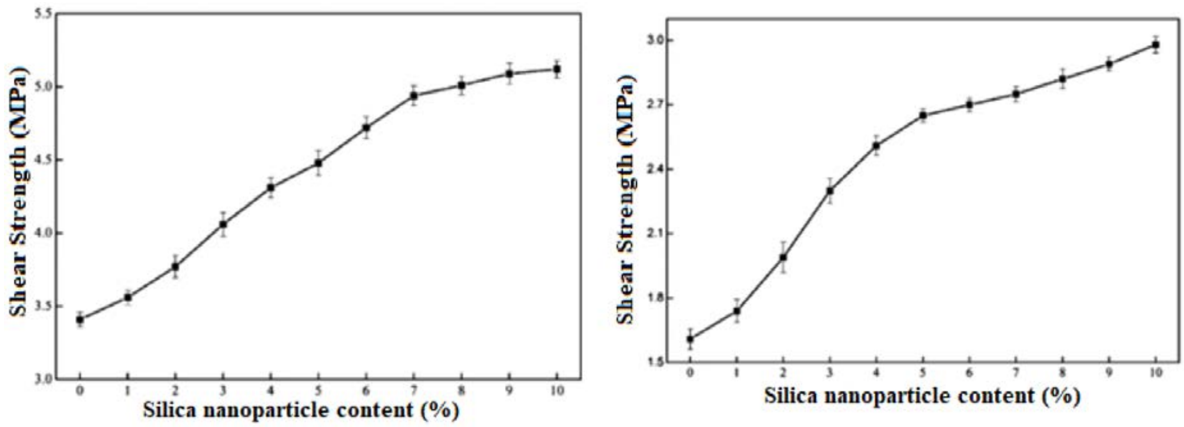


Figure 10. Relationship between silica nanoparticle contents of starch-based wood adhesives and their shear strength in dry state and wet state. Reprinted with the permissions from ScienceDirect[110]. Copyright, ScienceDirect, 2011.

New generation surface coatings and adhesives produced using nanotechnology can provide a large degree of corrosion resistance and resistance to moisture. In this way, the service life of wooden materials in particular extends automatically. Considering the competition with steel and concrete, which are the leading building materials, structural safety and fire protection of wood products stand out as an important issue.

The reduction of leaching out of dangerous substances and of VOC emissions in new architectural projects is of great environmental importance. Emission of VOC's from wood composites produced during engineering has become a very important environmental problem. In terms of reducing the emission of VOCs, nanotechnology offers various solutions. The production of high performance resins that do not contain formaldehyde may be one of the most important inventions in the wood industry. [111].

## 16. Research gap and future perspectives

Most of the thermosetting adhesive resins used for bonding in furniture and wood industry today are dependent on petrochemicals. UF resins are extensively used in the forestry industry and are formaldehyde emitters. Formaldehyde was advertised carcinogenic by IARC in 2004. For this reason, limitations on formaldehyde emissions for wood-based adhesives have become more than strict. It can be assumed that the further decrease of the current legal formaldehyde emission limit will be determined by the legislation for all wood-based materials. Additionally, society considers the protection of health and the environment and consequently the use of synthetic products as big environmental problems, thereby promoting the retainable use of regenerable natural resources. The exterminating of air pollution, inert petrochemicals, and water forced the industry to replace it with environmentally friendly materials and remained aware of environmental problems. In this sense, the preferred bonding material for wood bonding is of great importance. In recent years, new high solids content low viscosity adhesive systems as well as new systems with significantly improved water resistance have been developed. However, unlike synthetic adhesives, it may be having almost no harm to human health, or it will be vegetable-based. When applied, adhesives can be developed that can simply penetrate in the wood form and material a quality bonding. Such an adhesive can capture a bigger market share [112].

## Conclusion

In furniture products industry, "wood adhesives" play a significant role in the development and effective use of wood-based products. Wood product producers are the biggest users of adhesive materials. Wood adhesive materials offer more than 65% by volume of adhesives used in the world[113]. Glue is the most used material in wooden products. The purpose of this study is to evaluate the aspects of efficient wood bonding of furniture products and to present a selective review of wood adhesives literature. In many cases even within one furniture, several different adhesives are used for bonding the different elements: bonding veneer, bonding solid wood connectors, bondig edge bands, bonding pins, and dowels etc.

The non load bearing wood adhesives have different properties, they must be selected according to the expected performance of the furniture or furniture part (strength, water resistance, etc.). Different types of non-load bearing wood adhesives are classifyed in this study. The bonding theory and the wetting phenomenon are also explained and the state of research regarding different adhesive types is also reported. The quality and the service life of a multiple bonded wood furniture is strongly influenced by the right choice of adhesive and the most convenient bonding technique. The review refers to the new achievements in wood adhesive development due to nanotechnology too. This paper brings a contribution towards a good orientation in selecting the most appropriate wood furniture adhesive.

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