Effect of Adhesives on Bonding Performance of Softwood and Hardwood Plywood

Dalila Belaidi Aadarsha Lamichhane Suman Pradhan
Mostafa Mohammadabadi Rubin Shmulsky Xiping Wang

Abstract

In this study, the effects of adhesives on the bonding performance of both southern yellow pine (SYP) and red maple plywood were investigated. Phenol–formaldehyde (PF), polymeric diphenylmethane diisocyanate (pMDI), phenol–resorcinol–formaldehyde (PRF), and polyurethane (PUR) were evaluated. This allowed us to understand the difference between thermosetting and cold-setting adhesives, as well as phenolic and isocyanate ones. Three-ply plywoods were fabricated using red maple veneers (*Acer rubrum*) for hardwood plywood specimens and using SYP (*Pinus* spp.) for softwood plywood specimens. The bonding was evaluated using lap shear and cyclic tests. According to ASTM D906, approximately 40 specimens per adhesive per species were subjected to a lap shear test to determine their shear strength. Wood failure of the shear specimens was evaluated visually and using an image processing software, ImageJ. In accordance with the American National Standards Institute for Hardwood and Decorative Plywood/Hardwood Plywood and Veneer Association (ANSI/HPVA HP-1 2020), 12 specimens per adhesive per species were tested for delamination. These specimens underwent three cycles of soaking in water for 4 hours followed by drying for 19 hours. The findings of this study indicated that the isocyanate-based adhesives produced superior bonding, particularly PUR for red maple and pMDI for SYP. PF resin could potentially substitute for these isocyanate-based adhesives, as the observed difference was not statistically significant.

Over the past 50 years, adhesives have significantly enhanced resource and industrial efficiency and play a crucial role in more than 70 percent of all wood-based materials in use today (Conner 2001, Frihart 2011). The conventional adhesives that are commonly used include (1) phenolic-based types such as phenol–formaldehyde (PF) and phenol–resorcinol–formaldehyde (PRF); (2) amino-based types such as urea–formaldehyde, melamine–formaldehyde, and melamine–urea–formaldehyde; and (3) isocyanate-based types such as polymeric diphenylmethane diisocyanate (pMDI) and polyurethane resin (PUR) (Conner 2001, Ferdosian et al. 2017, Pang et al. 2018, Li et al. 2021, Dziurka et al. 2022). Plywood is one of the most important structural wood products fabricated by bonding thin wood veneers with adhesive (Stalnaker and Harris 1997, Bekhta et al. 2020). The selection of these adhesives to manufacture plywood is critical because of factors such as cure time, exterior performance (including resistance to moisture), and the variation in wood species (Ülker, 2016). Essentially, for structural plywood, adhesives must pass ASTM D2559 (ASTM International 2024). Consequently, many studies have been conducted to understand the effect of types of adhesives on various properties of plywood made of different species, as shown in Table 1.

Use of thermosetting resins to produce plywood or other panel-based products like oriented strand board and particleboard is common because of their ability to quickly cure through efficient heat transfer in such products, as well as their cost effectiveness, rapid reactivity, exceptional strength, and adaptability to various curing conditions (Ong et al. 2018, Bekhta et al. 2020, Mousavi et al. 2021). Consumption of thermal energy, which is related to carbon emission and global warming, could be another issue with thermosetting adhesives. In contrast, cold-setting adhesives are available and common to produce high-performance wood products, particularly thick products such as cross-laminated timber and glulam. In recent decades, technological

The authors are, respectively, Ph.D. Student, Ph.D. Student, Ph.D. Student, Assistant Professor, and Professor and Head, Dept. of Sustainable Bioproducts, Forest and Wildlife Research Center (FWRC), College of Forest Resources (CFR), Mississippi State Univ., Starkville (db3049@msstate.edu, al2409@msstate.edu, sp2344@msstate.edu, mm5132@msstate.edu [corresponding author], rs26@msstate.edu); and Research Forest Products Technologist, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin (xwang@fs.fed.us).

Forest Prod. J. 75(1):16–25.
doi:10.13073/FPJ-D-24-00044

Table 1.—Summary of studies investigating the effect of adhesive types on various properties of plywood made from different wood species.

Authors	Adhesives[a]	Wood species	Objective
Setter et al. (2021)	UF and PF	Parica and pine	Comparison of physical and mechanical properties
Bal and Bektaş (2014)	UF, MUF, and PF	Eucalyptus, beech, and poplar	Investigation of the mechanical properties
Demirkir et al (2013)	PF and MUF	Scots pine, maritime pine, and European black pine	Evaluation of the effect of peeling and drying temperature on the mechanical properties
Li et al. (2017)	Polyols mixed with pMDI	Yellow poplar	Investigation of the effect of recycled polyols on bonding performance of plywood
Lin and Lee (2018)	MUF and PF	Lauan	Investigation of the effect of curing temperature on bonding strength of plywood made with PF
Öncel et al. (2019)	PF	Uludağ fir, alder, Scots pine, and Samsun poplar	Investigation of the effect of wood type on adhesion quality
Qin and Teng (2022)	PF	Plywood	Evaluation of hot press temperature and time on mechanical properties of plywood
Kallakas et al. (2020)	PF	Gray alder, black alder, and aspen	Evaluation of the effect of various layup schemes and wood species on mechanical properties
Iwakiri et al. (2013)	PF	Genus *Eucalyptus*	Assessment of nine *Eucalyptus* species for veneer and plywood production
Reis et al. (2019)	PF	*Acrocarpous fraxinifolius* and *Pinus oocarpa*	Analysis of the physical–mechanical properties of *Acrocarpus fraxinifolius* and *Pinus*
Fitrianum et al. (2023)	PF	Rubber	Evaluation of the effect of catalysts on PF resin's adhesive properties and strength
Karthäuser et al. (2023)	PF	Scots pine	Modification of plywood with PF resin
Savov et al. (2022)	PF and lignin	Pulp (beech, oak, pine)	Develop a new fiberboard manufacturing technology using reduced PF resin and hydrolysis lignin
Fleckenstein et al. (2017)		Beech	Performance evaluation of LPF-modified LVL compared with PF-modified LVL
Ozbay et al. (2015)	PF	Scots pine, sawdust, and beech wood	Evaluation of the bonding performance of PF adhesive modified with pyrolysis bio-oil
Hong et al. (2018)	PF	Poplar	Synthesis of PF resin for fast manufacturing of LVL
Slabohm et al. (2022)	PF or PRF	Beech	Increase dimensional stability and durability of LVL
Papadopoulos (2006)	UF and pMDI	Pine and fir	Comparison of the physical properties of conventional particleboard using UF and pMDI
Knorz et al. (2015)	PRF, MUF, PUR, and EPI	Ash	Investigation of the influence of three surfacing methods using four different adhesives
Hamid et al. (2013)	PRF	Kapur and kelat	Determination of the effect of different pressure on bonding strength and adhesive penetration

[a] UF = urea–formaldehyde; MUF = melamine–urea–formaldehyde; PF = phenol–formaldehyde; pMDI = polymeric diphenylmethane diisocyanate; LPF = lignin–phenol–formaldehyde; LVL = laminated veneer lumber; EPI = emulsion polymer isocyanate; PRF = phenol–resorcinol–formaldehyde; PUR = polyurethane.

progress has encouraged researchers to create high-performance, fast-curing adhesives that work at room temperature. Currently, the development of Henkel's LOCTITE HB X adhesives, which also meet stringent heat and fire safety standards, exemplifies the industry's efforts to address these concerns. These adhesives allow a curing time (assembly time along with pressing time) ranging from about 10 minutes to 4 hours (LOCTITE HB X PURBOND-LINE). Similarly, some researchers have tried to adopt cold-setting adhesives to produce plywood. Sari et al. (2023) demonstrated the feasibility of producing ecofriendly plywood panels using a cold-setting adhesive made from polyvinyl alcohol, tannin, and hexamine through a cold-pressing process as an alternative to conventional plywood. Lubis et al. (2023) prepared a formaldehyde-free cold-setting plywood adhesive using a 1:1 mix of natural rubber latex and polyvinyl alcohol with 0, 1, 3, or 5 percent polymeric 4,4-diphenylmethane diisocyanate. Mousavi, S. Y et al. (2021) prepared three-ply plywood panels using soy protein isolated–bisphenol A diglycidyl ether–polyethylenimine adhesives through a cold-press process, subsequently evaluating the panels for water resistance and shear strength. Lubis et al. (2022) demonstrated the feasibility of fabricating ecofriendly plywood bonded with polyvinyl alcohol–lignin–hexamine-based adhesive using cold pressing as an alternative to conventional plywood.

Despite extensive research on wood bonding, there is a lack of studies examining the effect of different types of adhesives on the bonding performance of hardwood and softwood plywood. Existing studies usually focus on a single type of plywood or adhesive as shown in Table 1, leaving a big gap in understanding the performance of numerous adhesives across

Table 2.—Pressing methods and corresponding adhesive types.

Pressing method	Adhesive	Type
Hot pressing	Phenol–formaldehyde Polymeric diphenylmethane diisocyanate	Thermosetting
Cold pressing	Phenol–resorcinol–formaldehyde Polyurethane	Cold setting

Figure 1.—An even distribution of phenol–formaldehyde resin on softwood veneer.

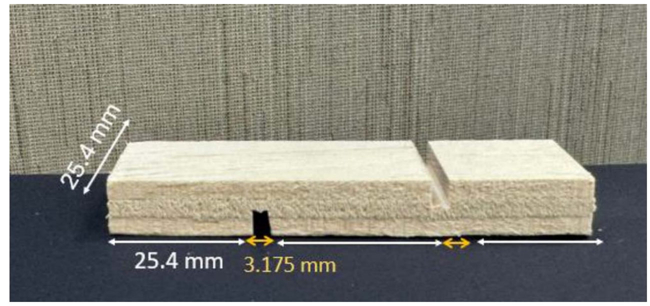

Figure 2.—Configuration and dimensions of the plywood specimens for lap shear test.

a range of wood species under different testing conditions. This study aims to address this gap by evaluating and comparing the bonding performance of four adhesives—PF, pMDI, PRF, and PUR—by conducting lap shear and cyclic tests on plywood made from red maple (*Acer rubrum*) and southern yellow pine (*Pinus* spp.; SYP). The research focuses on red maple as a raw material for its superior mechanical properties, which include its high durability and strength, but also due to its growth dominance over the last 3 decades compared with other species in the northeastern United States (Alderman et al. 2005). Another raw material, SYP, was primarily selected for its abundant availability in the wood industry. It is the most widely used softwood species globally, largely due to its rapid growth in plantation settings (Shmulsky et al. 2021).

These distinct characteristics highlight the necessity of gaining a deeper understanding of adhesives' effect on these types of wood species, offering new opportunities to enhance their application in the wood industry.

Materials and Methods

The SYP veneer was obtained from Winston Plywood & Veneer (Louisville, MS, USA), with an average thickness of 0.38 cm and an average density of 607 kg/m^3. SYP is one the most common wood species used in the United States because of its widespread availability, primarily sourced from fast-grown plantation trees (Mirabile and Zink-Sharp 2018, Shmulsky et al. 2021). Due to its rapid growth, SYP has lower mechanical properties. Therefore, developing value-added products from SYP can expand the market for such fast-growing species.

The red maple veneer was obtained from Great Lake Veneer (Marion, WI, USA). Average thickness was 0.33 cm and average density was 588 kg/m^3. Red maple exceeds the criteria for structural applications, according to studies done by Janowiak et al. (1995). However, the high cost of the raw material remains a significant obstacle to its acceptance as a structural material (Grisez et al. 1972, Janowiak et al. 1995).

The adhesives used in this study included PF, PRF, pMDI, and PUR. The PF adhesive, provided by Hexion, had a solid content of 56 percent, a viscosity range of 120 to 300 cPs, and a pH between 9.5 and 10.5. The PRF adhesive, also from Hexion, was a two-part adhesive consisting of Cascophen 4001-2 and Cascoset 5830E featuring a viscosity range of 1,500 to 2,500 cPs and a density of 1.15 to 1.21g/cm^3. The pMDI adhesive, known as Rubinate 1840, with a solid content of 100 percent and a density of 1.23g/cm^3, was supplied by Huntsman. The PUR adhesive, LOCTITE UR 5153, with a solid content of 100 percent, gel time of 30 minutes, cure time of 60 minutes, viscosity of 5,000 cPs, and a density of 1.12 g/cm^3, and its corresponding primer, LOCTITE PR 3105 PURBOND, were obtained from Henkel. It should be mentioned that PF and pMDI are hot-pressing, whereas PRF and PUR are cold-pressing adhesives.

Manufacturing process

Veneers were conditioned in an environmental chamber to reach a moisture content of 10 percent. Three plies of randomized veneers from the same wood species were

Table 3.—Experimental setup and specimen distribution for evaluating adhesive bonding strength in red maple and southern yellow pine.

Adhesive	Wood species	Lap shear test		Cyclic	
		No. of specimens	Dimension (mm)	No. of specimens	Dimension (mm)
Phenol–formaldehyde	Red maple	40	25.4 × 82.6	12	50.8 × 127
	Southern yellow pine	40	25.4 × 82.6	12	50.8 × 127
Polymeric diphenylmethane diisocyanate	Red maple	40	25.4 × 82.6	12	50.8 × 127
	Southern yellow pine	40	25.4 × 82.6	12	50.8 × 127
Phenol–resorcinol–formaldehyde	Red maple	40	25.4 × 82.6	12	50.8 × 127
	Southern yellow pine	40	25.4 × 82.6	12	50.8 × 127
Polyurethane	Red maple	40	25.4 × 82.6	12	50.8 × 127
	Southern yellow pine	40	25.4 × 82.6	12	50.8 × 127

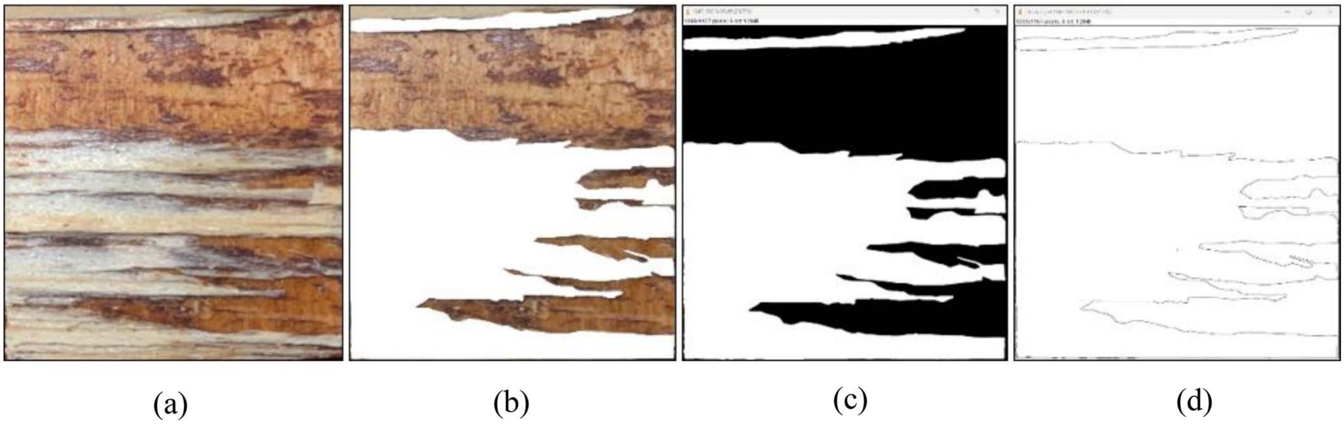

Figure 3.—Wood failure evaluation using ImageJ software. (a) High-resolution image of the lap shear test specimen with wood failure. (b) Marking and filling the wood failure areas using polygon selection tool. (c) Adjustment of threshold. (d) Analyzing the particles to quantify failure areas after making image binary.

oriented 90° to each other to fabricate plywood measuring 41 by 41 cm. After applying the resin to a single adherend surface, a process known as single spread, the three plies of veneers were bonded using either a cold-pressing or hot-pressing technique, depending on the adhesive type, as shown in Table 2.

The application rate of 195 g/m^2 was chosen for all adhesives. Attention was given to ensuring even distribution of adhesives on the veneers. An even distribution of PF resin on SYP veneer using a sprayer is presented in Figure 1. The thermosetting resins, PF and pMDI, were applied using a sprayer because of their low viscosity, followed by curing under hot-press conditions with temperatures of 160°C and 150°C, respectively, and pressure of 1.24 MPa (180 psi) for 5 minutes. For PF resin, the veneers were dried in an oven to a moisture content of around 4 percent to minimize the chance of blowing during hot pressing. PRF and PUR were applied using a roller because of their high viscosity and then cold pressed at room temperature under a pressure of 0.83 MPa (120 psi) for 7 hours and 1 hour, respectively. The PRF resin was prepared using a mix ratio of 2.5 parts resin (Cascophen) to one part hardener (Cascoset) by weight. PUR, the LOCTITE PR 3105 PURBOND primer, and water were mixed by weight in the ratio of 1:19 (5%). The solution was applied on the surface at a rate of 20 g/m^2 before applying the adhesive.

Lap shear test

Following the ASTM D906-98R17 standard test method, test specimens cut from plywood were subjected to a lap shear test to determine the shear strength of the adhesive bond. Approximately 40 specimens per adhesive per species with an average dimension of 25.4 mm wide and 82.6 mm long were tested, as shown in Table 3, with detailed dimensions of shear specimens provided in Figure 2.

Wood failure evaluation

To differentiate wood failure from glue failure after a lap shear test, the image processing software ImageJ was used. Initially, high-resolution images of the failure areas were captured with a camera as shown in Figure 3a. The polygon selection tool was used to mark the wood failure areas, and the selected area was filled with a color using the color picker tool, as shown in Figure 3b. The modified image was then converted to grayscale for better contrast (Figure 3c), and Gaussian blur was applied with the Sigma (Radius) adjusted between 0 and 2. The image was converted to binary, as shown in Figure 3d, and further processed by eroding and dilating. The "Analyze Particles" function was applied to quantify the areas of failure, distinguishing between wood and glue failures on the basis of the color differences, as shown in Figure 3.

Three-cycle soak test

In accordance with the American National Standards Institute for Hardwood and Decorative Plywood/Hardwood Plywood and Veneer Association (ANSI/HPVA HP-1-2020), the adhesive bond was evaluated under varying moisture conditions. Twelve specimens per adhesive per species with average dimensions of 5.08 by 12.70 cm (2 in by 5 in) were cut as shown in Table 3, immersed in 24°C water for 4 hours, and then dried at 50°C for 19 hours. This soaking and drying process was repeated three times. Delamination of each specimen after each cycle was measured with a 0.08-mm-thick feeler gauge and subsequently recorded. A specimen is considered failed when any delamination between two plies is longer than 5.08 cm, deeper than 0.635 cm, and wider than 0.08 mm. According to the

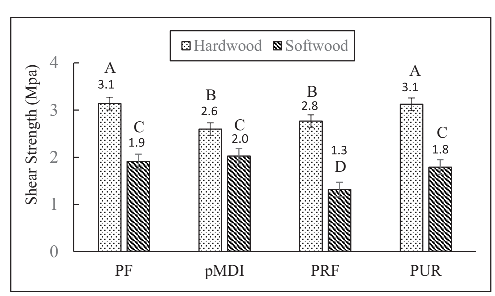

Figure 4.—Shear strength of red maple and southern yellow pine plywood manufactured using different adhesives. There is a significant difference between bars labeled with different letters at $\alpha = 0.05$; those with the same letters represent no statistical difference. PF = phenol–formaldehyde; pMDI = polymeric diphenylmethane diisocyanate; PRF = phenol–resorcinol–formaldehyde; PUR = polyurethane.

Table 4.—ANOVA summary for shear stress of different adhesives and wood species.

Factors	df	Sum of squares	Mean square	*F* value	*P* value	Partial eta squared
Adhesives	3	248,745.3	82,915.1	27.6	<0.0001	0.2
Wood species	1	2,352,490.3	2,352,490.3	784.8	<0.0001	0.7
Interaction	3	210,408.9	70,136.3	23.4	<0.0001	0.1
Model	7	2,787,910.9	398,273	132.9	<0.0001	
Error	330	989,130.8	2,997.4			
Corrected total	337	3,777,041.8				

standard guidelines (ANSI/HPVA HP-1 2020), an adhesive passes a three-cycle soak test if five of six specimens pass the first cycle and four of six specimens pass the third cycle.

Statistical analysis

Considering 40 shear specimens per adhesive per wood species, the Tukey test was conducted to determine whether statistical differences among adhesives and wood species could be detected in a two-way analysis of variance (ANOVA). The statistical analysis was conducted using OriginPro software at the significant value of 0.05 ($\alpha = 0.05$).

Results and Discussion

Lap shear

The average shear strength for red maple and SYP plywood manufactured with different adhesives is given in Figure 4. For red maple veneers, PUR and PF resulted in better bonding performance. The shear strength of red maple plywood manufactured with PUR and PF was about 13 and 21 percent higher than those of PRF and pMDI, respectively. Although pMDI resulted in the weakest bonding in red maple plywood, the difference between pMDI and PRF is not statistically significant. The results of the ANOVA test are indicated by letters on each bar in Figure 4.

Among the four adhesives evaluated, pMDI had the highest shear strength for SYP plywood, whereas PRF exhibited the lowest. The shear strength of SYP plywood manufactured with pMDI was about 57 percent higher than that of PRF, and it was also about 6 and 14 percent higher than those of PF and PUR, respectively. However, the statistical analysis revealed that the difference among the shear strength of SYP plywood manufactured by pMDI, PUR, and PF is not statistically significant.

Lap shear test results revealed that PUR and PF adhesives achieved the highest shear strength for red maple plywood, whereas pMDI demonstrated superior bonding performance for SYP plywood. Moreover, PRF resulted in the weakest bond for both SYP and red maple plywood.

The results of the Tukey test to examine the influence of two groups—adhesive type and wood species—on the shear strength of plywood are given in Table 4. A high *F* value indicates that the variability of group means is large compared with the variability within each group, suggesting that one group differs significantly from the other. A high *F* value and a low *P* value together suggest that group means differences are statistically significant, and the observed differences are unlikely to be due to chance alone. Results given in Table 4 also reveal that the interaction between

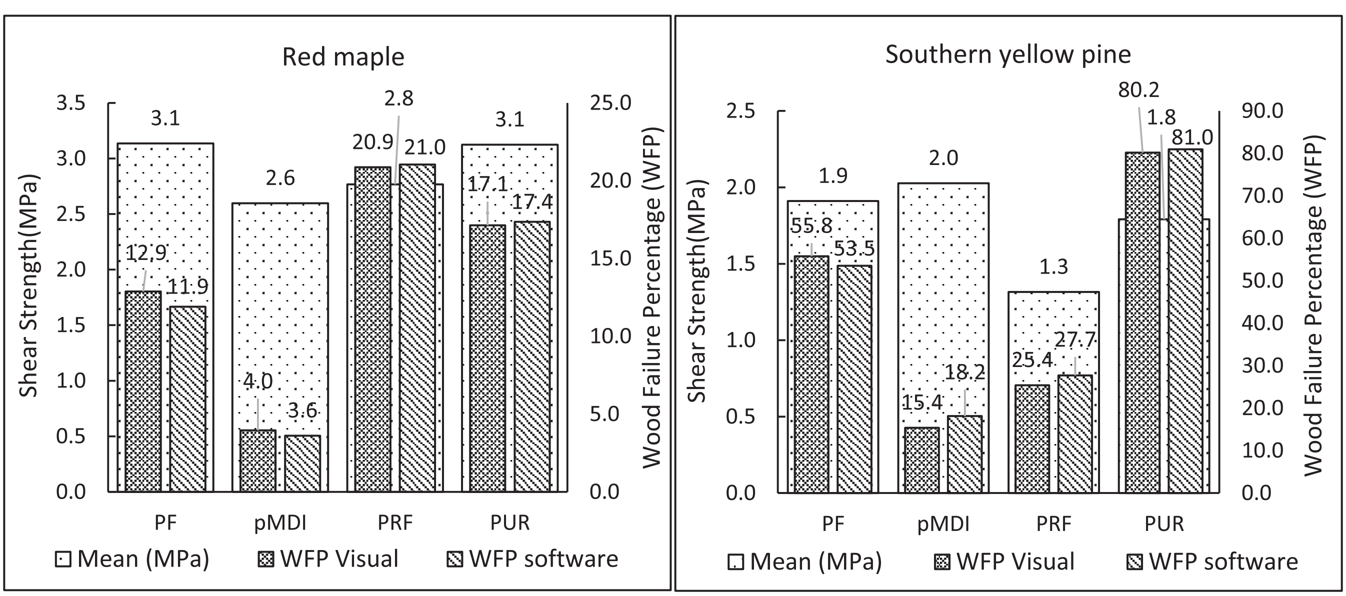

Figure 5.—Shear strength and wood failure percentage (WFP) for red maple and southern yellow pine using different adhesives (Note: WFP obtained from visual means are all the round numbers; decimal values come because of the average values of all the specimens). PF = phenol–formaldehyde; pMDI = polymeric diphenylmethane diisocyanate; PRF = phenol–resorcinol–formaldehyde; PUR = polyurethane.

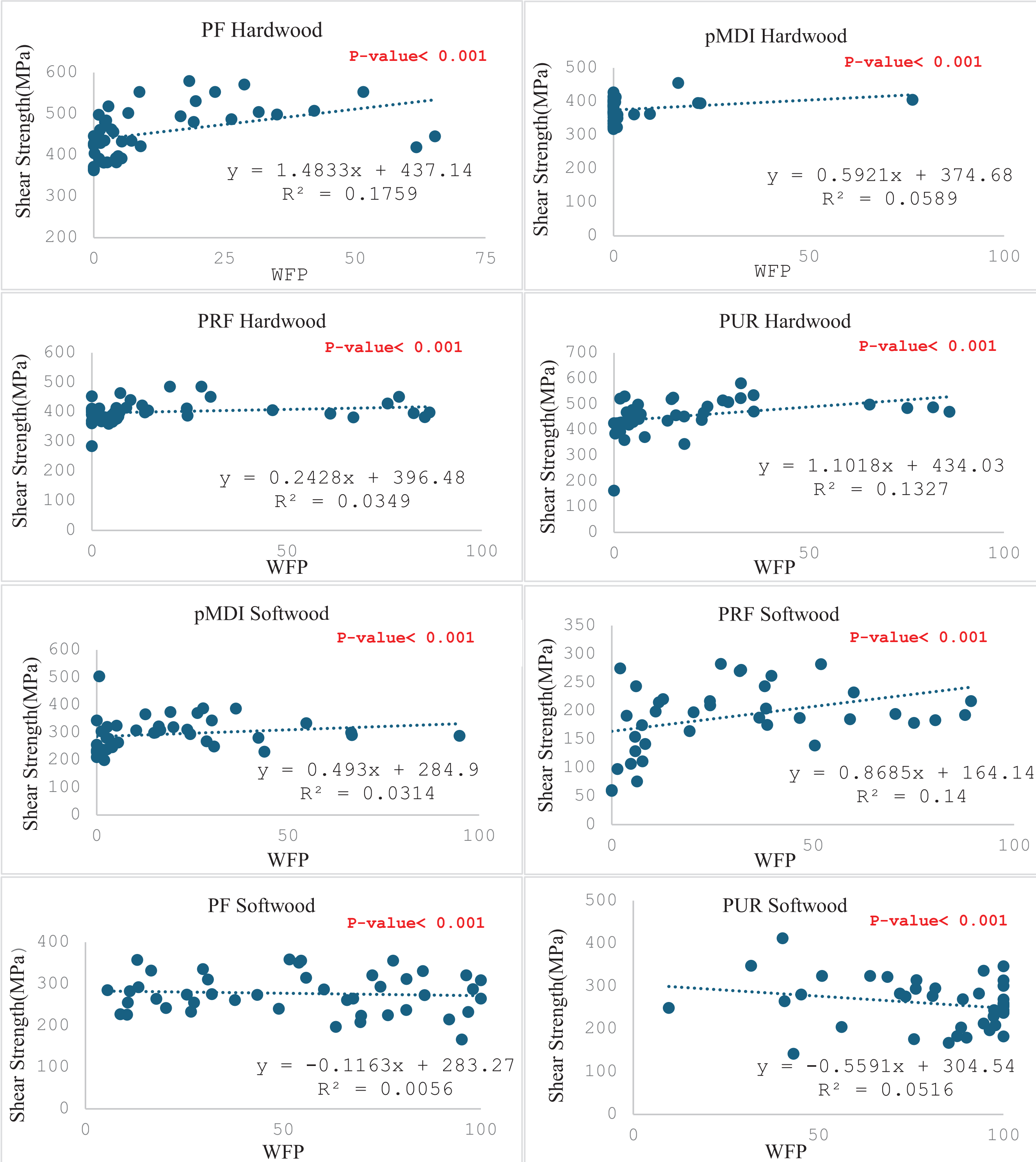

Figure 6.—Scatter plots between wood failure percentage (WFP) and shear strength for both red maple and southern yellow pine using different adhesives. PF = phenol–formaldehyde; pMDI = polymeric diphenylmethane diisocyanate; PRF = phenol–resorcinol–formaldehyde; PUR = polyurethane.

wood species and different types of adhesives has a substantial impact on shear strength.

To further understand the relative importance of these factors, the partial eta squared (η_p^2) was calculated and presented in Table 4. This provides insights into which factor has the most significant influence on shear strength. For adhesive type, $\eta_p^2 = 0.2$, indicating that 20 percent of the variance in shear strength is explained by the type of adhesive, which represents a relatively small effect. In contrast, for the wood species $\eta_p^2 = 0.7$, indicating that 70 percent of the variance in shear strength is explained by the wood species. This highlights a much stronger effect

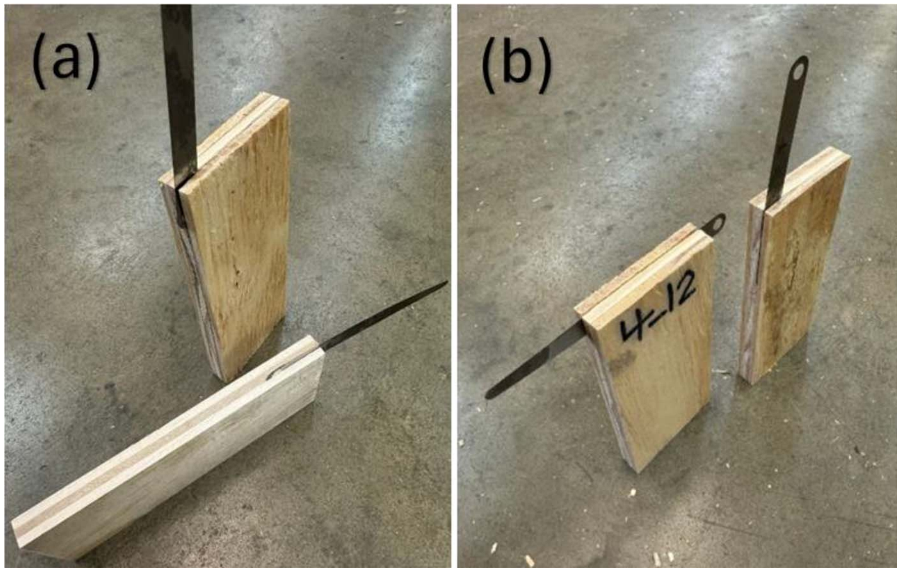

Figure 7.—Specimens evaluated using a feeler gauge. (a) Passed the test with minor cracks and (b) failed because of having long and wide cracks.

of wood species on shear strength compared with adhesive type.

Wood failure percentage

After processing the images using ImageJ software, the percentage of wood failure for all specimens was evaluated. Moreover, two different people evaluated the percentage of wood failure visually. Two methods were used to determine whether technology could offer more accurate results and a faster process compared with traditional visual assessment. However, the results showed minimal differences between the two methods, as shown in Figure 3; the visual assessment indicated 50 percent wood failure, whereas an analysis using ImageJ yielded a result of 52 percent. In contrast, using ImageJ was relatively time consuming, requiring multiple steps such as image capture, file uploading, and subsequent processing.

Among red maple specimens, those bonded using PRF demonstrated the highest wood failure percentage (WFP) values, achieving 20.8 percent visually and 21.0 percent through image analysis. PUR followed closely with WFP of 17.14 percent visually and 17.36 percent through software. Specimens bonded by pMDI exhibited the lowest WFP at 3.95 percent visually and 3.61 percemt through software.

Table 5.—Numbers of failed and cracked specimens after the third cycle.

Wood species	PF[a]	pMDI	PRF	PUR
Red maple				
Failed	0	0	0	0
Cracked	0	1	1	0
Southern yellow pine				
Failed	0	1	0	2
Cracked	2	9	5	6

[a] PF = phenol–formaldehyde; pMDI = polymeric diphenylmethane diisocyanate; PRF = phenol–resorcinol–formaldehyde; PUR = polyurethane.

For SYP specimens, those bonded by PUR showed the highest WFP, with 80.2 percent visually and 81.0 percent through software, followed by PF at 55.8 percent visually and 53.5 percent through software. Similar to red maple, SYP specimens bonded by pMDI also demonstrated the lowest WFP, with 15.4 percent visually and 18.2 percent through software. PRF ranked second lowest at 25.4 percent visually and 27.7 percent through software.

It is challenging to conclude whether a specific type of adhesive, either phenolic or isocyanate based, cold setting or thermosetting, yields optimal bonding for both wood species, as the adhesive's chemical composition and interaction with wood fiber could play a significant role in the bonding process.

Relation between WFP and shear strength

Figure 5 presents the average shear strength and WFPs for all adhesives and species, aiming to determine if there is a direct relationship between these two properties. For red maple bonding, statistical results indicated that pMDI and PRF adhesives exhibited the lowest shear strength, with values of 2.6 and 2.8 MPa, respectively. Of note, pMDI recorded the lowest WFP at 3.6 percent, whereas PRF had the highest WFP at 21 percent, as shown in Figure 5. Conversely, PF and PUR adhesives demonstrated the highest shear strengths at 3.1 MPa, with WFPs of 11.9 and 17.4 percent, respectively. This disparity suggests that WFP alone cannot accurately indicate bonding performance.

For SYP, pMDI had the highest shear strength, whereas its WFP was the lowest (as shown in Figure 5). SYP specimens fabricated with PUR had the highest WFP, and these specimens, along with those bonded with pMDI and PF, demonstrated the highest shear strength in the statistical analysis. These findings complicated the establishment of a clear correlation between WFP and shear strength in both red maple and SYP plywood. However, it was found that although PUR provided consistently high shear strength for both species, it also yielded high WFPs, being the highest for SYP and the second highest for red maple.

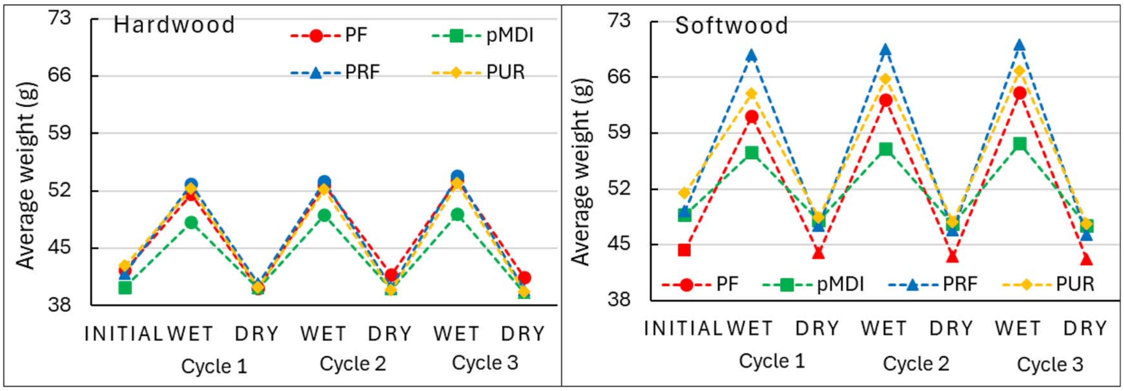

Figure 8.—Change in average weight of specimens during the three cycles of soaking and drying. PF = phenol–formaldehyde; pMDI = polymeric diphenylmethane diisocyanate; PRF = phenol–resorcinol–formaldehyde; PUR = polyurethane.

Figure 6 shows shear strength versus WFP for red maple and SYP specimens, aiming to establish a correlation between bonding performance and the mechanical properties of plywood. The resulting R^2 and P values were very low for most cases, indicating no correlation and statistical significance respectively.

The regression analysis indicates that establishing a clear, direct relationship between WFP and shear strength is challenging. WFP can provide useful insights, especially about bonding performance, but cannot be used as the sole predictor for evaluating shear strength. This suggests that other factors may be influencing the relationship. Inherent variations in the wood, such as differences in density and microstructure, and manufacturing parameters, such as resin distribution and variation in veneer thicknesses, tend to significantly affect shear strength. For example, a weak midlayer in shear specimens can lead to a high WFP but low shear strength.

Wetting–drying cycles

After each drying cycle and meticulous evaluation regarding crack and delamination, most of the red maple and SYP specimens showed positive results. For red maple plywood, all adhesives successfully passed the three-cycle soak test, with no specimens failing. It should be mentioned that only one red maple specimen that was manufactured with pMDI showed a small crack but did not fail. Figure 7 shows failed and cracked specimens as they were evaluated using a feeler gauge.

In contrast, only phenolic adhesives PF and PRF passed the soak–dry cyclic test for SYP plywood, with no specimens showing failure. However, some specimens fabricated with isocyanate adhesives did not pass the test and experienced failure. Specifically, one specimen bonded with pMDI and two specimens bonded with PUR exhibited failure. It should be noted that many of the SYP specimens showed small cracks but not failure. The results of the soak–dry cyclic test, including failed and cracked specimens, are given in Table 5.

During each cycle, the weights of the specimens were recorded both after soaking and after drying, and the results are presented in Figure 8. SYP specimens absorbed more water than red maple specimens. This higher rate of water absorption may partially account for the higher incidence of failure or crack development in SYP specimens compared with red maple specimens. Increased water uptake resulted in greater thickness swelling, subsequently increasing the probability of crack initiation and propagation. The method of veneer peeling and the development of lathe checks may also influence this water absorption.

For both red maple and SYP, specimens made with isocyanate adhesive, especially pMDI, had lower rates of water absorption, whereas those fabricated with phenolic adhesive, especially PRF, had the highest rates, as shown in Figure 8. Regardless of wood species, these results show that isocyanate adhesives pMDI and PUR exhibited better water resistance compared with phenolic adhesives PF and PRF. However, it cannot be concluded that they are more suitable for exterior application, as during the drying process some of the SYP specimens made with these adhesives experienced failure, whereas those with phenolic resin did not.

Conclusions

This study aimed to evaluate the bonding performance of SYP (softwood) and red maple (hardwood) plywood manufactured using four different adhesives: PF, pMDI, PRF, and PUR. The key findings of this study are:

(1) Among the adhesives evaluated, bonding with pMDI resulted in the highest shear strength for SYP plywood, whereas bonding with PF and PUR achieved the highest shear strength for red maple plywood.

(2) For softwood plywood, there is no statistical difference in the shear strength of specimens bonded by pMDI, PF, and PUR, indicating that these three adhesives perform similarly in terms of bonding strength. However, a statistical difference was observed between these adhesives with PRF. It should be highlighted that both isocyanate adhesives—pMDI and PUR—developed a good bond between softwood veneers.

(3) For red maple, the shear strength of specimens bonded by PF and PUR is the same; however, a statistical difference exists between these two adhesives with pMDI and PRF.

(4) Regardless of wood species, plywood manufactured with PUR and PF have higher shear strength than those manufactured with pMDI and PRF.
(5) Regardless of wood species, isocyanate adhesives pMDI and PUR showed a lower water uptake rate than phenolic resins PF and PRF.
(6) Statistical analysis revealed that wood species have a more significant effect on shear strength compared with adhesive type.
(7) For both red maple and SYP plywood, PUR resulted in the highest shear strength and relatively highest bonding performance, meaning the highest WFP for SYP and the second highest WFP for red maple.
(8) Both visual assessment and ImageJ software produced similar results for WFPs, with minor differences. However, ImageJ was more time consuming.
(9) WFP cannot serve as the sole predictor of bonding strength.
(10) Regarding energy consumption and carbon emissions, PUR adhesive, a cold-setting binder, is a superior choice for fabricating SYP and red maple plywood.

Acknowledgments

The authors acknowledge the support from the USDA Forest Service Forest Products Laboratory in Madison, Wisconsin as a major contributor of technical assistance, advice, and guidance to this research. In accordance with Federal law and U.S. Department of Agriculture policy, this institution is prohibited from discriminating on the basis of race, color, national origin, sex, age or disability. (Not all prohibited bases apply to all programs.) To file a complaint of discrimination: write USDA, Director, Office of Civil Rights, Room 326-W, Whitten Building, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410 or call (202) 720-5964 (voice and TDD). USDA is an equal opportunity provider and employer. The authors also acknowledge the support from Winston Plywood & Veneer, Great Lake Veneer, Hexion, Henkel, and Huntsman for supplying wood veneers and adhesives. This publication article is a contribution of the Forest and Wildlife Research Center at Mississippi State University.

Literature Cited

Alderman, D. R., Jr., M. S. Bumgardner, and J. E. Baumgras. 2005. An assessment of the red maple resource in the northeastern United States. North. J. Appl. Forestry 22(3):181–189.

ASTM D2559-12a (2024). Standard Specification for Adhesives for Bonded Structural Wood Products for Use under Exterior Exposure Conditions. ASTM lnternational; West Conshehoken, PA.

Bal, B. C. and I. Bektaş. 2014. Some mechanical properties of plywood produced from eucalyptus, beech, and poplar veneer. Maderas Ci. Tecnol. 16(1):99–108. https://doi.org/10.4067/S0718-221X2014005000009

Bekhta, P., M. Müller, and I. Hunko. 2020. Properties of thermoplastic-bonded plywood: Effects of the wood species and types of the thermoplastic films. Polymers 12(11):1–19. https://doi.org/10.3390/polym12112582

Conner, A. H. 2001. Wood: Adhesives. In: Encyclopedia of Materials: Science and Technology. 2nd ed. Elsevier, Amsterdam. pp. 9583–9599.

Demirkir, C., Ş. Özsahin, I. Aydin, and G. Colakoglu. 2013. Optimization of some panel manufacturing parameters for the best bonding strength of plywood. Int. J. Adhes. Adhes. 46:14–20. https://doi.org/10.1016/j.ijadhadh.2013.05.007

Dziurka, D., A. Derkowski, D. Dukarska, J. Kawalerczyk, and R. Mirski. 2022. The effect of periodic loading of glued laminated beams on their static bending strength. *Materials* 15(11):3928. https://doi.org/10.3390/ma15113928

Ferdosian, F., Z. Pan, G. Gao, and B. Zhao. 2017. Bio-based adhesives and evaluation for wood composites application. Polymers 9(2):70. https://doi.org/10.3390/polym9020070

Fitrianum, F.; Lubis, M.A.R.; Hadi, Y.S.; Sari, R.K.; Maulana, M.I.; Kristak, L.; Iswanto, A.H.; Mardawati, E.; Reh, R.; Sedliacik, J. Adhesion and Cohesion Strength of Phenol-Formaldehyde Resin Mixed with Different Types and Levels of Catalyst for Wood Composites. J. Compos. Sci. 2023, 7, 310. https://doi.org/10.3390/jcs7080310

Fleckenstein, M., Biziks, V., Mai, C. et al. Modification of beech veneers with lignin phenol formaldehyde resins in the production of laminated veneer lumber (LVL). *Eur. J. Wood Prod.* 76, 843–851 (2017). https://doi.org/10.1007/s00107-017-1275-7

Frihart, C. R. 2011. Wood adhesives: Vital for producing most wood products. Forest Prod. J.61(1):4–12. doi: https://doi.org/10.13073/0015-7473-61.1.4

Grisez, T. J. and J. J. Mendel. 1972. The rate of value increase for black cherry, red maple, and white ash. Research Paper NE-231. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania. 26 pp.

Hamid, N. H. A., M. Ahmad, M. N. Suratman, M. N. Azhar, and N. A. Rosli. 2013. Adhesive bonding strength and adhesive penetration of two Malaysian medium hardwoods. *Adv. Mater. Res.* 748:170–174. https://doi.org/10.4028/www.scientific.net/amr.748.170

Hong, S., Gu, Z., Chen, L., Zhu, P., & Lian, H. (2018). Synthesis of phenol formaldehyde (PF) resin for fast manufacturing laminated veneer lumber (LVL). *Holzforschung*, 72(9), 745–752. https://doi.org/10.1515/hf-2017-0184

Iwakiri, S., J. Luis, M. De Matos, J. Guilherme Prata, R. Trianoski, and L. Soares Da Silva. 2013. Evaluation of the use potential of nine species of genus *Eucalyptus* for production of veneers and plywood panels. *Cerne* 19(2):263–269.

Janowiak, J. J., H. B. Manbeck, R. Hernandez, R. C. Moody, P. R. Blankenhorn, and P. Labosky. 1995. Efficient utilization of red maple lumber in glued-laminated timber beams. Research paper FPL-RP-541. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 23 pp.

Kallakas, H., A. Rohumaa, H. Vahermets, and J. Kers. 2020. Effect of different hardwood species and lay-up schemes on the mechanical properties of plywood. Forests 11(6):1–13. https://doi.org/10.3390/f11060649

Karthäuser, J., Biziks, V., Frauendorf, H. et al. Substituting phenol in phenol–formaldehyde resins for wood modification by phenolic cleavage products from vacuum low-temperature microwave-assisted pyrolysis of softwood kraft lignin. *Cellulose* 30, 7277–7293 (2023). https://doi.org/10.1007/s10570-023-05295-5

Knorz, M., E. Neuhaeuser, S. Torno, and J. W. G. van de Kuilen. 2015. Influence of surface preparation methods on moisture-related performance of structural hardwood adhesive bonds. Int. J. Adhes. Adhes. 57:40–48. https://doi.org/10.1016/j.ijadhadh.2014.10.003

Li, M., S. Zhang, Y. Gong, Z. Tian, and H. Ren. 2021. Gluing techniques on bond performance and mechanical properties of cross-laminated timber (Clt) made from *Larix kaempferi*. Polymers 13(5):1–9. https://doi.org/10.3390/polym13050733

Li, Q., M. Li, C. Chen, G. Cao, A. Mao, and H. Wan. 2017. Adhesives from polymeric methylene diphenyl diisocyanate resin and recycled polyols for plywood. Forest Prod. J. 67(3–4):275–282. https://doi.org/10.13073/FPJ-D-16-00054

Lin, W. S. and W. J. Lee. 2018. Influence of curing temperature on the bonding strength of heat-treated plywood made with melamine–urea–formaldehyde and phenol–formaldehyde resins. Eur. J. Wood Wood Prod. 76(1):297–303. https://doi.org/10.1007/s00107-016-1154-7

LOCTITE HB X PURBOND-LINE. (n.d.). www.henkel-adhesives.com/engineered-wood

Lubis, M. A. R., F. Falah, D. Harini, Sudarmanto, A. Kharisma, B. Tjahyono, W. Fatriasari, B. Subiyanto, L. Suryanegara, and A. H. Iswanto. 2023. Enhancing the performance of natural rubber latex with polymeric isocyanate as cold-pressing and formaldehyde free adhesive for plywood. J. Adhes. 99(1):58–73. https://doi.org/10.1080/00218464.2021.1999233

Lubis, M. A. R., A. Labib, Sudarmanto, F. Akbar, A. Nuryawan, P. Antov, L. Kristak, and A. N. Papadopoulos 2022. Influence of lignin content and pressing time on plywood properties bonded with cold-setting adhesive based on poly (vinyl alcohol), lignin, and hexamine. *Polymers* 14(10):2111. https://doi.org/10.3390/polym14102111

Mirabile, K. V. and A. Zink-Sharp. 2018. Fundamental bonding properties of Douglas-fir and southern yellow pine wood. Forest Prod. J. 67(7–8):435–447. https://doi.org/10.13073/FPJ-D-17-00019

Mousavi, S. Y., J. Huang, and K. Li. 2021. A cold-set wood adhesive based on soy protein. Int. J. Adhes. Adhes. 106. https://doi.org/10.1016/j.ijadhadh.2020.102801

Öncel, M., H. Vurdu, H. A. Osman, E. Özkan, and A. Kaymakci. (n.d.). The tensile shear strength of outdoor type plywood produced from fir, alnus, pine, and poplar wood *Wood Res*. 64(5):913–920.

Ong, H. R., M. M. R. Khan, D. M. R. Prasad, A. Yousuf, M. N. K. Chowdhury. 2018. Palm kernel meal as a melamine urea formaldehyde adhesive filler for plywood applications. Int. J. Adhes. Adhes. 85:8–14. https://doi.org/10.1016/j.ijadhadh.2018.05.014

Özbay, G., & Ayrilmis, N. (2015). Bonding performance of wood bonded with adhesive mixtures composed of phenol-formaldehyde and bio-oil. *Industrial Crops and Products*, 66, 68–72. https://doi.org/10.1016/j.indcrop.2014.12.028

Pang, B., M. K. Li, S. Yang, T. Q. Yuan, G. B. Du, and R. C. Sun. 2018. Eco-friendly phenol–urea–formaldehyde co-condensed resin adhesives accelerated by resorcinol for plywood manufacturing. *ACS Omega* 3(8):8521–8528. https://doi.org/10.1021/acsomega.8b01286

Papadopoulos, A. N. 2006. Property comparisons and bonding efficiency of UF and PMDI bonded particleboards as affected by key process variables. *Bioresources* 1:201–208.

Qin, Z. and K. Teng. 2022. Mechanical model and changed chemical structure of phenol–formaldehyde adhesive on plywood with different hot press process. *J. Adhes*. 98(15):2348–2365. https://doi.org/10.1080/00218464.2021.1970545

Reis, A. H. S., D. W. Silva, A. P. Vilela, R. F. Mendes, and L. M. Mendes. 2019. Physical–mechanical properties of plywood produced with *Acrocarpus fraxinifolius* and *Pinus oocarpa*. Floresta Ambient. 26(4). https://doi.org/10.1590/2179-8087.015717

Sari, R. A. L., M. A. R. Lubis, R. K. Sari, L. Kristak, A. H. Iswanto, E. Mardawati, W. Fatriasari, S. H. Lee, R. Reh, J. Sedliacik, M. I. Maulana, L. Suryanegara, B. Subiyanto, and S. Maulana. 2023. Properties of plywood bonded with formaldehyde-free adhesive based on poly(vinyl alcohol)–tannin–hexamine at different formulations and cold-pressing times. J. Compos. Sci. 7(3). https://doi.org/10.3390/jcs7030113

Savov, V.; Valchev, I.; Antov, P.; Yordanov, I.; Popski, Z. Effect of the Adhesive System on the Properties of Fiberboard Panels Bonded with Hydrolysis Lignin and Phenol-Formaldehyde Resin. *Polymers* 2022, 14, 1768. https://doi.org/10.3390/polym14091768

Setter, C., U. L. Zidanes, E. H. de Novais Miranda, F. M. S. Brito, L. M. Mendes, and J. B. G. Junior. 2021. Influence of wood species and adhesive type on the performance of multilaminated plywood. Environ. Sci. Pollut. Res. 28(36):50835–50846. https://doi.org/10.1007/s11356-021-14283-w

Shmulsky, R., F. J. N. França, J. T. Ratcliff, B. Farber, C. A. Senalik, R. J. Ross, and R. D. Seale. 2021. Compression properties of small clear southern yellow pine specimens tested across five decades. *Forest Prod. J*. 71(3):240–245. https://doi.org/10.13073/FPJ-D-20-00039

Slabohm, M., Mayer, A. K., & Militz, H. (2022). Compression of Acetylated Beech (Fagus sylvatica L.) Laminated Veneer Lumber (LVL). *Forests*, 13(7), 1122. https://doi.org/10.3390/f13071122

Stalnaker, J. J. and E. C. Harris. 1997. Plywood and similar wood products. *In:* Structural Design in Wood. 2nd ed. Springer, Boston. pp. 249–270. https://doi.org/10.1007/978-1-4615-4082-3_11

Ülker, O. 2016. Wood adhesives and bonding theory. *In:* Adhesives. A. Rudawska (Ed.). IntechOpen. https://doi.org/10.5772/65759