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EVALUATION OF THE ADHESION BEHAVIOR OF KHAYA IVORENSIS WOOD TO MANUFACTURE GLUED PRODUCTS

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ABSTRACT: This paper evaluates the adhesion behavior of *Khaya ivorensis* (African mahogany) for the production of glued products. Nine 10-year-old thinning trees (25 cm diameter at breast height and 13 m tall) were harvested. The logs were sawed to obtain specimens to evaluate glue line shear strength (fgv,0) and finger-joint flexure strength according to ASTM standards. For fgv,0 tests, two adhesives (PVAc and PUR) at same spread rate (200g/m^2), two surface preparations (sanding and planing) and two assembly pressure level (0.7 and 1.0 MPa) were evaluated. It was found that PVAc yielded statistically higher fgv,0 values than PUR, however both adhesives types showed higher fgv,0 values than that observed in solid wood. PVAc fgv,0 values were not affected by surface preparation, but the assembly pressure had a positive effect. On the other hand, PUR samples presented higher fgv,0 values when surface was sanded and assembly pressure about 1.0 MPa was applied. Wood failure of at least 65% was observed for all samples tested. PVAc bonded finger-joints showed be stronger and stiffer than those bonded with PUR. It could be concluded that the wood material tested here showed a great potential to manufacture glued products.

KEYWORDS: glue-line shear strength, finger-joint strength, polyurethane, crosslinked poly(vinyl acetate), thinning

1 – INTRODUCTION

In 2021, planted forests covered 9.2 million hectares in Brazil, primarily comprising eucalyptus and pine species. However, other species have also been extensively planted, such as *Tectona grandis*, *Acacia mangium*, *Hevea brasiliensis* and *Schizolobium amazonicum*. *Khaya ivorensis*, commonly known as African mahogany, belongs to the Meliaceae family. It is native to West Africa, specifically the Ivory Coast, Ghana, Togo, Benin, Nigeria, and southern Cameroon [1]. These West African countries share similar soil and climate characteristics with some regions of Brazil, which may explain the species' successful adaptation there. Species of the genus Khaya were introduced to Brazil in the 1970s and have become established due to their high resistance to the mahogany shoot borer (*Hypsipyla grandella*), the main pest of Brazilian mahogany (*Swietenia macrophylla*), coupled with their good growth performance and the ban on the sale and harvesting of Brazilian mahogany wood.

African mahogany has adapted well in Brazil at altitudes between 100 and 1,200 meters, with rainfall between 1,200 and 2,400 mm per year, and is found from Santa Catarina to Pará. It thrives in fertile soils with rainfall above 1,500 mm, distributed over six to eight months, in climates with hot summers [2]. Its wood ranges in color from reddish to pale brown, with distinct growth rings that differentiate the heartwood from the sapwood [3].

From seven to eight years onward, it can exhibit good growth rates, with the ideal time for clear-cutting being from 15 years of age [4]. The wood is soft and light, highly durable, easy to work with and dry, and has a moderate shrinkage rate. However, tension wood and stresses can lead to defects during drying. It has a wide range of uses, including furniture, small objects, veneers, window frames, panels, stairs, and doors, as well as pulp and charcoal production. It is used in both light construction, such as flooring, and heavy construction, such as shipbuilding and vehicle bodies, among other applications [1].

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Currently, Brazil has approximately 40,000 hectares of planted African mahogany forests, with ages ranging from zero to 20 years.

In this context, this paper aims to evaluate the bonding behavior of *Khaya ivorensis* (African mahogany) for the production of glued products, specifically assessing the effects of adhesive type, surface preparation, and assembly pressure on this behavior. The research group behind this project has been studying the bonding behavior of tropical woods since 2010 [5-9].

2 – EXPERIMENTAL SETUP

2.1 WOOD MATERIAL

The wood used in this study originated from Fazenda Rohsal, a commercial planting in the municipality of Nerópolis, Goiás, Brazil (16°18'28.85"S, 49°13'3.80"W), at an altitude of 852 m. The region experiences a humid, rainy summer and a dry, relatively cool winter. The climate is classified as Aw according to the Köppen system, characterized by humid, rainy summers and dry, relatively cool winters. The average annual rainfall is 1,432 mm, with average temperatures of 20.4°C in the coldest months and 24.4°C in the hottest months. The soil is classified as Red Latosol. The forest was established in 2008 with a spacing of 5 x 4 meters, and the trees were 10 years old at the time of harvesting (second thinning).

Nine *K. ivorensis* trees were felled (cut 0.50 m above ground level) and sectioned every 1.50 m, utilizing the entire commercial portion of the log (up to the first branch). The trees had an average diameter at breast height (DBH) of 25 cm and an average total height of 13 meters. For this project, boards measuring 1.5 m in length, 50 mm in thickness, and varying widths were used. The material was selected to minimize natural defects and drying defects (warping and cracking). The wood was air-dried for two months, then kiln-dried at 45°C for one week, and finally acclimatized in a controlled environment (22 ± 2°C and 63 ± 2% relative humidity) until reaching a moisture content of 12%.

2.2 MATERIAL TESTING

Initially, 20 solid wood specimens were made to determine the shear strength parallel to the grain ($f_{v,0}$) of the solid wood according to [10]. The test was performed on a universal testing machine (INSTRON 2550) at a constant speed of 0.6 mm/min.

To evaluate the glue line shear strength ($f_{gv,0}$) two types of adhesives were used: Titebond II Premium Wood Glue, based on polyvinyl acetate (PVAc) and Kleiberit 501 adhesive based on polyurethane (PUR), both class D4 according to DIN/EN 204. The application of the adhesives on the surface was done manually, controlling the amount of adhesive for each face (200 g/m²).

Two presseure levels (0.7 and 1.0 MPa for 3 hours) and two surface preparation were tested (planing and sanding). The samples were sanded manually using 60 grit sanding 40 times. The wood failure (%) was also visually analised using a transparent grid. This way, eight treatments were evaluated, which varied in relation to the type of adhesive, preparation of the surface and assembly pressure (Table 1).

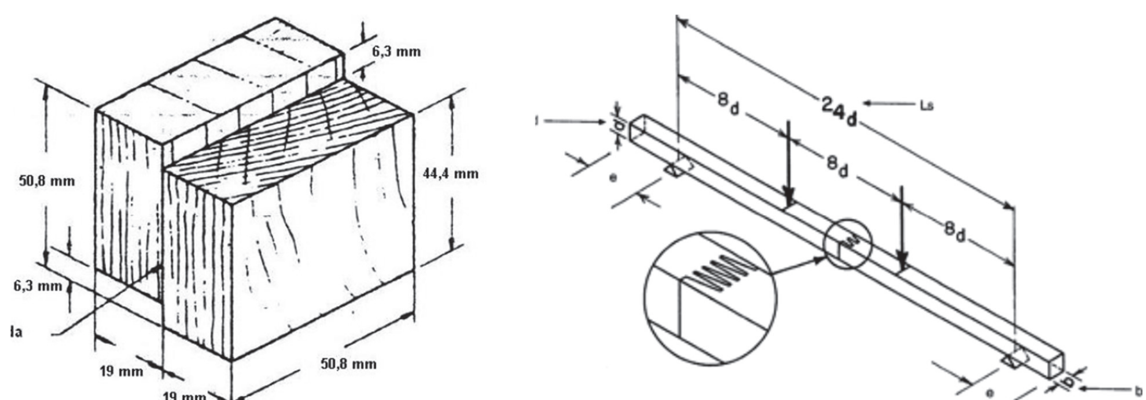

Figure 1. Samples dimensions for the glue line shear strength and the finger-joint bending strength and stiffness testing according to [11] and [12], respectivelly.

After the gluing process, the samples were placed in a climate-controlled chamber with a temperature of 22±2ºC and relative humidity of 63±2% for 20 days to stabilize the moisture content (12%), and subsequently, tested according to [11] (Figure 1).

Table 1: Experimental design to determine glue line shear strength (fgv,0) of the K. ivorensis *wood*

Adhesive	Surface Preparation	Pressure	Treatment
PVAc	Planing	0.7	T1
		1.0	T2
	Sanding	0.7	T3
		1.0	T4
PUR	Planing	0.7	T5
		1.0	T6
	Sanding	0.7	T7
		1.0	T8

The finger joint bending properties were determined according to [12] (Figure 1) and 20 samples for each type of adhesive (PVAc and PUR) was tested in bending to determine modulus of rupture (f_m, MPa) and modulus of elasticity (E_M, MPa) according equations 1 and 2, respectively.

$$f_m = \frac{P_{rup}\,L}{bh^2} \quad (1)$$

$$E_M = \frac{P_{pl}\,L^3}{4.7bh^3d} \quad (2)$$

Where: P_{rup}, rupture load (N); L, beam span, mm; b, beam width, mm; h, beam heigh, mm; P_{pl}, load at proportional limit, N; d, beam deflection, mm.

2.3 STATISTICAL ANALYSIS

The results of $f_{gv,0}$ were analyzed by means of analysis of variance (ANOVA) followed by Tukey's test at 5% significance to identify difference between the means of the treatments. Subsequently, the results of were analyzed using a factorial design (2x2x2), evaluating the effect of the adhesive (PVAc and PUR), the surface preparation procedure (planing and sanding) and the assembly pressure (0.7 MPa and 1.0 MPa) on the $f_{gv,0}$. To analyse separately, the effect of surface preparation and assembly pressure within each type of adhesive on the $f_{gv,0}$ a double factorial analysis (2x2) was performed. One-way ANOVA was run to evaluate the effect of the adhesive type on bending properties (f_m and E_M) of the finger joints.

3 – RESULTS

In this study, the value of the shear strength of the solid wood ($f_{v,0}$) was about 11.4 MPa. In a study of 19-year-old *K. ivorensis* wood from a plantation in Brazil, it was founded $f_{v,0}$ values of 12.6 MPa for solid wood [3]. Appiah-Kubi [13], studying 43-year-old *K. ivorensis* in Ghana (the species' country of origin), reported a shear strength of 14.31 MPa for solid wood.

Figure 1 shows $f_{gv,0}$ values obtained in this study and it can be seen that values ranged from 11.36 to 15.54 MPa.

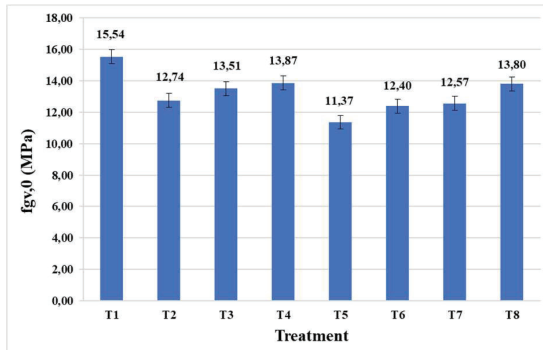

Figure 2: Glue line shear strength ($f_{gv,0}$) according to the treatment.

T1: PVAc/planing/0.7 MPa; T2: PVAc/planing/1.0; T3: PVAc/sanding/0.7; T4: PVAc/sanding/1.0; T5: PUR/planing/0.7 MPa; T6: PUR/planing/1.0; T7: PUR/sanding/0.7; T8: PUR/sanding/1.0

It can be also observed that most of the treatments presented $f_{gv,0}$ higher than $f_{v,0}$ except for T5 treatment whose value was lower. It means that both adhesive tested (PVAc and PUR) yielded bonding strength enough to be used for manufacturing bonded products. It is possible to observe that T1 showed the greater $f_{gv,0}$ wood and while treatments T3, T4, T5, and T8 the lowest.

In general, treatments using PUR adhesive (T5-T8) resulted in lower $f_{gv,0}$ compared to the PVAc bonded samples. The ASTM standard [11] further requires that all specimens within each treatment correspond to 30% of the shear strength of solid wood at 12% moisture content. And this value (30%) must be achieved by 90% of the specimens tested.

Table 2 shows the percentage of wood failure according to [11], which requires that each treatment must respect an average of 60% wood failure. It is observed that all the analysed treatments complied with the standard. However, treatments T5 and T6 showed a lower percentage of wood failure, indicating lower $f_{gv,0}$, value, which means that the PUR adhesive provides less bonding strength to this type of material.

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Table 2: Wood failure according to the treatments.

Treatment	WF (%)	Treatment	WF (%)
T1	72.3	T5	66.7
T2	89.5	T6	60.7
T3	71.5	T7	88.4
T4	73.7	T8	89.0

T1: PVAc/planing/0.7 MPa; T2: PVAc/planing/1.0; T3: PVAc/sanding/0.7; T4: PVAc/sanding/1.0; T5: PUR/planing/0.7 MPa; T6: PUR/planing/1.0; T7: PUR/sanding/0.7; T8: PUR/sanding/1.0

It is worth mentioning that both (T5 and T6) were bonded with PUR adhesive and a planer was used to prepare the bonding surface, which shows that this type of surface preparation did not favor the adequate adhesion of the wood. In general, the PVAc adhesive showed greater bonding strength for *K. ivorensis* wood, allowing us to say that PVAc has better efficiency compared to the PUR adhesive, where the average percentage of wood failure was 76.75 and 76.24%, respectively.

Table 3 presented the result of the statistical analysis for each factor separately. It was observed that there was a significant difference between the PVAc and PUR adhesives when this variable was analyzed separately. When analyzing the surface preparation variable, it is noted that there was no significant difference when using a planing or sanding.

The assembly pressure variable also did not differ statistically. The significant difference between the adhesives shows that the specimens bonded with PVAc had superior bonding strength compared to those bonded with the PUR adhesive

Table 3: Effect of adhesive type, surface preparation and assembly assembly pressure on the glue line shear strength ($f_{gv,0}$) of K. ivorensis.

Source of Variation		$f_{gv,0}$ (MPa)	Standard Deviation
Adhesive*	PVAc	13.96	2.59
	PUR	12.54	1.65
Surface Preparation^{NS}	Planing	13.03	2.55
	Sanding	13.44	1.97
Pressure^{NS}	0.7	13.25	2.74
	1.0	13.23	1.67

NS: non-statistically significant; * statiscally significant at 5%

Iwakiri et al. [14] found an average shear value of 7.10 MPa, obtained for *Cryptomeria* glued joints with PVAc adhesive, with a spread rate of 200 g/m², and the wood failure percentage values ranged from 54.50% to 87.50%. Vital et al. [15] found, for *Eucalpytus saligna* and *Eucalyptus grandis* woods glued with PVAc adhesive, wood failure percentages of 35.69% and 52.44%, respectively. In a study on *Eucalyptus benthamii* wood for the production of edged glued panels (EGP), Martins et al. [9] obtained $f_{gv,0}$ of 11.14 MPa for wood glued with PVAc adhesive and $f_{gv,0}$ of 10.72 MPa for wood glued with PUR adhesive, and wood failure percentages equivalent to an average of 95.06% for PVAc adhesive and 78.96% for PUR adhesive.

Recently, seven tropical wood have been evaluated regarding glue line shear strength and it was found that PVAc-bonded joints presented higher values of maximum load in comparison with those bonded using PUR [16]. On the other hand, the bonding behavior of further six tropical woods was studied and it was observed than the polymeric emulsion of isocyanate based adhesive yeield stronger joints than PVAc [17]

When analyzing sanding as the surface preparation, assembly pressure did not significantly influence bond strength. However, with planing, a pressure of 0.7 MPa resulted in greater bond strength. This difference can be explained by the fact that sanding creates a surface with greater exposure of wood pores, allowing the less viscous PVAc adhesive to achieve good wetting and penetration, regardless of the applied pressure. On the other hand, the surface prepared with the planer results in a vitrified surface, so the PVAc adhesive, being less viscous, can move excessively when receiving a assembly pressure above the necessary, that is, the adhesive runs off, forming an inefficient glue line.

Table 4 shows the effect of surface preparation and assembly pressure on glue line shear strength of PVAc-bonded wood. The surface preparation did not affect the $f_{gv,0}$ value, but the assembly pressure did.

Table 4: Effect of surface preparation and assembly pressure on the glue line shear strength ($f_{gv,0}$) of K. ivorensis *PVAc bonded wood joint.*

Source of Variation		$f_{gv,0}$ (MPa)	Standard Deviation
Surface Preparation^{NS}	Planing	14.26	2.72
	Sanding	13.69	2.46
Pressure*	0.7	14.53	3.07
	1.0	13.35	1.78

NS: non-statistically significant; * statiscally significant at 5%

The effect of surface preparation and assembly pressure was also evaluated within PUR-bonded wood joints (Table 5). It is possible to observe that surface preparation and assembly pressure had a significant effect on glue line shear strength of the PUR-bonded wood joint. Sanded surface and higher pressure yielded higher values of $f_{gv,0}$.

Table 5: Effect of surface preparation and assembly pressure on the glue line shear strength ($f_{gv,0}$) of K. ivorensis *PUR bonded wood joint.*

Source of Variation		$f_{gv,0}$ (MPa)	Standard Deviation
Surface Preparation*	Planing	11.87	1.73
	Sanding	13.19	1.28
Pressure*	0.7	11.97	1.53
	1.0	13.12	1.57

NS: non-statistically significant; * difference statiscally significant at 5%

The shear strength of wood bonded with PUR varied depending on the combination of surface preparation (sanding or planing) and assembly pressure (0.7 or 1.0 MPa). A more detailed analysis of the PUR adhesive's behavior could be obtained by investigating the interaction between surface preparation and assembly pressure.

PUR adhesive shear strength was influenced by both surface preparation and assembly pressure. With both planed and sanded surfaces, shear strength increased with increasing assembly pressure. The highest shear strength was observed with sanded surfaces at 1.0 MPa pressure. This behavior may be related to the higher viscosity of PUR adhesive. PUR likely requires a more porous surface (provided by sanding) and greater assembly pressure during pressing to achieve ideal adhesion. Planing, conversely, produces a smoother, less porous surface, which, combined with lower assembly pressure, may hinder the bonding process.

Regarding the modulus of elasticity and modulus of elasticity of the *K. ivorensis* wood, there was a significant difference between the PVAc and PUR adhesives (Table 6). The PVAc adhesive showed superiority over the PUR in terms of bending behavior of the finger joints.

Table 6. Effect of surface preparation and assembly pressure on the glue line shear strength ($f_{gv,0}$) of K. ivorensis *PUR bonded wood joint.*

Property	Adhesive	Mean (MPa)	Standard Deviation
Bending Strenght (f_m)*	PVAc	55.21	11.89
	PUR	29.77	4.34
Bending Stiffness (E_M)*	PVAc	9238.79	937.26
	PUR	8067.65	1947.33

*difference statiscally significant at 5%

The modulus of rupture in static bending was higher in the specimens that were bonded with the PVAc adhesive (55.21 MPa), then those bonded with PUR adhesive (29.77 MPa). The same behavior was observed for modulus of elasticity

Martins et al. [9] found values for *Eucalyptus benthamii* referring to the use of PUR and PVAc class D4 adhesives, where the PVAc adhesive proved to be superior to the PUR in relation to static bending strength, whose values were 68.0 MPa for PVAc D4 and 46.4 MPa for PUR.

Studying glued joints in *Fagus sylvatica* wood, using PVAc adhesive, Vassiliou et al. [18] found modulus of rupture values equivalent to 46.20 MPa, 64.45 MPa and 78.64 MPa for class D1, D2 and D3 adhesives, respectively. Karastergiou et al. [19] when evaluating the static bending strength using PVAc adhesive, obtained modulus of rupture values of 68.6 MPa for class D1 adhesives and 85.6 MPa for class D3 adhesives.

A recent study examined the influence of humidity and adhesive type on the bending strength and modulus of elasticity of finger-jointed beech wood [20]. Beech wood samples at different moisture contents were end-joined using PVAc and PUR adhesives and subjected to bending tests. The study found that PVAc adhesive resulted in better bending strength and modulus of elasticity compared to PUR adhesive.

Research on two lesser-used Mozambican wood species, messassas (*Brachystegia spiciformis* and *Julbernardia globiflora*), explored their potential for edge-glued panel production [21]. The results indicated that both species have medium density, and high extractive and lignin content, typical of tropical woods. Emulsion polymer isocyanate adhesive demonstrated better performance compared to PVAc D3 and D4 adhesives.

4 – CONCLUSION

The PVAc adhesive yeilded higher glue line shear strength to *K. ivorensis* wood, than PUR adhesive. The highest bonding strength was obtained by the specimens that were glued with the PVAc adhesive, using sanding for surface preparation of bonding and 0.7 MPa pressure.

Regarding the use of the PUR adhesive, the shear strength was influenced by the surface preparation and assembly pressure. The strength was greater when sanding and a assembly pressure of 1.0 MPa were used.

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All tested samples reached the required values according to the ASTM standard regarding strength and wood failure. The PVAc bonded finger joints showed to be stronger and stiffer in bending than those bonded with PUR.

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