Evaluation of Shear Strength and Wood Failure of Two African Mahogany Species Planted in Brazil

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Abstract

Interest in the wood industry of African mahogany (*Khaya* spp.) has increased in Brazil because of the quality of the wood and the similarity to the highly demanded Brazilian mahogany (*Swietenia macrophylla* King). The objective was to study the shear strength and wood failure of joints of 19-year-old plantation African mahogany species (*K. ivorensis* and *K. senegalensis*) bonded with four different commercially used adhesives in order to better evaluate the potential use of this material as a suitable replacement for Brazilian mahogany wood. The resins used in this study were urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), and emulsion polymeric isocyanate (EPI), and cross-linking polyvinyl acetate (PVAc) was used as a thermoplastic adhesive. PVAc yielded statistically higher shear strength for both species. For *K. ivorensis*, MUF, EPI, and PVAc reached the minimum value for shear strength as specified by ASTM International. However, with *K. senegalensis*, PVAc was the only adhesive to meet the standard. For *K. ivorensis*, PVAc and MUF resulted in statistically higher wood failure, and MUF, EPI, and PVAc met the required percentage of wood failure. In *K. senegalensis*, MUF and PVAc met the minimum requirement for wood failure. Based on the classification given by ASTM standards, the adhesives MUF, EPI, and PVAc can be used for nonstructural lumber products for *K. ivorensis*, and PVAC can be used in both species tested.

Wood is an excellent material for many different end uses. However, defects of wood, such as knots, splits, and decay, reduce the quality and quantity of material that can be used in the wood industry. Wood is considered easy to bond, and this property allows us to produce engineered wood products and to use wood in a more efficient way (Frihart and Hunt 2010).

High-density wood species are harder to glue because of lower glue penetration as well as a greater loss of adhesive at the edges of the part to be bonded, causing less effective bonding (Brady and Kamke 1988). The function of an adhesive is to bond two materials and to flow and fill empty spaces between the two surfaces to be bonded. This shorter distance between the material surface and the adhesive enhances interactions between the adhesive and the material itself (Pizzi 1994).

The use of glued wood is important because the transformation makes it a product of greater added value, mainly when there is greater use of the raw material, which may contribute to the definition of the final price of the product. This best use should be analyzed based on the quality and durability of the finished product (Gonçalves et al. 2016).

The adhesives used for glued lumber are thermosets or thermoplastics. Thermosets cure by the action of heat and/or a catalyst. The joints are stiff and more resistant to a moist or hot environment than other types of adhesives, such as phenolics, ureics, and melamines, which are examples of thermosets adhesives. Thermoplastics adhesives, such as

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polyvinyls, can be solidified by evaporation of the solvent (water), resulting in a low thermal and moisture resistance bonding (Gierenz and Karmann 2001).

Wood from reforestation has been increasing considerably, especially in sectors such as building construction, packing, wood panels, and furniture (Motta et al. 2014). The correct choice of adhesive type is decisive for the success of the gluing operation because it has an auxiliary function in the transference and distribution of loads between the components, increasing the rigidity of wood products (Frihart and Hunt 2010). Eucalyptus and pine are the major plantation grown species planted in Brazil. Other wood grown includes *Acacia mearnsii*, *Hevea* spp., *Tectona grandis*, *Schizolobium amazonicum*, and *Araucaria angustifolia*. In addition to these species, African mahogany has attracted interest as a lumber product in Brazil because of its similarity in quality to Brazilian mahogany (*Swietenia macrophylla*).

African mahogany wood finishes and stains well, provides a satisfactory adhesive bond, and is widely used for veneer and lumber products (Kukachka 1969). However, there is lack of information about the gluing properties of this wood planted in Brazil. Therefore, the objective of this study was to evaluate the shear strength of bonded joints of two African mahogany species (*Khaya ivorensis* and *Khaya senegalensis*) from Brazil with four types of adhesives.

Materials and Methods

Test specimens

Five 19-year-old trees of each species (*K. ivorensis* and *K. senegalensis*) were obtained from an experimental plantation located in Sooretama, Brazil. Each tree was cut into logs approximately 3 m in length (for this study, the second log was used) from which 8.0-cm-thick planks were cut. The planks selected for this study were located under the bark and had the presence of sapwood and heartwood. The planks were then air-dried for a period of 5 months. Samples measuring 40.0 by 5.0 by 2.5 cm (length by width by thickness in the radial direction) were cut from these planks (Fig. 1). For both species, the average moisture content was 10.8 percent.

Adhesives properties

For this study, three thermosetting adhesives, melamine-urea-formaldehyde (MUF), urea-formaldehyde (UF), and emulsion polymer isocyanate (EPI), and one thermoplastic adhesive, cross-linking polyvinyl acetate (PVAc), were evaluated. The adhesives used in this research are commercially available and could be used with no need for preparation or addition of other components. Table 1 shows a summary of the applications for the adhesives used in this study.

The pH, solid contents, and viscosity of each adhesive were determined. To determine the pH, three replicates were used. Since UF and PVAc have a light color, a dye (aniline) was used to facilitate the determination of wood failure.

The pH was determined using a benchtop digital pH meter at room temperature. The viscosity was determined using a Brookfield viscometer, and the test followed ASTM D1084 (ASTM International 2016).

The solid contents were determined according to ASTM D1582-98 (ASTM International 2017). To determine the solid content, 3 g of adhesives was put into the aluminum

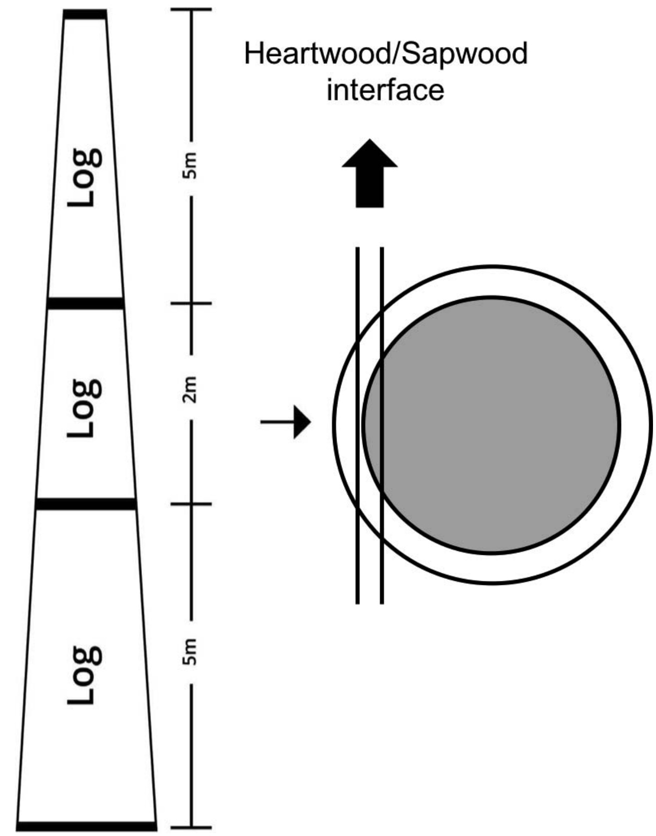

Figure 1.—Schematic cross section of African mahogany logs identifying sampling locations.

weighting dish, and the initial weight was recorded. For this test, three replicates of each adhesives were used. The samples were placed into the oven in a temperature of 103°C ± 2°C for 24 hours.

Adhesive preparation and mechanical tests

The adhesives were applied using a spatula to better distribute the adhesives through the pieces. The amount of the adhesive recommended by the manufacturers for MUF is 400 to 450 g/m^2, for UF is 80 to 280 g/m^2, for EPI is 150 to 300 g/m^2, and for PVAc is 120 to 250 g/m^2. This study used standardized granules for all adhesives tested. A total rate of about 300 g/m^2 of glue line for each piece was applied (150 g/m^2 applied on each piece that was bonded). Approxi-

Table 1.—Summary of adhesive applications.[a]

Adhesives	Applications of adhesive[b]
MUF	Composite panels, particleboard, and medium-density fiberboard (MDF)
UF	Particle board, plywood, and MDF
EPI	Solid wood panels, parquet, window frames, furniture parts, plywood, finger joints, glulam beams, and I-beams
PVAc	Plywood boards, laminates, and furniture

[a] MUF = melamine-urea-formaldehyde resin; UF = urea-formaldehyde resin; EPI = emulsion polymeric isocyanate; PVAc = cross-linking polyvinyl acetate.
[b] Source: AkzoNobel.

mately 15 minutes after the pieces were glued, the bonded joints were pressed on an EMIC hydraulic press for 6 hours at a pressure of 1 MPa at a room temperature of 25°C ± 2°C (Fig. 2).

After pressing, samples were conditioned for a period of 30 days in accordance with the adhesive manufacturers' recommendations for adhesive curing and subsequent preparation of the samples following ASTM D905-08 (ASTM International 2013b).

The shear strength test of the glue line was conducted according to ASTM D905-08 (ASTM International 2013b) on a universal testing machine with a capacity of 10 tons. Wood failure was evaluated according to ASTM D5266-13 (ASTM International 2013a). A total of 120 samples per species (30 for each adhesive) were tested.

Statistical analysis

SAS version 9.4 software (SAS Institute Inc. 2014) was used to perform the statistical analysis. Differences in shear strength and percent wood failure between adhesives and species were compared using the Tukey test ($\alpha = 0.05$).

Results and Discussion

A summary for the adhesives properties is shown on Table 2. All adhesives were inside the expected pH as stipulated by the manufacturer. The viscosity obtained in this study (47.11 Pa/s) was higher than the expected value specified by the manufacturer. However, the values were lower compared with the viscosity found by Gonçalves et al. (2016) and Segundinho et al. (2017) (72.42 Pa/s). According to Iwakiri (2005), the high viscosity of UF can make the

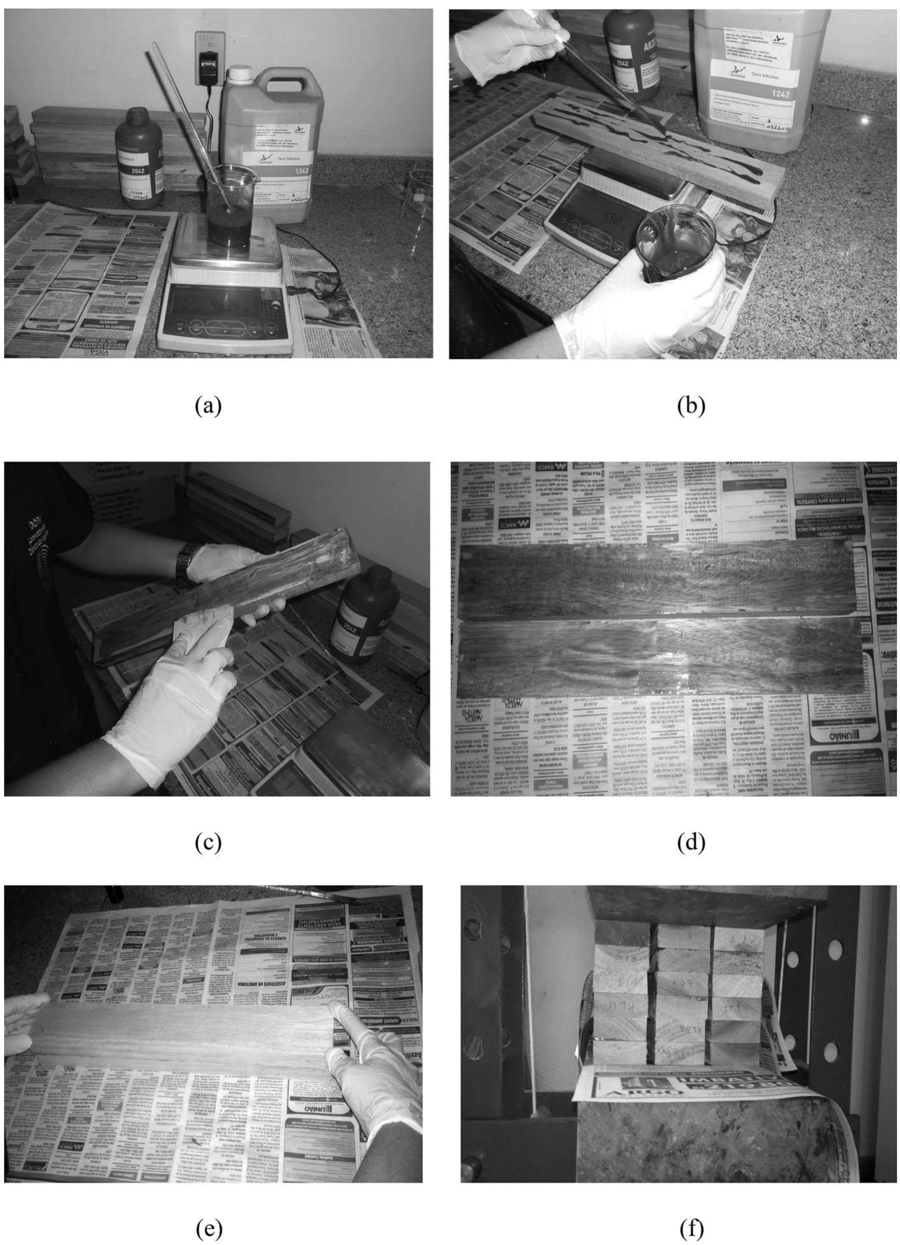

Figure 2.—Sequence of application of the adhesives on wood specimens: (a) weighting the adhesive, (b) adhesive application, (c) distribution of the adhesives, (d) sample with adhesive, (e) samples joined with adhesive, and (f) samples being pressed.

Table 2.—Physical and chemical properties of the adhesives tested.[a]

Adhesives	pH expected[b]	pH found	Viscosity expected (Pa/s)[b]	Viscosity found (Pa/s)	Solid contents expected (%)[b]	Solid contents found (%)
MUF	7.8–8.5	8.8	11 (12 rpm)	10.85 (12 rpm)	62	70
UF	7.5–9.0	7.6	31 (1.5 rpm)	47.11 (1.5 rpm)	64	58
EPI	7.0–8.5	7.1	8–15 (6 rpm)	9.28 (6 rpm)	53–55	53
PVAc	2.5–3.5	2.7	1.5–4 (60 rpm)	3.95 (60 rpm)	43–45	54

[a] MUF = melamine-urea-formaldehyde resin; UF = urea-formaldehyde resin; EPI = emulsion polymeric isocyanate; PVAc = cross-linking polyvinyl acetate.
[b] Source: AkzoNobel.

adhesive more difficult to spread and also lower the penetration into the wood, affecting shear strength values. For solid contents, EPI was the only adhesive that met the solid contents expected, and MUF showed the highest solid content mean values.

Table 3 shows the mean values of shear strength and the coefficients of variation for both species. For shear strength, there was a significant difference between adhesives ($P < 0.05$). The adhesive PVAc showed the highest significant mean values for *K. ivoresnsis* and *K. senegalensis* (12.2 and 11.6 MPa, respectively). For *K. ivorensis*, UF and EPI (6.1 and 7.1 MPa, respectively) had a significantly lower shear strength value. For *K. senegalensis*, UF (5.5 MPa) was significantly lower than the other adhesives tested, followed by EPI (8.0 MPa).

There was no significant difference in shear strength between adhesives within the species, except for MUF, where the shear strength of *K. senegalensis* (9.7 MPa) was significantly greater ($P < 0.0259$) than that of *K. ivorensis* (8.0 MPa).

According to ASTM D5751-99 (ASTM International 2012), the average shear strength (parallel to grain) should reach 60 percent of the shear strength of solid wood. França et al. (2015) evaluated the mechanical properties of *K. ivorensis* and *K. senegalensis* wood (same material used in this study) and found shear strengths of 12.7 and 18.7 MPa, respectively.

In accordance with this standard, MUF, EPI, and PVAc for *K. ivorensis* reached the minimum value of shear strength (9.0, 7.1, and 12.2 MPa, respectively). However, only PVAc (11.6 MPa) reached the minimum value of shear strength for *K. senegalensis*.

Table 4 shows the mean values and coefficients of variation for wood failure for both species. Overall, *K. ivorensis* showed the higher mean values. There was a significant ($P < 0.05$) difference between adhesives, where the thermosetting MUF and the thermoplastic PVAc showed significantly higher wood failure for *K. ivorensis*.

MUF was significantly ($P < 0.05$) higher in percentage of wood failure for *K. senegalensis*. There were significant differences between species for UF ($P < 0.0285$), EPI ($P < 0.0001$), and PVAc ($P < 0.0044$).

In accordance with ASTM D5751-99 (ASTM International 2012), the minimum request of wood failure for hardwood species is 30 percent. In the present study, MUF, EPI, and PVAc for *K. ivorensis* reached the minimum required at the standard for wood failure; for *K. senegalensis*, only MUF and PVAc met the standard for wood failure. According to Vital et al. (2005), high wood failure is indicative of good bond quality, and the high percentage of wood failure with PVAc may justify the high shear strength.

The mean value for density of *K. senegalensis* (0.59 g/cm^3) is higher than that of *K. ivorensis* (0.49 g/cm^3) (França et al. 2015). The higher density of *K. senegalensis* may explain the lower shear strength for UF and the lower wood failure for UF, EPI, and PVAc of *K. senegalensis*. Anatomical characteristics also have an influence on the adhesive performance. According to Frihart and Hunt (2010), high-density wood has thicker cell walls and smaller lumen diameters that reduce the penetration of the adhesive into the wood.

França et al. (2015) reported that the vessel diameter of *K. ivorensis* (132.31 μm) was significantly larger than that of *K. senegalensis* (98.68 μm) wood. The extractives may interfere with the cure of the adhesive. Another influence may be the extractives, where França (2014) reported that *K. ivorensis* was significantly higher than *K. senegalensis* wood for all extractives tested (ethanol:toluene; hot water and cold water).

Lima et al. (2007) studied the influence of anatomical characteristics and chemical influence on bonding with UF resins of different *Eucalyptus* clones and found that vessel diameter and extractives content have an influence on the performance of the adhesives, where clones with larger vessels and lower extractive content showed better shear strength and wood failure values.

Lima et al. (2016) evaluated the quality of bonded joint of *K. ivorensis* planted in Brazil using resorcinol-formaldehyde, phenol-formaldehyde, and UF. UF had the lowest shear strength and wood failure among the adhesives tested, similar to this study. However, for shear strength (3.1 MPa)

Table 3.—Shear strength means and coefficients of variation (%, shown in parentheses) in 19-year-old Khaya ivorensis *and* Khaya senegalensis *planted in Brazil with different types of adhesives.*[a]

Species	Shear (MPa)			
	MUF	UF	EPI	PVAc
K. ivorensis	8.0 Bb (29.4)	6.1 Ca (29.4)	7.1 BCa (29.4)	12.2 Aa (29.4)
K. senegalensis	9.7 Ba (36.9)	5.5 Da (36.9)	8.0 Ca (36.9)	11.6 Aa (36.9)

[a] Means with the same letter designation are not significantly different (P value > 0.05). Uppercase letters represent comparisons among adhesives, and lowercase letters are comparisons between species. MUF = melamine-urea-formaldehyde resin; UF = urea-formaldehyde resin; EPI = emulsion polymeric isocyanate; PVAc = cross-linking polyvinyl acetate.

Table 4.—Percentage of wood failure and coefficients of variation (%, shown in parentheses) for 19-year-old Khaya ivorensis *and* Khaya senegalensis *planted in Brazil.*[a]

Species	Wood failure (%)			
	MUF	UF	EPI	PVAc
K. ivorensis	80.0 Aa (22.9)	29.2 Ba (22.9)	35.0 Ba (22.9)	85.0 Aa (22.9)
K. senegalensis	69.0 Aa (27.7)	18.3 Cb (27.7)	18.0 Cb (27.7)	55.0 Bb (27.7)

[a] Means with the same letter designation are not significantly different (P value > 0.05). Uppercase letters represent comparisons among adhesives, and lowercase letters are comparisons between species. MUF = melamine-urea-formaldehyde resin; UF = urea-formaldehyde resin; EPI = emulsion polymeric isocyanate; PVAc = cross-linking polyvinyl acetate.

and wood failure (47.2%), the results were lower compared with the present study.

Armstrong et al. (2007) tested the shear strength in the glue line with UF resin of 32-year-old *K. senegalensis* wood planted in Australia. The samples used in this study were obtained approximately to breast height position with no sapwood. The mean value of shear strength for the solid wood was 17.3, MPa, while the mean shear value for the glued samples was 16.9, which is higher than the mean value found in the present study, and the glued samples reached 97 percent of the shear value for solid wood. This higher shear strength may be due to the age of the trees, which implies a greater amount of mature wood compared to the trees used in this study. According to Groom and Leichti (1994), younger trees have a greater proportion of juvenile wood, which decreases the physical and mechanical properties of the material.

The behavior of the adhesives found in this study are similar to studies in the literature for other species. Martins et al. (2013) studied the bonding behavior of *Eucalyptus benthamii* wood planted in Brazil used to manufacture edge-glued panels using PVAc and polyurethane (PUR). PAVc had a higher shear strength and higher wood failure than the PUR-based adhesives.

Motta et al. (2014) evaluated shear strength of bonded joints using UF and PVAc for 15-year-old teakwood planted in Brazil. Similar to this study, PVAc had the highest glue line shear strength compared with the other adhesives tested. Wang et al. (2012) evaluated the behavior of *Picea abies* exposed to temperatures between 20°C and 60°C with four different adhesives (PUR, PVAc, EPI, and MUF). PVAc also showed the best results for all temperatures and adhesives.

Conclusions

This study investigated the shear strength and wood failure of *K. ivorensis* and *K. senegalensis* wood planted in Brazil. The results of this study show the following.

- The adhesive PVAc yielded a higher shear strength mean value for both species tested.
- For *K. ivorensis*, the adhesives MUF, EPI, and PVAc reached the minimum shear strength value stipulated by the standard.
- For *K. senegalensis*, PVAc was the only adhesive that reached the minimum shear strength value stipulated by the standard.
- The *K. ivorensis* glued joints with PVAc was the only adhesive to have a shear strength value inside the range for solid wood.
- There was no significant difference in shear strength mean value between species for MUF, where *K. senegalensis* was significantly higher than *K. ivorensis*.
- MUF and PVAc were significantly higher in wood failure for *K. ivorensis* wood.
- MUF was significantly higher in wood failure for *K. senegalensis* wood.
- For *K. ivorensis*, all adhesives tested reached the minimum wood failure value required by the standard.
- For *K. senegalensis*, MUF and PVAc reached the minimum wood failure value required by the standard.

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