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Enhancing Structural Application: Assessing the Suitability of Sawn and Glue Laminated *Albizia zygia* (Ayunre) Timber for Sustainable Construction

Olurotimi Olusegun Ekundayo[1], Chinwuba Arum[2,3], and Lovelt Temilola Shittu

[1]*Department of Building Technology, Federal University of Technology, Akure, Nigeira*

[2]*Department of Civil and Mining Engineering, JEDS Campus, University of Namibia, Namibia*

[3]*Department of Civil Engineering, Federal University of Technology, Akure, Nigeria*

Corresponding author's Email: ooekundayo@futa.edu.ng

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ABSTRACT

Leading economies are moving towards a bio-based economy for sustainability, but Africa struggles to utilize its bio- resource such as timber for advanced engineering application due to its natural limitations. Nevertheless, glue lamination (glulam) is promising for enhancing wood for structural application. Hence, this study investigated the shear strength of glue laminated (glulam) joints of *Albizia zygia* (*A. zygia*) timber species bonded with polyurethane (PUR) adhesive and other essential physical and mechanical properties in line with relevant standards. Briefly state the methodology before results to ensure flow. The results showed that the mean density of the wood species is 519 kg/m^3 at a mean moisture content of 12%. The wood recorded a mean volumetric shrinkage and volumetric swelling of 1.17% and 6.52% respectively. Other properties include mean bending strength at 53.89N/mm^2, mean stiffness at 6106 N/mm^2, compressive strength parallel to grain at 32.70N/mm^2 and mean tensile strength at 33.61N/mm^2. Furthermore, the lap shear strength for glue laminated joints was tested according to EN 302-2013 standard and compared to control solid beams. The mean shear strength for glulam was 2.32N/mm^2 while it was 1.64N/mm^2 for the control beams. Thus, the glued joints performed better in shear than the control specimen. Finally, the residual shear strength of the joints was a mean value of 1.28N/mm^2 after subjecting them to accelerated aging tests (AAT). This is equivalent to 44.83% decrease of the shear strength in the dry use state. Hence, glue laminated *A. zygia* using PUR is not suitable for external use due to weathering effects on its shear strength. Based on the findings in this study, *A. zygia* is a moderately dense wood suitable for structural use but for interior application when laminated with PUR. It is shown that locally sourced *A. zygia* can be enhanced through glue lamination for structural joints in service class 2 according to Eurocode 5.

Keywords: Glued joints, adhesives, Polyurethane, Tensile shear strength and *Albizia zygia*

INTRODUCTION

In recent years, there has been an emergence of global sustainability campaign. The United Nations established Sustainable Development Goals (SDGs) in 2015 to achieve balance in economic, social, and environmental development by 2030 (Rosati and Faria, 2019). CO_2 emissions and environmental preservation have since then become the rallying points of social development (Wang and Wang, 2018). Wood is a preferred green building material because of its low carbon footprint (Martinez, 2015) and efficient strength-to-weight ratio (Ramage et al., 2017). However, biodegradability and dimension constraints limit its robust application. Hence, due to these limitations, technological solutions such as glue lamination have been developed. Wood is a lignocellulose polymer, adaptable for high quality engineered wood products (EWP), such as glued laminated timber (glulam) (Ekundayo et al. 2022). Glulam, utilizing structural adhesives for lapped wood joints, offers superior strength compared to sawn timber (Nadir and Nagarajan, 2014). Structural adhesives have long been utilized to enhance the load-bearing capacity of wood products intended for structural use.

Glulam is not an entirely new endeavor in Nigeria, as some research efforts have explored adhesive use to enhance properties of local wood species (Adebayo, 2020; Ekundayo et al., 2021; Ekundayo et al. 2022). Furthermore, studies on hard wood species like *Albizia zygia* indicate its durability and diverse uses, including structural applications (Ogunwusi, 2012; Jimoh et al., 2017). However, despite significant interest in this wood species and its properties, its gluing capability for engineered wood products especially at joints is

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unreported. This study therefore aims to investigate the performance of glued joints using industry-standard adhesives like polyurethane (PUR) which is important for structural use. Successful stress transfer at joints using glue lamination is critical for engineered wood product as this offers flexibility in design, CO_2 mitigation, and efficient stress transfer without the typical failure modes common to other fastening methods such as bolts, staples, pins and dowels which can damage wood fibre extensively.

Furthermore, Polyurethane Resin (PUR) adhesive was selected for this study due to its availability, versatility, ease of application, and compatibility with various wood types, including hardwood, softwoods, and modified wood (Shirmohammadli et al., 2023; Sastri, 2022). Notably, it bonds well to untreated high-moisture wood and is formaldehyde-free, gaining traction in the engineered wood product industry (Lehringer and Gabriel, 2014; Shirmohammadli et al., 2023). Although optimal at low temperatures, its bond strength weakens above 150°C (Sastri, 2022). PUR adhesives produce durable bonds with solvent and chemical resistance, offering adaptability in curing shapes and penetration into wood bonding sites (Sastri, 2022). One-part PUR can penetrate active bonding sites in wood for polymerization and curing to around 9.5 mm limited only by moisture dispersion (Sastri, 2022). The use of wood in Nigeria is still largely rudimentary hence this research is an attempt at enhancing the mechanical performance of local wood species for what will be strategic in the transition to sustainable construction.

MATERIALS AND METHODS

Sample preparation

The two major materials used for this research work were *A. zygia* timber and polyurethane resin (PUR) adhesive. The timber specie was sourced and sawn from Igbara-oke town in Ondo state of Nigeria. The wood was gathered as planks with the dimensions 50 mm x 300 mm x 3600 mm and was inspected to ensure it was free of defects and rot. It was thereafter transported in a pick-up van to the building department workshop and also Forest and Wood Technology workshop of the Federal University of Technology, Akure which is the study area located at 7°15′0″N 5°11′42″E as shown Figure 1 (Bing images, 2024). The one-part polyurethane adhesive was sourced from Lagos, Nigeria as the bonding agent.

Wood samples of 20 mm × 20 mm × 60 mm were prepared for the determination of basic physical properties (moisture content, density, volumetric shrinkage and swelling) and compressive strength test. The moisture content of the samples was determined by placing them in an electric oven at a temperature of 105°C for 24 hours. The weight measurements for calculating the density were taken using an electronic weighing balance that shows values up to 0.1 decimal place.

All the mechanical properties test were done on a universal testing machine equipped with a computerized data acquisition system at the Department of Agricultural Engineering, Federal University of Technology, Akure. Wood samples with dimensions 20 mm × 20 mm × 300 mm and 5 mm × 20 mm × 180 mm were prepared for bending strength and tensile strength tests respectively according to ASTM D143-21 (2021) Planks for producing glued laminated specimens were glued and clamped as shown in Figure 2 for 24 hours. After 24 hours, the samples were resized to 6 mm×20 mm×150 mm as shown in Figure 3 for evaluating lap shear strength.

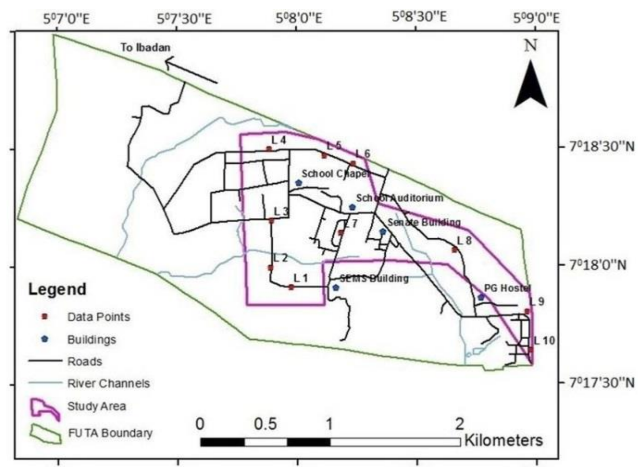

Figure 1. Map of the Federal University of Technology, Akure


Figure 2. Clamping of laminates

Figure 3. Resized, glued joints specimen.

Moisture content and density

Moisture content was determined according to (Eq.1) after subjecting the green samples to oven drying for 24 hours at 103±2°C.

$$MC = \frac{Mw - M_d}{M_d} \times 100 \quad (1)$$

Where; M_w is green weight in grams; M_d is dry weight in grams.

Also, the wood density was determined using (Eq.2):

$$\rho = \frac{M}{V} \quad (2)$$

where M is the mass of wood in kilograms; V is the volume of wood in cubic meter

Volumetric shrinkage and swelling

The volumetric shrinkage was determined according to (Eq.3) after subjecting the green samples to oven drying for 72 hours at 103±2°C.

$$S_s = \frac{Vw - V_{od}}{V_{od}} \times 100 \quad (3)$$

where S_s is the volumetric shrinkage value; V_{od} is the oven dried volume (final volume); V_w is the initial wet volume.

Similarly, the volumetric swelling was determined according to (Eq.4) after immersing dry wood samples in water for 72 hours.

$$S_w = \frac{Vw - V_{od}}{Vod} \times 100 \quad (4)$$

where S_w is the volumetric swelling value; V_{od} is the oven dried volume (initial volume)

V_w is the final wet volume

Bending strength

Bending strength, was determined for a total of nine (9) wood samples (Figure 4). The bending strength that is the modulus of rupture (MOR) was determined through a three-point test on a universal testing machine (Figure 5) and calculated using (Eq 5):

$$f_b = \frac{3 \times P_{max} \times L}{2 \times b \times h^2} \quad (5)$$

where: f_b is the bending strength; P_{max} is the maximum load; L is the loading span, b is the breadth; h is the thickness.

Figure 4: Samples after bending strength test

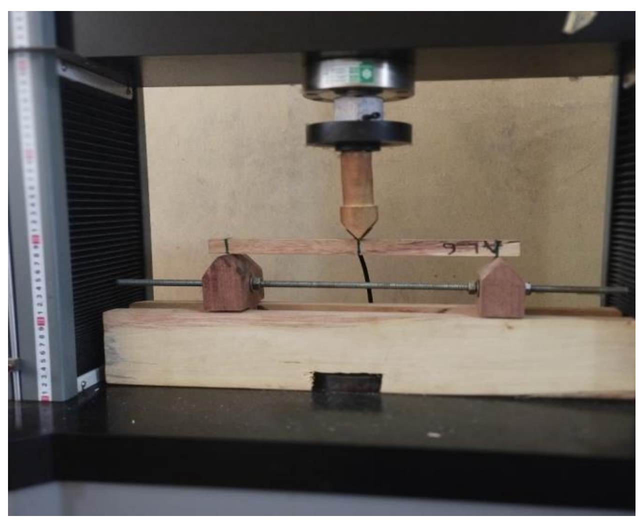

Figure 5: Bending strength sample on UTM

Modulus of elasticity (MOE)

Furthermore, modulus of elasticity in bending was determined for the wood species using (Eq 6):

$$MOE = \frac{PL^3}{4 \times \Delta \times b \times h^3} \quad (6)$$

where; P is maximum load within the limit of proportionality; L is span of the test specimen within the limit of proportionality; b is breadth of the test specimen; h is depth or mean thickness of the test specimen (mm); Δ is the deflection within the elastic limit.

Tensile strength

Tensile strength was determined on the wood sample using a universal testing machine. It is obtained using (Eq.7).

$$f_t = \frac{P}{A} \quad (7)$$

where: f_t is the tensile strength; P is the maximum tensile load; A is the cross-sectional area

Compressive strength

Compressive strength was determined on the wood sample using a universal testing machine. Compressive strength was determined using (Eq.8).

$$f_c = \frac{P}{A} \quad (8)$$

where: f_c is the compressive strength; P is the failure load; A is the cross-sectional area of the specimen

Lap shear strength

Lap shear test was determined on the wood specimens (Figure 6 and 7) using a universal testing machine, according to EN 302-1:2013. The cross-head displacement control rate was 1 mm/min. With F as the applied load and A as the bonded area (approximately 120 mm^2), tensile shear strength was then determined as the maximum stress at the breaking point of the material, according to (Eq.9).

$$f_{st} = \frac{P}{A} \quad (9)$$

where: f_{st} is the tensile shear strength; P is the failure load in tension; A is the cross-sectional area

Figure 6. Samples on UTM.

Figure 7. Wood samples after testing

Accelerated aging tests (AAT)

Accelerated aging test was carried out on the glulam wood sample by boiling for two hours, and freezing for two hours in three repeated cycles for a total of twelve hours (six hours for boiling and six hours for freezing). Then, the shear strength of the glued lapped joints subjected to accelerated aged glulam was tested on the universal testing machine and calculated using (Eq. 9).

RESULTS AND DISCUSSION

Density

The mean density of *A. zygia* wood was 519 $\mathrm{kg/m^3}$ at a standard moisture content of 12%. Wood having density of between 500 kg/m^3 and 650 kg/m^3 is classified as moderately heavy (Panda., 2008). Therefore, *A. zygia* is found to be a moderately heavy wood.

Volumetric Shrinkage and Swelling

Table 1 shows the result for volumetric shrinkage and volumetric swelling for the wood samples. Dimensional stability behavior in timber is a critical design consideration especially for wood that is to be deployed for structural engineering application. Dimensional movements occur in timber because it is a hygroscopic material which responds to ambient moisture content within the environment. For *A. zygia* , the values of the mean shrinkage as a result of moisture loss were 1.17% for shrinkage and 6.52% for swelling. The swelling values obtained are smaller compared to hard wood species such as *Celtismildbraedii* (11.36 %), *Khayaivorensis* (10.46 %), *Meliceaeexcelsa* (10.12 %), *Afzeliaafricana* (7.5 %)

(Jamala et al., 2013). It is however similar to *Triplocyton scleroxylon* (6.44 %) and 9.57 %, 8.83 % and 7.74 % for the top, middle and basal portion of Gmelina arborea according to Owoyemi et al. (2015). Based on a similar study by Sadiku, (2018). *A. zygia* is grouped as a small movement wood species in terms of its dimensional stability and falls in the same class with wood species such *V. paradoxa, A. africana,* and *Ivorensis doka*

Table 1. Results of basic physical properties of sawn *A.zygia*

Specimen	Density (kg/m^3)	Volumetric Shrinkage (%)	Volumetric Swelling (%)
1	458.00	1.58	6.18
2	592.00	0.29	4.65
3	450.00	2.04	6.25
4	629.00	1.54	6.09
5	608.00	0.42	9.44
Mean	547.40	1.17	6.52

Bending strength of sawn A. zygia

The mean bending strength of *A. zygia* was 53.89 $\mathrm{N/mm^2}$ at a mean moisture content of 12% is slightly lower than the existing range of 55.51- 86.00 N/mm^2 reported in literature (Adegoke et al., 2011). The mean bending strength complies with BS 5268 part 2 for D30 strength class. This implies that it is comparable to wood species such as Oak. The result is however lower than the Mozambiquan variant with an internationally published value of 69.75 N/mm^2 (Mepepe (*Albizia zygia*) | ITTO, n.d). This can be due to the effect a tree's origin has on its growth in response to prevailing climatic conditions. Fréjaville et al. (2019) observed that the environment in which a tree grows impacts on the tree's phenotype thus leading to variations in properties, such as wood quality. Similarly, Munalula et al. 2016 also highlighted that wood quality is influenced by variations in climatic conditions (which also vary between different regions) affecting the growth of the parent tree.

The relationship between the MOR values and density at 12% moisture content is shown in Figure 8. From the graph, it can be deduced that the higher the density, the higher the bending strength of wood.

Modulus of elasticity of sawn A.zygia

Table 2 shows the values of MOE for the nine samples of *A.zygia* subjected to bending strength test. The mean value of MOE in bending was 6106 N/mm^2 which is lower than the mean values of 14092.18 N/mm^2 and 10462 N/mm^2 reported by Jimoh et al. 2017 and Mepepe (*Albizia zygia*)| ITTO, n, d) respectively. However, it is unclear in both cases if the 2 in standard or the 2 cm standards of BS 373 (1957) similar to ASTM D143 (2014) was used Recast for clarity. However, the values reported in this study are in line with the 2 cm standard of BS373 (1957) which is similar to ASTM D143. Nevertheless, the calculated mean stiffness value is within the range specified in BS 5268 part 2 (6000 N/mm^2 to 9500 N/mm^2) for D 30 strength class.

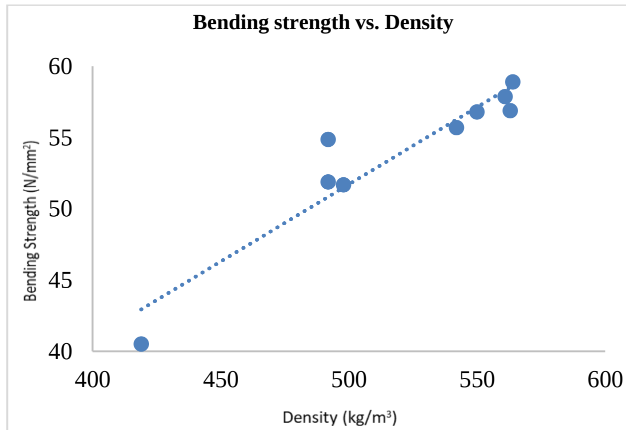

Figure 8. Graph of MOR against density at 12% moisture ontent

Table 2: Results of Modulus of elasticity in bending

Specimen	P_{max} (N)	f_b (N/mm^2)	Deflection (mm)	MOE (N/mm^2)
1	831	40.49	4.23	5400
2	1064	51.87	4.95	5900
3	1060	51.68	5.06	5750
4	1125	54.86	5.15	6000
5	1142	55.68	4.98	6300
6	1165	56.78	5.16	6200
7	1187	57.87	5.26	6200
8	1167	56.87	4.93	6500
9	1208	58.89	4.95	6700
Mean	1105.44	53.89	4.96	6106

Tensile strength of sawn A.zygia

Table 3 shows the tensile strength results at a mean moisture content of 12.10% check this value. The tensile strength of wood contributes to the engineering property of elements such as beams. Similarly, it ensures that wood structural elements subjected to large load variations can undergo gradual failure that give warning signs and allow for possible repair interventions.

Table 3. Tensile strength results.

Specimen	Failure load (N)	Tensile strength (N/mm^2)	Density (kg/m^3)	Moisture content (%)
1	1887	36.28	440	12.2
2	1886.1	36.27	433	11.7
3	1578.2	30.35	378	12.1
4	1747.2	33.6	428	12.1
5	1639	31.51	456	12.4
Mean	1747.5	33.61	427	12.1

Compressive strength of sawn A.zygia

Table 4 shows the compressive strength for *A.zygia* wood specimens at a mean moisture content of 12%. The mean value of the compressive strength is 42.70 N/mm^2 at mean moisture content of 12%. This is similar to the findings of Rahmon and Jimoh (2020), who recorded a mean compressive strength value of 36.84 N/mm^2.

Table 4. Compressive strength parallel to grain

Specimen	Failure load (N)	Compr. strength (N/mm^2)	Density ($kg/m3$)	Moisture content (%)
1	18172.00	45.43	642.00	12.5
2	19596.00	48.99	600.00	10.8
3	18444.00	46.11	529.00	11.7
4	14470.00	36.18	454.00	12.2
5	14724.00	36.81	475.00	13.2
Mean	17081.20	42.70	540.00	12.08

Lap shear strength

Figure 9 shows the shear strength of glue laminated specimens at a mean moisture content of 7.17%. There were notable differences between the shear strength of the control beams and the glue laminated specimens (Figure 9). The glued laminated lapped joints had a mean shear strength of $2.32N/mm^2$ while the control beams had a mean shear strength of $1.64N/mm^2$. This shows that the glue laminated specimens had greater shear strength than the control specimens. Figure 9 shows the shear strength of control specimens (sawn wood) at a mean moisture content of 7.68%. However, it was observed that the values obtained in this study were evidently lower than those reported by Olaniran et al. (2021) who used similar specimens downscaled from the recommendations of EN 302:2013. The specimens in this current study were however further downscaled as a result of the limitation in the maximum thickness the jaws of the universal testing machine can accommodate. This clearly led to a reduction in the shear capacity of the wood specimen and the shear area of the glue line. Consequently, size effects played a crucial role in the shear capacity of the lapped joints as attested to by Sahin and Akpinar (2021).

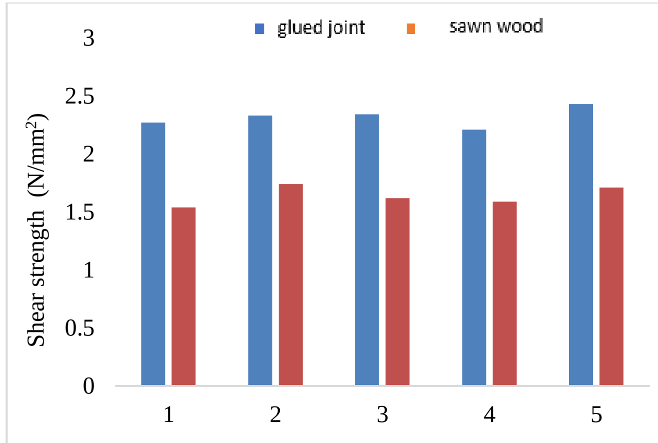

Figure 9. Lap shear strength of glued joints vs control specimen

Accelerated aging test

After three cycles of boiling and freezing the glue laminated specimens for a total of 12 hours, they had the following shear strength recorded in Table 5. The values of the strength are seen to reduce as a result of repeated cycles of boiling and freezing which affected the glued joints coupled with the increase in the moisture content of the samples as a result of prolonged soaking in water. Thus, upon subjecting the samples to AAT, 45 % of the strength in the dry use state was lost. This aligns with the findings of Raftery et al. 2024 who reported general strength reduction in the shear strength of 1C-PUR bonded wood specimens subjected to vacuum-pressure soak.

Table 5. Results of AAT on bonded lap joints

Specimen	Failure load (N)	Shear strength (N/mm^2)
1	375	1.25
2	384	1.28
3	369	1.23
4	393	1.31
5	390	1.30
Mean	384	1.28

Failure mode of joints

Specimens of the lapped joints even though stronger than the control specimen failed along the glue lines after the accelerated ageing test due to the effect of repeated cycle of heating and freezing, wetting and drying as shown in Figure 10a. This demonstrates that wood joints bonded with PUR adhesive under severe moisture and temperature exposure conditions will eventually suffer in-service delamination. Wood failure is the desired failure mode in laminated joints which was prominent in the specimens in the dry use condition as shown in Figure 10b.

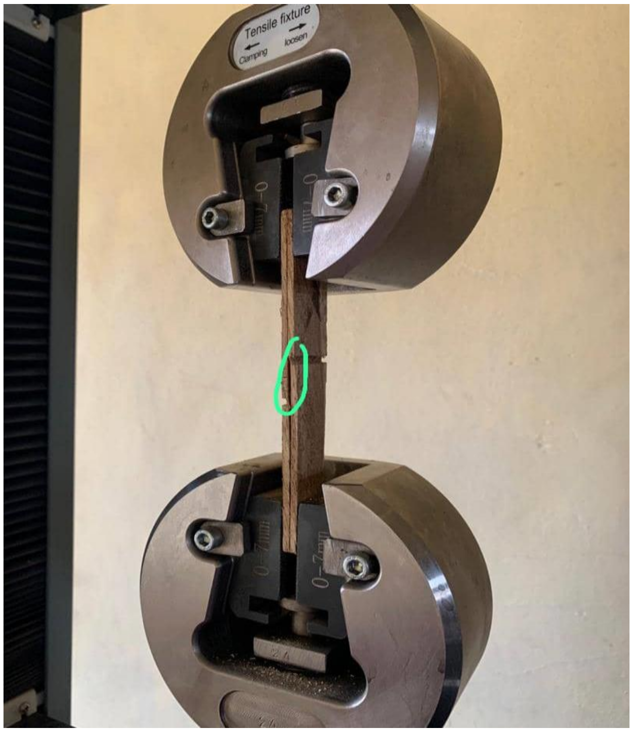

Figure 10a. glued joint between tensile loading jaw

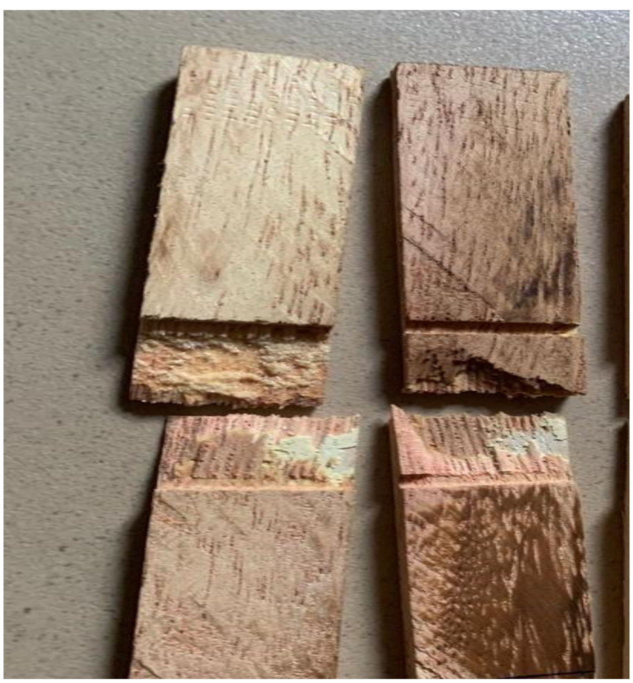

Figure 10b. wood failure in glued joints

CONCLUSION

Albizia zygia shows desirable characteristics for construction, with a density of 519.1 kg/m³ and strong dimensional stability, as shown by the minimal shrinkage values (1.17%) and swelling (6.52%). Its mechanical properties, including bending strength (53.89 N/mm²), tensile strength (33.61 N/mm²), and compressive strength (42.70 N/mm²), categories the wood species in strength class D30, which is suitable for structural applications. Furthermore, it's excellent bonding properties makes its suitability for glued laminated timber (glulam) production, showing higher shear strength (2.32 N/mm²) compared to solid wood (1.64 N/mm²). However, after assessment under accelerated aging conditions, the glulam joints exhibited a significant strength reduction (45%), making it unsuitable for external use. This limits the application of PUR bonded *A. zygia* joints to internal service class 2 application, though its potential for environmentally friendly engineered wood products remains promising.

DECLARATIONS

Corresponding Author

Correspondence and requests for materials should be addressed to O.O. Ekundayo; E-mail: ooekundayo@futa.edu.ng; ORCID: 0000-0003-1816-2393

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Authors' contribution

First Author designed and supervised the experiments, analysed the data obtained while the third author performed the experiments and wrote the manuscript. Second Author revised the manuscript. Both the first and second authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

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