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STRENGTH CHARACTERISATION AND CLASSIFICATION OF COMBINED GLULAM BEAM MADE FROM OPEPE (*Nauclea diderrichii*) AND OBECHE (*Triplochiton scleroxylon*) TIMBERS

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ABSTRACT

Quality timber species are declining due to over-exploitation in Nigeria. This has propelled the utilisation of low-grade timbers species that are considered for low-end constructions in the past which called for concern. This study establishes the viability of a typical beam made from locally sourced non-durable Obeche (*Triplochiton scleroxylon*) with highly durable Opepe (*Nauclea diderrichii*) timber specie in a combined glulam form, using polyvinyl acetate (PVA) adhesive which serves the impact of environmental sustainability and reduced cost of engineering construction. Seasoned timber samples and PVA adhesive were all obtained locally in Nigeria. Beam specimens were tested in the Department of Civil Engineering, Ahmadu Bello University, Zaria according to EN 338 (2009). Based on tests, it is evident that solid Opepe and Obeche timber specimens exhibited more durable characteristics than their homogenous glulam when fabricated with PVA adhesive. The combined Opepe/Obeche (GLc OP/OB) glulam beam specimen was proposed into GL18c strength class according to EN 338 based on minimum constraints which it satisfies, reflecting a 41 % greater Modulus of Elasticity (MoE) in comparison with EN 338 experimental value. This study recommends the enhancement of the bending strength, density and modulus of elasticity of a typical non-durable solid Obeche timber beam by 38 %, 47 % and 35 % respectively with 40 % durable Opepe timber in a combined glulam form using PVA adhesive for engineering construction purposes.

Keywords: Opepe, Obeche, Timber, PVA Adhesive, Glulam, Beam, Strength

INTRODUCTION

Timbers are globally regarded as environmentally sustainable and renewable construction material with lesser and cheaper processing energy than as required by concrete and steel (Osuji & Inerhunwa, 2017; Olusegun & Olaniyi, 2018). The Nigerian forests is enriched with abundant natural trees for timber production due to the country's geographical location in the tropics, with the engineering construction industry accounting for approximately 80 % of the nation's annual timber output estimated at 20 million m^3, utilised based on its availability, affordability and workability (Dahunsi & Adetayo, 2015; Abimaje & Baba, 2014). Nevertheless, Nigeria experiences an annual loss of about 3.5 % of its 96,000 km^2 forest area and the excessive harvesting of trees for timber development has diminished the yield of valuable timber species, despite the existence of Timber Export Decree No. 1 of 1998 which prohibits the export of timber and wood in rough forms (Aruofor, 2001). Consequently, the timber market is now witnessing a shift towards less valuable timber species due to the scarcity of high-quality ones. This trend has led to an increased reliance on fast-growing trees commonly used as raw materials for paper production and prone to rapid deterioration under biological and physical influences due to the low durability of their fibres (Herawati *et al*, 2010; Famuyide *et al*, 2012; Owoyemi & Olaniran, 2014).

Low durable timbers can be incorporated into glulam (glue-laminated timber) by combining high and low quality timber species for outer and core laminations respectively (Levan-Green & Livingston, 2001; Nadir & Nagarajan, 2014). This mirrors the engineering configuration of an I-section steel beam with broad flanges to withstand elevated stresses on the upper and lower surfaces. Also, with slender diaphragm in the middle to endure shear stresses and maintain separation between the flanges, as the materials in the beam centre experiences lower stress levels (Kretschmann & Hernandez, 2006). A study carried out on glulam with 33 % Coconut (*Cocos nucifera*) timber as the outermost lamination and 67 % Sengon (*Albizia falcatara*) timber as core lamination indicated an improved shear strength, flexural strength and elastic modulus by 34 %, 13 % and 28 % respectively using urea-formaldehyde resin powder (UF) adhesive (Kusnindar *et al*, 2018). Theoretical concepts and experimental evaluations have been developed in several literatures permitting the combination of various timber species into glulam of various sizes, shapes and configurations due to the processes of manufacturing which addresses the extent of variation in the mechanical characteristics of timber and reduces lapses like knots and cracks due to an increase in number of laminations (Ezeagu *et al*, 2015; Alayande *et al*, 2019).

There are several kinds of timbers available in Nigeria, irrespective of their location and usage which Opepe (*Nauclea diderrichii*) and Obeche (*Triplochiton scleroxylon*) were selected based on their grading in NCP 2, 1973 with both timber species classified as hardwood, while Opepe is graded into N-1 (very durable) and Obeche is N-6 (non-durable). Generally, structural timbers are usually classified as either hardwood or softwood based on their leaf-like structure, hardwood originates from angiosperm or deciduous trees, whereas softwood is sourced from coniferous trees characterised by needle-like leaves. These names can be confusing since some softwoods exhibits greater strength properties than some hardwoods and vice versa (Ohagwu & Ugwuishiwu, 2011). Subjecting Nigerian grown timbers to engineering investigations is to establish adequate data and sufficient information for it to be adequately managed and help in building more confidence in identifying their specific areas of usage for structural safety (Aguwa *et al*, 2015; Mohammed, 2017; Rahmon & Jimoh, 2020). This is expected to lessen the over-dependence on foreign materials for structural applications and to create more employment opportunities that will impact the country's economy (Aguwa *et al*, 2015).

The development of local contents has to be encouraged towards infrastructural developments in developing countries like Nigeria using sustainable and environmentally-responsive approach (Bakar *et al*, 2004; Aguwa & Sadiku, 2011). This study proposed the strength performance of a typical beam made from a non-durable timber specie enhanced with a highly durable timber specie in a combined glulam form, using locally sourced Obeche (*Triplochiton scleroxylon*) and Opepe (*Nauclea diderrichii*) timber species using PVA adhesive. This encourages the utilisation of poorly graded timbers in wider structural applications in Nigeria which serves the impact of sustainability, reduced wastage of timber resources and reduced cost of engineering construction. Additionally, it verifies and establishes the use of PVA adhesives readily available at local markets in Nigeria to ascertain its strength properties in locally fabricated glulam in comparison with solid timber of same species.

MATERIALS AND METHODS

Materials

The study utilised the following materials; Opepe (*Nauclea diderrichii*) and Obeche (*Triplochiton scleroxylon*) timber and polyvinyl acetate (PVA) adhesive. Seasoned timber samples were obtained from a timber market in Ondo Town in Ondo State, Nigeria while PVA adhesives (top bond), a general purpose white glue was obtained at Samaru market in Zaria, Kaduna State, Nigeria in sealed plastic containers produced by Purechem Manufacturing Limited in Nigeria.

Methods

Material Preparation

Glulam must have a minimum of two seasoned solid timber laminates pieces ranging from 6 to 45 mm glued together in a controlled environment (Jacob *et al*, 2018). Also, manufacturing tolerances were established for glulam beams with nominal sizes ranging from 50 mm - 300 mm in width and 100 mm - 2500 mm in depth (EN 390, 1995). Solid timber beams were fabricated according to EN 14081-1: 2012 and allocated into strength class in EN 338 (2009). Also, glulam beams were fabricated according to EN 14080: 2013 and allocated into strength class based on values given in EN 338 (2009) and derived values according to principles given in EN 1194 (1999). All beam specimens in the study were fabricated in the Carpentry Workshop, Department of Civil Engineering, Ahmadu Bello University, Zaria into 50 mm by 100 mm cross-sectional area, comprising of solid and glulam timber on the basis of comparative evaluation as shown in Plate I.

To form glulam, PVA was applied to laminates and joined together by clamping for 24 hours with excess adhesive and timber thickness trimmed off to achieve a neatly finished surface. Specimens were then cut into respective sizes for the series of tests. Since EN 386 (2001) prescribes a maximum lamination thickness of 45 mm for softwoods and 40 mm for hardwood and the primary objective of the study is to improve the utilisation of poorly graded Obeche timber due to its affordability and widespread availability, while minimizing the use of Opepe timber due to its scarcity and higher cost, glulam beams were fabricated to 100 mm depth with five 20 mm laminates (representing 20 % each of the build-up) glued together using PVA adhesive, which complies with size limitations of minimum of 4-laminations in a beam for it to be allocated to EN 1194: 1999 glulam strength class in the following order as given in Figure 1:

i. OP: solid Opepe timber beam,
ii. OB: solid Obeche timber beam,
iii. GLh OP: homogenous glulam beam made from laminates of Opepe timber,
iv. GLh OB: homogenous glulam beam made from laminates of Obeche timber and
v. GLc OP/OB: combined glulam beam made from laminates of Opepe timber at tension and compression zones with Obeche timber at core zone, accounting for 60 % Obeche and 40 % Opepe timber utilisation.

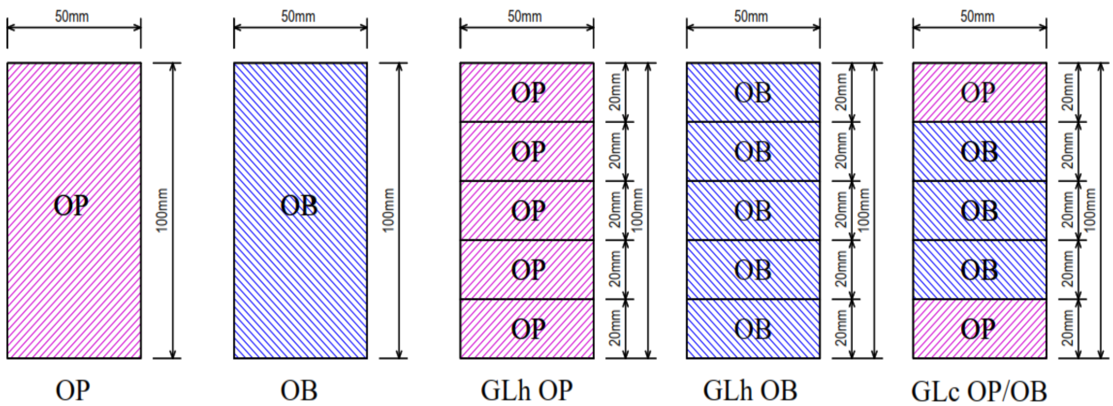


Figure 1: Beam specimens comprising of solid and glulam timber with OP and OB representing Opepe and Obeche timbers respectively
Source: Adapted from Muraleedharan and Reiterer (2016

Plate 1: Fabrication process of various test specimens in the Carpentry Workshop, Department of Civil Engineering, Ahmadu Bello University, Zaria

Laboratory Tests

Density and Moisture Content Test

The test was executed in the Laboratory in accordance with (EN 384, 2004) and EN 13153-1 (2002). The densities of samples were determined by equations (1) and (2) as given:

Wet density, $\rho_b = \frac{m_b}{v}$ (1)

Dry density, $\rho_d = \frac{m_o}{v}$ (2)

The moisture content (MC) of samples was obtained by equation (3) as given:

MC (%) $= \frac{m_b - m_o}{m_o} \times 100$ (3)

Where, ρ_b is the bulk density of sample in kg/m^3, ρ_d is the dry density in kg/m^3, m_b is the bulk mass in kg, m_o is the oven dry mass in kg and v is the volume of sample in m^3.

The Four-Point Bending Test

Applying a load at the central third of the test specimen is done to ascertain the timber's modulus of elasticity through a four-point bending test method (Mohammed, 2014).

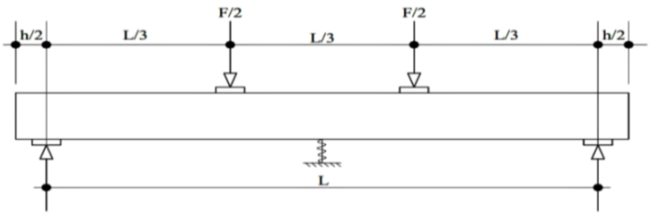


Figure 2: EN 408:2004 Four-point bending test set-up
Source: Adopted from Mohammed, (2014)

Test was conducted on beam specimens to assess their global modulus of elasticity (MoE) and bending strength using the four-point bending test technique in accordance with EN 408 (2004), considering bending deflection over the entire span relative to the end supports. Beams were fabricated to the same length, width and depth of 1000 mm × 50 mm × 100 mm specimens for each test series based on the available Universal Testing Machine (UTM).

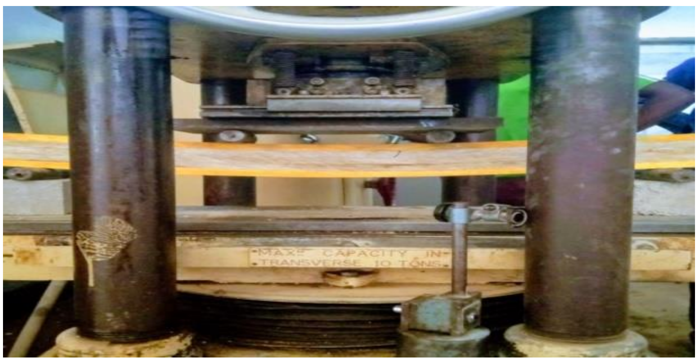


Plate 2: Four-point bending test set-up under loading according to EN 408 (2004).

The Modulus of Elasticity, MoE (E_m) was calculated for each specimen by the application of linear regression analysis on the load-deflection data collected between applied load levels of 2000 N to 6000 N and the maximum recorded load using equation (4) as given:

$E_m = \frac{L^3(F_2 - F_1)}{4.7bh^3(w_2 - w_1)}$ (4)

Where, $\frac{(F_2 - F_1)}{(w_2 - w_1)}$ is the slope of the least square regression line, $(F_2 - F_1)$ is the increment of load on the straight line of the load deformation least square regression line in N, $(w_2 - w_1)$ is the increment of deformation corresponding to $(F_2 - F_1)$ in mm, L is the span between the beam supports in mm, b is the width of test piece in mm and h is the depth of test piece in mm. Slopes of the least square regression line of each specimen were determined using Microsoft Excel.

The Bending Strength, f_m, was calculated based on the maximum recorded load using equation (5) as given:

$$f_m = \frac{aF_{max}}{2W} \quad (5)$$

Where, a is the distance between one load and the nearest support in mm, F_{max} is the maximum load at piece rupture in N and W is the section modulus of the beam in mm^3.

Material Properties Adjustment Based on Moisture Content

According to Mohammed (2014), the NCP 2 (1973) was established upon 18 % reference MC, while 12 % for EN 384 (2004). The material properties (density, bending strength and MoE) were adjusted from various MC of timber specimens obtained in the test to 12 % reference MC, then 18 % using linear interpolation with Microsoft Excel.

The 12 % MC adjustment equation for bending strengths is given by:

$$f_{m,12\%} = \frac{f_{measured}}{1+0.0295\,(12-u)} \quad (6)$$

Where, $f_{m,12\%}$ is the bending strength at 12 % MC, $f_{measured}$ is the bending strength at the measured MC, u is the measured MC in %.

The 12 % MC adjustment equation for MoE is given by:

$$E_{m,12\%} = \frac{E_{measured}}{1+0.0143\,(12-u)} \quad (7)$$

Where, $E_{m,12\%}$ is the MoE at 12 % MC, $E_{measured}$ is the MoE at the measured MC, u is the measured MC in %.

The 12 % MC adjustment factor for density is given by:

$$\rho_{12\%} = \rho_w\left(1 - \frac{0.5(u-12)}{100}\right) \quad (8)$$

Where, $\rho_{12\%}$ is the density at 12 % MC, ρ_w is the density measured MC, u is the measured moisture content in %.

Material Properties Adjustment Based on Bending Strength

The test specimens were expected to be systematically loaded in bending over a span 18 times its depth according to EN 408 (2004) with reference depth of 150 mm. However, for test specimens that do not correspond with EN 408 (2004) dimension specification, EN 384 (2004) recommends adjustment factors for bending strengths.

Bending strength was adjusted to 150 mm reference depth using adjustment factor, k_h as given in equation (9).

$$k_h = \left(\frac{150}{h}\right)^{0.2} \quad (9)$$

Where, h is the actual depth of specimen used in the test in mm.

Also, for length other than that specified in the EN 408 (2004), the bending strength be adjusted by with an adjustment factor k_1 obtained using equation 10.

$$k_1 = \left(\frac{L_{es}}{L_{et}}\right)^{0.2} \quad (10)$$

Where, L_{es} is the length of specimen used in the test in mm and L_{et} is the standard length of the specimen in mm. They are calculated using equations (11) and (12) respectively.

$$L_{es} = L_s + 5a_{fs} \quad (11)$$

$$L_{et} = L_t + 5a_{ft} \quad (12)$$

Where, L_t is the actual length of specimen used in the test in mm, a_{ft} is the distance between the point loads of the actual length of specimen used in the test, in mm, L_s is the standard length of specimen which is 18 times standard depth of 150 mm and a_{fs} is the distance between the point loads of the standard length of specimen in mm.

Therefore the 12 % and 18% adjusted reference bending strength, σ_a to 150 mm standard depth and length (18 times depth) is given by:

$$\sigma_a = \sigma\,.k_h.k_1 \quad (13)$$

Where, σ is the adjusted bending strength for reference 12 % and 18 % MC. Moisture adjusted reference material properties are presented in Figures 3 to 4.

Characteristic Material Properties

Determination of characteristic values of material properties is necessary in other to allocate timber into strength classes according to EN 338 (2009). Characteristic values are determined as the mean of sample lower 5th percentiles for strength properties and density, while 50th percentile (average mean) of sample is used for determining modulus of elasticity, which are be represented by the following statistical distribution equations (Harte, 2009; Lamidi *et al*, 2022). The characteristic value of density, ρ_k and characteristic mean density, ρ_{mean} in kg/m^3 are given by equations (14) and (15) respectively:

$$\rho_k = \rho_{05} = \rho - 1.65s \quad (14)$$

$$\rho_{mean} = 1.2\rho_k \quad (15)$$

Where, $\rho_{0.05}$ is the 5th percentile value of density, ρ is the mean density (adjusted reference 12% MC) and s is the standard deviation of densities of specimen obtained from test.

The characteristic value of bending strength, f_k and the 5th percentile value of bending strength, f_{05}, in N/mm^2 is given by equations (16) and (17) respectively:

$$f_{m,k} = 1.12f_{05} \quad (16)$$

$$f_{05} = f_m - 1.65s \quad (17)$$

Where, f_m is the mean bending strength (bending strength adjusted reference 12% MC) obtained from test.

The characteristic value of MoE, E_{mean} and the fractile 5th percentile value of MoE parallel to grain, $E_{0,05}$ in N/mm^2 are given by equations (18) to (19) respectively:

$$E_{mean} = \left(\frac{\sum E_i}{n}\right)1.3 - 2690 \quad (18)$$

$$E_{0,05} = 0.84E_{0,mean} \text{ for hardwoods} \quad (19)$$

Where, E_i is the ith value of MoE in bending, n is the number of specimen and $E_{0,mean} = E_m$ is the mean MoE parallel to grain.

Derived Material Properties

According to Mohammed 2017, the density, modulus of elasticity and bending strength of timber determined through laboratory tests serves as reference properties of timber. Other strength and stiffness properties are calculated from the reference properties in accordance with the guidelines outlined in EN 384 (2004) or extracted from Table 1 of EN 338 (2009) (Lamidi *et al*, 2022).

Allocation of Strength Class

The classification of tested timber beam specimens into various hardwood strength classes was carried-out based on the characteristics bending strength, mean values of density and MoE, taking into account the limiting values of material properties from Table 1 of EN 338 (2009). For timber in bending, the characteristic mean MoE of timber should meet or exceed 95 % of the value given for that strength class (Mohammed, 2014). The allocation of strength classes is intended to facilitate the specification of timber into groups regardless of its species. EN 1194 (1999) specifies a strength class system for glulam allowing combinations of different timber grades to be classified together with a common set of strength and stiffness properties. Strength and stiffness characteristic values for other glulam strength classes can be computed using formulae given in Table 1 in conjunction with strength class characteristic values outlined in EN 338 (Harrington *et al*, 2006).

Table 1: EN1194 Characteristic Material Properties for Glulam

Material Properties	Formulae	
Bending Strength (N/mm^2)	$f_{m,g,k}$	$= 7 + 1.15\, f_{t,0,l,k}$
Modulus of Elasticity, MoE (kN/mm^2)	$E_{0,g,mean}$	$= 1.05\, E_{0,l,mean}$
Density (kg/m^3)	$\rho_{g,k}$	$= 1.10\rho_{l,k}$

Source: Adapted from Harrington *et al* (2006)

Where, $f_{t,0,l,k}$ is the characteristic tension of the timber laminates, $E_{0,l,mean}$ is mean Modulus of Elasticity of the timber laminates in kN/mm^2 and $\rho_{l,k}$ is the characteristic density of the timber laminates. For combined glulam the formula applies to the properties of individual parts of the cross-section.

Analytical Calculation

The theory of composite beams (γ-method) for the evaluation of stiffness and strength properties of beams with inhomogeneous cross-section based on linear elasticity is expressed in the Annex of Eurocode 5 (EN 1995-1-1: 2004). In the case of glulam beams, the elasticity in the joint between the different beam-sections is not considered, only for mechanically joined beams with fasteners. The cross-section and normal-stresses in the beam is shown in Figure 3. This is based on a simply-supported beam with uniformly distributed loading where the composite section stretches from support to support. The effective bending stiffness can be calculated using mean values of MoE, E with equation (20) as given:

$$(EI)_{ef} = \sum_{i=1}^{3}(E_i I_i + \gamma_i E_i A_i a_i^2) \quad (20)$$

The connector stiffness parameter was taken as $\gamma_i = 1$ due to glulam.

$$(EI)_{ef} = (E_1 I_1 + E_1 A_1 a_1^2) + (E_2 I_2 + E_2 A_2 a_2^2) + (E_3 I_3 + E_3 A_3 a_3^2) \quad (21)$$

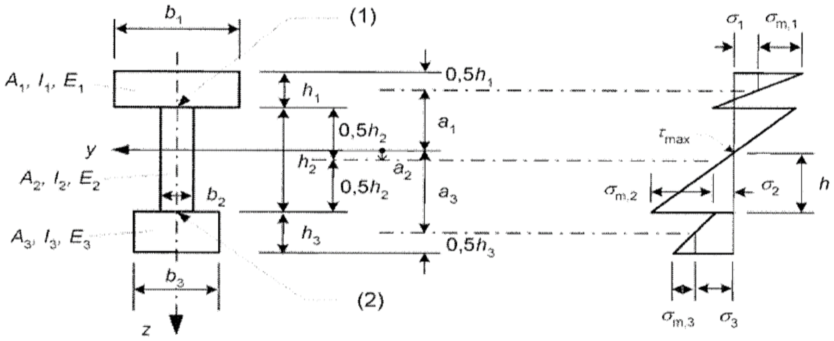


Figure 3: EN 1995-1-1: 2004 cross-section and bending stress for composite beams
Source: Annex of Eurocode 5 (EN 1995-1-1: 2004)

Where E_i is the Modulus of Elasticity of the member in kN/mm^2, I_i is the inertia of the member in mm^4, γ_i is the connector stiffness parameter, A_i is the cross-sectional area of the member in mm^2, h is the height of the member in mm, b is the width of the member in mm, a_i is the height from the centroid of composite member to the neutral axis of the entire beam. Material values were chosen from Table 1 of EN 338 (2009) for the two timber grades. Calculations were done for a cross-sectional beam size of 50 mm x 150 mm width and depth (adjusted standard depth) with 40 % volume of Opepe and 60 % of Obeche in the core. The effective bending stiffness, $EI_{(ef)}$, was determined based on the symmetrical build-up of the combined Opepe/Obeche glulam beam (GLc OP/OB), the value of MoE was then extracted in kN/mm^2.

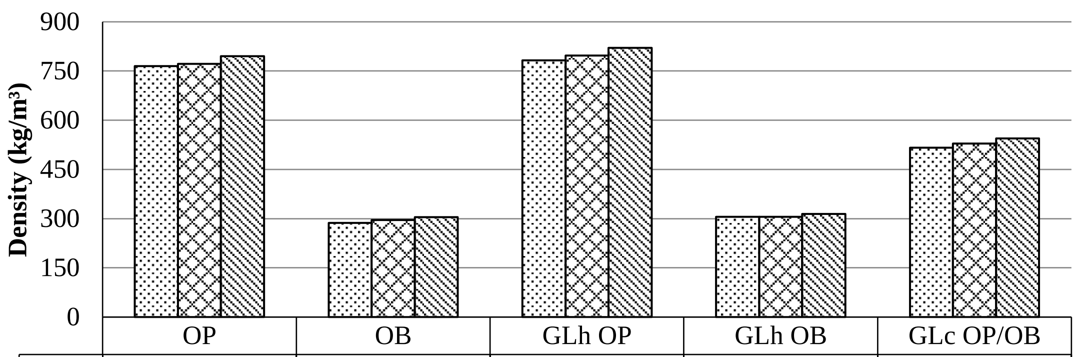
RESULTS AND DISCUSSION

Moisture Adjusted Test Results and Discussion

The change in moisture content (MC) of timber is in reaction to daily or seasonal atmospheric humidity which is the major source of their structural problems. Generally, timber will experience loss or gain of moisture content after slicing, forming equilibrium moisture content with atmospheric humidity of its environment (Eckelman, 1998). The swelling of glulam is expected which could be due to the PVA adhesive applied which is a water soluble adhesive comprising of about 50 % water (Klauser, 2014).

Density Test

The density test result is presented in Figure 4. This result implies a general increment in densities of glulam specimens compared with their respective solids which could be due to the presence of solidified PVA adhesive film between laminates that have filled the cracks in the timber grains making it more compact and denser. Studies indicated that water migrates into the glulam as its adhesive dries up, leading to the swelling of glulam and shrinkage of PVA adhesive film (Sonderegger, 2011). While the shrinkage of homogenous Opepe glulam could be attributed to the laminates of Opepe timber being highly compact and smooth after slicing, with relatively no pores for moisture absorption from the PVA adhesive losing some quantity of its moisture content to the environment. Obeche laminates might have also lost some moisture content after slicing, but were rough with visible pores permitting absorption of more moisture from PVA adhesive during the fabrication process of beam specimens.

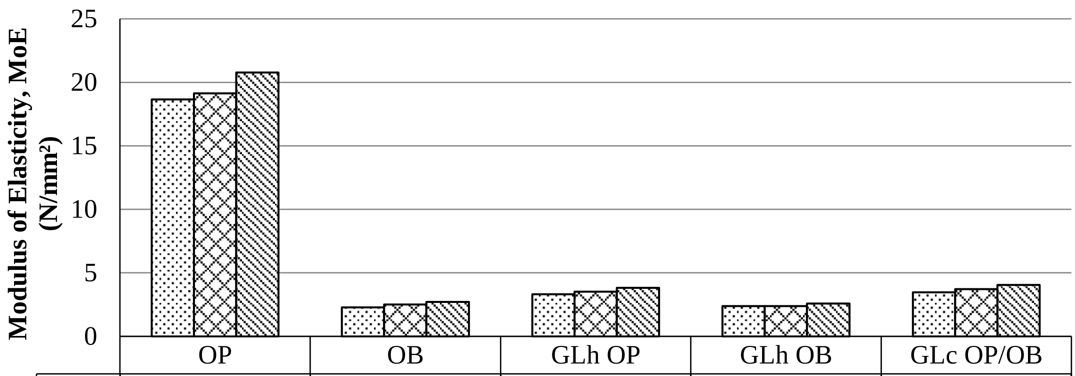


	OP	OB	GLh OP	GLh OB	GLc OP/OB
Test	765.24	287.17	782.36	305.92	516.44
12%	772.05	295.49	797.58	305.29	528.71
18%	795.01	304.11	821.05	314.47	544.2

Figure 4: Reference Moisture Adjusted Density

Modulus of Elasticity (MoE) Test

The MoE test result is presented in Figure 5. This result implies an increase in MoE of homogenous Obeche glulam by 4 % and combined Opepe/Obeche glulam by 34 % when compared with solid Obeche timber. But in the case of Opepe, the MoE of homogenous Opepe glulam reduced drastically by 82 % when compared with solid Opepe which shows the ineffectiveness in the lamination of highly durable timber homogenously. This is in confirmation to why glulam is mostly made from non-durble in Europe based on complexity of the internal cell structure of durable timber. The proposal for a new strength class was made for combined glulam (Muraleedharan & Reiterer, 2016).



	OP	OB	GLh OP	GLh OB	GLc OP/OB
Test	18.66	2.29	3.31	2.39	3.48
12%	19.14	2.50	3.51	2.38	3.73
18%	20.79	2.71	3.81	2.58	4.05

Figure 5: Reference Moisture Adjusted Modulus of Elasticity, MoE

Bending Strength Test

The bending strength test result is presented in Figure 6. This result implies that solid Opepe lost 50 % bending strength when laminated homogenously into glulam which could be due to insufficient bonding force of the PVA adhesive causing laminates to split during loading. Also, solid Obeche lost 18 % strength when in its homogenous glulam form. But in the case of combined Opepe/Obeche glulam, the presence of Opepe (40 % volume) improved the bending strength by 58 % when compared with solid Obeche. Generally, it can be deduced that the closely packed nature of Opepe timber grains is a contributing factor to the poor bond of the PVA adhesive between Opepe to Opepe laminates compared with Obeche to Obeche and Opepe to Obeche laminates. The stiffness behaviour of adhesives towards timber surface depends on the timber species and its chemical-physical compatibility with the adhesive which determines the failure rate (Hass *et al*, 2013).

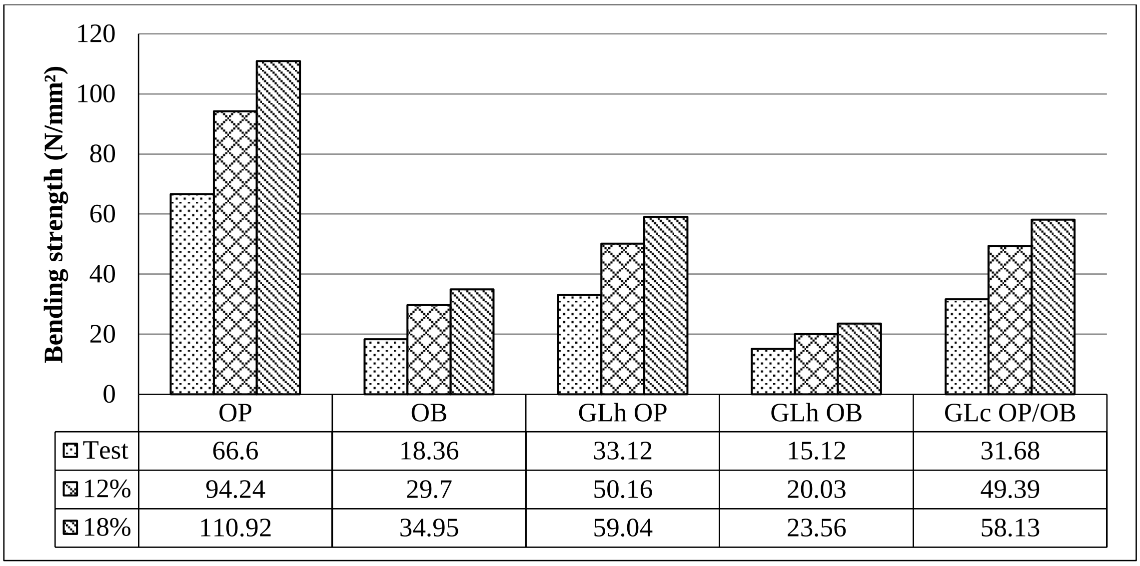


Figure 6: Reference Moisture Adjusted Bending Strength to Standard Depth and Length

Characteristic Material Properties and Strength Class Allocations

Each of the five timber specimen tested was then assigned to appropriate timber strength class as presented in Table 2 and compared with the EN 1194 required strength class for glulam in Table 3.

Table 2: Proposed EN 338 Allocations of Strength Class for Test Specimens

Timber Specimen	Characteristic Bending Strength (N/mm^2)	Characteristic Density (kg/m^2)	Mean Modulus of Elasticity, MoE (kN/mm^2)	Proposed Strength Class Allocation
	$f_{m,k}$	ρ_k	$E_{0,mean}$	EN 338
OP	84.91	743.60	19.14	D60
OB	26.87	247.70	2.50	D18
GLh OP	41.19	749.57	3.51	GL18h
GLh OB	18.65	268.18	2.38	GL18h
GLc OP/OB	43.19	469.43	3.73	GL18c

Based on Table 2, solid Opepe (OP) was allocated into D60 strength class considering that all values for bending strength, density and mean MoE fits into limiting values of D60, but with 29 % greater bending strength than the selected class. The characteristic material properties of Opepe established in this study conforms to that carried-out by Aguwa *et al*, (2015), Opepe was characterised with a density of 813 kg/m^2, MoE of 16.03 kN/mm^2 and bending strength of 131.54 N/mm^2 making it fit into the D60 strength class. Solid Obeche (OB) was allocated into D18 strength class considering that, density and MoE were within the limiting values of D18, but with 33 % greater bending strength than the class selected. In studies carried-out by Jimoh and Rahmon (2019) and Mohammed (2014), these respective characteristic material properties were established for Obeche, 514.32 kg/m^2 and 371.07 kg/m^2 as density, 0.63 kN/mm^2 and 6.59 kN/mm^2 as MoE and 19.97 N/mm^2 and 45.63 N/mm^2 as bending strength, then allocated into D18 strength class.

Table 3: Required EN 1194 Allocations of Strength Class for Glulam Specimens

Timber Specimen	Characteristic Bending Strength (N/mm^2)	Characteristic Density (kg/m^2)	Mean Modulus of Elasticity, MoE (kN/mm^2)	Required Strength Class Allocation
	$f_{m,g,k}$	$\rho_{g,k}$	$E_{0,g,mean}$	EN 1194
GLh OP	48.40	990.00	17.85	GL48h
GLh OB	19.65	352.00	9.45	GL18h
GLc OP/OB	31.15	607.20	12.81	GL30c

Similarly, homogeneous Opepe glulam (GLh OP) was allocated into D18 strength class considering the mean MoE obtained falls within the limiting MoE for D18, while the bending strength and mean density obtained were respectively 56 % and 47 % greater than the class selected. Homogenous Obeche glulam (GLh OB) was allocated into D18 strength class considering bending strength, density and MoE were all within the limiting values for D18 strength class. Combined Opepe/Obeche glulam (GLc OP/OB) was not allocated into any strength class greater than D18 considering that, the MoE obtained falls within limiting MoE for D18, while the bending strength and density obtained were respectively 58 % and 15 % greater than the selected class.

Analytical Results and Discussion

The result in Figure 4.4 indicates about 70 % deficiency in value of MoE from the EN 338 (2009) experimental result when compared to Eurocode 5 analytical result for combined

Opepe/Obeche (GLc OP/OB) glulam beam, which could be attributed to the stiffness deficiency of PVA adhesive used for the lamination. Similar flaws were observed in the case of homogenous glulam specimens (Table 2 and 3).

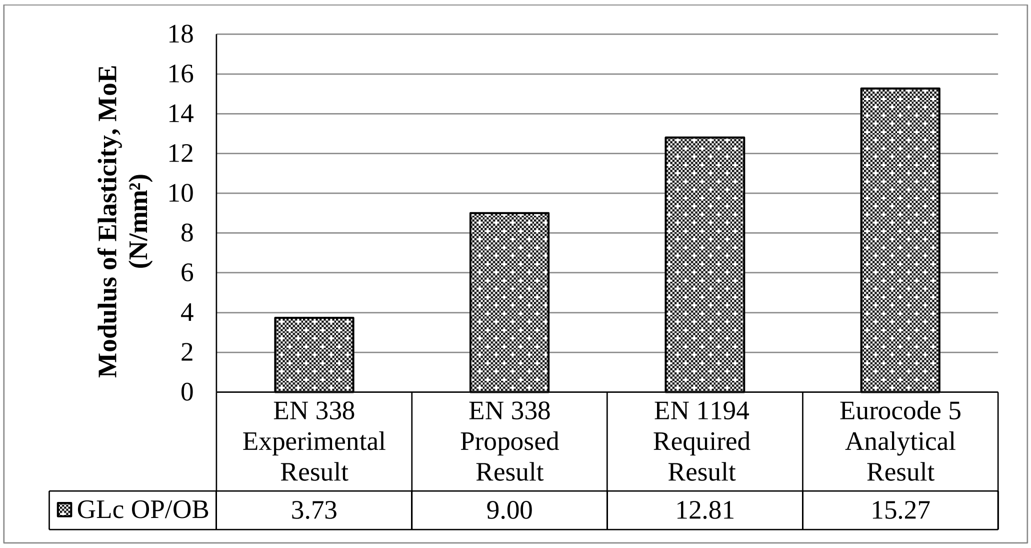


Figure 7: Comparison of Results of Modulus of Elasticity (MoE) for Combined Opepe/Obeche Glulam (GLc OP/OB) Beam

CONCLUSION

Based on the material properties of tested beam specimens, it is evident that solid Opepe and Obeche timber specimens exhibited more durable characteristics than their homogenous glulam when fabricated with PVA adhesive. The combined Opepe/Obeche (GLc OP/OB) glulam beam specimen was proposed into GL18c strength class according to EN 338 (2009) based on the minimum constraints which it satisfies, reflecting 41 % greater value of MoE in comparison with the EN 338 experimental value. This study recommends the enhancement of the bending strength, density and modulus of elasticity of a typical non-durable solid Obeche timber beam by 38 %, 47 % and 35 % respectively with 40 % durable Opepe timber in a combined glulam form using PVA adhesive which is a suitable material in the construction of structural timber structures where lessen self-weight is an advantage.

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