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Investigation of the physical and mechanical properties of Shea Tree timber (*Vitellaria Paradoxa*) used for structural applications in Kwara State, Nigeria

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ABSTRACT: This study investigated the physical and mechanical properties of Shea Tree timber (V. paradoxa) for structural use obtained at different areas of Kwara State, Nigeria. Physical properties of the samples like moisture content, specific gravity and density was evaluated and the mechanical tests were tensile strength, modulus of rupture, modulus of elasticity, compression, shear and hardness. Results show that, the density of the specie varied from 1.05 to 1.48 (g/cm3), and specific gravity varied from 0.98 to 1.39. For the mechanical properties, the results revealed that at 18% moisture content and 80% grade stress, mean MOR of 28.91(N/mm2), mean MOE of 9,108 (N/mm2), compressive strength parallel to grain of 24.7 (N/mm2), compressive strength perpendicular to grain of 8.99 (N/mm2), shear strength of 2.01 (N/mm2), and tensile strength parallel to grain of 16.15 (N/mm2). Finally, according to BS 5268-2 (2002) the specie was characterised into strength classes between D50 and D70. The results obtained showed that Shea Tree is a hardwood and suitable to be used for structural engineering purposes.

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Keywords: *Vitellaria paradoxa*, Physical properties, Mechanical properties, Structural timber, Green Construction.

Timber is a complex building material owing to its heterogeneity and species diversity. Timber does not have consistent, predictable, reproducible and uniform properties as the properties vary with species, age, soil and environmental conditions (Kliger, 2000). The need for local content in construction of engineering infrastructure is now a serious challenge in Nigeria. This is because vast quantities of local raw materials which must be processed and used for cost effective construction abound. Construction activities based on these locally available raw materials are major steps towards industrialization and economic independence for developing countries. This explains huge interest and considerable intellectual resources being invested in understanding the mechanical or structural properties of the Nigerian timber (Aguwa and Sadiku, 2011).

The primary goal of engineered construction is to produce a structure that optimally combines safety, economy, functionality and aesthetics. Timber, like other building materials, has inherent advantages that make it especially attractive in specific applications (Afolayan and Adeyeye, 1998). Structural timber is the timber used in framing and loadbearing structures, where strength is the major factor in its selection and use. The main issue is to find design methods ensuring that the relevant performance criteria are met with a certain desired level of confidence . That means that the risk of non-performance should be sufficiently low.

The main challenge in design with timber as structural member is to be acquainted with sufficient data about a given species of timber to ensure that the relevant performance criteria are met, as specified in relevant standards and codes. This implies that failure risk is reduced to the extent to which structural information about a given species of timber is readily available to timber designers, specifiers and construction regulators. A significant element of uncertainty is associated with lack of information on the physical variability as well as structural behaviour of material under load, (Aguwa, 2012). The question of strength characteristic of these timber species is therefore aimed at reducing the structural risk of using them for supporting and sustaining loads in structural systems.

Shea butter tree (Vitellaria Paradoxa), (synonymous to Butyrospermum parkii and Butyrospermum paradoxum) is a member of the family Sapotaceae and is wildly distributed in the west and central part of Africa. (Djekota et al., 2014)

Vitellaria paradoxa commonly referred to as Igi Emi in Yoruba is a small to medium-sized tree (7-25) m high; much branched, dense, spreading, round to hemispherical crown. In mature trees the bole is short, usually 3-4 m but exceptionally 8 m, with a diameter ranging from 0.3 to 1 m, but most frequently 0.6 m. Bark conspicuously thick, corky, horizontally and longitudinally deeply fissured; protects older trees against bush fires. Slash pale pink, secreting white latex, as do broken twigs or petioles (Orwa et al., 2009).

In 2015, Ataguba et al., did a comparative study of the mechanical properties of Gmelina Arborea, Parkia Biglobosa and Prosopis Africana timbers for structural use and concluded that the three species proved to have physical and mechanical properties that make them suitable for structural engineering use as hardwoods by grading them into strength classes between D30 – D70 when compared with Table 8 of BS 5268. It was part of his

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recommendation that tree species like Shea tree should be characterized for structural use.

Zziwa et al., (2009) characterized timbers for building construction in Uganda. Seventeen timber species were characterized according relevant Ugandan code of practice. After the study, four strength groups namely SG4, SG8, SG12 and SG16 were derived in view of the anticipated loading categories in building construction.

It is on this back-drop that this study aims at characterising V. Paradoxa by examining its physical and mechanical properties.

MATERIALS AND METHODS

Three stems of the timber species were gotten from different areas of Kwara state and transported to Irewolede estates sawmill in Ilorin for processing. The tree stems were 3.8m to 4.1m long and varied from 0.32m to 0.39m in diameter. The stems were sawn into commercial sizes in green state and seasoned in open air. Samples were taken along the stem and marked top, middle and bottom as in figure 1. It was ensured that the selected timber was free of defects and was as straight as possible.

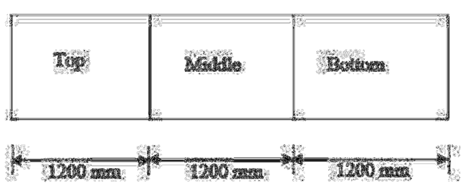

Fig 1: Schematic diagram of sample preparation

A total of 418 samples were prepared but 351 samples were used for this study for each timber specie. For the physical properties, there were 18 samples for each test (6 samples each from the top, middle and bottom position). Forty-five (45) samples were used for each mechanical test which equates to 15 samples each from the top, middle and bottom position). The specimens were prepared in accordance with BS 373:1957 (Methods of testing small clear specimens of timber). The code stated both the 2cm and 2inch standard of testing small clear specimens. The two (2) cm standard was used in this work. The test was done using Universal Testing Machine (UTM) of capacity 100kN at National Centre for Agricultural Mechanization (NCAM) in Ilorin, Kwara State, Nigeria.

The physio-mechanical properties of wood were determined at the moisture content of 12% as standard. Reduction of the failure strength at given moisture content to the strength at a moisture content of 12%, is given by

$$F_{12} = F_w(1 + \alpha(W - 12) \qquad (1)$$

where F_{12} is the failure stress at 12% moisture content, W is the moisture content at the time of testing, F_w is the failure stress at the moisture content at the time of testing, α is a correction factor given in table 1 below. The reduction formula is valid for moisture content of 8% to 23%.

Table 1: Correction Factor, α

State of stress	α (for all wood specie)
Modulus of Elasticity (MOE)	0.02
Modulus of Rupture (MOR)	0.04
Shear Parallel to grain	0.03
Compression parallel to the grain/perpendicular	0.05
Tensile parallel to grain	0.05

Source: *Karlsen G. and Slitskouhov Yu (1989), Zziwa et al. (2010)*

Equation (1) converts the failure stress of the mechanical properties at the existing moisture content to values at moisture content of 12% and these values were thereafter converted to their respective values at moisture content of 18% using equation (2) (this is the acceptable moisture content of timber to be used in Nigeria) while equations (3) to (8) gives the basic stresses.

$$\text{Stress at 18\% moisture content} = \frac{F_{12}\text{x}18}{12} \qquad (2)$$

Where F_{12} = failure stress at 12% moisture content.

Eighty percent (80%) grade stress of the timbers was calculated as well as 95% and 99% confidence limits of the failure stress. Analysis of Variance (ANOVA) was used to determine if there is significance difference between the top middle and bottom positions of the timber species.

The basic bending stresses parallel to the grain for the species were determined using the failure stresses from tests by (Ozelton and Baird, 1981)

$$f_{b\,par} = \frac{f_m - 2.33\sigma}{2.25} \qquad (3)$$

Where $f_{b\ par}$ = basic bending stress parallel to the grain

f_m = mean value of the failure stresses

σ = standard deviation of the failure stresses

The basic tensile stresses parallel to the grain for the species were determined using the failure stresses from tests by (Ozelton and Baird, 1981)

$$t_{b\,par} = \frac{f_m - 2.33\sigma}{2.25} \qquad (4)$$

The basic compressive stresses parallel to the grain for the species were determined using the failure stresses from tests by (Ozelton and Baird, 1981)

$$c_{b\,par} = \frac{f_m - 2.33\sigma}{1.4} \qquad (5)$$

The basic compressive stresses perpendicular to the grain for the species were determined using the failure stresses from tests by (Ozelton and Baird, 1981)

$$c_{b\ per} = \frac{f_m - 1.96\sigma}{1.2} \quad (6)$$

The basic shear stresses parallel to the grain for the species were determined using the failure stresses from tests by (Ozelton and Baird, 1981)

$$v_{b\ par} = \frac{f_m - 2.33\sigma}{2.25} \quad (7)$$

The formula below gives the relationship between the E_{mean} and the statistical minimum value of E appropriate to the number of species acting together, (Ozelton and Baird, 1981)

$$E_N = E_{mean} - \frac{2.33\sigma}{\sqrt{N}} \quad (8)$$

where E_N is the statistical minimum value of E appropriate to the number of pieces N acting together (where N=1, E_N becomes the value for E_{min}) and σ is the standard deviation.

Analysis of Variance (ANOVA) with the help of SPSS software was used to check if a significant difference existed between the bottom, middle and top positions of the timber specie.

RESULTS AND DISCUSSION

Tables 2 and 3 below shows the results obtained from the laboratory research work carried out on the physical and mechanical properties of the timbers under investigation as well as the 80% grade stress with 95% and 99% confidence limits of the failure stress. Likewise, the results of the ANOVA statistical test are presented in Table 4 to Table 10. Similarly, Figure 2 shows the typical Stress-Strain curve of the timber specie.

From the results obtained and analyzed, *Vitellaria paradoxa* has higher grade stress in compression parallel to the grains (24.70 N/mm^2) than perpendicular to the grains (8.99 N/mm^2). Similarly, *Vitellaria paradoxa* performed better in tension than in shear. The results of tensile grade strength was 16.15 N/mm^2 while that of shear was 2.01 N/mm^2. The modulus of elasticity (MOE) and the static bending strengths (flexural strengths) also show that the timber is an hardwood of higher strength classes (between strength classes D50 – D70) when compared with Table 8 of BS 5268. The densities obtained ranged from 1050 to 1480 kg/m^3 also show that the timber investigated is hardwood since the values obtained are greater than 640 kg/m^3. The moisture content results obtained showed that the values are below saturated moisture level of 25%.

Table 2: Physical properties of Shea Tree

	Minimum	Maximum	Mean	Standard Deviation
Moisture content (%)	12.96	24.23	19.89	6.67
Density (g/cm^3)	1.05	1.48	1.22	0.18
Specific gravity	0.98	1.39	1.15	0.17
Radial Hardness (kgf)	555.07	621.52	595.38	35.65
Tangential Hardness (kgf)	461.63	603.13	527.45	75.31

Table 3: Mechanical properties of Shea Tree at 18% moisture content

	Failure Stress	95% Confidence limit	99% Confidence limit	Basic stress	80% Grade stress
Bending stress (N/mm^2)	91.37	59.61, 62.21	59.18, 62.65	36.13	28.91
Compressive stress parallel to grain (N/mm^2)	49.17	32.01, 33.54	31.75, 33.80	30.87	24.70
Compressive stress perpendicular to grain (N/mm^2)	20.15	12.41, 14.46	12.07, 14.80	11.23	8.99
Tensile stress (N/mm^2)	108.66	64.28, 80.59	61.55, 83.33	20.19	16.15
Shear stress (N/mm^2)	14.21	8.09, 10.85	7.63, 11.31	2.51	2.01
Modulus of Elasticity (N/mm^2)	12698	7958, 8973	7787, 9144	11385	9108

The ANOVA analysis was carried out using 2-way method, with duplication, in three phases: (i) for all the seven mechanical properties, with ANOVA result shown in Table 4, (ii) for five mechanical properties without hardness result shown in Table 5 and (iii) for hardness result only with ANOVA result shown in Table 6.

Hardness was treated separately because of its peculiar unit (kgf) as against N/mm^2 for other properties. For table 4, where ANOVA was carried out on the 7 properties, at α = 0.05, F obtained is greater than the critical F and P is less than α, showing that the differences among the means for the positions and among the means for the properties are significant and also, there is a statistical significant interaction between the position and the properties. In Table 5 where 5 of the seven properties were tested, similar result was obtained. In table 6, where only hardness was tested, unlike in above, in this case F is less than the critical and P is greater than α, thus, there is no significant difference in the means of the positions and in the means of the hardness properties, and there is also no interaction of the positions on the hardness properties.

Table 4: 2-way ANOVA result for all Mechanical properties (tension, compression parallel and perpendicular to grain, shear, bending and hardness in radial and tangential direction).

Source of Variation	SS	df	MS	F	P-value	F crit	Remark
Sample	14329.83	2	7164.913	8.042086	0.000398	3.026466	F>Fcrit& P<0.0 5
Columns	17885375	6	2980896	3345.835	2.9E-267	2.129473	F>Fcrit & P<0.05
Interaction	47107.2	12	3925.6	4.406196	1.76E-06	1.785196	F>Fcrit & P<0.05
Within	261932.6	294	890.9272				

Table 5: 2-way ANOVA results for some mechanical properties (tension compression parallel and perpendicular, shear and bending)

Source of Variation	SS	df	MS	F	P-value	F crit	Remark
Sample	1561.931	2	780.9657	9.353292	0.000128	3.038877	F>Fcrit & P<0.05
Columns	141042	4	35260.5	422.2999	3.6E-99	2.414642	F>Fcrit & P<0.05
Interaction	11397.02	8	1424.627	17.06215	1.9E-19	1.98269	F>Fcrit& P<0.05
Within	17534.23	210	83.49635				

Table 6: 2-way ANOVA results for hardness in radial and tangential

Source of Variation	SS	df	MS	F	P-value	F crit	Remark
Sample	44298.87	2	22149.44	7.612786	0.000915	3.105157	F>Fcrit & P<0.05
Columns	103808.6	1	103808.6	35.67913	5.41E-08	3.954568	F>Fcrit & P<0.05
Interaction	4179.209	2	2089.604	0.718199	0.490599	3.105157	F<Fcrit & P>0.05
Within	244398.4	84	2909.504				

Stress Strain Curve

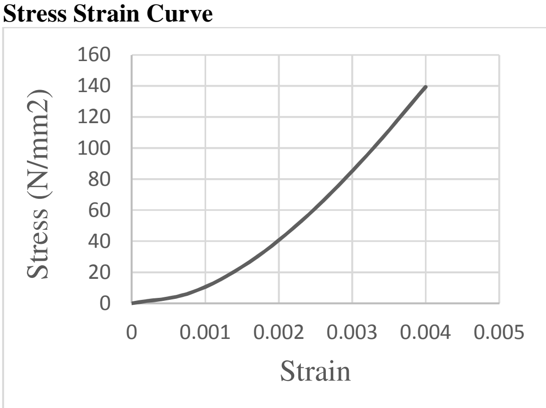

Fig 2: Typical Stress-Strain curve for Shea Tree

The stress-strain curve above is like that of a brittle material. It can therefore be concluded that Shea tree is a brittle material.

The stress-strain equation is given as;

$$Y = -8E8X^3 + 2E7X^2 - 106525X + 216.22 \quad (3.01)$$

These results obtained compare favorably with other known structural timbers such as mahogany, afara, iroko, obeche, owen, etc which are commonly known timbers in use within the tropics.

Conclusion: The timber type investigated, *Vitellaria paradoxa* have proved to have physical and mechanical properties that make it suitable for structural engineering use as hardwood. Structural Engineers, carpenters, etc are encouraged to explore and use it for structural and nonstructural uses. In view of this, the mechanical properties can be enhanced with adequate seasoning if these timbers are for structural purposes. More research work is needed in determining the suitability of other widely grown trees in this part of Nigeria for use as structural timbers in construction. Finally, massive afforestation practices should be promoted to reduce the dearth of some notable species of trees in the forest in this study area.

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