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INVESTIGATION OF COMPRESSIVE STRENGTH CHARACTERISTICS OF STRUCTURAL-SIZED ARERE (*Triplochiton scleroxylon*) AND EMI (*Vitellaria paradoxa*) TIMBER COLUMNS GROWN IN NIGERIA

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Abstract: Structural reliability was examined on the lesser-used species such as Arere (*Triplochiton scleroxylon*) and Emi (*Vitellaria paradoxa*) which can be good substitute to the well-known species. The strength and physical properties of these timber species were determined to predict the suitability of the species as structural material. Twenty lengths of timber species of 50 x 50 mm cross-section were purchased from timber market in Ilorin, Nigeria. The prevailing environmental conditions during the test were 31°C and 64% relative humidity. The properties tested included; air dry density, moisture content and compressive strength parallel to grain of twenty (20) test specimens each of lengths, 200, 400, 600 and 800 mm done in accordance with the British Standard BS 373 (1957). Mean air-dried moisture content for Arere and Emi were 14.48 and 15.89 % respectively. Mean density of Arere and Emi were 514.32 and 1147.75 kg/m^3 respectively. The reliability index of Arere and Emi timber species are 0.64 and 0.65 respectively for a service life of 50 years, assuming all other design conditions are met.
Keywords: Arere; Compressive strength; Emi; Reliability; Slenderness ratio

1. INTRODUCTION

The need for local content in the construction of engineering infrastructure is now a serious engineering challenge in Nigeria. This is because vast quantities of local raw materials, which must be processed and used for cost effective constructions abound (Aguwa and Sadiku, 2011). Timber is an important structural material in technological advancement and high level engineering production (Aguwa, 2010). It is one of the few natural and renewable construction materials that exists but has its limitations in general use for construction, carpentry and upholstery (Apu, 2003). Also, timber is an organic material and thus is subject to deterioration with time (Robert, 2010). Structural timber is the timber used in framing and load-bearing structures, where strength is the major factor in its selection and use (Aguwa, et al., 2015; Jimoh, et al., 2017). Most woods used in the building construction are softwoods but in structures like bridges and railway sleepers, hardwoods are specially used (Karlsen and Slitskouhov, 1989; Rahmon, et al., 2017).

The main characteristic of these timbers under investigation is their buckling characteristics when subjected to compressive load (Jimoh, et al., 2018). According to Robert (2006) buckling is a mode of failure that generally results from structurally unstable member due to compressive action on the said member and it depends on the geometric properties of the member. This study brings to focus current reasoning and the integration of advanced technologies to suit the available climatic, natural and human resources to solve the problem of transportation, by making cheaper, better and more reliable structural system in highways (Aguwa, 2011). The environment, the weather condition and the soil affect the growth of trees as well as their strength properties. Most of the timber strength properties recorded in British and European codes were based on timber obtained from trees on those areas and the laboratory tests were conducted there (Rahmon, et al., 2017). Since all our timber structures are constructed of timber from Nigeria, there is the great need to determine their strength properties and subject them to structural reliability analysis in order to prove their degree of structural performances. (Aguwa, 2010).

The reliability, R(t) of an item is defined as the ability of an item to perform a required function under stated conditions without failure for a stated period of time (Ajamu, 2014). Reliability coefficients range from 0.00 to 1.00, with higher coefficients indicating higher levels of reliability. However, reliability specifically measures the consistency of an item. According to Leitch (1988), reliability index using constant failure rate (CFR) model is as given in equation (1):

$$R(t) = e^{-\lambda t} \quad (1)$$

where: R(t) = reliability index; λ = constant rate of failure; t = variable time and the failure rate (λ) is express as in equation (2):

$$\lambda = \frac{1-d}{T} \quad (2)$$

where: T is the time (years), expected life span of timber, and d: the average compressive strength rate.

Nowak (2004) defines structural reliability as the probability that a structural system will satisfy the purposes for which it was designed and efficiently serve the period for which it was designed to without attaining a given limit state. Structural reliability and probabilistic methods have gradually grown to be important in modern structural engineering practice, especially when it involves naturally occurring materials like timber. Structural reliability could currently be used in the formulation of new generation design codes, evaluation of existing structures and probability risk assessment. One of the

Objectives for structural design is to fulfill certain performance criteria related to safety and serviceability. One of such performance criteria is usually formulated as a limit state, that is, a mathematical description of the limit between performance and non-performance (Thelandersson, 2003). Parameters used to describe limit states are loads, strength and stiffness parameters, dimensions and geometrical imperfections; since the parameters are random variables, the outcome of a design in relation to limit state is associated with uncertainty (Aguwa, 2011). A significant element of uncertainty is also introduced through lack of information about the actual physical variability.

The aim of this study is to evaluate the compressive strength characteristics of structural-sized Nigerian grown Arere and Emi timber species columns using constant failure rate reliability method. The specific objectives are: to conduct experiments on the Nigerian Arere and Emi timber species with a view to establishing their physical and strength properties; to derive continuous column design equations for the Nigerian Arere and Emi timber species as column structural material; to estimate the reliability of the Nigerian Arere and Emi timber species; and to add value to our locally available and affordable structural material.

2. MATERIALS AND METHODS

— Material procurement

Triplochiton scleroxylon (Arere) and *Vitellaria paradoxa* (Emi) timber species were bought from Tanke, Odo-Okun and Saboline sawmills in Ilorin, Kwara State, Nigeria. They were naturally seasoned for seven months for the samples to attain moisture content equilibrium environmentally. The natural seasoning was chosen over artificial seasoning which is faster because the proposed timber structure is column which is always completely exposed to natural atmospheric weather conditions. The timber samples were prepared and tested in accordance with the British Standard BS EN 408 (2003) Test for physical and mechanical properties of structural timbers at the Wood section of the Civil Engineering Department, University of Ilorin, Nigeria. Timber lengths of 50 x 50 mm section obtained from each sawmill was cut into lengths 200, 400, 600 and 800 mm. A maximum height of 800mm was used due to the limited height of the testing machine. The physical property tests of the timber species was carried out at the structural laboratory of Civil Engineering Department, University of Ilorin, while the mechanical strength test was carried out using a Universal Testing Machine (UTM) of capacity 300 kN at the Agricultural Engineering Laboratory, Faculty of Engineering and Technology, University of Ilorin, Kwara State, Nigeria.

— Physical property tests

Moisture Content - In Accordance with BS 373 (1957) immediately after each mechanical test has been conducted, a small sample for determination of moisture content was cut from each test piece. The sample size was 50 x 50 x 50 mm and consists of a transverse section from near the point of fracture. The sample was weighed and then dried in an oven at a temperature of 103 ± 2 °C (217 ± 4 °F) until the weight is constant. The loss in weight expressed as a percentage of the final oven-dry weight is taken as the moisture content of the test piece.

Percentage Moisture content, (m.c) is given as:

$$\text{m.c.}\% = \frac{W_a - W_0}{W_0} \text{ x } 100\% \qquad (3)$$

where: W_a = Air-dried weight of sample at test in grams, W_0 = Oven-dried weight of sample in grams.

Density - Density of a material is the ratio of the mass to the volume. In the 50mm x 50mm standard given by BS 373 (1957), all test pieces weight and dimensions were determined before test. The density is given as:

$$\rho = \frac{W_a}{V_a} = \frac{W_a}{BxDxH} \qquad (4)$$

where: ρ = density in kg/m^3, B = Breadth in cm, D = Depth in cm, H = height in cm, W_a = Air-dry weight of sample at test in grams (g), V_a = Air-dry volume of sample at test in cubic centimeters (cm^3).

— Mechanical property test

Compressive Strength - Compressive strength test was carried out using a Testometric Universal Testing Machine. The following procedures were carried out:

- The timber was cut into various sizes (200, 400, 600 and 800 mm); twenty samples for each of the sizes and then labeled.
- The machine height was now adjusted to the sizes of the specimen. Then the timber was fixed for loading.
- The speed of the test was calculated according to BS 373 (1957) standard as 13.020, 26.040, 39.060 and 52.075 mm/min for the length 200, 400, 600 and 800 mm respectively.
- The nominal length, the test speed, weight, breadth, width of the samples was inputted into the computer.
- The machine was started and load deflection curve can be seen on the computer, the machine was stopped when the sample fails or when the curve starts to deflect downward.
- The buckling was measured, and the sample taken out of the machine.
- The steps were repeated for the remaining samples.
- From the load deflection curve obtained after the test, the stress and strain were calculated as follow.

$$\text{Stress, } \sigma\ (\mathrm{N/mm^2}) = \frac{\mathrm{P}}{\mathrm{A}} \quad (5)$$

$$\text{Strain, } \varepsilon\ (\%) = \frac{\Delta\mathrm{H}}{\mathrm{H}} \quad (6)$$

Member slenderness was calculated as follows:

$$\text{Slenderness ratio, } \lambda = \frac{\mathrm{Le}}{\mathrm{r}} \quad (7)$$

where: Le = 1.0L, $r = \sqrt{\frac{I}{A}}$, $I = \frac{BD^3}{12}$, A = B*D and λ = Slenderness Ratio, Le = effective length, r = radius of gyration, I = moment of inertia, A = cross-sectional area, L = Length, B = Breadth, D = Depth.

3. RESULTS & DISCUSSION

The density of an air-dried timber has a direct relationship with the strength of the timber. Hence, the higher the density the higher the strength of the timber and vice versa. The average density of *Triplochiton scleroxylon* (Arere) and *Vitellaria paradoxa* (Emi) are 514.32 and 1147.75 kg/m^3, respectively.. This implies that Emi is denser than Arere which leads to Emi with a higher yield strength than Arere.

Table 1: Average density of timber species

Specie	Average density (kg/m^3)	
	Arere	Emi
Minimum	400.23	1130.44
Maximum	582.31	1170.21
Mean	514.32	1147.75
Standard deviation	8.60	20.33
COV (%)	16.73	17.72
95% Confidence limit	510.55 < x < 518.09	1138.84 < x < 1156.66
99% Confidence limit	509.37 < x < 519.27	1136.04 < x < 1159.46

Table 2: Average moisture content of Arere and Emi

Specie	Average moisture content (%)	
	Arere	Emi
Minimum	11.73	13.43
Maximum	19.49	17.76
Mean	14.48	15.89
Standard deviation	3.02	1.79
COV (%)	20.90	11.26
95% Confidence limit	13.16 < x < 15.80	15.11 < x < 16.68
99% Confidence limit	12.74 < x < 16.22	14.86 < x < 16.92

The average moisture content for Arere and Emi were 14.48 and 15.89% respectively as presented in Table 2. This result is satisfactory, since it is less than the maximum recommended moisture content of 20% for an air-dried sample. At this moisture content the likelihood of decay of the timber species is greatly reduced.

— Failure modes

A structural size timber column will normally fail by buckling, compression or a combination of both buckling and compression depending on the ratio of its height to its cross-sectional dimension. From the test carried out, it was observed that all 200 mm samples failed by crushing, while the 400, 600 and 800 mm samples fail by buckling. The minimum and maximum shortening for Arere timber was 5mm for a height of 400 mm and 21 mm for a height of 800 mm, while that of Emi timber was 7 mm for 400 mm height and 30 mm for 800 mm height. This re-affirms the previous deduction that Arere is stronger than Emi, since it experiences lesser lateral deflection. The compression failure of the 200 mm samples was expected as it is the standard dimension for compression test.

— Relationship between Mean Stress at yield, Young's Modulus and slenderness ratio

Slenderness is usually given as the ratio of the effective height to the radius of gyration of a compression member. The effect of geometry on strength is expressed in terms of the member's slenderness. For a compression member like column, as the member slenderness increases, the mean yield stress decreases. From the results presented in Table 3, it was observed that the average yield stress of both timber species decreases with increase in height. An exception is Emi timber with 400 mm height having a lower average yield stress than the 600 mm height. This may be due to defects in the timber sample.

Table 3: Slenderness ratio, Stress & Yield and Young's Modulus relationship for Arere and Emi

Mean height (mm)	Mean Slenderness ratio, λ		Mean Stress @ Yield, σ (N/mm^2)		Young's Modulus (N/mm^2)	
	Arere	Emi	Arere	Emi	Arere	Emi
200.00	14.46	14.12	22.60	35.48	921.88	2175.91
400.00	28.94	28.85	20.74	33.33	649.30	1693.17
600.00	45.51	42.52	18.98	31.17	560.62	1183.76
800.00	57.80	57.16	17.54	27.56	407.11	1047.82
Average			19.97	31.89	634.73	1525.17

— Verification of design equations

In other to derive a continuous column design equation for both Arere and Emi timbers, statistical regression analysis was performed on the stress at yield and slenderness ratio results for Arere and Emi timber column. The result of the regression analysis yields Equation 8 and 9 which is the desired column design equation for both Arere and Emi timbers respectively.

$$\sigma = 21.689e^{-0.002\lambda} \quad (8)$$

$$\sigma = 39.230e^{-0.006\lambda} \quad (9)$$

To examine how well the theoretical equation best fit the experimental results obtained, the values of stress at yield were obtained from the design equation with the experimental slenderness ratio as input alongside the experimental stress at yield. The ratio of the theoretical to the experimental yield stress was also calculated. It was observed that the ratio of the theoretical to experimental yield stress ranges between 77 and 121 % for Arere timber, and between 67 and 149 % for Emi timber, both having a mean value of unity. This implies that the theoretical result is in close agreement with the experimental results.

Also a single factor Analysis of Variance (ANOVA) was performed on the theoretical and experimental stress at yield using the null hypothesis (H_0: μ1 = μ2) that the means are equal at 95% confidence interval. For both timber specie, it was observed that F < Fcrit and α (0.05) < P-value. Hence, we accept the null hypothesis H_0 that the means of both the theoretical and experimental values are equal at 0.05 level of significance. This means that the theoretical stress at yield derived from the design equation agrees with the experimental results. Therefore Equation 8 and 9 can be used for the rational design of Arere and Emi timbers respectively.

— Reliability Analysis

The result of the reliability analysis shows that the timber specie has a reliability index of 0.65 (which is greater than 0.5, the minimum index for a reliable structure according to Adedeji (2008), Ajamu (2014) and Abdulraheem (2017) for a service life of 50 years, assuming other serviceability conditions are met.

Table 4: Strength Analysis of Arere timber

Height (mm)	Average Strength (σ) (N/mm²)	Cumulative Strength (Q_i) (N/mm²)	Remaining Strength (R_i) (N/mm²)	Strength Rate (d_i)
200	22.60	22.60	57.26	0.3947
400	2074	43.34	36.52	0.3622
600	18.98	62.32	17.54	0.5197
800	17.54	79.86	0	1.0000

Average Strength rate, $d = \frac{0.3947+0.3622+0.5197+1.0000}{4} = 0.5692$

Failure rate, $\lambda = \frac{1-d}{t}$, assuming a service life of 50 years and that other serviceability conditions are met, the reliability of the Arere timber column is evaluated as shown below using Constant Failure Rate (CFR).

$$\lambda = \frac{1 - 0.5692}{50} = 0.008616/\text{years}$$

Table 5: Reliability using CFR

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.206	0.2994
20	0.172	0.8420	160	1.379	0.2518
40	0.345	0.7082	180	1.551	0.2120
60	0.517	0.5963	200	1.723	0.1785
80	0.689	0.5021	220	1.896	0.1502
100	0.862	0.4223	240	2.068	0.1264
120	1.034	0.3556	260	2.240	0.1065

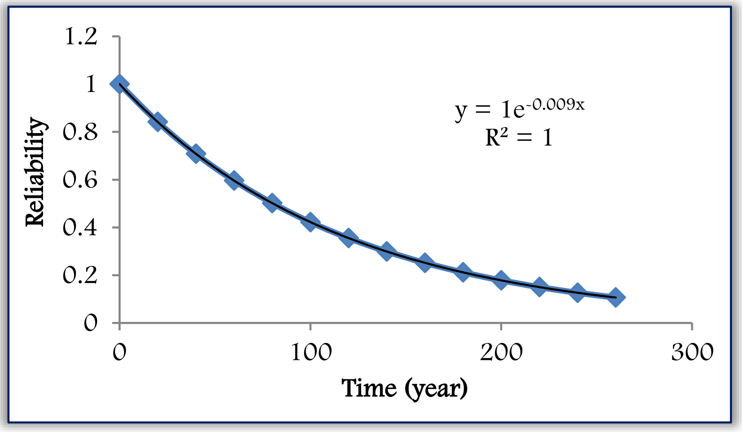

Figure 1: Reliability of Arere timber

Table 6: Strength Analysis of Emi timber

Height (mm)	Average Strength (σ) (N/mm²)	Cumulative Strength (Q_i) (N/mm²)	Remaining Strength (R_i) (N/mm²)	Strength Rate (d_i)
200	35.48	35.48	92.06	0.3854
400	33.33	68.81	58.73	0.3621
600	31.17	99.98	27.56	0.5307
800	27.56	127.54	0	1.0000

Average Strength rate, $d = \frac{0.3854+0.3621+0.5307+1.0000}{4} = 0.5696$

Failure rate, $\lambda = \frac{1-d}{t}$, assuming a service life of 50 years and that other serviceability conditions are met, the reliability of the Emi timber column is evaluated as shown below using Constant Failure Rate (CFR).

$$\lambda = \frac{1-0.5696}{50} = 0.008608/years$$

Table 7: Reliability using CFR

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.205	0.2996
20	0.172	0.8419	160	1.377	0.2523
40	0.344	0.7089	180	1.549	0.2124
60	0.516	0.5969	200	1.721	0.1789
80	0.688	0.5025	220	1.893	0.1506
100	0.861	0.4227	240	2.065	0.1268
120	1.032	0.3562	260	2.238	0.1067

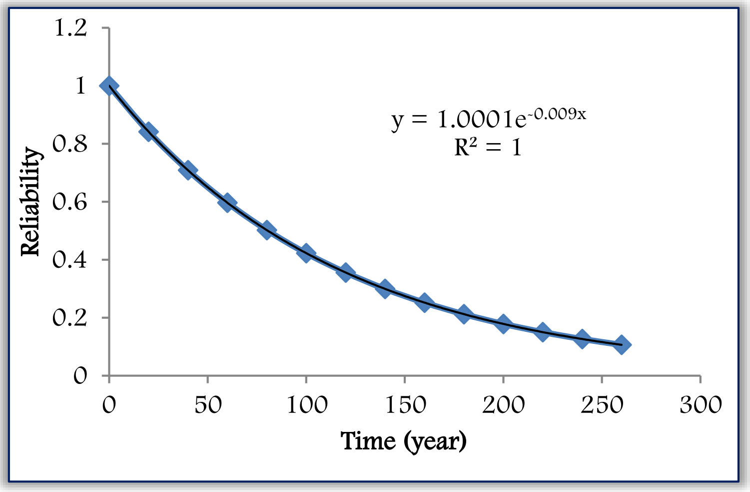

Figure 2: Reliability of Emi timber

4. CONCLUSIONS

The overall conclusions emerging from this study indicates that Arere has higher yield strength than Emi and thus will be more suited for Structural use. Direct relationship exists between physical properties such as moisture and density, and mechanical properties such as yield strength and elastic modulus. The equations derived from the regression analysis on the experimental results can be used to obtain the stress at yield if the slenderness ratio of a structural size timber column from the specie is known. With the results obtained and the associated equations derived, the strength of both timber species can be accurately predicted, thereby encouraging the use of these natural as sustainable construction materials.

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