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EVALUATION OF BUCKLING CHARACTERISTICS OF STRUCTURAL-SIZE *Pycnanthus angolensis* AND *Vitex doniana* AS TIMBER COLUMN UNDER COMPRESSION

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Abstract: Structural reliability was examined on the lesser-used timber species such as Akomu (Pycnanthus angolensis) and Eriri (Vitex doniana) which can be good substitute to the well-known species. The strength and physical properties of these timber species were determined to predict their suitability as structural material. Forty lengths of timber species of 50 x 50 mm cross-section were purchased from timber markets in Ilorin, Kwara State, Nigeria. The prevailing environmental conditions during the test were 31 °C and 64 % relative humidity. The properties tested were air dry density, moisture content and compressive strength parallel to grain of forty test specimens each of lengths, 200, 400, 600 and 800 mm in accordance with the British Standard BS 373 (1957). Mean air-dried moisture content for Akomu and Eriri were 11.12 and 13.29 %, respectively. Mean density of Akomu and Eriri were 644.58 and 889.84 kg/m^3, respectively. The typical derived equations to relate the stress and strain for Akomu and Eriri were $y = 1097.8x - 2.9858$ and $y = 1033.7x - 2.5309$, respectively. Results of reliability analysis show that Akomu and Eriri timber have reliability index of 0.68 and 0.63, respectively for a service life of 50 years, provided other serviceability conditions are met.
Keywords: Akomu, Buckling characteristics, Compressive strength, Eriri, Reliability

INTRODUCTION

Timber, a natural and renewable material, has a high strength-to-weight ratio and is easy to work on (Apu 2003). Different timber species have different strength characteristics, and also within a species these characteristics may vary. Therefore, in practice, a classification system of strength classes is used. Strength properties mean the ultimate resistance of a material to applied loads. Timber strength varies significantly depending on species, loading condition, load duration, and a number of assorted material and environmental factors (Jimoh et al. 2018). The exact quantity of wood and non-wood forest products in Nigeria cannot be easily estimated (Alamu and Agbeja 2011). However, studies have revealed that forest reserves occupy about 10 million hectares in Nigeria, which accounts for about 10% of a land area of approximately 96.2 million hectares (Alamu and Agbeja 2011; NPC 2006). Physical properties are the quantitative characteristics of timber and its behaviour to external influences other than applied forces. Familiarity with physical properties is important because they can significantly influence the performance and strength of wood used in structural applications (Winandy 1994).

Mechanical properties are the characteristics of a material in response to externally applied forces. They include elastic properties, which characterize resistance to deformation and distortion, and strength properties, which characterize resistance to applied loads (Rahmon, et al. 2017). Since timber is anisotropic, mechanical properties also vary in the three principal axes. Property values in the longitudinal axis are generally significantly higher than those in the tangential or radial axes. Flexural (bending) properties are critical. Bending stresses are induced when a material is used as a beam, such as in a floor or rafter system (Jamala et al. 2013).

The main characteristic of these timber species under investigation is their buckling characteristics when subjected to compressive loading (Jimoh et al. 2017). 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. 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. 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) and λ is assumed constant with time.

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

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 reported that the structural reliability is the probability that a structural system will satisfy the purpose for which it was designed and efficiently serve the period for which it was designed to without attaining a given limit state. 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 2010). A significant element of uncertainty is also introduces through lack of information about the actual physical variability. The evaluation of structural safety requires therefore, the consideration of the uncertainties (Benu et al. 2004). The aim of this study is to evaluate the structural reliability of Nigerian grown Akomu and Eriri timber species as a column material under compression. The specific objectives are; to conduct experiments on the Nigerian Akomu and Eriri timber species with a view to establishing their physical and strength properties, to determine the buckling behaviours of the selected timber species for different heights, to predict the critical buckling load for the selected timber species, derive continuous equations for the selected timber species as column structural material, to estimate the reliability of the Nigerian Akomu and Eriri timber species, and to add value to our locally available and affordable structural material thereby increasing the local content of the construction industry in Nigeria, resulting in less dependence on foreign materials.

MATERIALS AND METHOD

The study was conducted in Kwara State, North central, Nigeria. It is a state that lies within longitudes $5^0$00′00″East of Greenwich meridian and latitudes $8^0$30′00″ North of the Equator. To achieve the aims and objectives of the project, the physical and mechanical properties were carried out in accordance with BS EN 408 (1995) and BS 373 (1957).

A survey was carried out at eight timber markets within Ilorin, Nigeria. Forty lengths of each sample was cut from six randomly picked logs of timber from sawmills. It was ensured that the logs selected were free of defects and were as straight as possible before purchase. The timber samples were marked to distinguish individual timbers from different logs.

The tests were carried out on pieces which were conditioned at the standard environmental temperature of (30 ± 2) °C and (65 ± 5) % relative humidity. The timber species were naturally seasoned naturally for seven months to attain moisture content equilibrium environmentally.

The wood species were sized to standard size of 50 x 50 mm with heights of 200, 400, 600 and 800 mm at the University of Ilorin wood workshop for the compression test, 50 x 50 x 25 mm for the determination of moisture content of the timber specimens. Forty test specimens were prepared for each test.

— Physical Properties

» **Density determination** - In this study, only the air dry density has been determined. The specimens for density determination were completely free from knots, checks, flaws and any other defects. The volume of the specimens was calculated measuring the dimensions of length, width and thickness with the help of a Vernier scale. The density was obtained by determining the air-dry mass per unit volume for each of the test specimens.

» **Moisture Content -** The moisture content of the test piece was determined on each section taken from each test pieces. The sections were full cross section (50 x 50 mm), free from knots and resin pockets. And also those pieces were cut from a region where failure occurred for moisture content determination. The test specimen has dimension 50 x 50 x 50 mm. The pieces were weighed and then dried in an oven at a temperature of 103 ± 2 °C (217 ± 4 °F) until the weights were constant.

The percentage moisture content is mathematically calculated from equation (3) as;

$$W = \frac{M_1 - M_2}{M_2} \text{ x } 100 \qquad (3)$$

where: M_1 is the initial weight; in grams and M_2 is the mass, in grams, after oven drying.

— Compressive Strength Parallel to Grain Determination

A universal testing machine (UTM), also known as a universal tester, materials testing machine or materials test frame, at the Department of Agricultural and Biosystems Engineering, Faculty of Engineering and Technology, University of Ilorin, Ilorin was used to test the compressive strength of materials. The "universal" part of the name reflects that it can perform many standard tensile and compression tests on materials, components, and structures.

» **Buckling load determination**

UTM was used to determine the mechanical properties of Akomu (*Pycanthus angolensis)* and Eriri (*Vitex doniana)*.

» **Procedures:**

preparation of specimens, nominal size (50 x 50 x 200 mm), (50 x 50 x 400 mm), (50 x 50 x 600 mm) and (50 x 50 x 800 mm)
placing the specimen vertically between the cross heads.
input specimen dimensions and weight.
input the speed rate of the applied load (13.02, 26.04, 39.06 and 52.08 mm/min) for (200, 400, 600 and 800 mm) respectively.
run test.
a load-defection curve and other relevant data (stress and strain at yield, stress and strain at failure, maximum load and young's modulus etc.) are generated and shown on the output device.
stop test at the point of failure. point of failure was observed from load-deflection curve.
failure mode of specimen such as shear, split, lateral deflection and crushing were recorded before the applied load is lifted.

$$\text{Speed rate} = \frac{A_2 \text{ x } l_2}{A_1 \text{ x } l_1} \text{ x v} \qquad (4)$$

Where, A_1 is standard cross-sectional area and its equal to (20 x 20 mm^2), L_1 is standard specimen height and its equal to (60 mm), A_2 is the nominal cross-sectional area of test specimen and its equal to (50 x 50 mm^2), L_2 is the nominal height of test specimen and its equal to (200, 400, 600 and 800 mm), v is the standard load speed rate and its equal to 0.625 mm/min.

Example:

For 200 mm specimen:

$$\text{Speed rate} = \frac{50 \text{ x } 50 \text{ x } 200}{20 \text{ x } 20 \text{ x } 60} \text{ x } 0.625 = 13.02 \text{ mm/min}$$

— Stress and Strain Relationship

Stress and strain values are generated from Load against deflection curves which plotted automatically by the Universal Testometric Machine.

$$\text{Stress } (\sigma) = \frac{\text{Force(N)}}{\text{Area(mm}^2)} \qquad (5)$$

$$\text{Strain } (\varepsilon) = \frac{\text{Deflection(mm)}}{\text{Length(mm)}} \qquad (6)$$

RESULTS AND DISCUSSION

— Results of Density

The density of timber is its mass per unit volume at a specified value of moisture content of each sample. The density of an air-dried timber has a direct relationship with the strength of the timber. Hence, the strength properties increase as the timber density increases, that is, the higher the density, the higher the strength of the timber. From the experimental results, it was observed that the average density of Akomu is 644.58 kg/m^3 with standard deviation of 59.72 and coefficient of variation of 9.22 while that of Eriri is 887.84 kg/m^3 with standard deviation of 31.05 and coefficient of variation of 3.48 as presented in Table 1. This implies that Eriri has higher yield strength than Akomu. This can be confirmed from the results of compression test.

Table 1: Average density of Akomu and Eriri Timber species

Species	Average Density (kg/m^3)	
	Akomu	Eriri
Minimum	487.87	851.04
Maximum	720.02	957.75
Mean	644.58	887.84
Standard Deviation	31.05	59.72
COV (%)	3.48	9.22
95% Confidence limit	634.96<x<654.20	869.33<x<906.34
99% Confidence limit	631.93<x<657.23	863.52<x<912.16

— Results of Moisture Content

Moisture content is the ratio of the weight of water present in the air-dried timber sample to the oven-dry weight. It was observed that the average moisture content for Akomu timber was 11.12 % with standard deviation of 16.42 and coefficient of variation of 14.75 and for Eriri was 13.29 % with standard deviation of 10.77 and coefficient of variation of 8.14 as can be seen in Table 2. This result is satisfactory, since it is less than the maximum recommended moisture content of 25 - 30 % for an air-dry sample. At this moisture content the likelihood of decay of the timber is greatly reduced. The strength of timber is also affected by its moisture content increasing as the moisture content reduces and vice versa.

Table 2: Average moisture content of Akomu and Eriri Timber species

Species	Average Moisture Content (%)	
	Akomu	Eriri
Minimum	9.09	5.26
Maximum	13.73	45.68
Mean	11.12	13.29
Standard Deviation	10.77	16.42
COV (%)	8.14	14.75
95% Confidence limit	7.78<x<14.46	8.20<x<18.38
99% Confidence limit	6.73<x<15.51	6.60<x<19.98

— Failure modes of Akomu and Eriri samples

A structural size timber 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. The slenderness ratio affords a means of classifying columns and their failure mode. A short column under the action of an axial load will fail by direct compression before it buckles, but a long column loaded in the same manner will fail by buckling. The buckling mode of deflection generally occurs before the axial compression stresses can cause failure of the material by yielding of that compression member. This is demonstrated in Table 3. It was observed that the long sections (400, 600 and 800 mm) exhibited buckling while the short sections (200 mm) failed mostly due to shear. Figure 1 – 3 shows the various failure modes experienced.

Table 3: Failure modes of specimens

Akomu				Eriri			
Specimen ID	Height (mm)	Failure mode	Observed deflection (mm)	Specimen ID	Height (mm)	Failure mode	Observed deflection (mm)
A1	208.00	Shear	-	D1	200.00	Shear	-
B1	205.00	Shear	-	E1	200.00	Shear	-
C1	200.00	Shear	-	F1	202.00	Splitting	-
A2	402.00	Buckling	5.0	D2	398.00	Buckling	13.0
B2	403.00	Buckling	5.0	E2	397.00	Shear	-
C2	402.00	Buckling	10.0	F2	401.00	Buckling	3.0
A3	597.00	Buckling	25.0	D3	598.00	Buckling	14.0
B3	598.00	Buckling	10.0	E3	600.00	Buckling	14.0
A4	801.00	Buckling	14.0	F3	595.00	Buckling	5.0
B4	800.00	Buckling	40.0	D4	803.00	Buckling	22.0
C4	801.00	Buckling	23.0	E4	801.00	Buckling	15.0
				F4	812.00	Buckling	21.0

Figure 1: Failure mode of 200mm (Shear)

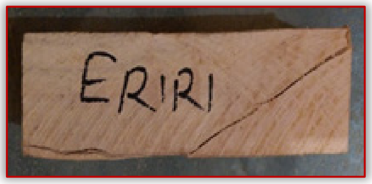

Figure 2: Failure mode of 200mm (Splitting)

Figure 3: Failure mode of 200mm (Buckling)

— Stress-strain relationship results

The results of the stress-strain relationship are presented in the Table 4 and 5. The mean stress in compression at yield for 200, 400, 600 and 800 mm heights of Akomu were; 30.104, 29.544, 18.530 and 15.434 N/mm^2 respectively. The mean stress in compression at yield for 200, 400, 600 and 800 mm heights of Eriri were; 26.429, 30.774, 33.311 and 26.365 N/mm^2 respectively.

The equations of stress-strain relationship of Akomu and Eriri timber species are shown in equation (7) and (8) as presented in the Figures 4 and 5. The maximum stress of Akomu sections can be estimated using the equation:

$$y = 1097.8x - 2.9858 \quad (7)$$

The maximum stress of Eriri sections can be estimated using the equation:

$$y = 1033.7x - 2.5309 \quad (8)$$

Table 4: Typical Stress-Strain Relationship for Akomu

Strain	Stress (200mm)	Stress (400mm)	Stress (600mm)	Stress (800mm)	Average Stress
0.000	0.000	0.000	0.000	0.000	0.000
0.001	0.065	0.052	0.078	0.086	0.070
0.002	0.296	0.237	0.404	0.295	0.308
0.003	0.772	0.657	0.905	0.591	0.731
0.005	1.228	1.162	1.449	0.859	1.174
0.006	2.153	2.089	2.290	1.294	1.957
0.007	3.265	3.363	3.204	1.817	2.912
0.008	5.037	4.782	4.288	2.509	4.154
0.009	7.051	6.498	5.380	3.431	5.590
0.011	9.117	8.391	6.709	4.310	7.132
0.012	11.509	10.313	8.126	5.444	8.848
0.013	13.958	12.484	9.693	6.588	10.681
0.014	16.375	14.511	11.193	7.684	12.441
0.015	18.758	16.635	12.688	8.930	14.253
0.016	20.864	18.580	14.006	10.052	15.875
0.017	22.787	20.435	15.270	11.016	17.377
0.019	24.405	22.244	16.218	12.014	18.720
0.020	25.818	23.944	17.066	12.691	19.880
0.021	27.003	24.622	17.605	12.985	20.553
0.022	27.828	25.435	17.903	13.133	21.075

Table 5: Typical Stress-Strain Relationship for Eriri

Strain	Stress (200mm)	Stress (400mm)	Stress (600mm)	Stress (800mm)	Average Stress
0.000	0.000	0.000	0.000	0.000	0.000
0.002	0.041	0.052	0.454	0.077	0.156
0.003	0.365	0.260	1.420	0.275	0.580
0.005	1.103	0.699	2.519	0.679	1.250
0.007	2.735	1.387	4.116	1.380	2.405
0.009	4.471	2.764	6.001	2.515	3.938
0.010	6.827	4.559	8.193	3.827	5.852
0.012	9.393	7.209	10.550	5.536	8.172
0.014	12.201	10.393	13.097	7.527	10.805
0.015	15.047	13.876	15.745	9.647	13.579
0.017	17.539	17.295	18.443	12.048	16.331
0.019	19.618	20.476	20.940	14.237	18.818
0.020	21.093	23.297	23.425	16.531	21.087
0.022	22.245	25.527	25.748	18.630	23.038
0.024	23.095	27.190	27.790	20.390	24.616
0.026	23.708	28.352	29.374	21.944	25.845
0.027	24.255	29.178	30.655	23.235	26.831
0.029	24.677	29.728	31.296	24.259	27.490
0.031	24.973	29.924	31.504	25.092	27.873
0.034	25.336	29.400	31.504	25.686	27.982

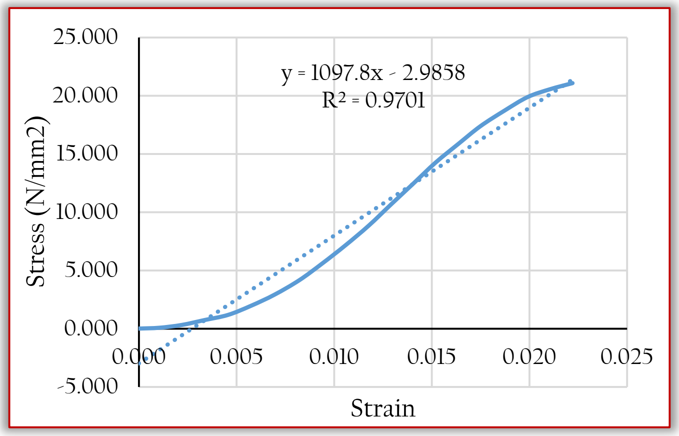

Figure 4: Typical Stress-strain curve for Akomu

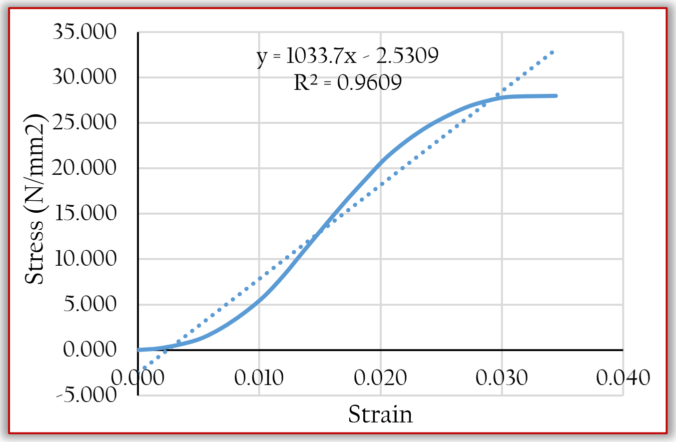

Figure 5: Typical Stress-strain curve for Eriri

Table 6 presents the relationship that exists between the timber species stress, strain, slenderness ratio and Young's Modulus. The stress at which a column buckles decreases as slenderness ratio increases and the mean length increases as well.

Table 6: Slenderness ratio, Stress @ Yield and Young's Modulus relationship for Akomu and Eriri

Mean Height (mm)	Mean Slenderness ratio, λ		Mean Stress @ Yield, σ (N/mm^2)		Young's Modulus (N/mm^2)	
	Akomu	Eriri	Akomu	Eriri	Akomu	Eriri
202.50	15.93	14.25	30.10	26.43	2045.71	1535.07
400.50	31.94	28.80	29.54	30.77	1465.74	1350.13
599.67	45.73	43.55	18.53	33.31	723.13	1091.83
803.00	58.31	57.77	15.43	26.37	418.43	918.17
Average			23.40	29.22	1163.25	1223.80

— Reliability Analysis results

The Tables 7, 8, 9 and 10 show the reliability analysis of Akomu and Eriri timber species using Constant Failure Rate model, while Figure 6 and 7 show the reliability index of the studied specimens.

The results of the reliability analysis show that the timber species Akomu and Eriri has reliability index of 0.68 and 0.63 respectively (which are both greater than 0.5, the minimum index for a reliable structure according to Abdulraheem (2016), Adedeji (2008) and Ajamu (2014), for a service life of 50 years, assuming other serviceability conditions are met.

Table 7: Strength Analysis of Akomu timber

Height (mm)	Average Strength (σ) (N/mm²)	Cumulative Strength (Q_i) (N/mm²)	Remaining Strength (R_i) (N/mm²)	Strength Rate (d_i)
200.00	30.104	30.104	63.508	0.4740
400.00	29.544	59.648	33.964	0.4652
600.00	18.530	78.178	15.434	0.5456
800.00	15.434	93.612	0	1.0000

Average Strength rate

$$d = \frac{0.4740 + 0.4652 + 0.5456 + 1.0000}{4} = 0.6212$$

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 Akomu timber column is evaluated as shown below using Constant Failure Rate (CFR).

$$\lambda = \frac{1 - 0.6212}{50} = 0.007576/\text{years}$$

Table 8: Reliability of Akomu using CFR

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.061	0.3461
20	0.152	0.8590	160	1.212	0.2976
40	0.303	0.7386	180	1.364	0.2556
60	0.455	0.6345	200	1.515	0.2198
80	0.606	0.5455	220	1.667	0.1888
100	0.758	0.4686	240	1.818	0.1624
120	0.909	0.4029	260	1.970	0.1395

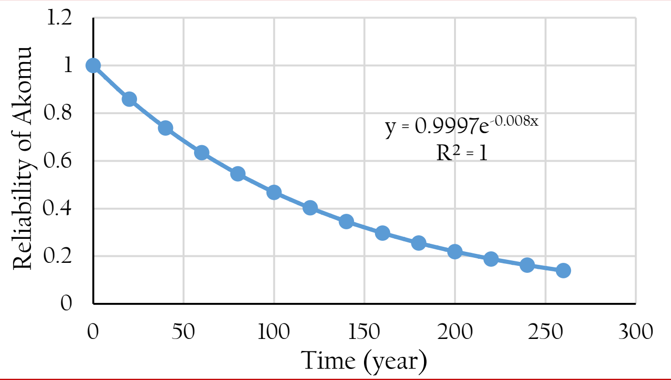

Figure 6: Reliability of Akomu Timber

Table 9: Strength Analysis of Eriri timber

Height (mm)	Average Strength (σ) (N/mm²)	Cumulative Strength (Q_i) (N/mm²)	Remaining Strength (R_i) (N/mm²)	Strength Rate (d_i)
200.00	26.429	26.429	90.450	0.2922
400.00	30.774	57.203	59.676	0.3402
600.00	33.311	90.514	26.365	0.5582
800.00	26.365	116.879	0	1.0000

Average Strength rate

$$d = \frac{0.2922 + 0.3402 + 0.5582 + 1.0000}{4} = 0.5477$$

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 Eriri timber column is evaluated as shown below using Constant Failure Rate (CFR).

$$\lambda = \frac{1 - 0.5477}{50} = 0.009046/\text{years}$$

Table 10: Reliability of Eriri using CFR

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.266	0.2820
20	0.181	0.8344	160	1.447	0.2353
40	0.362	0.6963	180	1.628	0.1963
60	0.543	0.5810	200	1.809	0.1638
80	0.724	0.4848	220	1.990	0.1367
100	0.905	0.4045	240	2.171	0.1141
120	1.086	0.3376	260	2.352	0.0952

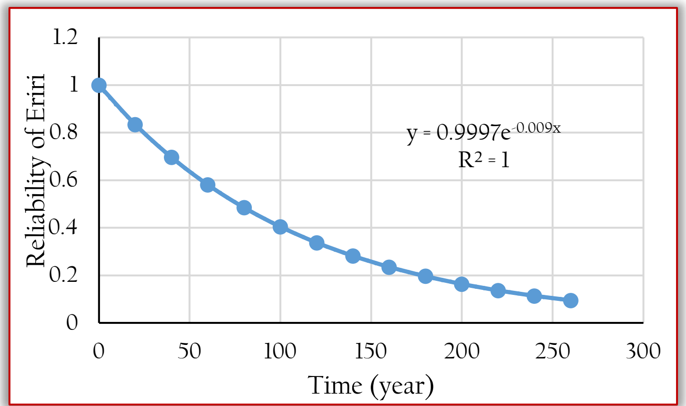

Figure 7: Reliability of Eriri Timber

CONCLUSIONS

The overall conclusions emerging from this study are:

— The result shows that Eriri has higher yield strength than Akomu and thus will be more suitable for Structural use. The result further illustrates the direct relationship that exists between physical properties such as moisture and density, and mechanical properties such as yield strength and elastic modulus.

— The maximum stress of Akomu and Eriri sections can be estimated using the equation: $y = 1097.8x - 2.9858$ and $y = 1033.7x - 2.5309$ respectively. The stress at which a column buckles decreases as slenderness ratio increases.

— A short column under the action of an axial load will generally fail by shear, but a long column will fail by buckling.

— 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 and sustainable construction materials.

— The result of the reliability analysis show that the timber species Akomu and Eriri has reliability index of 0.68 and 0.63 respectively for a service life of 50 years, assuming other serviceability conditions are met.

— However further research is required to determine other strength properties such as bending strength, tensile strength and the determination of these strength properties for different structural sizes should also be carried out. This will enable not only an effective design, but also a holistic design procedure to be developed for both Akomu and Eriri timbers.

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