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Reliability-Based Investigation on Compressive Strength Characteristics of Structural-Sized Iroko (Meliceae Excelsa) and Mahogany (Khaya Ivorensis) Timber Column Found in Nigeria

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ABSTRACT

This research work examined the reliability of the Nigerian grown Iroko and Mahogany timber species as column materials. The strength and physical properties of these timber species were determined to predict the suitability of the species as a structural material. Forty lengths of timber species of 50mm x 50mm 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 the grain of forty test specimens each of lengths, 200, 400, 600 and 800mm done in accordance with the British Standard BS 373(1957). Mean air-dried moisture content for Iroko and Mahogany were 12.09 and 14.81% respectively. Mean density of Iroko and Mahogany were 500.8 and 830.1kg/m^3 respectively. The derived continuous equations for the design of Iroko column and Mahogany column are $\sigma = 37.552e^{-0.005\lambda}$ and $\sigma = 37.125e^{-0.007\lambda}$ respectively. The results of the reliability analysis show that Iroko and Mahogany timber species have reliability index of 0.64 and 0.65 for a service life of 50 years, assuming other serviceability conditions are met. This design procedure is distinct and more effective than the usual procedure of classifying compression members as short, intermediate and long using their slenderness ratios.

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1. Introduction

Timber is one of the materials used in construction and is a sustainable resource [1]. It is also a natural and renewable material and has a high strength-to-weight ratio and easy to work with [2]. It is an organic material and thus is subject to deterioration with time [3]. Load-carrying structures may fail in a variety of ways, depending upon the type of structure, the conditions of support, the kinds of loads, and the materials used. The similar study considered specifically the buckling of columns, which are long, slender structural members loaded axially in compression [4]. Buckling is one of the major causes of failures in columns, and therefore the possibility of buckling should always be considered in the design. Buckling is a mode of failure in which there is a sudden deformation in a direction or plane normal to that of the loads or moments acting [5].

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 [6]. According to [7], Reliability is often understood to equal the probability that a structure will not fail to perform its intended function. Reliability-based designs are efficient because they make it achieve both to design a more reliable structure for a given cost and to design a more economical structure for given reliability. 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 [8], reliability index using constant failure rate (CFR) model is as given in equation (1):

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

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

$$\lambda = \frac{1-d}{T} \tag{2}$$

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

[9] defines structural reliability as 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. 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. The target reliability is a design constraint that assures the required safety level for structures [10]. Established an optimization procedure to determine the target reliability for structures with consideration of the construction cost, failure cost, maintenance cost, structural lifetime, discount rate, time-dependency of the load and resistance, and important structural factor. The contour concept approach was adopted to establish the above relationship. 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 [11].

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 [12–14]. A significant element of uncertainty is also introduced through lack of information about the actual physical variability.

However, [15] developed a reliability index for non-normal distributions of limit state functions using statistical parameters of the load and/or resistance. This will aid in calculating the safety level of the structures or its components. The probability of failure and the reliability index was computed based on the summation of the reliability index of two normal distributions.

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

2. Materials and methods

2.1. Material procurement

Meliceae excels (Iroko), and *Khaya ivorensis* (Mahogany) timber species were bought from Tanke, Odo-Okun, and Saboline sawmills in Ilorin, 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 the column which is always completely exposed to natural atmospheric weather conditions. The timber samples were prepared and tested in accordance with [16], Test for physical and mechanical properties of structural timbers at the Wood section of the Civil Engineering Department, University of Ilorin, Nigeria. Timber length of 50mm x 50mm section obtained from each sawmill was cut into lengths 200, 400, 600 and 800mm. A maximum height of 800mm was used due to the limited height of the testing machine. A typical nomenclature is given in Figure 1.

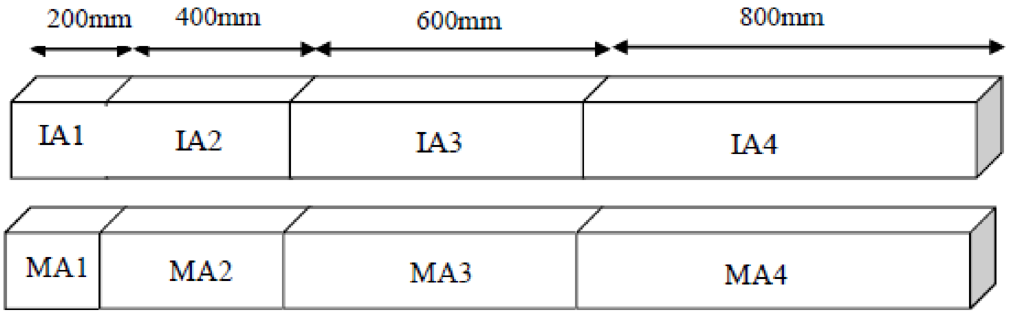

Fig. 1. Lengths of Timber species.

The physical property tests of the timber species were 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 300kN at the Agricultural Engineering Laboratory of University of Ilorin, Kwara State, Nigeria.

2.2. Physical property tests

Moisture Content - In Accordance with [17] 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:

$$m.c.\% = \frac{W_a - W_0}{W_0}\, x\, 100\% \tag{3}$$

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

Density - Density of a material is the ratio of the mass to the volume. In the 50 mm by 50 mm standard given by [17], all test pieces weight and dimensions were determined before the test. The density is given as:

$$\rho = \frac{W_a}{V_a} = \frac{W_a}{BxDxH} \tag{4}$$

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 (m^3).

2.3. Mechanical property test

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

i. The timber was cut into various sizes (200, 400, 600 and 800mm); twenty samples for each of the sizes and then labeled.

ii. The machine height was now adjusted to the sizes of the specimen. Then the timber was fixed for loading.

iii. The speed of the test was calculated according to [17].

Table 1
Test speed.

Sample length (mm)	Test speed (mm/min)
200.00	13.020
400.00	26.040
600.00	39.060
800.00	52.075

iv. The nominal length, the test speed, weight, breadth, width of the samples was inputted into the computer.

v. 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.

vi. The buckling was measured, and the sample taken out of the machine.

vii. The steps were repeated for the remaining samples.

viii. From the load-deflection curve obtained after the test, the stress and strain is calculated

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

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

- Member slenderness was calculated as follows:

$$\text{Slenderness ratio, } \lambda = \frac{\mathrm{Le}}{\mathrm{r}} \tag{7}$$

Where: Le = 1.0L,

$$\text{Radius of gyration, } r = \sqrt{\frac{I}{A}} \tag{8}$$

$I = \frac{BD^3}{12}$, 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.

Fig. 2. Failure mode Mahogany (400mm).

Fig. 3. The failure mode Mahogany (600mm).

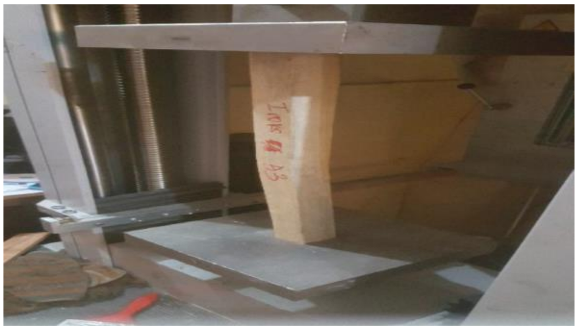

Fig. 4. The failure mode of Iroko (600mm).

3. Results and discussion

This section presents the results and discussions of the experimental works. The timber properties considered include: density, moisture content, compressive strength and buckling load estimation.

Density - The results for density are shown in Table 2. From the results, it was observed that the average density of *Milicia excelsa* (Iroko) is 500.8kg/m³ while that of *Khaya ivorensis* (Mahogany) is 830.1kg/m³. This implies that Mahogany has higher yield strength than Iroko.

Table 2
The average density of Iroko and Mahogany

Specie	Average density (kg/m^3)	
	Iroko	Mahogany
Minimum	474.8	736.6
Maximum	528.5	881.9
Mean	500.8	830.1
Standard deviation	45.44	54.91
COV (%)	4.54	5.47
95% Confidence limit	$480.89 \leq x \leq 520.72$	$806.04 \leq x \leq 854.17$
99% Confidence limit	$474.63 \leq x \leq 526.97$	$798.47 \leq x \leq 861.73$

Moisture content - The minimum, maximum and average moisture content of Iroko after compression test is 5.26%, 16.00%, and 12.09% and that of Mahogany are 12.09%, 16.67%, and 14.81% respectively. 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 is greatly reduced.

Table 3
The average moisture content of Iroko and Mahogany.

Specie	Average moisture content (%)	
	Iroko	Mahogany
Minimum	5.26	12.90
Maximum	16.00	16.67
Mean	12.09	14.81
Standard deviation	4.01	6.53
COV (%)	35.43	42.68
95% Confidence limit	10.33≤x≤13.85	11.95≤x≤17.67
99% Confidence limit	9.78≤x≤14.40	11.05≤x≤18.57

Stress-strain relationship of Iroko and Mahogany timber

The continuous column design equations of stress-strain relationship of Iroko and Mahogany timber species was obtained from the regression analysis as given in equation (9) and (10). The continuous equations are as follows:

$$\boldsymbol{\sigma = 37.522e^{-0.005\lambda}} \tag{9}$$

$$\boldsymbol{\sigma = 37.125e^{-0.007\lambda}} \tag{10}$$

Table 4
Young's Modulus, Stress@Yield, Slenderness Ratio relationship.

IROKO			
Average Length (mm)	**Young's Modulus**	**Average Stress @ Yield**	**Average Slenderness Ratio, λ**
200.67	1726.16	35.40	13.91
402.67	1373.71	32.18	27.82
600.00	1142.17	30.08	41.44
802.67	1000.17	28.76	54.93

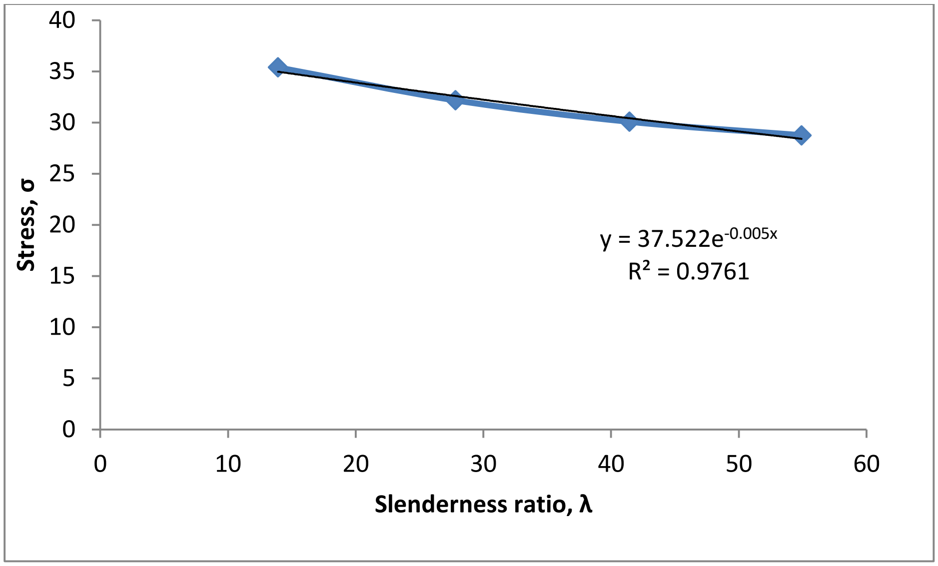

Fig. 5. Average Stress @ Yield vs Slenderness Ratio Curve for Iroko.

Table 5
Young's Modulus, Stress@Yield, Slenderness Ratio relationship.

MAHOGANY			
Average Length (mm)	**Young's Modulus**	**Average Stress @ Yield**	**Average Slenderness Ratio, λ**
200.67	2020.66	32.996	14.21
402.67	1594.56	30.995	28.63
600.67	1036.18	27.411	42.52
802.67	764.32	24.283	58.27

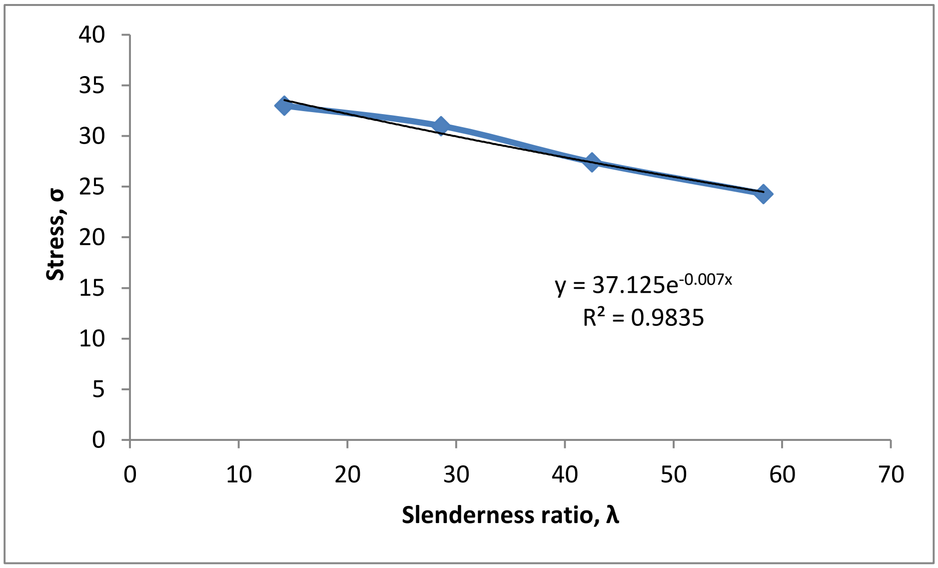

Fig. 6. Average Stress @ Yield vs. Slenderness Ratio Curve for Mahogany.

4. Verification of design equations

Table 6 and 8 show the relationship between experimental stress at yield and the theoretical stress using equation at yield for *Milicia excelsa* (Iroko) and *Khaya ivorensis* (Mahogany) respectively. The results of One-way Analysis of Variance (ANOVA) on experimental stress at yield and the theoretical value at 0.05 significance level is given in Table 7 and 9 for Iroko and Mahogany respectively.

In other to derive a continuous column design equation for both Iroko and Mahogany timbers, statistical regression analysis was performed on the stress at yield and slenderness ratio results for Iroko as presented in Table 6 and Mahogany as presented in Table 8. The result of the regression analysis yields Equation 9 and 10 which is the desired column design equation for both Iroko and Mahogany timbers respectively.

$$\boldsymbol{\sigma = 37.522e^{-0.005\lambda}} \tag{9}$$

$$\boldsymbol{\sigma = 37.125e^{-0.007\lambda}} \tag{10}$$

The curve of fit for Equation 9 is shown in Figure 5, while the corresponding curve for Equation 10 is given in Figure 6.

Table 6
Theoretical Stress @ Yield and Slenderness Ratio for Iroko.

EXPERIMENTAL-THEORETICAL STRESS RELATIONSHIP FOR IROKO

Specimen	Slenderness Ratio, λ	Experimental Stress @ Yield, σ_1 (N/mm^2)	Theoretical Stress @ Yield, σ_2 (N/mm^2)	σ_2/σ_1
A1	13.62	36.45	35.37681	0.970557
B1	14.27	34.58	35.26181	1.019717
C1	13.86	35.17	35.33418	1.004668
A2	26.98	34.47	33.09005	0.959967
B2	29.50	27.38	32.67515	1.193395
C2	26.97	34.70	33.09123	0.953638
A3	41.29	29.15	30.80443	1.056756
B3	42.73	26.94	30.58409	1.135267
C3	40.29	34.15	30.95940	0.906571
A4	56.01	34.32	28.61961	0.833905
B4	53.61	28.70	28.96446	1.009214
C4	55.18	23.27	28.73848	1.235001

Table 7
ANOVA Analysis for Iroko.

ANOVA: SINGLE FACTOR

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	12	379.28	31.60667	18.20186
Column 2	12	383.4997	31.95831	6.52446

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.741911	1	0.741911	0.06001	0.808751	4.30095
Within Groups	271.9895	22	12.36316			
Total	272.7314	23				

Table 8
Theoretical Stress @ Yield and Slenderness Ratio for Mahogany.

EXPERIMENTAL-THEORETICAL STRESS RELATIONSHIP FOR MAHOGANY

Specimen	Slenderness Ratio, λ	Experimental Stress @ Yield, σ_1 (N/mm^2)	Theoretical Stress @ Yield, σ_2 (N/mm^2)	σ_2/σ_1
A1	13.89	33.30	33.87014	1.017121
B1	14.28	32.70	33.77698	1.032935
C1	14.45	32.99	33.73654	1.022629
A2	28.00	30.67	30.68338	1.000436
B2	29.50	30.01	30.34495	1.011161
C2	28.30	32.31	30.61879	0.947657
A3	42.31	25.91	27.75861	1.071347
B3	44.01	26.40	27.43044	1.039032
C3	41.22	29.93	27.97206	0.934583
A4	58.58	21.30	24.77054	1.162936
B4	58.12	23.45	24.85129	1.059757
C4	58.10	28.11	24.85534	0.884217

Table 9
ANOVA Analysis for Mahogany.

ANOVA: SINGLE FACTOR

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	12	347.08	28.92333	15.53202
Column 2	12	350.6691	29.22242	12.08924

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.536723	1	0.536723	0.038863	0.84553	4.30095
Within Groups	303.8339	22	13.81063			
Total	304.3706	23				

5. Reliability analysis result

The Tables 10, 11, 12 and 13 show the reliability analysis of Iroko and Mahogany timber species using Constant Failure Rate model. The result of the reliability analysis shows that the timber species have reliability index of 0.64 and 0.65 (which is greater than 0.5, the minimum index for a reliable structure according to [18] and [6] for a service life of 50 years, assuming other serviceability conditions are met.

Table 10
Strength Analysis of Iroko timber.

Height (mm)	Average Strength (σ) (N/mm^2)	Cumulative Strength (Q_i) (N/mm^2)	Remaining Strength (R_i) (N/mm^2)	Strength Rate (d_i)
200.00	35.40	35.40	91.02	0.3889
400.00	32.18	67.58	58.84	0.3535
600.00	30.08	97.66	28.76	0.5112
800.00	28.76	126.42	0	1.0000

Average Strength rate, $d = \frac{0.3889+0.3535+0.5112+1.0000}{4} = 0.5634$

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 Iroko timber column is evaluated as shown in Table 11 using Constant Failure Rate (CFR) model.

$$\lambda = \frac{1-0.5634}{50} = 0.00873/year$$

Table 11
Reliability using CFR.

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.2222	0.2946
20	0.1746	0.8398	160	1.3968	0.2474
40	0.3492	0.7053	180	1.5714	0.2078
60	0.5238	0.5923	200	1.7460	0.1745
80	0.6984	0.4974	220	1.9206	0.1465
100	0.8730	0.4177	240	2.0952	0.1230
120	1.0476	0.3508	260	2.2698	0.1033

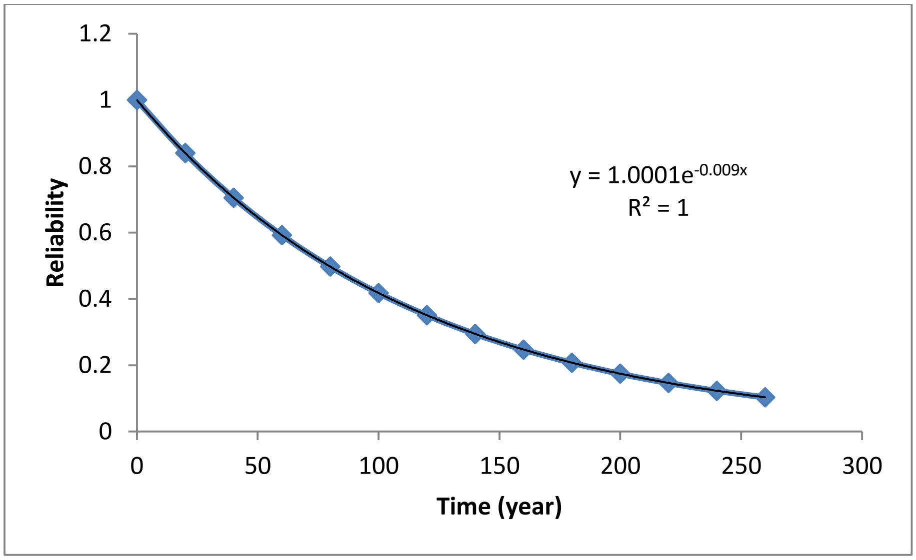

Fig. 7. Reliability of Iroko timber.

Table 12
Strength Analysis of Mahogany timber.

Height (mm)	Average Strength (σ) (N/mm^2)	Cumulative Strength (Q_i) (N/mm^2)	Remaining Strength (R_i) (N/mm^2)	Strength Rate (d_i)
200.00	32.996	32.996	82.689	0.3990
400.00	30.995	63.991	51.694	0.3748
600.00	27.411	91.402	24.283	0.5303
800.00	24.283	115.685	0	1.0000

Average Strength rate, $d = \frac{0.3990+0.3748+0.5303+1.0000}{4} = 0.5760$

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 Mahogany timber column is evaluated as shown in Table 13 using Constant Failure Rate (CFR) model.

$$\lambda = \frac{1 - 0.5760}{50} = 0.00848/year$$

Table 13
Reliability using CFR.

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.1872	0.3051
20	0.1696	0.8440	160	1.3568	0.2575
40	0.3392	0.7123	180	1.5264	0.2173
60	0.5088	0.6012	200	1.6960	0.1834
80	0.6784	0.5074	220	1.8656	0.1548
100	0.8480	0.4283	240	2.0352	0.1307
120	1.0176	0.3615	260	2.2048	0.1103

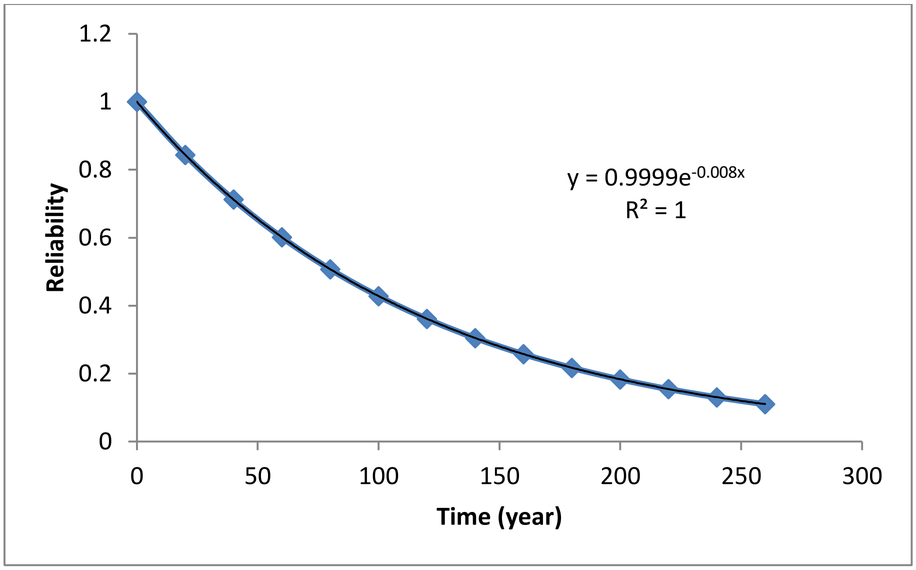

Fig. 7. Reliability of Mahogany timber.

6. Conclusions

The following are the conclusion derived from the test carried out on air dried Iroko and mahogany timber species.

1. The average density of mahogany is greater than the average density of Iroko.
2. The moisture content of the timbers was low which means the timber was well seasoned before the test.
3. It was found that the maximum stress of Mahogany timber is higher than that of Iroko since the ultimate stress of the material depends on its strength; hence Mahogany timber is of higher strength compared to Iroko timber.
4. The continuous equation for Iroko timber is $\boldsymbol{\sigma = 37.522e^{-0.005\lambda}}$ and that of mahogany timber is $\boldsymbol{\sigma = 37.125e^{-0.007\lambda}}$.
5. The result of the reliability analysis shows that the timber has a reliability index of 0.64 for a service life of 50 years, assuming the design load limit is not exceeded.

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