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INTEGRITY OF PHYSICAL AND STRENGTH PROPERTIES OF SOME SELECTED CONSTRUCTIONAL TIMBER SPECIES FROM SOUTHWESTERN NIGERIA AFTER CHARRING

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Abstract: Fire safety is the main precondition for the use of wood for constructional purposes and therefore an important criterion for the choice of material for buildings. The research investigated changes in post fire density and strength properties of Nigerian timber species used for construction. The selected species are: Terminalia superba (Afara), Milicia excels (Iroko), Nauclea diderrichii (Opepe), Khaya ivorensis (Mahogany), Mansonia altissima (Mansonia), Tectona grandis (Teak). Densities and strength properties of the species were determined at Moisture Contents (MC) of 9.0, 12.0, and 15.0%. Species were exposed to fire at various temperature ranges. The results revealed that at 9, 12 and 15%MC, Opepe had the highest density values of 630±28.85Kg/m^3, 686±22.64Kg/m^3 and 752±17.22Kg/m^3 respectively. At 9%MC, Mahogany had the lowest density (439±10.58Kg/m^3) while at 12 and 15%MC, Afara had the lowest density values of 444±4.18Kg/m^3 and 469±7.07Kg/m^3 respectively. Post fire exposure revealed that Afara had the highest percentage loss in density 29.2% and strength properties, while both Iroko and Mahogany exhibited the lowest percentage loss in both density and strength properties. Mahogany and Iroko species which had lowest overall post fire change in density and strengths values are useful and recommended to ensure the safety in case of fire outbreaks.

Keywords: Nigeria timbers, constructional purpose, wood density, strength properties, fire resistance

INTRODUCTION

Many buildings and civil engineering works are at high risk of fire. Therefore, accurate prediction of behaviour of the structures subjected to fire is of primary importance for the evacuation of persons, as well as for the safety of rescue teams. (Bednarek, 2008). Timber is one of man's oldest building materials. It is a renewable, naturally occurring organic polymer, unique in a world of synthetic and composite building materials. Today, timber is derived from sustainably managed forests and is one of our most environmentally friendly building materials. The wide distribution of timber, its ready availability, variety of uses and relative ease of handling and conversion, have all contributed to its wide acceptance in the building industry.

Timber is easy to form, saw, nail and fit; even with simple hand tools. Timber is natural and renewable. It has a high strength to weight ratio and is easy to work with, making it especially useful where only basic technology and procedures are available (Apu, 2003). The small tubular cells that are the fundamental structural elements of solid wood give timber its good properties for sound, electrical and heat insulation, for engineering requirements, and strong aesthetic appeal. Because of its wide range of properties, it is essential that for a particular application, the most suitable timber species is selected (Timber Manual Data file, 2004).

Timber as a building material has the disadvantage of being combustible. Consequently, timber structures are seen by many as creating an environment less safe than structures built of noncombustible materials such as steel and masonry. Until recently, the use of timber for major structures was viewed with suspicion, or at best accepted as a black art, practiced by a few privileged professionals. However during the past two decades, some very useful analytical tools have been developed, which enable the reliability of timber structures to be compared with the reliability of constructions with other structural materials such as steel and reinforced concrete. However, experience has shown that some timber structures have a fire resistance comparable, or greater than that of many noncombustible alternatives. Contrary to many people's expectations, timber used in construction performs well in fire. It will not flake, spall, melt, buckle or explode. Steel and concrete members (Bednarek, 1996) under fire have been extensively investigated in last decades. However, far fewer investigations have been carried out on timber structures (Bednarek, et al., 2002). Timber burns steadily at a predictable rate called charring. In the charring process charcoal is formed on the surface of the timber, which serves to insulate and protect the core. As a result, timber is now viewed as a respectable construction material.

Heavy wood members have long been recognized for their ability to maintain construction integrity while exposed to fire. Early mill construction from the 19th century utilized massive timbers to carry large loads and to resist structural failure from fire. Wood density is an important wood property for both solid wood and fibre products in both conifers and hardwoods (De Guth, 1980). Panshin and de Zeeuw (1980) reported that density is a general indicator of cell size and is a good predictor of strength, stiffness, ease of drying, machining, hardness and various paper making properties.

Brazier and Howell (1979) also expressed the opinion that density is one of the most important properties influencing the use of a timber. They emphasized that it affects the technical performance of wood and in particular the strength and processing behaviour of sawn wood and veneer, and the yields of wood fibre in pulp production. Cown (1992) reported that the density of wood is recognised as the key factor influencing wood strength. Indeed according to Schniewind (1989) much of the variation in wood strength, both between and within species, can be attributed to differences in wood density. Research has shown that higher density species tend to have stronger timber than lower density species (Addis Tsehaye et al., 1995; Walker & Butterfield, 1996).

The mechanical properties of wood are dependent on the density, moisture content, the amount of extractives, among other factors (Chrsitoforo et al., 2012), strength of wood increases as the wood density increases. When evaluating the density of wood, the level of moisture in which its mass and volume were measured must always be known. Mechanical properties most commonly measured and represented as "Strength properties" for design include maximum stress in compression parallel to grain, compressive stress perpendicular to grain.

BURNING BEHAVIOUR OF TIMBER

Timber hardwood species are used in the field of construction due to the particular qualities they can offer. Presently it is no longer possible to envisage the development of construction materials and products without taking into consideration the problem of their fire behaviour, and more particularly of their fire resistance. There are two distinct phases to a fire, the developing phase and the fully developed phase and material performance has to be categorized in respect of those two conditions. The developing phase incorporates a number of separate phenomena, the combustibility of the material, the ease of ignition, the speed of the spread of fire/flame across its surface and the rate at which heat is released (Buchanan, 2001).

The fully developed phase represents the post flash conditions where all combustible materials become involved in fire. The desirable properties are the ability to continue to carry load to contain the fire within the zone of origin without the escape of flames or hot gases and without conducting excessive heat to the unexposed face that may lead indirectly to fire being transmitted to adjacent areas. The ability to resist the fully developed fire is known universally as the fire resistance. But in general terms this can only relate to an element of construction rather than to a material. In the case of timber elements, this characteristic is mainly influenced by the charring rate of the external layers of the element. On the other hand, this charring rate is influenced by the density of the material. The charring rate and charred layer thickness are the starting points for determination of the undamaged core at any fire time and for determination of temperature layout inside the core (Plate 1).

The charring characteristics are important problems while determining the fire resistance of timber components by analytical method. The charring rate is dependent on a number of factors such as: timber species, timber density, timber thickness, moisture content, and chemical composition. Different timbers char at varying rates, largely as a function of their density with the higher density timbers charring more slowly (Adetayo & Dahunsi, 2018). For structural timbers listed in the code of practice for the design of structural timber, EN 1995-1-2, this rate of depletion is taken as 20 mm in 30 minutes from each exposed face. Certain of the denser hardwoods (>650kg/m^3) used for structural purposes merit rates of 15 mm in 30 minutes, e.g., keruing, teak, greenheart, jarrah. Timbers of lower density will char more quickly e.g. Western red cedar is quoted as 25mm in 30 minutes. The rate of charring is little affected by the severity of the fire, so for an hour's exposure, the depletions are 40 mm for most structural timbers and 30 mm for the denser hardwoods. This enables the fire resistance of simple timber elements to be calculated.

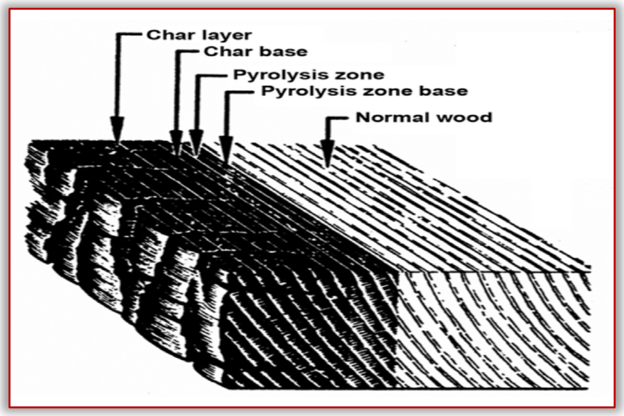

Plate 1. The changes in timber under influence of fire
Source: Charring rate of selected wood – transverse to grain (Schaffer, 1967)

Pyrolysis is essentially the thermal decomposition of organic matter under inert atmospheric conditions or in a limited supply of air, leading to the release of volatiles and formation of char (Plate 1). Pyrolysis in wood is typically initiated at 200°C and lasts till 450 - 500°C, depending on the species of wood. Pyrolysis has an important role in the combustion of wood since the products of this stage, namely, volatiles and char, subsequently undergo flaming and glowing combustion respectively to release thermal energy.

Timber is not readily ignited and there are very few recorded cases where timber will have been the first material to be ignited. Timber will require surface temperatures well in excess of 400°C if the material is to ignite in the medium to a short term without the pressure of a pilot flame. Even when a pilot flame is present, the surface temperature will have to be in excess of 300°C for a significant time before ignition occurs. The comparative fire resistance of wood and metal was never more graphically shown than the pictures taken after many hours of burning in the 1953 fire at a casein plant in Frankfort, New York (Plate 2).

Plate 2. Wood beam survives fire in casein plant Frankfort, NY.
Courtesy; Handbook of Wood Chemistry and Wood Composites Second Edition, 2013

The steel girders softened and failed at high temperature and fell across the 300mm by 400mm wood beams that were charred but still strong enough to hold the steel girders (Adetayo & Dahunsi, 2017). This charring protecting property of structural wood has found many applications, such as railroad wooden bridges (Handbook of Wood Chemistry and Wood Composites Second Edition, 2013).

MATERIALS AND METHODS

Preliminary studies were carried out to identify timber species used in the construction of structural members in Southwestern Nigeria. Six structural timber species were taken out of the ten mostly available species. All timber samples used in this research were taken from the heartwood region of the individual tree. And they were specially ordered from the lumber market.

The six species were:

- Afara (Terminalia superba)
- Iroko (Milicia excelsa)
- Mahogany (Khaya ivorensis)
- Mansonia (Mansonia altissima)
- Opepe (Nauclea diderrichii)
- Teak (Tectona grandis)

— Determination of Density and Moisture content

The specimens were cut into dimensions of 60mm x 20mm x 20mm for density and moisture content determination. Five samples were taken for each species and tested. The average results were then determined. Densities were determined by dividing the mass of the specimen by the volume as per equation 1.

$$\text{Density } \rho = \frac{m}{v} \qquad (1)$$

where m = the mass in gram, obtained from weighing directly using digital weighing balance,

v = the specimen volume, determined by multiplying (60 x 20 x 20) mm^3.

Corresponding value of density for each specimen was converted to kilogram cubic meter (kg/m^3). Density is moisture dependent, because moisture adds to the mass and may cause volume to swell. Moisture content is defined as the ratio of the mass of removable water (m_{water}) to the dry mass of wood (m_{dry}). The dry mass is obtained by oven drying at 103 ± 2 °C for 24hours as per ASTM D143-94. Moisture content can be expressed as a fraction or in percentage terms (Equation 2)

$$\text{Moisture Content (MC)} = \frac{m_{wet} - m_{dry}}{m_{dry}} (100\%) \qquad (2)$$

— Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

Test samples of 300 x 20 x 20mm were obtained from each sampling level. Thirty samples, five samples from each species were used for static bending test for MOE and MOR. The machine used for the measurements is the Hounsfield Tensiometer available in forest product development and utilization department at Forestry research Institute of Nigeria, Ibadan. The sample was prepared so that the growth rings are parallel to one edge and the sample was tested with the growth rings parallel to direction of loading i.e. it was loaded on the radial face: load of 1 ton (10,160N or 10.16KN) was applied at a speed of 0.1mm/s. The bending strength of these wood samples were presented as a modulus of rupture (MOR) which is the equivalent stress in the extreme fibres of the sample at the point of failure assuming that the simple theory of bending applies. The MOR is calculated in three points bending from the equation 3 below.

$$\text{MOR} = \frac{3PL}{2bh^2} \qquad (3)$$

where, MOR is in N/mm^2; P = load in Newton (N); L = span in mm; b = width in mm; h = height in mm

Also the bending strength was also presented as modulus of elasticity (MOE) which provides values of works to maximum load and total work, as well as a measure of toughness. The MOE is calculated as:

$$\text{MOE} = \frac{PL}{4bh^2\Delta} \qquad (4)$$

where, MOE is in N/mm^2; P = load in Newton (N); L = span in mm; b = width in mm; h = height in mm; Δ = angle of inclination derived from the graph.

The replicates of five samples from each species were used to obtain the mean values according with BS EN1957.

— Shear parallel to the grain

Shear is the ability to resist internal slipping of one part upon another along the grain. The samples sizes are 20mm x 20mm x 20mm and a load of 1tonne (approximately 10000N or 10KN) was applied to the piston of the cage at a rate of 0.01mm/s. The corresponding shear stress is calculated thus,

$$\text{Shear} = \frac{P}{\text{Area}} \qquad (5)$$

P = maximum shear force (load) in Newton (N); Area = L x b;
L= length in mm; b= thickness in mm

— Compression parallel and perpendicular to the grain

This test deals with obtaining the maximum crushing strength of the wood sample. The samples sizes is 60mm x 20mm x 20mm and a load of 1tonne (approximately 10000N or 10KN) was applied to the piston of the cage at a rate of 0.01mm/s. One of the precautions necessary in evaluating this property is the need to ensure that the samples do not buckle during loading, thereby subjecting it to a bending rather than a compressive stress. A special cage which ensures a uniform distribution of load over the cross-section was used.

The compressive strength in (N/mm2) was obtained by:

$$\text{Compression} = \frac{P}{\text{Area}} \qquad (6)$$

P = load in Newton (N); Area = L x b; L = Length in mm;
b= thickness in mm

— Fire Exposure Method

At time of test, the following data were recorded for the specimen properties:

- Species
- Ring orientation
- Specimen dimensions
- Specimen weight
- Specific gravity (dry)
- Moisture content (percent)

The specimen, were installed in the furnace, and the electric furnace was powered, the furnace temperature switched on was 20°C. At time of burner ignition, the following functions were done as simultaneously as possible.

- Automatic temperature recorder was started
- Stop watches started
- Furnace temperature controller started.

Specimens were exposed to fire in three batches; first batch went for time (0- 30) minutes, second batch for (0 -30) minutes and the last batch was for full (0- 60) minutes.

The first test for exposure period 0 – 30 minutes was stopped at the time when the stop watch reached 30 minutes, temperature ranging from 20°C to 230°C. Samples exposed during the second period were subjected to higher temperature 230°C to 600°C for 30 minutes (30 – 60 minutes). The third test, for exposure period 0 – 60 minutes was terminated when the furnace temperature reached 20°C to 300°C.

When testing completed, the charred wood was scrapped away from the samples and char depth measured millimetres. Charring rates were determined by dividing char depth with the corresponding fire exposure time (Adetayo & Dahunsi, 2018).

— Post Fire Strength Properties of Wood samples

The density and compressive strength of the wood samples that had charred were tested to determine their post fire strength after 0 – 60 minutes fire exposure and temperature ranging between 20°C to 300°C inside electric furnace, the char layers were easily scrapped off. The charred portion has no residual load capacity. The wood beneath the char layer has residual load capacity, but this residual capacity is less than the load capacity prior to fire.

RESULTS AND DISCUSSION

— Density and Moisture Content

Figure 1 illustrated the column chart of the values of density of each species at their corresponding Moisture Contents (MC) 9, 12 and 15%. The results showed that as timber species moisture content increases, the density increases. At 9% MC, Mahogany had the lowest density value of 439 ± 10.58 Kg/m^3. At 12 and 15% MC, Afara had the lowest density values of 444 ± 4.18 Kg/m^3 and 469 ± 7.07 Kg/m^3 respectively. At 9, 12 and 15% MC, Opepe had the highest density values of 630 ± 28.85 Kg/m^3, 686 ± 22.64 Kg/m^3 and 752 ± 17.22 Kg/m^3 respectively.

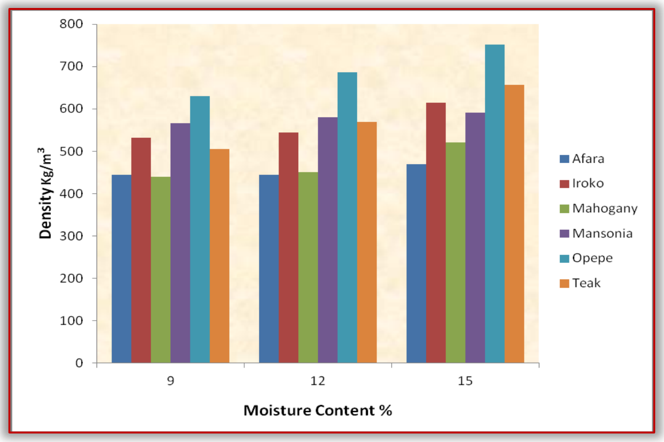

Figure 1: Density of selected Species at their corresponding Moisture Content

— Modulus of Elasticity

MOE is a useful property required in designing trusses for roofing structures, dry wood is often preferred in the design of wood structures to minimize shrinkage associated with in situ drying in service.

Figure 2 illustrated the column chart for the Modulus of Elasticity values of each species at their corresponding MC 9, 12, and 15%. It shows that MOE values increases as moisture content of wood sample reduces. At 15% MC, Teak had the lowest MOE value of 10269.20 ± 2049 N/mm2 while Mahogany had the highest value of 15368.20 ± 904.71 N/mm^2. Afara had the lowest MOE values of 12056.00 ± 2307.71 N/mm^2 at both 9 and 12% MC. Opepe had the highest MOE value of 15557.80 ± 4718.64 N/mm^2 at 12% MC and Iroko had the highest value of 19884.80 ± 7768.79 N/mm^2 at 9% MC.

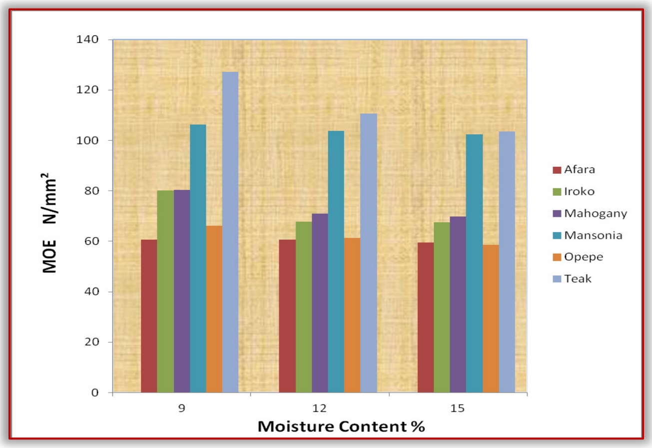

Figure 2: MOE of selected Species at their corresponding Moisture Content

— Modulus of Rupture

MOR is also one of the key mechanical properties of wood measured and presented as strength property for design. It is a reflection of the maximum load carrying capacity of a member in bending and is proportional to the maximum moment borne by the specimen.

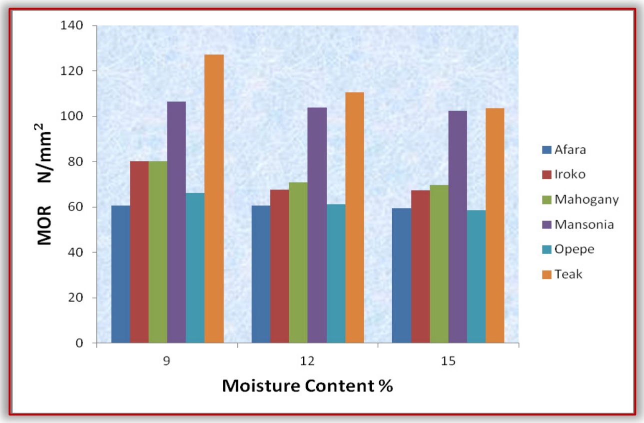

Figure 3: MOR of selected Species at their corresponding Moisture Content

Figure 3 illustrated the column chart for the Modulus of Rupture values of each species at their corresponding 9, 12, and 15% MC moisture content. It shows that MOR values increases as moisture content of wood sample reduces. At 15% MC Opepe had the lowest

MOR value of 58.50 ± 8.53 N/mm^2. At 9 and 12% MC, Afara had the lowest MOR values of 60.64 ± 2.10 N/mm^2. At 9, 12 and 15% MC, Teak had the highest MOR values of 127.14 ± 14.62 N/mm^2, 110.70 ± 12.67 N/mm^2 and 103.47 ± 10.17 N/mm^2 respectively.

— Compression Results

The mean values of compression strength parallel to the grain at 9, 12, and 15% MC for each species are given in Figure 4. Compression strength parallel to the grain is higher than perpendicular to the grain and the results are similar to previous results obtained from Odom et al., (1994) promotion of valuable hardwood plantations in the tropics and Excerpts from the rules for materials.

From the results, it showed that as timber species moisture content increases, the compressive strength parallel to the grain decreases. Afara of 9, 12 and 15% MC had the lowest Compression strength parallel to the grain values of 9.59 ± 1.08 N/mm^2, 9.59 ± 1.08 N/mm^2 and 8.13 ± 1.01 N/mm2 respectively, while Mahogany had the highest Compression strength parallel to the grain values of 16.57 ± 0.50 N/mm^2, 15.17 ± 0.49 N/mm^2 and 12.12 ± 0.42 N/mm^2 at the three MC levels.

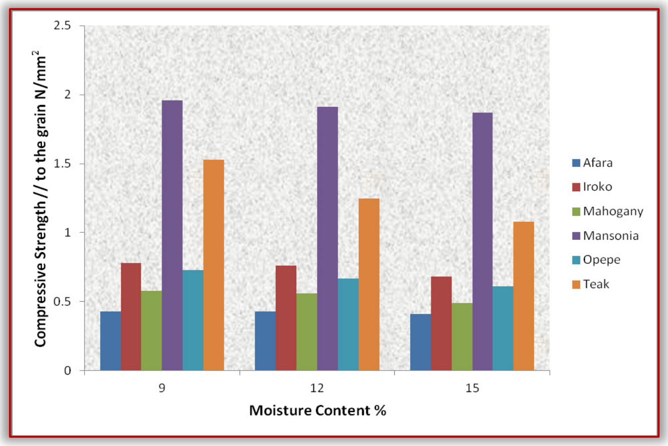

Figure 4: Compressive Strength parallel to the grain of selected Species at their corresponding MC

— Shear Results

The minimum, maximum and mean values of shear strength results parallel to the grain of the selected species at their corresponding MC 9, 12 1nd 15% are given in Figure 5.

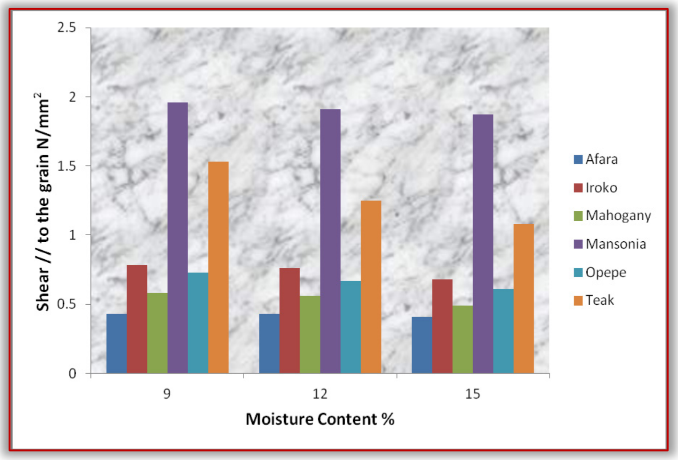

Figure 5: Shear parallel to the grain of selected Species at their corresponding Moisture Content

Afara had the lowest Shear strength parallel to the grain values of 12.05 ± 2.60 N/mm2 at both 9 and 12% MC, while Iroko had the lowest Shear strength parallel to the grain value of 10.43 ± 0.46 N/mm2 at 15% MC. At 9, 12 and 15%, Opepe had the highest Compression strength parallel to the grain values of 24.81 ± 1.56 N/mm2, 22.05 ± 1.23 N/mm2 and 19.11 ± 1.12 N/mm2 respectively.

— Post Fire Density of Samples

Table 1, showed the post fire densities values of samples. At fire exposure time of 0 - 60 minutes, 9, 12 and 15% MC, Afara had the highest percentage change in density values of 29.2, 29.1 and 28.6% respectively. At 9% MC, Iroko had the lowest percentage change in density values of 27.3%, while at 12 and 15% MC, Mahogany had the lowest percentage change in density values of 26.8 and 25.9% respectively.

Table 1: Post Fire Density of Samples and their corresponding Moisture Content (MC)

Species	MC (%)	Mean Density Before Charring test (Kg/m^3)	Mean Density After Charring test (Kg/m^3)	Percentage Loss
Afara	9	444.00	314.35	29.2%
	12	444.00	314.80	29.1%
	15	469.00	334.87	28.6%
Iroko	9	532.00	386.76	27.3%
	12	544.00	397.66	26.9%
	15	614.00	453.13	26.2%
Mahogany	9	439.00	318.71	27.4%
	12	451.00	330.13	26.8%
	15	521.00	386.06	25.9%
Mansonia	9	566.00	402.43	28.9%
	12	580.00	415.86	28.3%
	15	591.00	427.29	27.7%
Opepe	9	630.00	454.86	27.8%
	12	686.00	498.72	27.3%
	15	752.00	551.97	26.6%
Teak	9	505.00	366.13	27.5%
	12	569.20	414.94	27.1%
	15	657.00	483.55	26.4%

— Post Fire Modulus of Elasticity

Tables 2, showed the post fire MOE values of samples. At fire exposure time of 0 - 60 minutes, 9 and 15% MC, Afara had the highest percentage change in MOE values of 22.6 and 19.7% respectively while at 12% MC, both Afara and Mansonia had the same percentage change in MOE value of 21.3%.

At 9% MC, Iroko had the lowest percentage change in MOE value of 20.1%, while at 12% MC, Opepe had the lowest percentage change in MOE value of 19.4% and at 15% MC, both Mahogany and Teak had the lowest percentage change in MOE value of 18.6%.

— Post Fire Modulus of Rupture

Table 3, showed the post fire MOR values of samples. At fire exposure time of 0 - 60 minutes, 9, 12 and 15% MC, Afara had the highest percentage change in MOR values of 35.3, 34.8 and 34.3% respectively.

At 9% MC, Iroko had the lowest percentage change in MOR value of 30.6%, while at 12 and 15% MC; Opepe had the lowest percentage change in MOR values of 29.7 and 29.2% respectively.

Table 2: Post Fire MOE and their corresponding Moisture Content (MC)

Species	MC (%)	Mean MOE (N/mm^2) Before Charring test	Mean MOE (N/mm^2) After Charring test	Percentage Loss
Afara	9	12056.00	9331.34	22.6%
	12	12056.00	9488.07	21.3%
	15	11392.80	9148.42	19.7%
Iroko	9	19884.80	15887.96	20.1%
	12	15011.60	12009.28	20.0%
	15	13951.80	11287.01	19.1%
Mahogany	9	17883.00	14234.87	20.4%
	12	15284.40	12303.94	19.5%
	15	15368.20	12509.72	18.6%
Mansonia	9	14716.00	11478.48	22.0%
	12	14234.60	11202.63	21.3%
	15	13872.40	11084.04	20.1%
Opepe	9	17565.60	13964.65	20.5%
	12	15557.80	12539.59	19.4%
	15	14833.20	11940.73	19.5%
Teak	9	16015.80	12764.59	20.3%
	12	13429.40	10783.80	19.7%
	15	10269.20	8359.13	18.6%

Table 3: Post Fire MOR and their corresponding Moisture Content (MC)

Species	MC (%)	Mean MOR (N/mm^2) Before Charring test	Mean MOR (N/mm^2) After Charring test	Percentage Loss
Afara	9	60.64	39.23	35.3%
	12	60.64	39.54	34.8%
	15	59.62	39.17	34.3%
Iroko	9	80.11	55.60	30.6%
	12	67.69	47.32	30.1%
	15	67.50	47.52	29.6%
Mahogany	9	80.33	55.28	31.2%
	12	70.92	49.01	30.9%
	15	69.75	48.76	30.1%
Mansonia	9	106.39	69.79	34.4%
	12	103.78	68.70	33.8%
	15	102.38	68.70	32.9%
Opepe	9	66.13	45.70	30.9%
	12	61.34	43.12	29.7%
	15	58.50	41.42	29.2%
Teak	9	127.14	97.47	31.2%
	12	110.70	77.71	29.8%
	15	103.47	73.46	29.0%

— Post Fire Compression Results

Table 4, showed the post fire Compression parallel to grain values of samples. At fire exposure time of 0 - 60 minutes, 9, 12 and 15% MC, Afara had the highest percentage change in compression parallel to grain values of 83.6 and 82 and 82.1% respectively. At 9, 12 and 15% MC, Iroko had the lowest compression parallel to grain value of 81.8, 81.1 and 80.4% respectively.

— Post fire Shear Results

From Table 5, at fire exposure time of 0 - 60 minutes, 9 and 12% MC, Mansonia had the highest percentage change in shear parallel to grain values of 77.1 and 75.9% respectively, while at 15% MC, both Afara and Mansonia had the same percentage change in shear parallel to grain value of 75.2%. At 9, 12 and 15% MC, Iroko had the lowest percentage change in shear parallel to grain values of 73.8, 73.1 and 72.4% respectively.

Table 4: Post Fire Compression results parallel to grain and their corresponding Moisture Content (MC)

Species	MC (%)	Mean Compression (N/mm^2) Before Charring test	Mean Compression (N/mm^2) After Charring test	Percentage Loss
Afara	9	9.59	1.57	83.6%
	12	9.59	1.65	82.8%
	15	8.13	1.45	82.1%
Iroko	9	14.35	2.61	81.8%
	12	13.05	2.47	81.1%
	15	10.56	2.07	80.4%
Mahogany	9	16.57	2.87	82.7%
	12	15.17	2.73	82.0%
	15	12.12	2.27	81.3%
Mansonia	9	13.50	2.28	83.1%
	12	12.08	2.11	82.5%
	15	10.86	1.98	81.8%
Opepe	9	16.03	2.85	82.2%
	12	13.80	2.52	81.7%
	15	11.59	2.21	80.9%
Teak	9	14.69	2.57	82.5%
	12	12.15	2.21	81.8%
	15	9.52	1.80	81.1%

Table 5: Post Fire Shear results parallel to grain and their corresponding Moisture Content (MC)

Species	MC (%)	Mean Shear (N/mm^2) Before Charring test	Mean Shear (N/mm^2) After Charring test	Percentage Loss
Afara	9	12.05	2.82	76.6%
	12	12.05	2.92	75.8%
	15	11.40	2.83	75.2%
Iroko	9	14.19	3.72	73.8%
	12	12.90	3.47	73.1%
	15	10.43	2.88	72.4%
Mahogany	9	20.42	4.96	75.7%
	12	18.90	4.82	74.5%
	15	15.36	4.02	73.8%
Mansonia	9	16.01	3.67	77.1%
	12	14.65	3.53	75.9%
	15	13.38	3.32	75.2%
Opepe	9	24.81	6.40	74.2%
	12	22.05	5.82	73.6%
	15	19.11	5.20	72.8%
Teak	9	18.30	4.67	74.5%
	12	15.35	4.03	73.7%
	15	12.29	3.31	73.1%

CONCLUSIONS

In the study of the literature and laboratory tests results on material properties and external factors that influence the integrity of the timber members, the following properties and factors were found to have the largest influence:

- Moisture content: Moisture influences in wood charring process include a greater requirement of energy to burn the wood, increasing the thermal conductivity of the wood, and delaying the rise in temperature of the wood sample's core until the moisture is evaporated. The resulting lower temperatures and slower heating rates favor the formation of char that protects the inner core of the wood to maintain its initial strength.

- Density: Density is greatly influenced by the amount of moisture contained in timber at the time of measurement. The test results confirmed that density of wood influences significantly the charring rate, the charring rate increases with lower density, and higher density species have lower charring rate. At 9% moisture content, the highest percentage loss of density for all the selected species at 0 – 60 minutes fire exposure time (20 – 230°C) was 29% of the density before charring test. With over 70% density of the material still retained after fire exposure, the integrity of the material to continue structural functioning still intact before replacement.
- Species of timber: The properties of timber (e.g. density, composition, permeability) vary greatly and different species will exhibit different combustion behaviour when exposed to fire. From the results Afara had the lowest density 444 kg/m3 before charring and exhibited highest percentage loss in density 29.2% after charring as compared to Opepe with highest density of 752 kg/m3 and exhibited lower percentage loss in density 26.6% after charring.
- Grain orientation: Wood is an anisotropic material with most of its properties substantially different when considered along the grain or across the grain. Since the majority of the fire test calculations performed to evaluate the fire resistance of linear members are related to the transversal directions, little information regarding the longitudinal thermal properties of wood is available. However, it has been established that permeability for flow along the grains is 104 times that across the grains. Similarly thermal conductivity of wood along (parallel) the grain has been reported to be in the range 1.5 to 2.8 times the conductivity across the grain, with the average value being around 2. Charring rate of wood along the grain is higher than across the grain with ratio between them ranging from 1.3 to 2.0.
- Formation of char layer: Char layer and its fissures are important in wood charring; the layer being charred is thinner than the original thickness of the wood that has charred as a result of surface recession. The thinner insulative char layer is important in modeling of wood charring. The surface recession was due to the mechanical degradation or chemical oxidation at the surface or contraction of the char.
- Thickness: Wood thickness influences the rate at which heat is absorbed into the surface as well as the residual section of the unburnt timber. The charring rate of timber exhibited two peaks during fire tests, during the initial exposure before char layer is developed, and towards the end of the char interface approaches the unexposed surface. Thinner specimens exhibited higher level of charring rate.
- Thermal exposure: The low thermal conductivity of timber reduces the rate at which heat is transmitted to the interior, fire test showed that the thermal conductivity of timber is inversely proportional to the moisture content in the wood. Hence increasing moisture content (i.e. reducing thermal conductivity) will increase the rate of degradation of the wood. The charring rate increases with higher heat flux, better ventilation and more oxygen in the air.

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