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DETERMINATION OF CHARRING RATE OF NIGERIAN BLACK AND WHITE AFARA TIMBER

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Abstract

Timber as a natural and cheap construction material is combustible in nature, therefore there is a need to further examine timber with regards to its reaction to heat. In the design of timber structure, it is important to check the time dependent degradation of the timber specimen when exposed to fire (charring rate) it is the time it will take the occupants evacuate the building before any structural damage during fire outbreak. The charring rate is the ratio of the char depth (distance between the char line and the timber surface) and the fire duration. Two Nigerian timber species were used for this research Black Afara and White Afara timber species. The physical and mechanical property of the timber were determined, the charring rate at different density was determined by exposing the timber specimen for a duration of 30 minute using the standard fire curve changing the temperature at interval of 5 minutes, the furnace temperature were recorded and temperature time curve was plotted for the furnace temperature , regression analysis was perform on the result in which a model was gotten with charring rate as dependent variable and density as the independent variable, the result show that the charring rate decrease as the density of the timber increase for both white and black Afara timber species, the regression gave a model that best relate the charring rate (dependent variable) and density (independent variable) with R^2 values of 97.29% and 94.53% for black Afara and white Afara respectively. Sensitivity analysis carried out on both timber species revealed that the black Afara timber has a higher resistance to charring when compared to the white Afara timber

***Key words**:* Black and White Afara Timber, Density, Charring rate and Sensitivity analysis.

1.0 Introduction

Construction activities using locally available raw materials are major steps towards economic independence for developing countries that have more interest in timber. Structural timber is the timber used in framing and load-bearing structures, where strength is the major factor in its selection and use (Aguwa, 2012). Timber is a complex building material and owing to the diversity of its species, Nigeria is one of the countries that have timber in surplus quantity (Jimoh and Aina, 2017; Rahmon and Jimoh, 2018).

As a natural and renewable building material, timber has excellent ecological attributes. The energy needed for structural timber production is less compared to steel and concrete. Also, timber is unique in that it does not corrode. Corrosion, coupled with abrasion, may result in the loss of thickness in steel, or exposure of concrete reinforcement (Andrea, 2012). Experience has shown that some timber structures have a fire-resistance comparable, or greater than that of many non-combustible alternatives this is because it will not flake, spall, melt, buckle or explode (Ibukunolu, et al., 2015). If wood is subjected to sufficient heat a process of thermal degradation (pyrolysis) occurs producing combustible gases, accompanied by a loss in mass and cross-section. A surface char layer is formed, which, because of its low thermal conductivity, protects the interior of the timber cross-section against heat. On the other hand, the amount of heat transferred by surface burning to the unburnt part of the wood decreases as the char layer depth increases. The time-dependent thermal degradation of wood is quantified by the charring rate, which is defined as the ratio between the distance of the char-line from the original wood surface and the fire duration time. The charring rate of wood, which is the main parameter to describe the fire behavior of timber structures, is mainly determined by the species of wood (Frangi and Fontana, 2003). The fire resistance of a structural member may be defined as its ability to withstand exposure to fire without loss of its load-bearing function. This ability provides time to enable people to evacuate a building before it collapses in the event of fire.(Lie, 1977). In Nigeria, fire outbreak has led to an unquantifiable loss of lives, properties, and economic goods, ranging from damages incurred in market places, factories to residential buildings (Garba *et al.,* 1990). However fire retardant chemicals can assist during fire outbreaks (Okiy et al., 2018).

The combustibility of wood may be reduced with flame retardants or fire retardants. Fire retardants are use as protective agent against fully developed fire and may affect parameters such as charring rate, char yield, fire resistance, and mechanical properties. This field is less well known than that of protection against initial fire with flame retardants, even though the chemicals used are often of the same type (Nussbaum, 1988). This study therefore seeks to determine the charring rate of black and white afara timber.

2.0 Material and Method

2.1 Materials

2.1.1 Timber

Two selected timber species were obtained from Kaduna timber shed. The timber species and their scientific names are Black Afara (*Terminalia Ivorensis*), and White Afara (Terminalia Superba).

2.1.3 Furnace

Muffle electric furnace with highest temperature of 1200^0C and electric supply of 240volt AC was use for the research.

2.2 Methodology

The timber samples were tested in the concrete laboratory Ahmadu Bello University Zaria, Kaduna State. The timber specimen was cut into rectangle blocks size with dimensions 100mm X 100mm X 60mm for each of the timber species twenty (20) number of specimens were obtained.

2.2.1 Physical Property

Moisture Content: The specimen was dried for 48 hours before taking the moisture content base on EN13183-1(2002) that is the weight loss of the oven-dry sample; the weight of the sample was obtained using equation 1.

Moisture content (M.C) = $\frac{W_w - W_d}{W_w} \times 100$ (1)

Where W_w is the weight of wet sample, W_d is the weight of dry sample

Density: Density was calculated according to EN 1991-1-1:2002 by dividing the weight obtained by the volume of the specimen. The density was calculated using equation 2.

Density = $\frac{\text{Mass}}{\text{Volume}} = \frac{M}{V}$ (2)

Where M is the mass in (kg)

Vis the volume in (m^3).

2.2.2. Mechanical Property.

Compressive strength of Timber: the compressive strength of the timbers was conducted based on EN 14081-1. The property which is aligned with the grain direction is referred to as strength parallel to grain. Stresses across the direction of the grain is strength perpendicular to the grain. The compressive machine was use for this test; load was applied to the timber sample till all the fiber are crushed. The compressive strength was determine using equation 3.

Compressive strength = $\frac{\text{Force}}{\text{Area}} = \frac{F}{A}$ (3)

Where F is the resultant force and A is the surface area

Where W_a is weight of sample after treatment and W_b is weight of sample before treatment.

***Charring Rate*:** Twenty timber specimen were subject into an electric furnace (The sample were held horizontally and subjected to heat perpendicular to the grain according to both Eurocode and Australian Standard code AS 1720.4) at temperature 400^0C for time duration of 30 minutes.

The timber was then removed from the furnace, char depth result was obtained using a measuring instrument then the charring rate were calculated from the result. Fig i, shows the charred timber after removal from the furnace.

Fig. i. Charred timber samples

The charring rate (mm/min) were calculated using the linear formula given in equation 5 (Eurocode 5, 2004)

$$\beta = \frac{d_{char}}{t} \quad (5)$$

β = charring rate (mm/min)

d_{char} = thickness of char layer or char depth (mm)

t = time of exposure to fire (mm).

***Fire Test*:** Temperatures in most standard fires continue to rise over time whereas actual fires have growth, full development and decay phases. The fire tests was done in accordance with EN 1991-1-2. The fire exposure used is Standard Fire exposure test. An electric muffle furnace was used with a thermal power unit of 70kVA. A typical heating curve was used to regulate the temperature at interval of five minutes in accordance to EN 1995-1-2, for the duration of 30minutes, using the standard temperature-time curve in (EN 1991-1-2, 2003) is given by:

$$ø_g = 20 + 345\log_{10}(8t + 1) \quad (6)$$

where $ø_g$ is the gas temperature in the fire compartment [°C] and "t" the time [min].

2.2.3 Regression Analysis.

Regression analysis is a statistical tool that enables examination of the relationship between two or more variables. This is achieved through the development of a mathematical model that depicts the relationship between the predictor variable also known as the independent variable (X), and the response variable also known as the dependent variable (Y). Models generated from regression analysis are considered to be linear or polynomial function; with respect to the function that best describes the relationship between the dependent and independent variable. This research made use of regression analysis to describe the relationship between the densities of the black and white Afara timber species and their charring rates.

2.2.9 Sensitivity Analysis

The sensitivity analysis was done using COMREL (Component Reliability Software 10.0), and the limit state equation for the timber charring rate are given in Equations 7 and 8 for treated and untreated timber respectively.

Where;

$$F_{LIM}(1) = (T_a \times t) - (d_e \times b_c) \quad (7)$$

$$F_{LIM}(2) = (T_a \times t) - (d_e) \quad (8)$$

F_{LIM} is the Limit state function.

T_e is the temperature.

t is the time taken for timber to char.

d_e is the density of timber.

b_c is the borax concentration for the treated timber.

Probability Distribution Function (PDF)

In determining the Probability Density Function (PDF) of the parameters, the following hypotheses are used at a P-value of 0.05. The null and the alternative hypotheses are:

- H_0: the data follow the specified distribution;
- H_A: the data does not follow the specified distribution

Also, the Kolmogorov Smirnov (K-S) test was adopted in this study compared to the Anderson Darling and the Chi-square tests because; Kolmogorov Smirnov test do not depend on the specific distribution being tested. Kolmogorov Smirnov test is an exact test. This has overcome the disadvantage of Chi-square test, in which sufficient sample size is required for the Chi-square approximation to be valid.

3.0 Results and Discussion

3.1 Physical Properties of white and black Afara timber species

The moisture content and density of twenty (20) timber sample were determined in the laboratory using equation 3 and 4. Their average were calculated and recorded in Table 1 and 2.

3.1.1 Moisture Content.

The value of the moisture content from Table 1 and for white Afara was 17% which is 1% less than the 18% moisture content in the NCP 2 (1973) code while Table 2 shows 20% as the moisture content of black Afara is 2% higher than 18% from the NCP 2(1973) code.

Table 1. Moisture content and density of White Afara Timber Species

Timber Species	White Afara	Values from NCP 2 (1973)
Moisture Content (%)	17	18
Density (kg/m^3)	447	464

Table 2. Moisture content and density Black Afara Timber Species

Timber Species	Black Afara	Values from NCP 2 (1973)
Moisture Content (%)	20	18
Density (kg/m^3)	588	576

3.1.2 Density

The average density result from Table 1 the value of the density of white Afara at 17% show less value compare to the density at 18% recorded by NCP 2 (1973) code while the value of black afara timber at 20% shown in Table 2 gives higher value compare to the code.

3.2 Mechanical Properties of white and black Afara timber species

3.2.1. Compressive strength

The compressive strength perpendicular and parallel to the grain for Black Afara and white Afara timber were obtain using equation 5 and were recorded in Table 3 and Table 4 respectively.

Table 3. Compressive strength of White Afara Timber Species.

Timber Species	White Afara	Values from NCP 2 (1973)
Compressive strength Perpendicular to grain (N/mm^2)	2.50	2.00
Compressive strength Parallel to grain (N/mm^2)	9.50	9.00

Table 4. Compressive strength of Black Afara Timber Species.

Timber Species	Black Afara	Values from NCP 2 (1973)
Compressive strength Perpendicular to grain (N/mm^2)	3.60	3.15
Compressive strength Parallel to grain (N/mm^2)	13.33	14.00

The compressive strength result for white Afara timber from Table 3, gave a value greater than what was recorded in the NCP 2 (1973) code at 18% moisture for both perpendicular to the grain and Parallel to the grain. The compressive strength result for black Afara from Table 4, gave high result perpendicular to grain but less result parallel to grain compare to the result from NCP 2 (1973) code.

3.3 Temperature Time Curve.

A fire curve is a graphical representation of the behavior of fire, it's a graph of gas temperature in the environment of member surfaces as a function of time. Standard fire tests serve to compare the relative performance of building materials and small-scale assemblies, although they may not be representative of actual fires. The standard temperature curve was gotten from equation 4, this temperature was set into the furnace at interval of 5 minutes to get the process temperature (Furnace camber temperature).

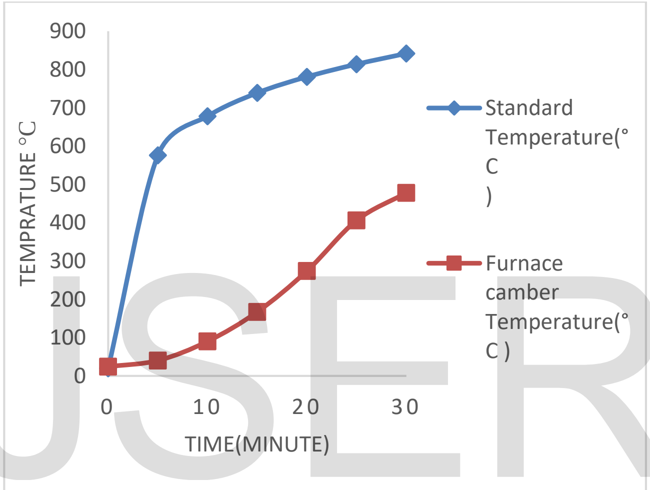

Fig ii Graph of temperature against time for standard Temperature/ time curve and the furnace camber.

Fig ii shows the temperature time curve recorded during the heating in the electric furnace in the time duration of thirty minutes this shows the changes in temperature of the timber at each minute, as the time increase the temperature increase that is the longer the timber stays in the furnace the higher the temperature been release to the timber.

3.4 Charring rate of Timber

3.4.1: Charring rate of Black Afara and White Afara Timber Species

Fig iii and Fig iv shows charring rate against density graph it could be seen that the charring rate of white Afara and black Afara timber reduces when the density of the wood increases this is because the denser the wood is the more its resistance to combustion this, gives a lesser value for the charring rate. This is in agreement with the following literature, Dahunsi and Adetayo, (2018). Timber with high density is needed for low charring rate for good fire resistance timber structure.

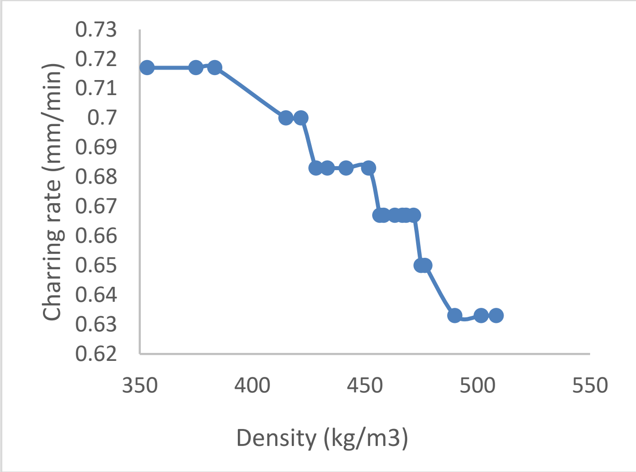

Fig iii Graph of charring rate of White Afara against Density.

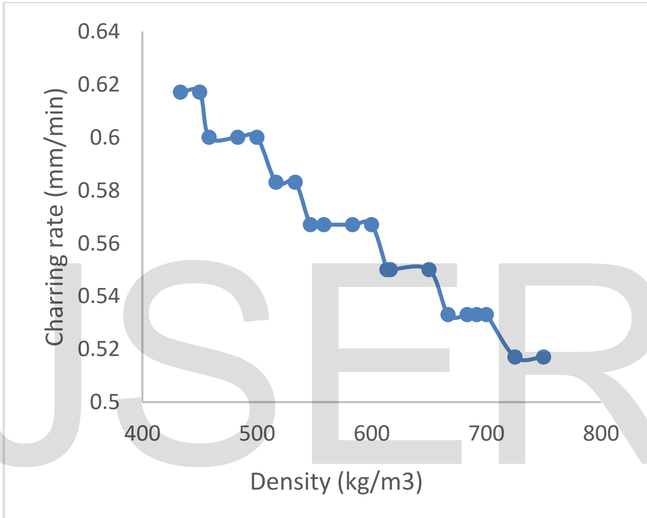

Fig iv Graph of charring rate of Black Afara against Density.

3.5 Regression Analysis.

The results of the regression analysis carried out to model the relationship between the densities and the charring rates of the black and white Afara timber species are as shown in Table 5.

Table 5: Regression models of the untreated black and white Afara.

Timber species	Regression Model	R^2 Value
Black Afara	$Y_{1a} = -0.00003X_1^2 - 0.005X_1 + 0.7228$	0.9729
White Afara	$Y_{1b} = 0.0000002X_1^2 - 0.0005X_1 + 0.8321$	0.9453

X_1 = Density

Y_{1a} = Charring rate for untreated white Afara timber

Y_{1b} = Charring rate for untreated black Afara timber

The relationships between the densities and the charring rates of the untreated black and white Afara timber species are described by the models developed in the tables. From the table the R^2 values calculated in the regression analysis shows that they are very reliable in describing the relationship between the dependent variable (charring rate) and the independent variable (density) this agrees with Dahunsi and Adetayo, (2018) and Wen, Han, and Zhou, (2016) in which they carried out multiple regression model relating charring rate and density (independent variable), the R^2 value shows that density is reliable in relating to charring rate.

3.7 Sensitivity Analysis

The result form Table 6 shows that for the white Afara timber, the mean values of the density, temperature, and time are 447.00 kg/m^3, 216.50^{o}C, and 15mins, while for the black Afara timber, the mean values of the density, temperature, and time are 588.00 kg/m^3, 216.50^{o}C, and 15mins. These values and their standard deviation were put in the limit state Equation 8 to obtain the sensitivity result which are presented.

Table 6: Parameters for Sensitivity Analysis (Untreated Afara)

Timber Specie	Parameters	Mean	Std. Deviation	PDF
Untreated white Afara	Density	447.00	40.29	Normal
	Temperature	216.50	144.20	Log-Normal
	Time	15.00	10.00	Log-Normal
Untreated black Afara	Density	588.00	94.39	Normal
	Temperature	216.50	144.20	Log-Normal
	Time	15.00	10.00	Log-Normal

The result of the sensitivity analysis from Fig. vii, shows that the density of white Afara timber have a sensitivity factor of -0.10, and the temperature and time have a sensitivity factor of +0.70 each. The outcome of this result shows that for white Afara, in low density timber increases the temperature and time contribution to the charring of the timber (i.e., 0.66 for treated timber). Hence, the density of timber has an impact of increasing the resistance of the timber to charring.

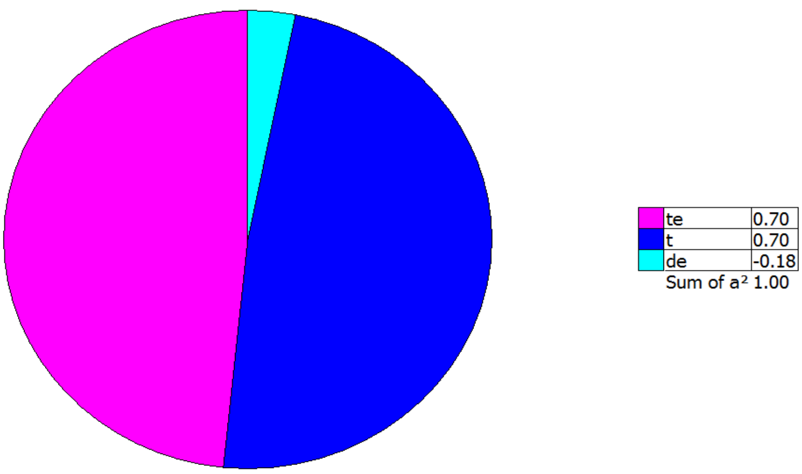

Fig v: Untreated white Afara Sensitivity Analysis.

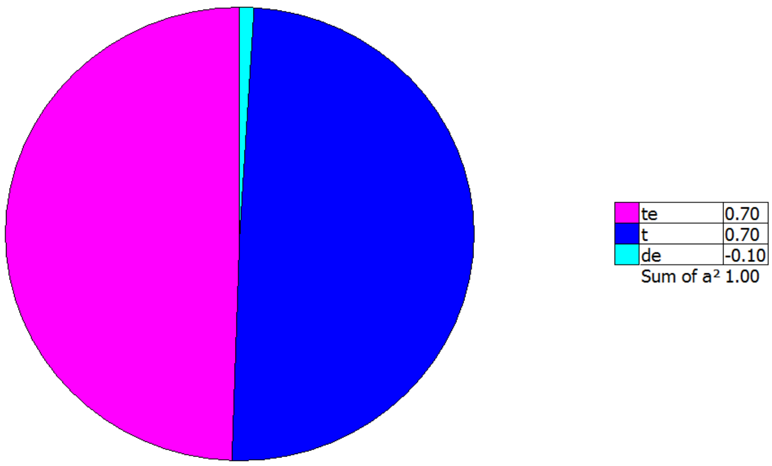

Fig vi: Untreated black Afara Sensitivity Analysis.

The result of the sensitivity analysis from Fig. vi, shows that density of the black Afara timber have a sensitivity factor of -0.18, and temperature and time both have a sensitivity factor of +0.70 each. The outcome of this result also proves that low density timber increases the temperature and time contribution to the charring of the timber (i.e., 0.66 for treated timber). However, it was also noticed that the density of the black Afara (-0.18) have a high resistance to charring more than the untreated white Afara (-0.10).

4.0 Conclusions

Base on the research finding the following conclusion and recommendation were made

I. The moisture content, density, compressive strength perpendicular and compressive strength perpendicular to the grain of white and black Afara timber species shows result of 17% and 19%, 447kg/m^3 and 588kg/m^3, 2.5N/mm^2 and 3.6N/mm^2 and 9.50N/mm^2 and 13.33 N/mm^2 respectively

II. The average charring rate of the white and black Afara timber species are 0.67mm/min and 0.56mm/min respectively which when compare to the charring rate in Eurocode 5, part 1. 2 the charring rate of white Afara have a closer value with the soft wood charring rate of 0.65mm/min, while black Afara have a charring rate closer to 0.5mm/min of hard work as recorded in the code.

III. The regression analysis carried out to model the relationship between the charring rate and density of the black and white Afara timber; yielded good R^2 value of 97.29%and 94.53% for black and white Afara timber respectively.

IV. The results of the sensitivity analysis carried out revealed that the density of timber has an impact of increasing the resistance of the timber to charring. Also, that the black Afara timber has a higher resistance to charring when compared to the white Afara timber

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