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CHARRING RATE CHARACTERISTICS OF SOME SELECTED SOUTHERN NIGERIA STRUCTURAL WOOD SPECIES BASED ON THEIR FIRE RESISTANCE ABILITY

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Abstract: The performance of Nigeria structural wood species under fire exposure to prevent structural collapse have not been adequately researched. This paper explores the charring rate of six identified structural wood species. They are: terminalia superba (Afara), milicia excelsa (Iroko), khaya ivorensis (Mahogany), mansonia altissima (Mansonia), nauclea diderrichii (Opepe), and tectona grandis (Teak). The densities of the wood species were determined at Moisture Contents (MC) of 9.0, 12.0, and 15.0%. Samples from each of the selected species, were exposed to fire at temperature ranges of 20° to 230°C for 30 minutes; 20° to 300°C for 60 minutes; 230° to 600° C for 30 minutes. Empirical statistical model was developed for charring rate of the samples. The models were analysed using ANOVA at α0.05. At 60 minutes (20° to 300°C), Opepe of 9.0, 12.0 and 15.0% MC had the lowest charring rates of 0.44±0.03mm/min, 0.46±0.05mm/min and 0.45±0.03mm/min respectively, while Afara exhibited the highest charring rates of 0.74±0.02mm/min, 0.74±0.02mm/min and 0.68±0.02mm/min at the three MC levels. At temperature ranges of 20° to 230°C, and 12% MC, it showed that at r = 0.836, there is a linear positive correlation between the experimental charring rate and predicted charring rate.
Keywords: Nigeria woods, structural collapse, moisture content, charring rate, linear correlation

INTRODUCTION

Wood is an indispensable engineering material that has served man throughout history. People relied on wood for needs varying from farming tools to building materials, fuel, weapons of hunting and warfare [1]. The rain forest zone of Nigeria is blessed with abundant natural forests because the geographical location of the country in the tropics has naturally favored the growth of trees, which is the source of abundant wood in Nigeria [2].

Wood as a perfect material for construction purpose is not easily ignitable but combustible. Wood is composed of a mixture of cellulose, hemicellulose, and lignin bound together in a complex network. Heating wood above 300°C causes decomposition or pyrolysis converting it to gases, tar and charcoal. At temperatures above 300°C the gases will flame vigorously but the charcoal requires temperatures of about 500°C for its consumption.

Wood most important property at elevated temperature is the formation of char after ignition [3]. The charring rate is the linear rate at which wood is converted to char [4]. A build-up of char tends to protect the unburnt wood from rapid pyrolysis. The unburnt timber, being a good insulator, results in the wood close to the char edge being unaffected by the fire. The charring rate is dependent on a number of factors such as: wood species, wood density, wood thickness, moisture content, and chemical composition. Of all the common physical properties of wood, density is one of the most important [5, 6].

Different wood char at varying rates, largely as a function of their density with the higher density woods charring more slowly [7]. The char layer does not usually burn because there is insufficient oxygen in the flames at the surface of the char layer for oxidation to occur. When the wood below the char layer is heated above 100°C, the moisture in the wood evaporates [8]. Some of this moisture travels out to the burning face, but some travels into the wood, resulting in an increase in moisture content of the heated wood a few centimeters below the char [9, 10].

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 wood and 30 mm for the denser hardwoods. This enables the fire resistance of simple timber elements to be calculated. The predictive method is published in EN 1995-1-2 Fire resistance of timber structures as shown in Table 1 [11].

Table 1: Notational rate of charring for the calculation of residual section

Species	Charring in 30 min	Charring in 60 min
All structural wood species	20mm depletion	40mm depletion
Hardwoods having a nominal density not less than 650kg/m^3 at 18% moisture content	15mm depletion	30mm depletion

Source: EN 1995-1-2 (2004)

Charring rate models use the charring rate concept to calculate the residual section of a wooden cross-section after a certain exposure to fire. It assumes that the charring rate of timber made of solid or glued-laminated hardwood decreases linearly with density, with a limit of 0.5 mm/min for density larger than 450 kg/m^3. For softwood species the standard provides a mean value of 0.7 mm/min for density larger than 290 kg/m^3. The fact that the charring rate really changes with wood density has been demonstrated by several authors from several countries [12, 13]. Thermal conductivity of solid wood depends on the moisture content as reported by several authors [14, 15, 16, 17].

The water content of wood has an influence on its thermal behaviour. The effects of changes in conductivity of wood below 300° C on the charring rate are not significant. The evaporation of water consumes energy, changing the apparent specific heat curve of the composite wood-water material. Temperature at any point in wood will remain approximately constant at about 100°C until the water has been evaporated.

The charring rate, β, is an important factor in the fire design of exposed structural timbers, because it determines how quickly the size of the load-bearing section decreases to a critical level. Design procedures for fire-resistant wood members in the U.S. model building codes [18] are based on work done by Lie in the early 1970's [19]. Lie assumed a constant charring rate of 0.6 mm/min, regardless of species and moisture content.

White performed extensive measurements of the charring rate of eight wood species exposed according to ASTM E 119 [20]. He found that the data could be correlated according to the following equation:

$$t = m{x_c}^{1.23} \tag{1}$$

with: t = time (min), m = char rate coefficient (min/mm$^{1.23}$), x_c = char depth (mm).

Based on the experimental data, an empirical model was developed that expresses m as a function of density, moisture content, and a char contraction factor. The latter is the ratio of the thickness of the char layer at the end of the fire exposure divided by the original thickness of the wood layer that charred. The char contraction is primarily a function of the lignin content in the wood.

METHODOLOGY

— Experimental research into the selected structural woods

In this study, we assumed the charring rate was a function of density, moisture content, and level of heat exposure. Samples of six different wood species out of ten samples mostly used for structural purpose were tested for charring rates.

The six species tested were Afara (Terminalia superba), Iroko (Milicia excelsa), Mahogany (Khaya ivorensis), Mansonia (Mansonia altissima), Opepe (Nauclea diderrichii) and Teak (Tectona grandis).

The samples were taken from the heartwood region of the individual tree. And they were specially ordered from lumber market.

— Charring Rate Tests

Wood specimens were tested in a big vertical electrical-fired furnace. Fifty-four samples tested were done in three groups. Nine specimens of overall dimension 150mm x150mm x 510mm (0.15m x 0.15m x 0.51m) blocks from one board of the six species.

In the first group of 18 tests, three specimens from one board of each of the six species were tested at moisture content levels of 9, 12, and 15 percent at the furnace exposure period of (0 – 30 minutes) temperature ranges of 20°C to 230°C . The second group of 18 tests, was tested at the furnace exposure period of (0 – 30 minutes) temperature ranges of 230°C to 600°C. The last group of 18 test was at the furnace exposure period of (0 – 60 minutes) temperature ranges of 20°C to 300°C.

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

- Species
- Ring orientation
- Specimen dimensions
- Specimen weight
- Moisture content (percent)
- Specimen density

The specimens were held horizontally and subjected to the nominated heat flux perpendicular to the wood grain. Traditionally and in the procedure, it would be assumed that the charring front reaches when its temperature indicates 300°C, assuming that ignition starts at this point.

The specimen, as installed in the furnace. 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.

The first test was terminated at the time when the fire-exposed time reached 30 minutes and temperature stopped climax 230°C.

Second test samples were immediately subjected to higher temperature 230°C to 600° C for 30 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. The charred specimens were also cut in half to obtain the thickness of the charred slab and the char layer measured millimetres.

The values of density of each species at their corresponding moisture content (MC) 9, 12 and 15% is shown in the column chart of Figure 1. 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.

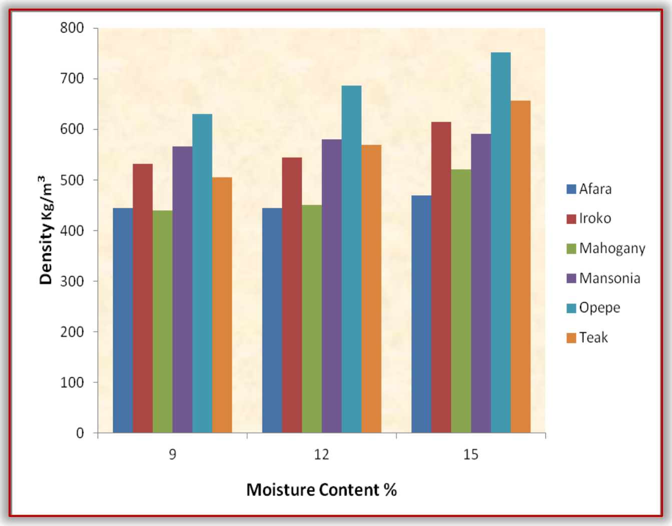

Figure 1: Density of selected Species at their corresponding Moisture Content

RESULTS AND DISCUSSION

As noted previously, charring rates were determined by dividing char depth with the corresponding fire exposure time.

In a cause and effect relationship, the predicted charring rate (the independent variable) is the cause, and the actual charring rate (the dependent variable) is the effect.

The predicted charring rate could be calculated based on existing linear models of Eurocode EC5 recommendation [ENV 1995] and the Australian standard AS 1720.4 [21].

Eurocode EC5 model is given as:

$$d_{char} = \beta_o t \qquad (2)$$

where, d_{char} = charring depth mm, β_o = charring rate (mm/min), usually between (0.5 to 0.8) mm/min, t = time in minutes

The Australian standard AS 1720.4 gives the following equation for the notional charring rate β (mm/min) as a function of wood density:

$$\beta = 0.4 + [280/\rho]^2 \qquad (3)$$

where, ρ is the wood density at 12% moisture content (kg/m3).

Experimental charring rates were determined by scrapping away the charred timber and measuring the average depth remaining (char depth), to determine the amount lost through charring in millimeters. This was divided by the exposure time (min) and is expressed in (mm/min) were determined using equation (6) as the ratio of the char depth (mm) and the exposure time (min).

The correlation coefficient between the experimental (actual) charring rate and predicted charring were determined from the linear relationship between the actual charring rates and the predicted charring rates for each wood samples moisture content, time of exposure and temperature range. The results were plotted in Figures 3 to 5. The correlation coefficient 'r' is given as:

$$r = \sqrt{R^2} \qquad (4)$$

where R^2 = coefficient of determination

From Figure 2, the coefficient of determination, R^2 = 0.6489, it implied that at r = 0.806, there is a very strong positive correlation of actual charring rate that can be explained by the relationship to the predicted charring rate.

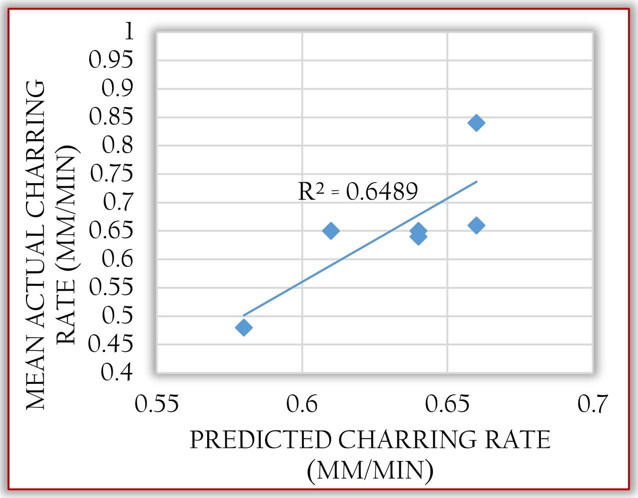

Figure 2: Linear correlation for samples exposed to 20°C to 230°C (9% MC, 0-30 minutes)

The coefficient of determination at 12% moisture content is R^2 = 0.6994 (Figure 3), it implied that a very strong positive correlation of actual charring rate can be explained by the relationship to the predicted charring rate with the correlation coefficient, r = 0.836.

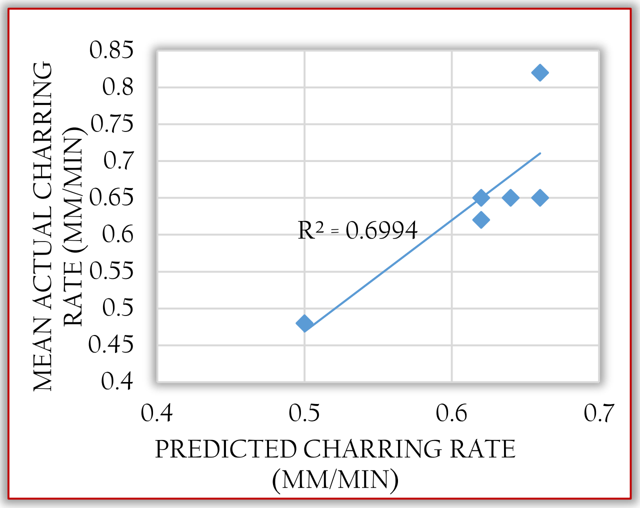

Figure 3: Linear correlation for samples exposed to 20°C to 230°C (12% MC, 0-30 minutes)

Figure 4 showed that at correlation coefficient, r = 0.737, there is a very strong positive correlation of actual charring rate that can be explained by the relationship to the predicted charring rate.

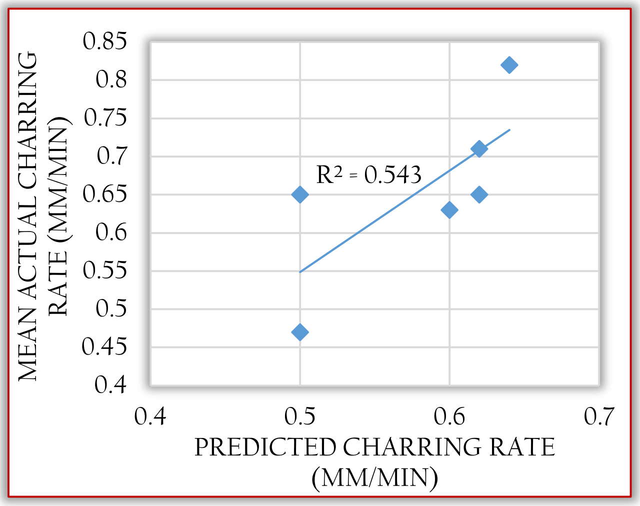

Figure 4: Linear equation for samples exposed to 20°C to 230°C (15% MC, 0-30 minutes)

From figures 5, 6, and 7 , there is negligible correlation of actual charring rate that can be explained by the relationship to the predicted charring rate from Figures 6, 7 and 8 at, r = 0.04, r = 0.1746, and r = 0.01 respectively.

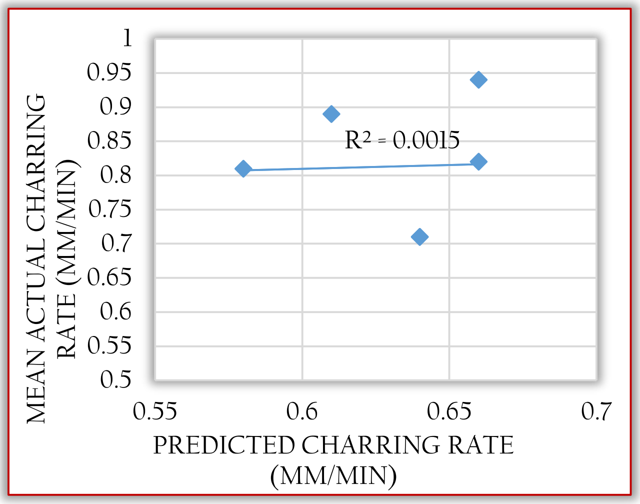

Figure 5: Linear correlation for samples exposed to 230°C to 600°C (9% MC, 30-60 minutes)

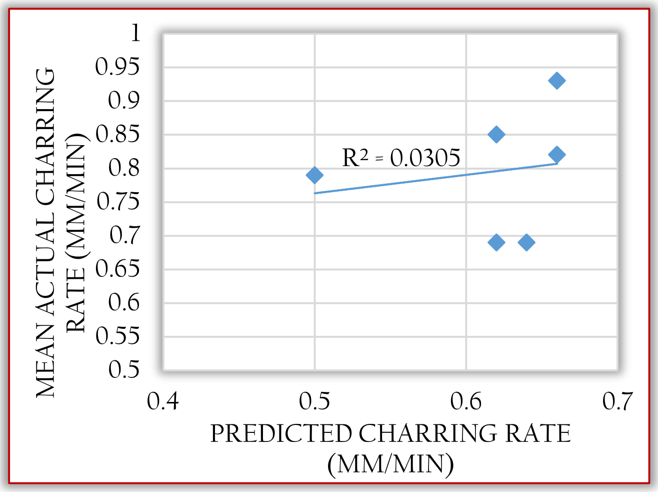

Figure 6: Linear correlation for samples exposed to 230°C to 600°C (12% MC, 30-60 minutes)

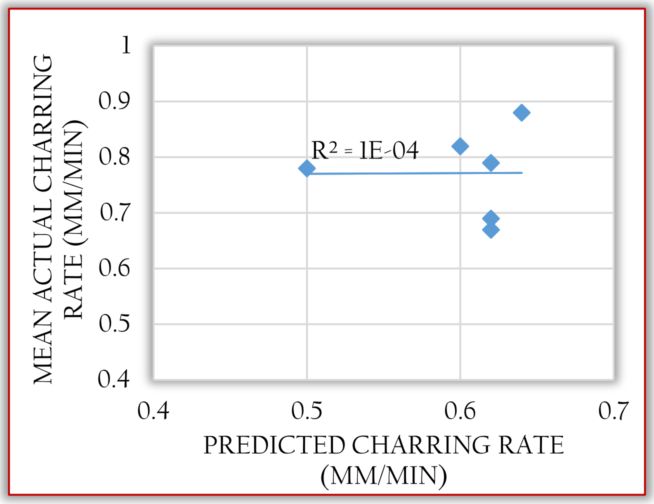

Figure 7: Linear correlation for samples exposed to 230°C to 600°C (15% MC, 30- 60 minutes)

Figures 8, 9, and 10 showed a strong positive correlation of actual charring rate that can be explained by the relationship to the predicted charring rate at, r = 0.682, r = 0.582, and r = 0.578 respectively.

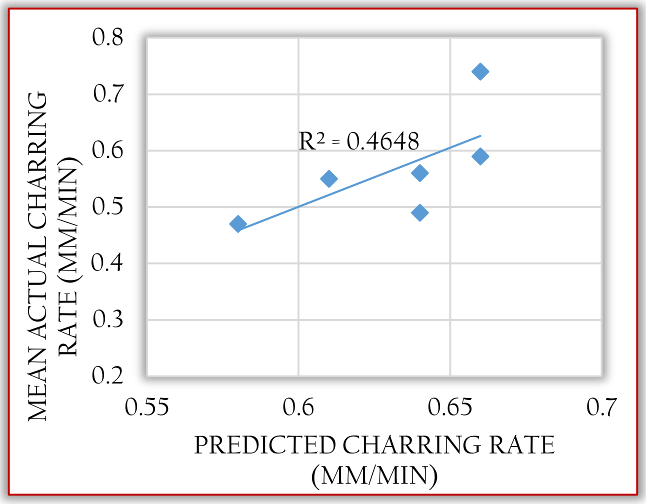

Figure 8: Linear correlation for samples exposed to 20°C to 300°C (9% MC, 0-60 minutes)

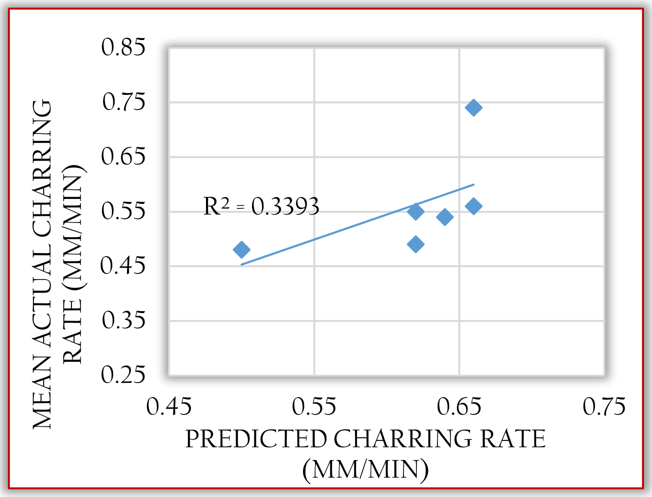

Figure 9: Linear correlation for samples exposed to 20°C to 300°C (12% MC, 0-60 minutes)

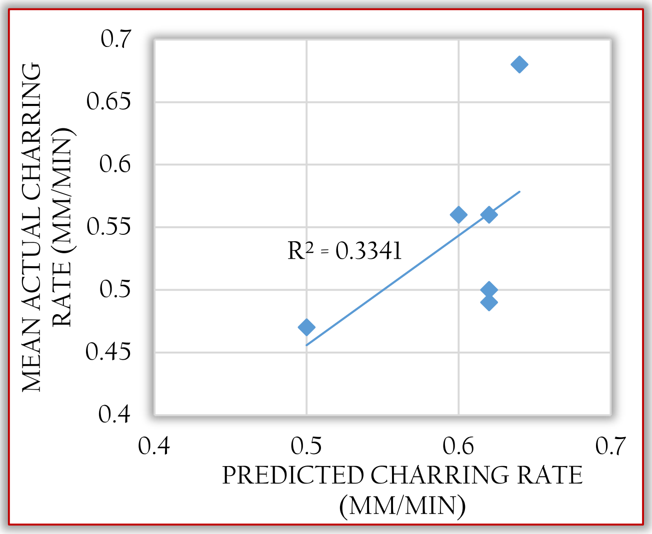

Figure 10: Linear correlation for samples exposed to 20°C to 300°C (15% MC, 0-60 minutes)

CONCLUSION

The fire resistance of constructional wood members has been studied through laboratory experiments and existing models calculations. Like most wood properties, fire performance and charring properties are affected by density, moisture content, level of heat influx, and chemical composition. In general, woods of higher density and moisture content have better charring rate. The rate of charring of wood is improved by increasing the residual char content.

The fire resistive nature of solid wood walls is a combination of the insulating response of the charred wood at the surface with the slow rate at which flame will spread along the wood surface. Under conditions of severe fires, but not absolute worst-case extreme conditions, heavy wood or similar members will char at similar rates to those found in fire-resistance furnace tests, roughly 0.5 to 0.8 mm/min.

The research showed that the charring rate of wood species was optimum at 12 percent moisture content with Opepe species which had the highest density exhibited the lowest charring rate of 0.48 mm/min.

Based on the results obtained in this study, the following recommendations are made:

- The charring rate of timber presented in this study was limited to only six timber species. There is the need to consider the charring rates of other timber species.
- Determination of the charring rate for different wood species with varying dimensions and checks their variations and similarities.
- Systematic research on how various material properties and external factors influence the charring rate of structural wood.

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