Development of Models for Charring Rate of Selected Construction Timber Species in South-western Nigeria

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Abstract- The performance of Nigeria timber species under fire exposure to prevent collapse of structure has not been adequately investigated. This study was to determine the charring rate models of some selected timber species mostly used for constructional purposes in Southwestern Nigeria. Six species out of ten identified timbers were selected for studies. They are: Afara, Iroko, Opepe, Mahogany, Mansonia, and Teak. The densities of the timber 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 40 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 timber species. The models were analysed using ANOVA at α=0.05. At 30 minutes fire exposure (20 to 230° C), Afara of 9.0, 12.0 and 15.0% MC had the highest mean charring rates of 0.84±0.02mm/min, 0.82±0.02mm/min and 0.82±0.02mm/min respectively, while Opepe had the lowest charring rates of 0.48±0.02 mm/min, 0.48±0.02 mm/min and 0.47±0.02 mm/min at the three MC levels. This study indicated that density was a major predictor of the charring rate of constructional timber. Opepe which had the highest density also exhibited the lowest charring rate of all the species tested and is useful and recommended to ensure the safety and comfort of occupants in case of fire outbreaks.

Keywords: Nigeria timbers, Construction collapse, Charring rate, Empirical models

1. INTRODUCTION

Wood is a perfect material for construction purpose, but has a shortcoming: wood is flammable. The charring rate is the linear rate at which wood is converted to char (Maciulaitis et al., 2006). The charring rate is dependent on a number of factors such as: timber specie, timber density, timber thickness, moisture content, and chemical composition. Of all the common physical properties of wood, density is one of the most important (Desch & Dinwoodie, 1996; Bowyer et al. 2003). Different timbers char at varying rates, largely as a function of their density with the higher density timbers charring more slowly (Dahunsi & Adetayo, 2015). 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 (Drysdale, 1998). 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 (Fredlund, 1993; White & Schaffer, 1981)

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/m³) 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. The predictive method is published in EN 1995-1-2 Fire resistance of timber structures as shown in Table 1

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/m3. For softwood species the standard provides a mean value of 0.7 mm/min for density larger than 290 kg/m3. Many models for wood charring are based on the standard conservation of energy equation. The basic differential equation for conservation of energy includes a term for each contribution to the internal energy balance. In the development of an empirical model for char rate, White (1988) tested four hardwood species. Species were hard marple (Acer sp.), yellow-poplar (Liriodendron tulipera), red oak (Quercus sp.) and basswood (Tilia sp.)

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

| Species                                      | Charring in 30mins | Charring in 60mins |
|----------------------------------------------|--------------------|--------------------|
| All structural wood species                  | 20mm depletion     | 40mm depletion     |
| Hardwoods having a nominal density not less  |                    |                    |
| than 650kg/m³ at 18% moisture content        | 15mm depletion     | 30mm depletion     |

Source: EN 1995-1-2 (2004)
2. MATERIALS
Preliminary studies were carried out to identify timber species used in the construction of structural members in Southwestern Nigeria. This was done through the use of structured questionnaires administered to construction workers in the study area. 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) and Teak (Tectona grandis).

3. METHODOLOGY
Wood samples were tested inside electrical-fired furnace, fifty-four samples, nine from each species of dimension 510mm x 150mm x150mm blocks. Plates 2.1 shows one board of the six species which was tested at moisture content level of 9, 12, and 15 percent. The specimens were held horizontally and subjected to the 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. At time of test, the following five data were recorded for the specimen properties: Species, Ring orientation, Specimen dimensions, Specimen weight and Moisture content (percent).

The specimen, was enclosed in the furnace as shown in Plate 2.2. The electric furnace was powered, the furnace temperature as the when 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 (30-60) minutes and the last batch was for full (0-60) minutes. The first test for exposure period (0 – 30) minutes was stopped at exactly when the stop watch reached 30 minutes, temperature reading was 20°C to 230°C. Samples exposed during the second period (30 – 60) minutes were subjected to higher temperature from 230°C to 600° C. The third test for exposure period (0 – 60) minutes, furnace temperature ranges between 20°C to 300°C. When testing completed, the charred wood was scrapped away from the samples and char depth measured (Plate 2.3). The charred specimens were also cut in half to obtain the thickness of the charred slab and the char layer. For each specimen three sets of data were produced.

4. RESULTS AND DISCUSSION
In this study, a non-linear charring model was developed. The char rate parameter; \( m = \frac{1}{t} \) (1)
where, \( t \) = time of fire exposure (min)

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\[ m = -0.147 + 0.000564\rho + 0.0121u + 0.532f_c \] (2)

where \( \rho \) = oven-dry density (kg/m³),
\( u \) = moisture content (percent), and
\( f_c \) = char contraction factor (dimensionless), defined as the thickness of the char layer at the end of the fire exposure divided by the original thickness of the wood layer that has charred (char depth).

The reciprocal char rate is given as

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An equation for this parameter for hardwood species is (White, 2002):

\[ f_c = 0.529 - 0.0036d - 0.000270\rho \] (3)

where \( d \) is a parameter reflecting the transverse treatability of the species (3 for low treatability to 36 for high treatability species. In the development of the model, \( d \) was the depth of penetration (in mm).
The Australian standard AS 1720.4 (1990) gives the following equation for the notional charring rate $\beta$ (mm/min) as a function of wood density:

$$\beta = 0.4 + \left[ \frac{280}{\rho} \right]^2$$

(4)

where, $\rho$ is the wood density at 12% moisture content (kg/m$^3$).

When determining the remaining effective residual section for structural purposes, both standards EC5 and AS 1720.4 calculate an effective charred depth by adding a constant thickness of 7.5mm to the calculated value in order to take into account the heat-affected zone. That is, effective depth of charring (in millimetres) is given by

$$dc = \beta t + 7.5$$

(5)

where, $dc$ = calculated effective depth of charring in millimetres (mm)

$\beta$ = notional charring rate in millimetres per minute (mm/min) as calculated
t = time of exposure to heating regime specified in AS 1530.4 (minutes)

The effective residual cross – section is obtained by subtracting the calculated effective depth of charring from all fire exposed surfaces of the timber member. The effect of corner charring is ignored. In the development of charring models, Eurocode 5 EN (1995) recommendation has a simple constant charring rate relationship as follows:

$$d_{charr} = \beta_0 t$$

(6)

where, $d_{charr} =$ charring depth mm

$\beta_0 =$ charring rate (mm/min), usually between (0.5 to 0.8) mm/min
t = time in minutes.

### 4.1 Charring Rate Results Modeling Using Multiple Regression

Charring rates (mm/min) were determined using equation (6) as the ratio of the char depth (mm) and the exposure time (min).

Multiple regression was used in making predictions and to explore the relationships among the variables. The general multiple regression equation is given as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_k$$

(7)

Where, $Y =$ Predicted dependent variable; $\beta_0 =$ constant; and $\beta_1, \beta_2, \beta_3, \beta_k = \text{coefficient independent variables } X_1, X_2, X_3, \ldots, X_k$ respectively.

#### 4.2 Development of Charring Rate Model

Tables 2 to 7 showed the data values of both predicted and mean actual charring rates of each species based on the density, moisture content, temperature, and exposure time. Equation (8) to (13) showed the correspondend model equation for each species.

| Density (Kg/m$^3$) | Moisture Content (%) | Temperature ($^\circ$C) | Time (min) | Predicted Charring Rate (mm/min) | Mean Actual Charring Rate (mm/min) |
|---------------------|----------------------|-------------------------|-------------|----------------------------------|----------------------------------|
| 533                 | 9.00                 | 20-300                  | 60          | 0.64                             | 0.56                             |
| 543                 | 12.00                | 20-300                  | 60          | 0.64                             | 0.54                             |
| 609                 | 15.00                | 20-300                  | 60          | 0.62                             | 0.50                             |
| 533                 | 9.00                 | 230-600                 | 30          | 0.64                             | 0.71                             |
| 543                 | 12.00                | 230-600                 | 30          | 0.62                             | 0.69                             |
| 609                 | 15.00                | 230-600                 | 30          | 0.62                             | 0.67                             |
| 533                 | 9.00                 | 20-300                  | 30          | 0.64                             | 0.65                             |
| 543                 | 12.00                | 20-300                  | 30          | 0.64                             | 0.65                             |
| 609                 | 15.00                | 20-300                  | 30          | 0.62                             | 0.65                             |

The regression model equation of charring rate for Afara species is given as

$$Y = 1.082 + 0.000001p - 0.719u + 0.000001T - 0.004t$$

(8)

where, $Y =$ Predicted Charring rate; $p =$ density; $u =$ moisture content; $T =$ temperature; and $t =$ time of exposure.

R$^2 = 0.903$ showed highly significant regression

| Density (Kg/m$^3$) | Moisture Content (%) | Temperature ($^\circ$C) | Time (min) | Predicted Charring Rate (mm/min) | Mean Actual Charring Rate (mm/min) |
|---------------------|----------------------|-------------------------|-------------|----------------------------------|----------------------------------|
| 609                 | 12.00                | 230-600                 | 30          | 0.62                             | 0.67                             |
| 533                 | 9.00                 | 20-300                  | 30          | 0.64                             | 0.65                             |
| 543                 | 12.00                | 20-300                  | 30          | 0.64                             | 0.65                             |
| 609                 | 15.00                | 20-300                  | 30          | 0.62                             | 0.65                             |

The regression model equation of charring rate for Iroko species is given as

$$Y = 0.836 + 0.000006p - 0.396u + 0.000001T - 0.004t$$

(9)

R$^2 = 0.891$ showed highly significant regression.
Table 4: Data Regression table for Mahogany Specie

| Density (Kg/m³) | Moisture Content (%) | Temperature (°C) | Time (min) | Predicted Charring Rate (mm/min) | Mean Actual Charring Rate (mm/min) |
|----------------|----------------------|------------------|------------|----------------------------------|----------------------------------|
| 439            | 9.00                 | 20 - 300         | 60         | 0.66                             | 0.59                             |
| 449            | 12.00                | 20 - 300         | 60         | 0.66                             | 0.56                             |
| 517            | 15.00                | 20 - 300         | 60         | 0.62                             | 0.56                             |
| 439            | 9.00                 | 230 - 600        | 30         | 0.66                             | 0.82                             |
| 449            | 12.00                | 230 - 600        | 30         | 0.66                             | 0.82                             |
| 517            | 15.00                | 230 - 600        | 30         | 0.62                             | 0.79                             |
| 439            | 9.00                 | 20 - 230         | 30         | 0.66                             | 0.66                             |
| 449            | 12.00                | 20 - 230         | 30         | 0.66                             | 0.65                             |
| 517            | 15.00                | 20 - 230         | 30         | 0.62                             | 0.71                             |

The regression model equation of charring rate for Mahogany species is given as:

\[ Y = 0.0654 + 0.000001p - 0.4676 + 0.000001T - 0.004t \]

\[ (R^2 = 0.931) \]  
\[ R^2 = 0.931 \] showed highly significant regression.

Table 5: Data Regression table for Mansonia Specie

| Density (Kg/m³) | Moisture Content (%) | Temperature (°C) | Time (min) | Predicted Charring Rate (mm/min) | Mean Actual Charring Rate (mm/min) |
|----------------|----------------------|------------------|------------|----------------------------------|----------------------------------|
| 563            | 9.00                 | 20 - 30          | 60         | 0.61                             | 0.55                             |
| 576            | 12.00                | 20 - 30          | 60         | 0.60                             | 0.55                             |
| 589            | 15.00                | 20 - 30          | 60         | 0.60                             | 0.56                             |
| 563            | 9.00                 | 230 - 300        | 30         | 0.61                             | 0.89                             |
| 576            | 12.00                | 230 - 300        | 30         | 0.60                             | 0.85                             |
| 589            | 15.00                | 230 - 300        | 30         | 0.60                             | 0.82                             |
| 563            | 9.00                 | 20 - 230         | 30         | 0.61                             | 0.65                             |
| 576            | 12.00                | 20 - 230         | 30         | 0.60                             | 0.62                             |
| 589            | 15.00                | 20 - 230         | 30         | 0.60                             | 0.63                             |

The regression model equation of charring rate for Mansonia species is given as:

\[ Y = 0.458 + 0.000001p - 0.6336 + 0.001T - 0.004t \]

\[ (R^2 = 0.954) \]  
\[ R^2 = 0.954 \] showed highly significant regression.

Table 6: Data Regression table for Opepe Specie

| Density (Kg/m³) | Moisture Content (%) | Temperature (°C) | Time (min) | Predicted Charring Rate (mm/min) | Mean Actual Charring Rate (mm/min) |
|----------------|----------------------|------------------|------------|----------------------------------|----------------------------------|
| 675            | 9.00                 | 20 - 30          | 60         | 0.58                             | 0.44                             |
| 698            | 12.00                | 20 - 30          | 60         | 0.50                             | 0.46                             |
| 772            | 15.00                | 20 - 30          | 60         | 0.50                             | 0.45                             |
| 675            | 9.00                 | 230 - 600        | 30         | 0.58                             | 0.81                             |
| 698            | 12.00                | 230 - 600        | 30         | 0.50                             | 0.79                             |
| 772            | 15.00                | 230 - 600        | 30         | 0.50                             | 0.78                             |
| 675            | 9.00                 | 20 - 230         | 30         | 0.58                             | 0.48                             |
| 698            | 12.00                | 20 - 230         | 30         | 0.50                             | 0.48                             |
| 772            | 15.00                | 20 - 230         | 30         | 0.50                             | 0.47                             |

The regression model equation of charring rate for Opepe species is given as:

\[ Y = 0.565 + 0.000001p + 0.495 + 0.001T - 0.001t \]

\[ (R^2 = 0.968) \]  
\[ R^2 = 0.968 \] showed highly significant regression.

Table 7: Data Regression table for Teak Specie

| Density (Kg/m³) | Moisture Content (%) | Temperature (°C) | Time (min) | Predicted Charring Rate (mm/min) | Mean Actual Charring Rate (mm/min) |
|----------------|----------------------|------------------|------------|----------------------------------|----------------------------------|
| 506            | 9.00                 | 20 - 30          | 60         | 0.64                             | 0.49                             |
| 572            | 12.00                | 20 - 30          | 60         | 0.62                             | 0.49                             |
| 661            | 15.00                | 20 - 30          | 60         | 0.50                             | 0.49                             |
| 506            | 9.00                 | 230 - 600        | 30         | 0.64                             | 0.71                             |
| 572            | 12.00                | 230 - 600        | 30         | 0.62                             | 0.69                             |
| 661            | 15.00                | 230 - 600        | 30         | 0.50                             | 0.68                             |
| 506            | 9.00                 | 20 - 230         | 30         | 0.64                             | 0.65                             |
| 572            | 12.00                | 20 - 230         | 30         | 0.62                             | 0.65                             |
| 661            | 15.00                | 20 - 230         | 30         | 0.50                             | 0.65                             |

The regression model equation of charring rate for Teak species is given as:

\[ Y = 0.806 + 0.0000166p - 0.1426 + 0.000001T - 0.006t \]

\[ (R^2 = 0.943) \]  
\[ R^2 = 0.943 \] showed highly significant regression.

The general regression model equation of charring rate for all species based on their densities, moisture contents, temperature and exposure time is given as;

\[ Y = 1.105 - 0.001p + 0.3926 + 0.000001T - 0.004t \]

\[ (R^2 = 0.680) \]  
\[ R^2 = 0.680 \] showed significant regression.
Equation (14) can be used to predict the charring rate of all the selected timber species.

Figure 1 shows the bar chart for the mean charring rate values of the selected species after 1-hour fire exposure, temperature range between 20 to 300°C.

![Charring Rate after 1-hour Fire Exposure](image)

Fig. 1: Mean Charring rate values of selected Species at their corresponding Moisture content

### 5. CONCLUSION

The charring rates behaviour of, constructional timber members has been studied through literature review, laboratory experiments and calculations. Under conditions of severe fires (but not absolute worst-case extreme conditions), heavy-timber or similar members will char at similar rates to those found in fire-resistance furnace tests, roughly 0.5 to 0.8 mm/min.

Thus, unless specific factors are known to be involved that would lead to extreme-case conditions, it may be assumed that charring rates in an actual fire will not exceed these test values. This value for post-flashover can be a useful tool in estimating a minimum burning duration of the room fire. For example, if 40 mm char depth was found on thick members supporting the ceiling, it may be credibly estimated that post-flashover conditions in the room lasted at least 40/0.8 = 50 minutes.

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