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Burning Characteristics of Some Selected Structural Timbers Species of Southwestern Nigeria

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Abstract: *Timber has been used for construction since prehistoric times. However, timber by its nature is combustible, and may be a source of building collapse during fire incidence. Hence, it warrants attention to ensure safety of the buildings. Unlike steel and concrete, the performance of timber species under fire exposure, particularly for species found in Southwestern Nigerian has not been adequately investigated. This paper determined the relationship between the physical, mechanical properties, and the burning characteristics of the selected Nigeria timber species used for structural purposes.*
Six species out of ten identified timber species that are used for structural purposes in building construction in Southwestern Nigeria were selected for studies in this paper. They are: Iroko (milicia excels), Teak (tectona grandis), Afara (Terminalia superb), Mansonia (mansonia altissima), Mahogany (khaya spp), and Opepe (Nauclea diderrichii). The densities of the timber species were determined at moisture contents of 9%, 12%, and 15%. Eighteen timber samples, three from each of the selected species of dimension 510mm x 150mm x 150mm, were exposed to fire for charring rate test at varying exposure time 0 – 29 minutes, 0 – 60 minutes, and 30 minutes – 60 minutes. The correlation coefficients of the predicted charring rate when compared with the actual charring rate were determined.
Keywords: *Structural timbers species, moisture content, density, charring rate, correlation coefficient.*

I. Introduction

Timber, for ages, remained one of the major structural materials for building construction worldwide due to its renewable nature, availability in various sizes, shapes and colours, affordability, relatively fatigue resistance and specific strength, ease of joining, durability, and aesthetic appeal. Also un-serviceable wooden building components are re-cyclable either for their structural properties, e.g., reused permanently as framing or temporarily as formwork, or for their heat content as fuel (Goldstein 1999).

In Nigeria, however, the major area of structural utilization of wood is in roof construction; with the building industry alone consuming about 80% of the country's estimated 20 million cubic meters of annual lumber production (Alade and Lucas, 1982, Lucas and Olorunnisola 2002).

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 and Kaliszuk, 2002). 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. 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.

The keyword for timber's behaviour in fire is predictability. Although it burns, this occurs at a predictable speed known as the charring rate. The charring rate effect on wood makes it have superior fire performance over other structural alternatives, as wood members are exposed to fire, an insulating char layer is formed that protects the core of the section. Thus, beams and columns can be designed so that a sufficient cross section of wood remains to sustain the design loads for the required duration of fire exposure. A standard fire exposure is used for design purposes. In North America, this exposure is described in the standard fire endurance test ASTM E 119.

Timber undergoes thermal degradation, also called pyrolysis when exposed to fire, (Hadvig, 1981), by converting the timber to char and gas pyrolysis results in a reduction in density. The resulting pyrolysis gas undergoes flaming combustion as it leaves the charred wood surface. Glowing combustion and mechanical disintegration of the char eventually erode the outer char layer (Fredlund, 1993).

The linear rate at which wood is converted to char is referred to as the charring rate. After a high initial charring rate and under standard fire exposure, the charring rates tend to be fairly constant. Determining the charring rate is critical to evaluating fire resistance, because char has virtually no load-bearing capacity. There is a fairly distinct demarcation between char and uncharred wood. The charring rate sometimes refers to the weight loss. This rate of weight loss is also called burning rate in some reports. 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 (BSI, 1987). This enables the fire resistance of simple timber elements to be calculated.

Many factors are involved in wood charring. Kanury and Blackshear (1970) examined various physic-chemical effects, including diffusion of condensable vapors inward, internal convection outward, kinetics of Pyrolysis, energetic of Pyrolysis and post-decomposition reactions. Lee and others (1976) mentioned others factors including the external heating rate, the total time of heating, and the anisotropic properties of wood and char relative to the internal flow of heat and gas.

Thomas (1960) noted that in the standard fire resistance test, the rate of heat transfer to the surface increases with time. While this results in a faster charring rate, the thicker char layer tends to slow down the charring rate. The net effect is that charring rates remain fairly constant after an initial faster charring rate.

In study of three species, Schaffer (1967) reported charring rates for White oak, Douglas-fir and Southern pine. The 75 x 250 x 500mm slabs were subjected to ASTM E 119 fire exposure. Schaffer used a characteristic char base temperature of 288°C to locate the border line between char and wood.

For a linear model, char rate, C (mm/min), is defined as

$$C = X_c / t \qquad (1)$$

Where t is time in minutes and X_c is the char depth in mm.

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II. Materials and Methods

Six structural timber species taken out of the ten mostly available species were considered in this paper.

The six species were:

1. Afara (Terminalia superb)
2. Iroko (Milicia excelsa)
3. Mahogany (Khaya spp.)
4. Mansonia (Mansonia altissima)
5. Opepe (Nauclea diderrichii)
6. Teak (Tectona grandis)

All timber samples used in this paper were taken from the heartwood region of the individual tree. And they were specially ordered from the lumber market

2.1 Specimen test preparation

Wood specimens were tested in a big vertical electrical-fired furnace. Fifty four samples tested were done in three groups. Three specimens of dimension 510mm x 150mm x150mm blocks from one board of the six species were tested at moisture content level of 9, 12, and 15 percent, at the furnace exposure period of (0 – 29 minutes), (30 minutes – 60 minutes), and (0 – 60 minutes). (Figures 1 to 4).

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℃, assuming that ignition starts at this point. At time of test, the following data were recorded for the specimen properties:

1. Species
2. Ring orientation
3. Specimen dimensions
4. Specimen weight
6. Specific gravity (dry)
7. Moisture content (percent)

The specimen, as installed in the furnace, is shown in figure 4.2. 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 for to fire in three batches; first batch went for time (0-29minutes), second batch for (30 -60minutes) and the last batch was for full 60minutes.

The first test for exposure period (0 – 29 minutes) was stopped at exactly when the stop watch reached 29 minutes, temperature reading was 230°C.

Samples exposed during the second period (30 minutes – 60 minutes) were subjected to higher temperature (600° C) and this increased according to the time – temperature curve AS 1530. 4, 1990 as the test progressed. Effects of increased level of irradiance on the charring rate were also observed.

The third test for exposure period (0 – 60 minutes) was terminated when the furnace temperature reached 300°C.

When testing completed, the charred wood was scrapped away from the samples and char depth measured. 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.

Results of the char rate were based on an interface temperature of 300°C. However, results were given only for the specimens that maintained a semi-infinite solid behaviour, i.e. the temperature in their central zone (uncharred zone) did not exceed 100°C.

Fig. 1: Taken specimen dimension for the fire test (510mm x 150mm x 1500mm)

Fig. 2: Oven dried specimen before taken for fire exposure

Fig. 3: Burning specimen inside furnace after expiration of 1-hour fire exposure

Fig. 4: Charred wood after 1-hour fire exposure

2.2 Charring rate results

The results of fire exposure test are illustrated in Tables 1 to 3, covering the exposure periods 0 - 29 minutes, 0 - 60 minutes, and, 30 minutes – 60 minutes respectively. Within tables, samples are grouped according to other parameters being examined.

Charring rates were determined by scrapping away the charred timber and measuring the average depth remaining, to determine the amount lost through charring in mm. This was divided by the exposure time and is expressed as charring rate in the tables.

Use was made of density and moisture content data (considered by many researchers to be the two major influences on char rate. Predictions (based on linear model) of char depth for the exposure time were calculated, converted into charring rates and entered in Tables 1 to 3

2.3 Exposure Time effect on charring rate

Exposure time affects charring rate; a char layer building over time acts as an insulating layer protecting the timber underneath, whereby reducing charring rate. However, this is somewhat offset by the increasing magnitude of the incident radiation as a fire resistance test progresses, or as a real fire develops.

The developed insulating layer responsible for the relatively low charring rate of the first half of heating period of samples (0 – 29 minutes). The char layer retards further degradation of the wood. As the exposure time increased (0 – 60 minutes), the charring rate gradually increasing. Samples exposed for the second half of the heating period (30 minutes - 60 minutes) experienced more intense heating in that period, and as expected, charred at a greater rate.

Table 1: Charring Rate Of Timber Samples (0 - 29 minutes) Exposure

Species	Moisture Content (%)	Density (kg/m^3)	Furnace Exposure Periods (minutes)	Char depth (mm)		Predicted Charring rate (mm/min)		Actual Charring rate (mm/min)	
				Side	Base	Side	Base	Side	Base
Afara	9	444	0 – 29	22.4	25.2	0.66	0.66	0.74	0.84
	12	444	0 – 29	23.9	24.6	0.66	0.66	0.80	0.82
	15	469	0 – 29	20.6	24.8	0.66	0.66	0.69	0.83
Iroko	9	532	0 – 29	18.3	19.3	0.66	0.66	0.61	0.64
	12	544	0 – 29	18.1	19.6	0.66	0.66	0.60	0.65
	15	614	0 – 29	17.9	19.5	0.60	0.60	0.60	0.65
Mahogany	9	439	0 – 29	20.1	19.7	0.66	0.66	0.67	0.66
	12	451	0 – 29	19.3	19.5	0.66	0.66	0.64	0.65
	15	521	0 – 29	18.6	21.3	0.66	0.66	0.62	0.71
Mansonia	9	566	0 – 29	17.6	19.4	0.66	0.66	0.59	0.65
	12	580	0 – 29	16.5	18.7	0.66	0.66	0.55	0.62
	15	591	0 – 29	16.5	18.9	0.66	0.66	0.55	0.63
Opepe	9	630	0 – 29	13.2	14.3	0.58	0.58	0.44	0.48
	12	686	0 – 29	13.6	14.4	0.50	0.50	0.45	0.48
	15	752	0 – 29	13.6	14.1	0.50	0.50	0.45	0.47
Teak	9	505	0 – 29	19.4	19.5	0.66	0.66	0.65	0.65
	12	569	0 – 29	17.4	19.4	0.66	0.66	0.58	0.65
	15	657	0 – 29	16.2	19.4	0.50	0.50	0.54	0.65

Table 2: Charring Rate Of Timber Samples (0 - 60 minutes) Exposure

Species	Moisture Content (%)	Density (kg/m^3)	Furnace Exposure Periods (minutes)	Char depth (mm)		Predicted Charring rate (mm/min)		Actual Charring rate (mm/min)	
				Side	Base	Side	Base	Side	Base
Afara	9	444	0 – 60	43.6	44.5	0.66	0.66	0.73	0.74
	12	444	0 – 60	44.7	44.5	0.66	0.66	0.75	0.74
	15	469	0 – 60	40.4	40.8	0.66	0.66	0.67	0.68
Iroko	9	532	0 – 60	32.8	33.4	0.66	0.66	0.55	0.56
	12	544	0 – 60	32.1	32.3	0.66	0.66	0.54	0.54
	15	614	0 – 60	25.6	30.2	0.60	0.60	0.43	0.50
Mahogany	9	439	0 – 60	38.5	35.7	0.66	0.66	0.64	0.59
	12	451	0 – 60	38.5	33.7	0.66	0.66	0.64	0.56
	15	521	0 – 60	33.6	33.9	0.66	0.66	0.56	0.56
Mansonia	9	566	0 – 60	35.2	33.2	0.66	0.66	0.59	0.55
	12	580	0 – 60	34.4	32.8	0.66	0.66	0.57	0.55
	15	591	0 – 60	34.1	33.7	0.66	0.66	0.57	0.56
Opepe	9	630	0 – 60	25.2	28.3	0.58	0.58	0.42	0.47
	12	686	0 – 60	23.4	28.6	0.50	0.50	0.39	0.48
	15	752	0 – 60	22.2	28.4	0.50	0.50	0.37	0.47
Teak	9	505	0 – 60	28.3	29.4	0.66	0.66	0.47	0.49
	12	569	0 – 60	29.3	29.2	0.66	0.66	0.49	0.49
	15	657	0 – 60	25.5	29.2	0.50	0.50	0.43	0.49

Table 3: Charring Rate Of Timber Samples (30 minutes - 60 minutes) Exposure

Species	Moisture Content (%)	Density (kg/m^3)	Furnace Exposure Periods (minutes)	Char depth (mm)		Predicted Charring rate (mm/min)		Actual Charring rate (mm/min)	
				Side	Base	Side	Base	Side	Base
Afara	9	444	30 - 60	48.4	54.9	0.66	0.66	1.56	1.77
	12	444	30 – 60	51.2	55.5	0.66	0.66	1.65	1.79
	15	469	30 – 60	51.2	55.5	0.66	0.66	1.65	1.79
Iroko	9	532	30 – 60	41.2	46.2	0.66	0.66	1.33	1.49

	12	544	30 – 60	41.85	45.9	0.66	0.66	1.35	1.48
	15	614	30 – 60	37.82	39.4	0.60	0.60	1.22	1.27
Mahogany	9	439	30 – 60	48.4	44.64	0.66	0.66	1.56	1.44
	12	451	30 – 60	47.4	45.88	0.66	0.66	1.53	1.48
	15	521	30 – 60	41.2	43.7	0.66	0.66	1.33	1.41
Mansonia	9	566	30 – 60	39.7	41.5	0.66	0.66	1.28	1.34
	12	580	30 – 60	40.9	41.2	0.66	0.66	1.32	1.33
	15	591	30 – 60	40.0	43.7	0.66	0.66	1.29	1.41
Opepe	9	630	30 – 60	31.3	38.6	0.58	0.58	1.01	1.25
	12	686	30 – 60	27.9	37.5	0.50	0.50	0.90	1.21
	15	752	30 – 60	27.9	38.1	0.50	0.50	0.90	1.23
Teak	9	505	30 – 60	41.2	44.6	0.66	0.66	1.33	1.44
	12	569	30 – 60	41.2	40.0	0.66	0.66	1.33	1.29
	15	657	30 – 60	30.4	40.0	0.50	0.50	0.98	1.29

III. Actual charring rate based on effectiveness of Predicted charring rate

To illustrate the effectiveness of the predicted charring rate, data from Tables 1, 2, 3 had been plotted on graphs in figure 5 for 0 - 29 minutes fire exposure, figure 6 for 0 - 60 minutes fire exposure, and figure 7 for 30 minutes - 60 minutes fire exposure. The corresponding total agreements between the predicted and actual values were determined. For the three exposure periods, coefficient of correlation was calculated with the following results.

Figure 5 illustrates the 29 minutes exposure results. The actual was in most cases close to the predicted charring rate, with a corresponding high coefficient of correlation 64.7%. At 64.7% there is a strong positive correlation of actual charring rate that can be explained by the relationship to the predicted charring rate.

Figure 6 illustrates the 60 minutes exposure time and show the lowest coefficient of 52.88%. It means that at 52.88%, there is a strong positive correlation of actual charring rate that can be explained by the relationship to the predicted charring rate.

Figure 7 illustrates the results for the exposure for the second part of the test (when the temperature and incident radiation are greater). The coefficient of correlation is 57.38%. It means that at 57.38%, there is a strong positive correlation of actual charring rate that can be explained by the relationship to the predicted charring rate.

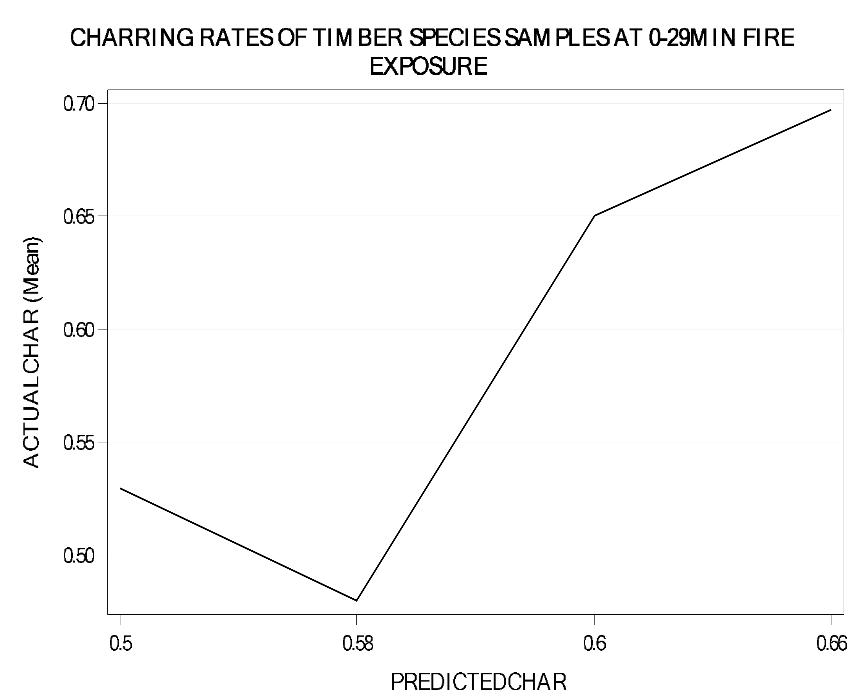

Fig. 5: Line graph of char rates for 0 - 29 minutes exposure

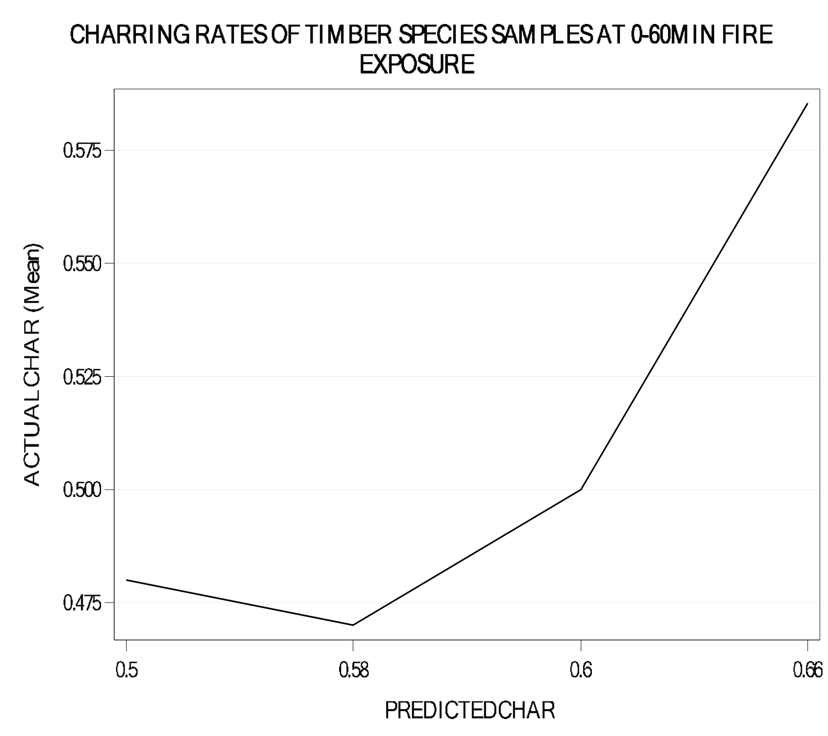

Fig. 6: Line graph of char rates for 0 - 60 minutes exposure

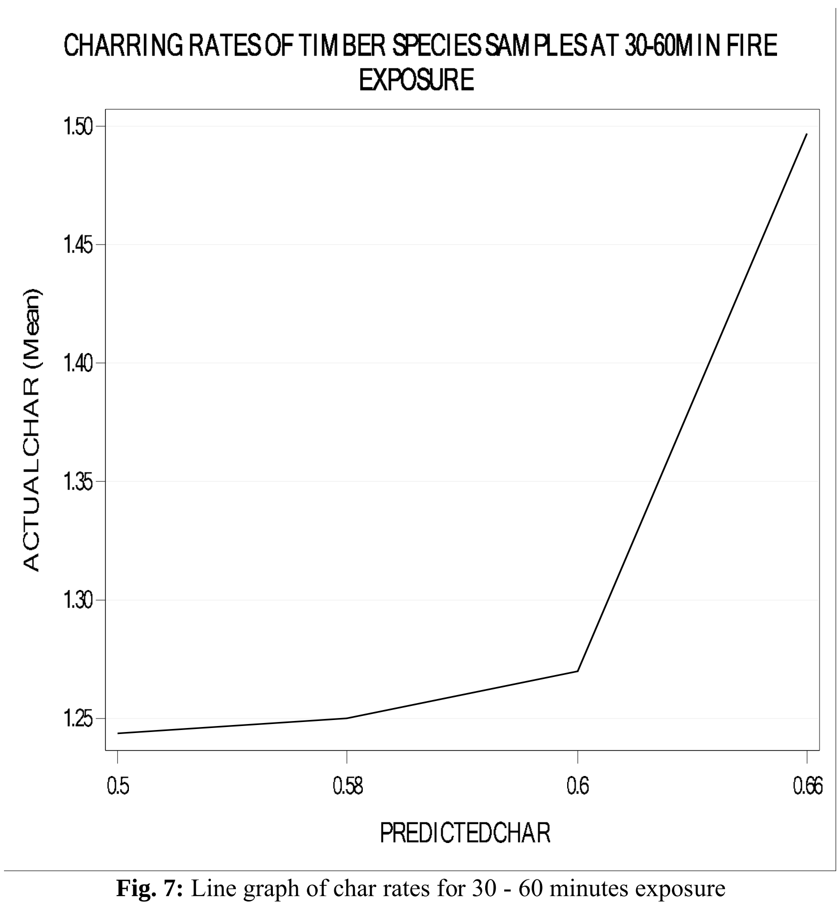

Fig. 7: Line graph of char rates for 30 - 60 minutes exposure

IV. Conclusion

The charring behaviour of solid wood, structural timber members has been studied through literature review, laboratory experiments and calculations. Under conditions of severe, post-flashover room fires (but not absolute worst-case extreme conditions), heavy-timber or similar members that 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 can be a useful tool in estimating a minimum value for post-flashover 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.

The predicted charring rates have been compared with the results of the actual charring rates from the experiments. This comparison shows that the results of the experimental charring rates were similar to the results obtained from the predicted charring rates.

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

- **Density**

Density is greatly influenced by the amount of moisture contained in timber at the time of measurement. For that reason, the density values are normally quoted at a standard moisture content MC of 12%. Also wood fibres have so much to do with wood density, if the fibres have thin cell wall, then the wood density would be light, and if the fibres have thick cell wall, wood density would be high, so the thinner the cell wall, the lighter the wood density and vice versa.

- **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.

- **Lignin content**

Lignin is an amorphous polymer that cements the cells together, thus providing resistance to compression and shear. Among the wood chemical composition, lignin being the one that shows the most significant mechanical property changes at the lowest temperatures. Lignin attains its glass transition at temperatures as low as 60°C when saturated with water, leading to a loss of binding strength between the fibres. The attainment of the glass transition has important effects on the modulus of elasticity and on thus on the mechanical behaviour of wood.

- **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.

- **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 10^4 times that across the grains. Similarly thermal conductivity of wood along 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.

- **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.

- **Oxygen concentration**

Oxygen concentration in a standard fire test depends on time, the oxygen concentration decreases up to about 20 minutes where after it remains constant.

Density and moisture content are the two main factors influencing the charring rate of timber considering these conditions;

- 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,
- Higher moisture content decreases the charring rate, but size of the change varies greatly,
- The charring rate increases with higher heat flux, better ventilation and more oxygen in the air.

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