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Experimental study of the charring rate of tropical hardwoods

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SUMMARY

This paper describes an experimental investigation of the charring rates of timber. An experimental procedure was designed for assessing the charring rate of 20 specimens exposed to fire in a single test, with one-dimensional heat transfer conditions.

Each test specimen was manufactured by gluing seven laminates together. Four thermocouples were inserted at different depths in four different laminates located in the middle of the test specimen. The test was conducted using a gas-fired furnace and specimens were exposed to the standard ISO 834 fire.

In order to evaluate the fire performance of tropical hardwoods, seven different species with densities ranging from 500 to 1000 kg/m^3 were used. For the purpose of verifying the experimental procedure against existing data, two softwood species (spruce and fir) and one European hardwood species (oak) were also examined.

Experimental results indicate that the test method and procedure can be used for assessing the charring rate of timber both for softwood and for hardwood species. They also show that the density of wood significantly affects the charring rate and that the values recommended in Eurocode 5 for high densities are somewhat too conservative. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: tropical hardwood; charring rate; density; fire test

1. INTRODUCTION

Tropical hardwood species are increasingly used in Belgium and in other parts of Europe for the particular qualities they can offer. This is true for structural as well as for separating elements.

It is presently no longer possible to consider the development of construction materials and products without taking into consideration the problem of their fire behaviour. Wood is practically the only combustible material used for the construction of structural elements. As far as the complex problem of the fire behaviour is concerned, both reaction and resistance to fire must be considered. The subject of this study only addresses aspects of fire resistance.

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The objective of fire resistance is to determine how a construction element is going to behave in the presence of fire. More precisely fire resistance is related to the period during which a construction element submitted to a thermal attack is able to maintain the function for which it has been designed (mostly bearing or separating function). During the development of fire a charred layer forms on the external part of timber elements that protects the underlying layers against the action of fire. Therefore, the residual section of the beam or the column decreases slowly, and the element gradually loses its structural capacity.

The main controlling factor in the study of the fire resistance of timber structural elements is the charring rate. Extensive charring rate data have been obtained from fire tests with temperature-time exposures as described in the ISO 834 [1] and ASTM E 119 [2] standards.

In most design codes dealing with fire resistance, charring rates are given for various timber species. These values are design values that can be used under certain conditions. Often these design charring rates are notional values since they may include the effect of strength and stiffness degradation due to elevated temperatures or the effect of increased charring at cross section corners and in cracked zones [3].

Parameters affecting the charring rate have been extensively studied in the United States [4,5], New Zealand [6], Sweden [3–7] and elsewhere. All these investigations show that the density of wood has a major influence on the charring rate.

Due to the lack of a standard test procedure for determining charring rates, no definition of the term charring rate is given in Eurocode 5 [8], nor is it specified how appropriate design charring rates should be derived from the results of fire tests. König and Waleij [3] proposed to define this characteristic by using the charring rate of a semi-infinite timber element submitted to one-dimensional heat transfer conditions.

The Fire Part of Eurocode 5 [8] assumes that the charring rate of solid or glued laminated hardwoods decreases with density, with a limit of 0.5 mm/min for densities greater than 450 kg/m^3. However, tropical hardwood species exhibit a wide range of densities between 140 kg/m^3 for balsa (*Ochroma pyramidale*) to 1200 kg/m^3 for ferreol (*Swartzia* spp.).

In order to apply the calculation procedures available in Eurocode 5 [8] to tropical hardwood timber products, it is imperative that experimental data on charring rates for such timber species be available.

The main objectives of this work consisted of the development of an experimental procedure for assessing the charring rate of wood for ISO 834 [1] exposure, the experimental determination of charring rates of high density tropical hardwoods and verification that tropical hardwoods char at a slower rate if the density exceeds 450 kg/m^3 contrary to what is specified in Eurocode 5 [8].

2. EXPERIMENTAL TECHNIQUE AND TEST SET-UP

2.1. Test set-up

The general test set-up (Figure 1) consists of a vertical gas-fired furnace. The test frame was filled with cellular concrete blocks, in which 20 holes measuring 280 × 170 mm were made to accommodate the specimens. The test frame formed the front vertical wall covering the furnace.

The test specimens were subjected on one side to the standard ISO 834 fire and the test was performed according to the detailed requirements of the Belgian standard for fire resistance of building construction elements, NBN 713-020 [9].

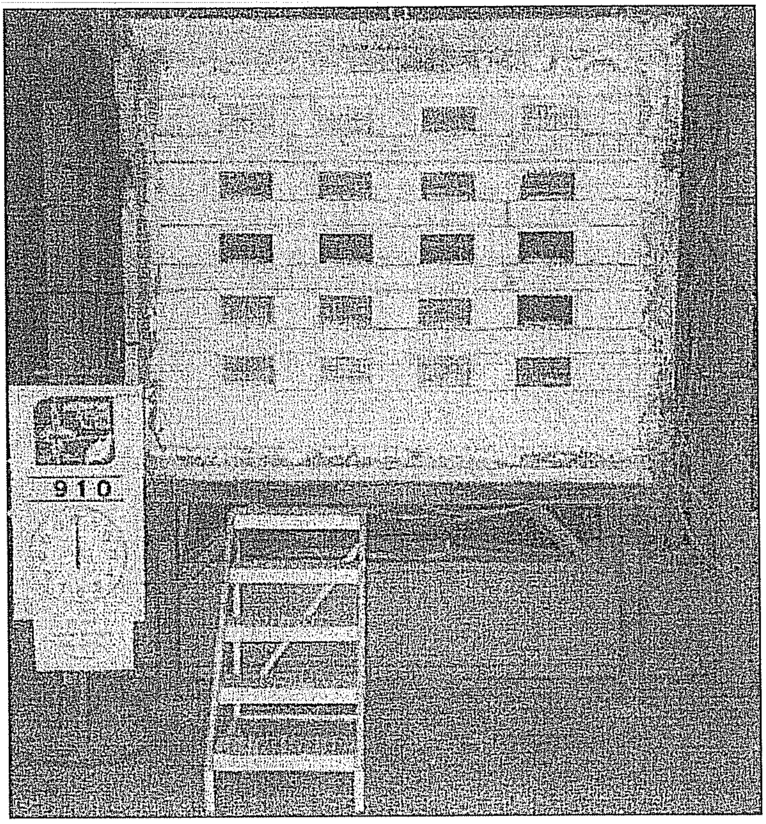

Figure 1. Test set-up.

As in previous studies [3], it was decided that the char front location corresponds to the 300°C isotherm, i.e. the temperature at which pyrolysis is significant. The test was therefore completed when all thermocouples reached a temperature of 300°C.

Species originating in South East Asia and Central Africa were chosen in order to cover a range of densities from 500 kg/m^3 for Meranti (*Shorea* spp.) to 1000 kg/m^3 for Azobe (*Lophira alata*).

The time for the char front to reach the hot thermocouple junction was determined for each laminate instrumented with a thermocouple. Curves of time versus char depth were then obtained for each test specimen and a linear regression was calculated. The slope of each of these regression lines was determined and its inverse is equal to the experimental charring rate of the specimen.

2.2. Test specimens

The size of the test specimens (Figure 2) was determined according to the dimensions of the vertical opening of the furnace (1870 × 1700 mm), the number of samples necessary for the test, and the need to minimize edge effects. The overall dimensions of the test specimens were 140 mm

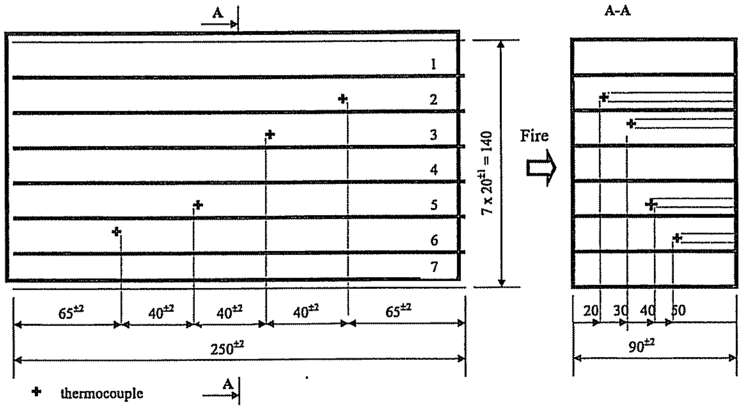

Figure 2. Size of specimen and position of thermocouples.

Table I. Test species and samples.

Common name	Scientific name	Nominal dimensions* (mm)	Number of specimens	Type†
Spruce	*Pinus sylvestris*	90 × 140 × 250	2	GL–S
Fir	*Abies alba*	65 × 135 × 250	1	GL
Oak	*Quercus robur*	85 × 140 × 250	1	GL
Azobe	*Lophira alata*	90 × 140 × 250	3	GL
		80 × 140 × 250	1	GL
Afzelia	*Afzelia bipindensis*	90 × 126 × 250	3	GL
		75 × 140 × 250	1	GL
		62 × 126 × 250	1	GL
Balau	*Shorea* spp	90 × 133 × 250	2	GL
Bilinga	*Nauclea diderrichii M.*	90 × 126 × 250	1	GL
Meranti	*Shorea rubro*	85 × 133 × 250	1	GL
		85 × 126 × 250	1	GL
Merbau	*Intsia* spp	90 × 140 × 250	1	GL
Wenge	*Millettia laurentii*	65 × 135 × 250	1	GL‡

*Depth × width × length.
†GL glued laminated, S solid.
‡Three laminates.

high, 250 mm wide and 90 mm thick. Charring occurred in the 90 mm direction, perpendicular to the laminates and to the grain of the wood (Figure 2).

Twenty specimens were manufactured for the test. The Wenge specimen was made of three 45 mm thick laminates. One specimen of spruce consisted of solid wood. All other specimens were constructed by gluing seven 18–20 mm thick laminates together with a standard adhesive for timber available in general stores (type EN 204 D3). Laminates were conditioned in a standard atmosphere of 20°C and 55% relative humidity for 3 months after sawing. Table I summarizes the characteristics of the samples. Figure 2 shows the drilling pattern for the insertion of thermocouples for medium and high density species.

Table II. Distance of thermocouples from the original fire-exposed surface.

No.	Class density	Species	Range of density (kg/m^3)	Position of thermocouples (mm)
1	Very heavy	Azobe, Wenge, Balau	900 to 1100	10, 20, 30, 40
2	Medium and Heavy	Afzelia, Merbau, Oak, Bilinga	600 to 900	20, 30, 40, 50
3	Light	Spruce , Fir, Meranti	400 to 600	15, 30, 45, 60

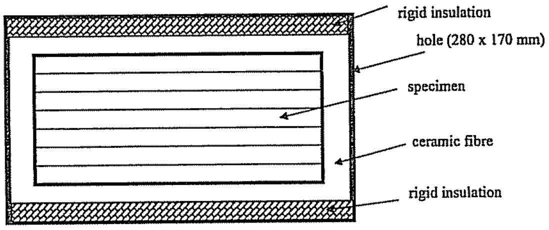

Figure 3. Specimen placement in the holder.

Four thermocouples were placed at four different distances from the exposed surface (Table II) by inserting the wires from the unexposed surfaces of the laminates. The thermocouples were of the type J iron and copper-nickel with a wire diameter of 0.50 mm.

As can be observed in Table II, the position of the thermocouples varies between the different species. In fact, the distances from the fire exposed surface increase with decreasing density. Based on theoretical values of charring rates given by Eurocode 5 [8] the thermocouples were positioned in such a way that it would take approximately 90 min for the char front to reach the most remote thermocouple.

The specimens were wedged tightly in the holes by inserting two 15 mm thick layers of rigid calcium silicate insulation in the top and the bottom and by fitting gaps around the perimeter with ceramic fibre (Figure 3).

2.3. Physical characteristics of specimens

2.3.1. Moisture content. The moisture content was determined by measurement of the weight loss of oven dried laminates according to European standard EN 408 [10].

The measurement consists of weighing three laminates before and after drying in an oven at 105°C for 4–6 days until a constant weight is reached. The moisture content of the species is equal to the mean value corresponding to the three laminates used for each species. Equation (1) gives the formula used

$$\omega(\%) = \frac{M_{\mathrm{H}} - M_{\mathrm{O}}}{M_{\mathrm{O}}} \times 100 \tag{1}$$

where M_{H} is the weight before drying (g), M_{O} is the constant weight after drying (g) and ω is the moisture content (%).

2.3.2. Density. Each laminate instrumented with a thermocouple was weighed and measured and its density calculated according to Equation (2).

$$\rho_{\mathrm{H}} = \frac{m_{\mathrm{H}}}{V_{\mathrm{H}}} \tag{2}$$

where m_{H} is the air-dried mass of the laminate (kg), V_{H} is the air-dried volume of the laminate (m^3) and ρ_{H} is the air-dried density ($\mathrm{kg/m}^3$).

The density of each wood species is the mean value corresponding to all laminates from the same species instrumented with a thermocouple.

Measurements of the density and moisture content of specimens were made 2 weeks before the test.

3. RESULTS AND DISCUSSION

3.1. Test methodology

Temperature-time curves were recorded at the four thermocouples within each specimen.

A typical example of these curves is given in Figure 4. All exhibit the same pattern. The temperature increased slowly up to 100°C. A plateau with varying length could then be observed corresponding to the evaporation of free water. Subsequent to the plateau the increase was much more rapid, which indicated that the dried material behaved quite differently.

There was no apparent slowdown at 300°C, which was assumed to be the temperature when the char front arrived at the location of the thermocouple. This indicated that this temperature value was somewhat arbitrary.

The time in min (t) corresponding to a temperature rise of 300°C could be obtained from these curves.

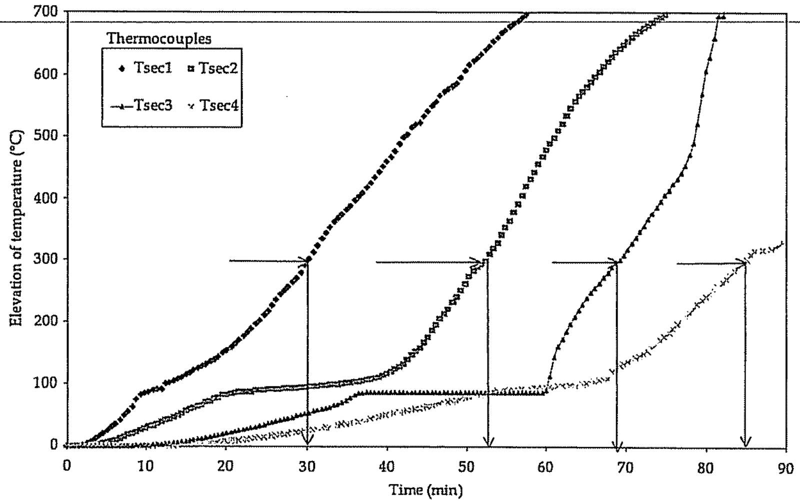

Figure 4. Temperature-time relationship—Azobe 1 specimen.

The distance from the original fire exposed surface (x_c) is the difference between the thickness of the laminate and the depth of the hole drilled in the laminate. Measurements of dimensions were made 3 days before the test.

3.2. *Charring rates for tested specimens and species*

Since no char layer was present at the start of the test, it is reasonable to assume that the charring rate was faster initially [5]. A char layer indeed provides protection for the wood due to its thermal resistance.

Nevertheless, for design purposes, a linear relationship between the time and char depth is usually considered for timber exposed to the standard fire [3–5]. It was decided to adopt this assumption, provided the linear regression obtained was representative of the entire set of results.

The following time-location relation model was therefore considered

$$t = m\ x_c \tag{3}$$

For each test specimen, four pairs of time and char depth were recorded. Values for the parameter m was obtained by linear regression of the time location data. The classical R^2 parameter of linear regression was calculated for all regression lines. These results are not presented here. Nearly all R^2 values were between 0.9 and 1, with a few between 0.8 and 0.9. For example, the graph presented in Figure 5 is based on the experimental results given in Figure 4, with a value of R^2 slightly larger than 0.9. It has to be mentioned that the tendency of the charring rate to increase with time that can be observed in Figure 5 is specific to this specimen and was not systematically observed. Generally speaking, the assumption of a constant charring rate was supported by the observation of the results.

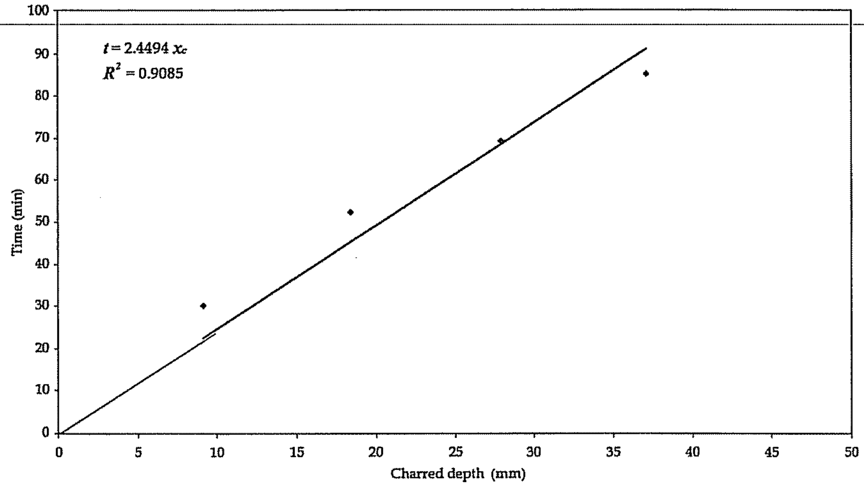

Figure 5. Time-location data and linear regression obtained from four thermocouples located at different depths—Azobe 1 specimen.

Table III. Experimental results.

Species	Specimen	Moisture content ω (%)	Density ρH (kg/m^3)	Charring rate β_{test} (mm/min)
Spruce	SRN1	9	480	0.62
	SRN2	9	476	0.57
Fir	Fir1	13	421	0.71
Oak	Oak1	10	557	0.59
Azobe	Azobe1	13	1050	0.41
	Azobe2	13	1040	0.41
	Azobe3	13	1000	0.41
	Azobe4	13	1060	0.47
Wenge	Wenge1	13	923	0.49
Afzelia	Afzelia1	13	863	0.36
	Afzelia2	13	836	0.43
	Afzelia3	11	833	0.49
	Afzelia4	12	800	0.51
	Afzelia5	20	968	0.37
Bilinga	Bilinga1	11	692	0.58
Balau	Balau1	9	939	0.40
	Balau2	9	984	0.41
Merbau	Merbau1	12	779	0.50
Meranti	Meranti1	10	522	0.54
	Meranti2	10	522	0.55

Regression analyses were performed with time (t) as the dependent variable and char depth (x_c) as the independent variable. This is consistent with the experiments in which times corresponding to the 300°C criterion were measured for fixed thermocouple locations.

~~The experimental charring rate β_{test} as it is normally reported (mm/min) is simply the inverse~~ of m.

The experimental results (physical characteristics and charring rates) are presented in Table III. Samples are grouped according to the type of species (softwood/hardwood) and density.

3.3. Influence of density on charring rate

Although it is not the main objective of this paper, it is interesting to examine the influence of density, considered by many researchers as the main parameter affecting the charring rate.

For this purpose, the tropical hardwood species used in this study were arranged according to their density. A comparison was made between the experimental results and the Eurocode 5 recommendations. As previously mentioned, Eurocode 5–1.2 [8] assumes that the charring rate decreases when density increases with a limit of 0.5 mm/min for densities higher than 450 kg/m^3.

The corresponding results are presented in Table IV. All densities were larger than 450 kg/m^3, and the EC5 recommended value was therefore 0.5 mm/min. As can be observed in Table IV, smaller values were obtained in this study, although the effect of density is quite obvious.

Table IV. Charring rates—comparison between experimental results and EC2 recommendation for tropical hardwood species with $\rho > 500\,\mathrm{kg/m^3}$.

Species	Specimen	Density ($\mathrm{kg/m^3}$)	Experimental charring rate (mm/min)	Charring rate ratio Exp/EC5
Bilinga	Bilinga1	692	0.58	1.16
Merbau	Merbau1	779	0.50	1.00
Afzelia	Afzelia1	863	0.36	0.72
	Afzelia2	836	0.43	0.86
	Afzelia3	833	0.49	0.98
	Afzelia4	800	0.51	1.02
	Afzelia5	968	0.37	0.74
Wenge	Wenge1	923	0.49	0.98
Balau	Balau1	939	0.40	0.80
	Balau2	984	0.41	0.82
Azobe	Azobe1	1050	0.41	0.82
	Azobe2	1040	0.41	0.82
	Azobe3	1000	0.41	0.82
	Azobe4	1060	0.47	0.94

4. CONCLUSIONS

The following conclusions can be drawn from this study:

1. The test set-up and the experimental procedure described in this paper are suitable for assessing the charring rate of different timber samples. Possible areas for improvement include better insulation at the edges of the samples, more careful sawing and gluing of the laminates, and the choice of the adhesive.
2. The experimental procedure developed here is based on the assumption that charring reaches the location of the thermocouple when its temperature indicates 300°C. Additional investigations are necessary to determine if this temperature is adequate in all cases and if different values should be adopted according to the timber species.
3. A linear regression is suitable to relate char depth and time. The traditional assumption of a constant charring rate therefore appears to be valid based on the experimental results obtained in this study.
4. The test results show that the density of wood significantly affects the charring rate. Smaller recommended values than proposed in Eurocode 5 can be adopted for tropical hardwoods with high density. More research is needed to confirm this finding.

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