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Charring Rate of Wood Exposed to a Constant Heat Flux

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Introduction

A critical factor in the fire endurance of a wood member is its rate of charring. Most available charring rate data have been obtained using the time-temperature curves of the standard fire resistance tests (ASTM E 119 and ISO 834) to define the fire exposure. The increased use of heat release calorimeters using exposures of constant heat flux levels has broadened the available database on wood charring. This paper presents such char rate data obtained with an Ohio State University (OSU) calorimeter. Results include char depth versus time models, char rates as function of other parameters, and temperature profiles in the remaining uncharred wood.

Several investigators have measured charring rates for fixed heat fluxes. Butler (1971) reviewed such data and found charring rate to be directly proportional to the incident flux for the range of 20 to 3000 kW/m^2. Nussbaum (1988) used a cone calorimeter to obtained charring rates for wood impregnated with low concentrations of fire retardants. Also with a cone calorimeter, Mikkola (1990, 1991) obtained charring rates for a variety of wood products at 50 kW/m^2 and for spruce at fluxes of 25 to 75 kW/m^2. Other charring data for specific constant heat fluxes have been reported by Fredlund (1988) and Cramer and White (1993).

Methods

We tested two specimens of each species at each of four nominal heat flux levels (15, 25, 35, and 50 kW/m^2). Test specimens were left over from a study on charring rates for wood exposed to standard ASTM E 119 fire exposures (White 1988, White and Nordheim 1992). An OSU calorimeter was used to expose the wood specimens to the constant heat flux. The 150- by 150- by 64-mm specimens were of four species: redwood *(Sequoia sempervirens)*, pine *(Pinus* sp.), red oak *(Quercus* sp.), and basswood *(Tilia* sp.). These four species represented a half-fraction of a factorial design of eight species used in the previous study (White 1988). The design was based on the parameters of density (low/high), permeability (low/high), and species type (softwood/hardwood). Softwoods generally have greater lignin content than hardwood species.

We glued 38-mm (or thicker) laminates together to obtain the total 150 mm height of the specimens. The 64-mm-thick specimens were tested so the heat flux was perpendicular to the grain of the wood and generally tangential to the annual rings. Five thermocouples were placed at 6, 12, 18, 24, and 36 mm from the exposed surface by inserting the wires in the ends of two laminates. A sixth thermocouple was attached to the exposed surface. The thermocouples were type-K chromel alumel with wire diameters of 0.12 mm. We conditioned specimens at 23°C, 50% relative humidity to obtain a moisture content of 8% to 9%.

The OSU or standard ASTM E 906 heat release calorimeter uses silicon carbide heater elements to expose the 150- by 150-mm specimen to a constant heat flux. A constant flow of air through the chamber was maintained. We tested the specimens in the vertical orientation. We collected data at 15-s intervals. A pilot flame was located above the specimen. An auxiliary heat flux meter recorded the heat flux during the test. The average heat flux during the test was calculated. The behavior of the radiant flux in the apparatus is such that there is a slight decrease when the specimen is inserted followed by a gradual increase in the actual incident flux during the test. This is believed to be due to the flames causing an increase in the temperature of the heating environment and reradiation back to the sample.

The 64-mm-thick specimens were tested using the standard OSU holder without insulation backing. Unexposed surfaces were wrapped with aluminum foil to reduce edge effects. Each of the 32 tests was stopped when the thermocouple at the 36-mm depth recorded 300°C, the temperature normally associated with the base of the char layer.

Results and Discussion

In this paper, we report the results for charring rate and the internal temperature profiles in detail. Results reflecting ignition time, heat release rate, mass loss rate, charring rate, and char properties (char contraction factor, char yield, and char density) were previously reported by Tran and White (1992).

Time-Location Models

Initial results of the tests were time-temperature curves for each location within the specimen. For purpose of calculating the charring rates, it was assumed that the base of the char layer can be defined by the temperature of 300°C. This temperature had previously been used in tests using the ASTM E 119 time-temperature tune as the fire exposure. We used two empirical models for wood charring to evaluate the data:

$$t = m_1 x_c \quad (1)$$

$$t = m_2 x_c^{a} \quad (2)$$

where

t = time for 300° C (min)

x_c = distance from original exposed surface (mm), and

m_1, m_2, a = constants to be estimated.

In the previous analysis of ASTM E l19 data (White and Nordheim 1992), four different models were considered. Equations (1) and (2) were the preferred models in that analysis. Regressions were done with time t as the dependent variable (Eqs. (1) and (2)), because that is consistent with the experiments. The charring rate, β, as it is normally reported (mm/min), was obtained by computing the inverse of m_1.

Obtaining a separate m_1 for each test, Equation (1) resulted in an overall root mean square error (RMSE) of 4.1 min. The RMSE is an estimate of the standard deviation of the error term in the predictive model. Average results for species/flux are listed in Table 1. Equation (1) provides a simple and reasonably accurate model to obtain the rates of charring. The analysis using Equation (2) did produce one interesting result. By specifying that a single value of a be used for each nominal flux level, the estimates for a were 1.01, 1.19, 1.34, and 1.43 for the 15,25,35, and 50 kW/m^2 nominal exposure levels, respectively (Table 2). These results suggest an increasingly nonlinear behavior as the-heat flux level is increased (Fig. 1). In the tests using ASTM E 119 exposure, an a of 1.23 was estimated (White and Nordheim 1992). Using values of 1.0, 1.2, 1.3, and 1.4 for a at the heat-flux levels of 15, 25, 35, and 50 kW/m^2, respectively; the Equation (2) model resulted in an RMSE of 3.7 min. Average results per species/flux using these values for a are listed in Table 1.

Table 1—Properties of specimens and test results.

Species	ρ (kg/m³)	f_c (-)	q (kW/m²)	Char Rates: m_1 of Eq.(1) (min/mm)	Char Rates: β (mm/min)	Char Rates: m_2 of Eq.(2)[a] (min/mm^a)	β/α of Eq.(8) (mm⁻¹)	d of Eq.(9) (mm)
				Nominal Heat Flux = 15 kW/m²				
Pine	447	0.46	17	2.27	0.45	2.27	0.083	38.0
Redwood	290	0.52	18	1.68	0.60	1.68	0.086	36.5
oak	682	0.56	18	2.56	0.39	2.56	0.079	38.2
Basswood	400	0.42	18	1.32	0.76	1.32	0.165	27.7
				Nominal Heat Flux = 25 kW/m²				
Pine	452	0.50	26	1.52	0.66	0.79	0.147	29.5
Redwood	301	0.54	26	1.37	0.74	0.70	0.102	35.7
oak	682	0.56	25	1.94	0.52	1.00	0.172	26.3
Basswood	432	0.42	27	1.24	0.80	0.64	0.160	27.6
				Nominal Heat Flux = 35 kW/m²				
Pine	450	0.46	39	1.25	0.80	0.46	0.197	26.4
Redwood	311	0.62	39	1.20	0.83	0.44	0.154	28.1
oak	682	0.62	38	1.64	0.61	0.60	0.150	27.9
Basswood	400	0.43	38	0.82	1.22	0.30	0.215	24.9
				Nominal Heat Flux = 50 kW/m²				
Pine	452	0.60	56	1.17	0.85	0.31	0.188	26.5
Redwood	333	0.79	55	0.98	1.02	0.26	0.211	24.9
oak	683	0.73	53	1.38	0.73	0.36	0.158	27.0
Basswood	400	0.52	52	0.76	1.31	0.20	0.267	22.1

[a] a = 1.0, 1.2, 1.3, and 1.4. for heat flux of 15.25, 35 and 50 W/m², respectively.

Char contraction factor (f_c) is defined as the linear volume fraction of the pyrolyzed wood that is converted to char. The char contraction factor was also greater at the higher heat flux level (Table 1). A thick char layer would serve as an insulative layer and decrease the rate of charring (longer times). The f_c values for the 50 kW/m² level are comparable to that reported for ASTM E 119 exposure and for heating in nitrogen environment (White 1988). The thinner residual char layer at the lower heat flux levels may be due to char oxidation at the surface. Constant air flow in the OSU chamber ensures adequate oxygen. A lower flow of pyrolysis gases from the surface would increase the likelihood that oxygen can reach the surface. The lengthy time period for the low flux levels is another possible explanation for the greater surface recession.

Predictive Parameter Models

We correlated the charring rate results for the individual tests with the material properties and heat flux levels (Table 1). Klason lignin content (percentage of ovendry, extractive-free wood) were 37.1, 27.9, 24.5, and 19.8% for redwood, pine, oak. and basswood, respectively Lignin content is an important factor in char formation. In the previous study (White 1988), char formation as represented by the char contraction factor was found to be a predictor of charring rate. Pine and basswood have high transverse permeability. and redwood and oak are relatively impermeable transverse to the grain. The char rate β (mm/min) increased (shorter times) with increased heat flux (Fig. 2). The single parameter model for all tests is

$$\beta = 0.0118q + 0.368 \qquad R^2 = 0.42 \ \text{RMSE} = 0.19 \qquad (3)$$

where q = average external heat flux over duration of test (kW/m^2).

Equation (3) for β is comparable to the theoretical relationship developed by Mikkola (1990). The coefficient of determination (R^2) is an estimate of the fraction of the total variation that is explained by the model. The R^2 for models without an intercepts need to be computed differently than for with an intercept; therefore, values for R^2 are not reported for models without an intercept. Adding density (ρ, kg/m^3) (ovendry mass and volume), resulted in the following:

$$\beta = 0.0119q - 0.000832\rho + 0.749 \qquad R^2 = 0.64, \text{RMSE} = 0.16 \qquad (4)$$

The addition of Klason lignin content (ℓ, %) resulted in the following:

$$\beta = 0.0121q - 0.00139\rho - 0.0199\ell + 1.527 \qquad R^2 = 0.89, \text{RMSE} = 0.09 \qquad (5)$$

An alternative model is to use the ratio of density and heat flux as the parameter, resulting in the following:

$$\beta = 8.8(q/\rho) \qquad \text{RMSE} = 0.23 \qquad (6)$$

$$\beta = 5.0(q/\rho) + 0.374 \qquad R^2 = 0.59, \text{RSME} = 0.16 \qquad (7)$$

A coefficient of 10 for Equation (6) was given by Butcher (1976) for initial charring. In Mikkola’s (1990) simplified model for wood charring, the char rate β is proportional to net heat flux to char front divided by the density.

These empirical equations relating parameters are based on the 32 tests reported in this paper. Empirical models can be affected by correlations between parameters. Significant correlations between the parameters include density and Klason lignin content (R = -0.52) and char contraction factor with heat flux (R = 0.60) and Klason lignin content (R = 0.41).

Table 2. Combined results per nominal heat flux level.

Nominal q (kW/m^2)	m_1 of Eq. (1) (min/mm)	m_2 of Eq. (2) (min/mm^a)		β (mm/min)	β/α of Eq. (8) (mm^{-1})	d of Eq. (9) (mm)
		a	m_2			
15	1.94	1.01	1.80	0.55	0.1037	34.4
25	1.52	1.19	0.79	0.68	0.1451	29.4
35	1.23	1.34	0.38	0.87	0.1791	26.8
50	1.07	1.43	0.26	0.98	0.1943	24.9

Temperature profiles

The temperatures at the five depths were used to develop equations for temperature profiles. Temperatures were noted for each location at times in which one location recorded 300°C. The data set for 300°C at 6 mm (corresponding temperatures at 12, 18,24, and 30 mm) provided the most complete set of data for the analysis. The exponential equation (Schaffer 1965) for the nondimensional temperature ratio was

$$\frac{T - T_i}{T_c - T_i} = \exp\left(-\frac{\beta}{\alpha}\xi\right) \tag{8}$$

where

T= temperature at location ξ,
T_i = initial temperature,
T_c = temperature of char front, 300° C,
β = char rate (mm/min),
α = thermal diffusivity (mm^2/min). and
ξ = distance from char front, $x - x_c$ (mm).

The power function equation (Janssens and White 1994) was the following:

$$\frac{T - T_i}{T_c - T_i} = \left(1 - \frac{\xi}{d}\right)^2 \tag{9}$$

where d = thermal penetration depth (mm).

Linear regression of the 6-mm data was used to obtain estimates for β/α of Equation (8) and d of Equation (9) (Tables 1 and 2). The exponential equation was generally better than the power function. The exponential and power functions (Eqs. (8) and (9)) are curves that cannot provide for the plateau in the time-temperature data associated with moisture vaporization at 100°C (Fig. 3). The 12-mm char depth data resulted in !ower β/α values (0.082 to 0.115 mm^{-1} for 15 to 50 kW/m^2 heat flux) and larger d estimates (36 to 30 mm for 15 to 50 kW/m^2 heat flux).

A linear correlation exists between the estimates for β (1 /m_1) and the estimates for β/α of Equation (8) (Table 2). Using linear regression of β with β/α, the estimate for a was 4.9 rnm^2/min or 0.82 x 10^{-7} m^2/s. Using the 300° C at 12-mm data, the estimate for a was 1.1 x 10^{-7} m^2/s. Given the simplicity of the model used to develop Equation (8), these estimates are in general agreement with the literature values around 2 x 10^{-7} m^2/s for thermal diffusivity of wood. As reflected in larger estimates ford at lower heat flux levels (Table 2), the depth of elevated temperatures is deeper when the 6-mm char depth is due to a low level heat flux. Times for the 6-mm char depths ranged for 1.8 to 21.8 min. Temperature profiles obtained in the tests using ASTM E 119 exposures were previously reported by Janssens and White (1994). For a char depth of 13 mm, the penetration depths d obtained from the related ASTM E 119 data were 32 to 35 mm.

Conclusions

Charring of wood exposed to a constant external heat flux can be considered a linear function of time. At high heat flux levels, the behavior may become nonlinear with greater times required for a given char depth. The charring rate is proportional to the ratio of external heat flux level over density. Temperatures within the uncharred wood can be represented by an exponential function. For a given char depth, the zone of elevated temperature will be deeper when heated by a lower, constant heat flux level.

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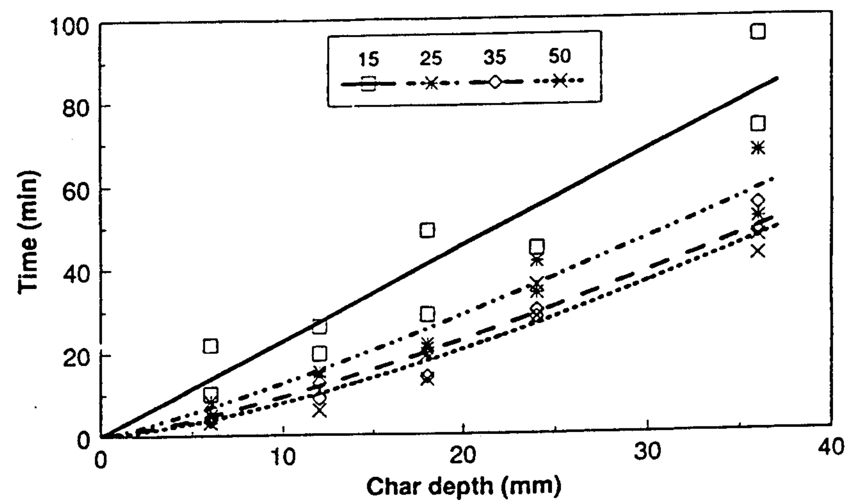

Fig. 1—Trees for 300°C versus distance from exposed surface for specimens of pine. Curves are Equation (2) *($t=m_2x_c^a$)* with *a* equal to 1.0, 1.2, 1.3, and 1.4 for nominal heat flux of 15, 25, 35, and 50 kW/m^2, respectively.

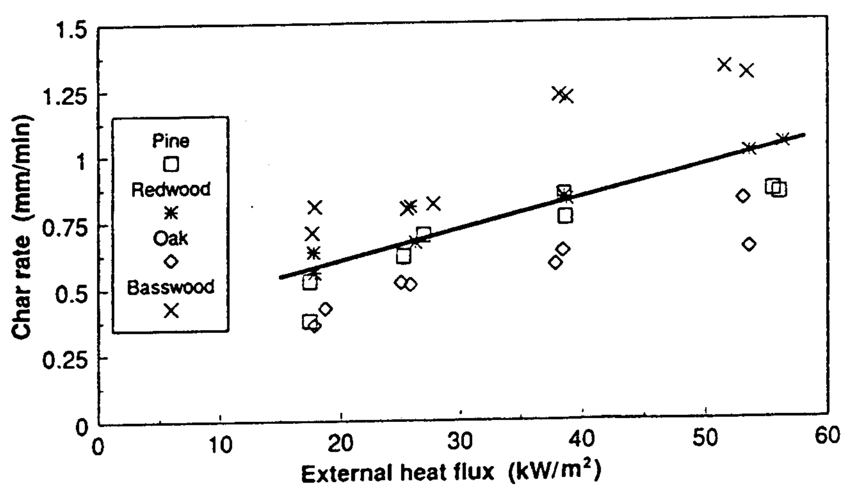

Fig. 2—Char rate β (l /m_1 of Eq. (l)) versus external heat flux. Line is Equation (3).

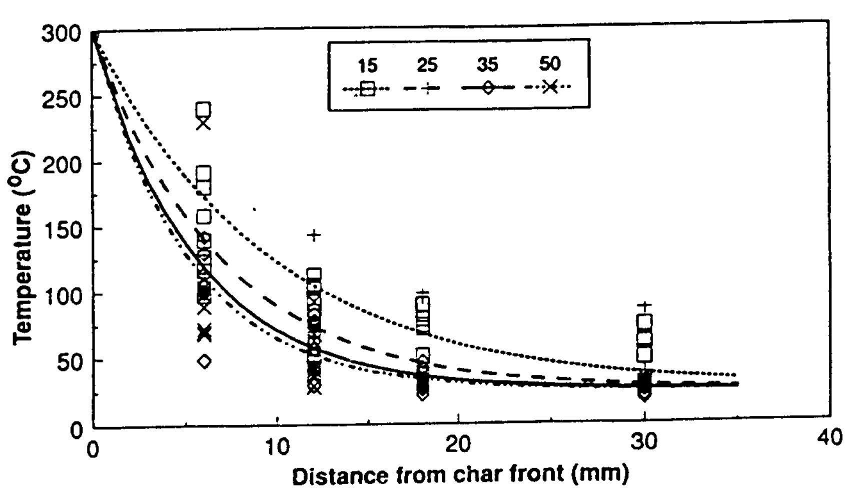

Fig. 3—Temperature profiles in uncharred wood when char front (300°C) is 6 mm from original exposed surface, based on combined data sets of same nominal heat flux level (15, 25,35, and 50 kW/m^2).