FIRE PERFORMANCE OF HARDWOOD SPECIES[1]

by
Robert H. White
USDA, FS, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53705-2398 USA
Tel: 1-608-231-9265, Fax: 1-608-231-9508, E-mail: rhwhite@fs.fed.us
http:/lwww.fpl.fs.fed.us

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INTRODUCTION

In this era of performance-based building codes, there is an increased need for models and data pertaining to the fire safety of building materials. In addition to data for the prescriptive regulatory fire tests, material property data are needed to optimize the advantages of the performance-based building codes that are being introduced worldwide. In this review of our research on the fire performance characteristics and fire safety engineering of wood products, we will present results on the fire performance of hardwood species. Two broad areas of fire safety engineering of materials are 1) Fire initiation and growth, and 2) Fire containment.

FIRE GROWTH

Fire initiation and growth include ignition, the spread of flames, and fire growth to flashover conditions. The introductions of heat release calorimeters in the 1980's reflect the changes from older prescriptive fire tests to tests that produce data suitable for fire safety engineering analysis. With information on ignition characteristics and heat release rates, it is increasingly possible to model the spread of flame over a material and the fire growth in a room The best known of the heat release calorimeter is the cone calorimeter. Worldwide use of the cone calorimeter increased the availability of information on ignition, heat release and smoke development of materials. In this section, we will initially review data for the 25-foot (7.6 m) tunnel test, the prescriptive flame spread test used to regulate building materials in North America. Results for cone calorimeter testing of various hardwood species will then be discussed. This section will conclude with a brief discussion of recent project on the full-scale room/corner test.

Flame Spread

Once the material is ignited, one factor that affects the hazard is how fast the flames will spread from the point of origin. Various tests have been used to measure surface flammability (Eickner 1977). Test results for flame spread are very dependent on the test procedures. The orientation of the materials, the direction of flame travel, the intensity of the external heat source, airflow, and other factors besides the material itself affects the results. In North America, the test method for flame spread is the 25-ft tunnel test or ASTM E-84 (ASTM 1998).

FPL does not have a 25-ft tunnel apparatus. Some ASTM E 84 flame spread indexes (FSI) found in the literature are given in Table 1. The E-84 flame spread index is a dimensionless value that historically was based on red oak flooring having a value of 100 and asbestos having a value of zero. Indexes are calculated from the times for the flames to spread down the 25-foot long tunnel. The actual calculation procedures used to obtain the flame spread index from the data has changed over the years. Thus, values in Table 1 depend on the year the tests were conducted and the procedure used. Generally, it is believed that the FSI's calculated for wood products using the current method (ASTM 1998) are lower than values calculated with the pre-1976 method. In the U.S. building codes, the regulation of interior finish are regulated based on Classes of I, II, and III. The corresponding flame spread indexes for Class I, II, and III are 0 to 25, 26 to 75, and 76 to 200, respectively.

In Figure 1, the flame spread indexes for sawn lumber of various hardwood species are plotted against published densities for the species (Forest Products Laboratory 1999). Except for the Gardner and Thomson data, densities of

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the actual specimens were not available. The plot suggests that the ASTM E 84 flame spread index is inversely related to the density of the wood. The R^2 was 0.56 and the standard error for the estimates was 28. In addition to the actual densities not being known, the data are for different calculation methodologies.

Table 1. ASTM E 84 flame spread indexes for sawn boards of some hardwood species.

Species [1,2]	**ASTM E84 Flame spread index**[3]	**Source**
Birch, yellow (*Betula alleghaniensis*)	105-110	UL (1971)
Cottonwood (*Populus* sp.)	115	UL (1971)
Oak (Quercus sp.)	100	UL (1971)
Sweetgum (*Liquidambar styraciflua*)	140-155	UL (1971)
Walnut (*Juglans nigra*)	130-140	UL (1971)
Yellow-poplar (*Liriodendron tulipifera*)	170-185	UL (1971)
Blackbutt (*Eucalyptus pilularis*) (17 mm)	48	Gardner and Thomson (1987)
Brush box (*Lophostemon confertus*) (17 mm)	45	Gardner and Thomson (1987)
Jarrah (*Eucalyptus marginata*) (17 mm)	26	Gardner and Thomson (1987)
Victorian ash (*Eucalyptus pilularis*) (17 mm)	51	Gardner and Thomson (1987)
Cherry (*Prunus serotina*)	76	American Wood Council (1999)
elm (*Ulmus* sp.)	76	American Wood Council (1999)
Oak, red (*Quercus* sp.)	84	American Wood Council (1999)
Oak, white (*Quercus* sp.)	77	American Wood Council (1999)
Pecan (*Carya* sp.)	84	American Wood Council (1999)
Walnut (*Juglans nigra*)	101	American Wood Council (1999)
Azobe/Bongossi (*Lophira alata*) (32 mm)	0	U.S. Testing Company (1983)
Greenheart (*Chlorocardium rodiei*)	54, 69[4]	Unknown. 1975 test.
Karri (*Eucalyptus diversicilar*) (32 mm)	69[5]	HPMA 1977
Jarrah (*Eucalyptus marginata*)	51[6]	HPMA 1977
Maple (*Acer* sp.)	104	CWC (1996)

[1]With the exception of Gardner and Thompson (1987) and 1977 HPMA tests, the scientific names were not provided by the original reference for the flame spread index values.
[2] Unless otherwise indicated, the sawn boards were nominal 1 in. thick (19 mm actual).
[3] The procedures for calculating the flame spread indices have changed over the years.
[4] Calculated with pre- 1976 method. Results were 40 and 46 when calculated with the GWL method.
[5] Calculated with pre- 1976 method. Result was 45 when calculated with the E84-76a method.
[6] Calculated with pre- 1976 method. Result was 42 when calculated with the E84-76a method.

The 8-ft tunnel test of ASTM E 286 was developed at the Forest Products Laboratory. To avoid the confusion with the regulatory test ASTM E 84, we no longer use this test method and it has been withdrawn as an ASTM standard. A similar inverse relationship between the ASTM E 286 Flame spread index and density was found using data for 29 species (R^2 = 0.56) (Holmes and Chudnoff 1981). The flame spread and density data used are from Research Note FPL-0186. No significant difference between hardwoods and softwoods was noted. A similar direct relationship for times for flame spread down tunnel (longer flame spread times corresponds to lower ASTM E 286 FSI) and density was found for red oak specimens of varying densities (density range of 560 to 750 kg/m^3) (Holmes and Chudnoff 1981). In a study of four wood composite materials as potential reference materials for fire tests, LeVan (1985) found that density was a significant factor and that higher densities resulted in higher flame spread times (lower FSI) in the 8-ft tunnel. It should be noted that the flame spread phenomenon of the two tunnel tests are different as the results of differences in their construction. A general correlation between the flame spread indexes of the 8-ft and 25-ft tunnels was not found for untreated wood species (softwood and hardwood). In tests of 19 Malaysian building timbers using an small-scale inclined panel test, Rashid and Malik (1982) also found that denser species were less likely to ignite and support flame spread.

Further validation of the relationship with ASTM E 84 FSI's of specimens of known densities and current FSI calculation method would improve the prediction of FSI's for hardwood lumber of species not listed. In addition to empirical models, FPL research is directed toward developing a physical flame spread model for the ASTM E 84 tunnel test based on data from the cone calorimeter. Cone calorimeter data will be discussed later.

The correlation between flame spread and density is only true for hardwood species. There is likely no such single parameter correlation for the softwood species. Douglas-fir and southern pine, the two dominant softwood species in North America, have similar densities but their FSI's are dramatically different. Reported FSI values for Douglas-fir are 70 to 100 while the reported range for southern pine was 130 to 195 (UL 1971). The low-density softwood, redwood (density of about 380 kg/m^3), is the best known of the softwood species with FSI of 75 or less. Chemical composition, both lignin content and extractives, are likely important factors in the FSI of softwood species. Higher lignin contents of softwoods likely reduce the FSI (higher residual char layer) but any presence of flammable extractives likely results in high FSI's.

Materials with FSI greater than 200 can only be used where there are no requirements for flame spread. The regression curve in Figure 1 suggests that hardwood species with densities less than 350 kg/m^3 may have FSI greater than 200. Thus, balsa (*Ochroma pyramidale*) lumber (density of 160 kg/m^3) may have a FSI in excess of 200. Given their densities, it is reasonable to assume that all domestic U.S. hardwoods are Class III. Low density domestic U.S. species include alder (410 kg/m^3) and aspen (380 kg/m^3). Reported FSI values for these two species include 155 for 4 mm thick factory finish red alder plywood and 196 for 6 mm thick factory finish aspen plywood.

Figure 1 suggests that hardwood species with densities greater than 700 kg/m^3 are potential Class II materials and species of densities greater than 970 kg/m^3 are potential Class I materials. Azobe/Bongossi has a reported density of 900 kg/m^3. In the case of the Azobe/Bongossi of Table 1, the FSI was 10 when the duration of the ASTM E84-81a test was extended to 30 minutes. The extended 30 minutes test is a requirement for fire-retardant-treated wood in U. S. codes. Fire-retardant treatments are used to obtain Class I flame spread with U.S. domestic wood products. Class I and II can be use in a wider range of applications in buildings where the interior finish is regulated.

The inverse relationship between FSI and density may not be true for thinner panel products in which temperatures on the back surface of the specimen become elevated. In early documents, Hardwood Plywood Manufacturers Association (now Hardwood Plywood & Veneer Association) noted that in certain wood panel products that had been tested, there was an implied relationship that the lower the density, the lower the flame spread. Aspen and yellow poplar were noted as exceptions (HPMA 1984a). In work with tropical woods, in the consideration of all commercial panel thicknesses, HPMA concluded that there was not such a clear-cut relationship. But, rather there was a thickness-density relationship which exhibits itself in the amount of available fuel in the first 8 to 12 feet of the 24-foot sample, and the rapidity at which burnthrough occurs exposing the back of the thin plywood panel. (HPVA 1984b).

The Hardwood Plywood & Veneer Association recently conducted a study on various hardwood plywoods. Results were (AWC 1999):

> "Flame spread of plywood is affected by the species of the face veneer but can also be influenced by the species of the underlying core veneer. Various panel constructions involving certain core species show a relatively high degree of variability and potential to yield flame spread values above 200. Panel constructions involving cores of aspen, sumauma, yellow poplar and white fir have exhibited this behavior with average flame spread indices ranging form 78 to 259. Other factors, in addition to species, including material and process variables related to specific manufacturer is particularly important in establishing the flame spread classification of the product."

The need to consider various factors is also the case for composite products. Reported values for various composite wood products can be found in the AWC DCA 1 (AWC 1999). ASTM E 84 testing was conducted as part of some FPL studies of flakeboards. A commercial 13 mm thick exterior grade structural flakeboard made of aspen flakes had an ASTM E 84 FSI of 189 (Holmes and others 1979). The density was 683 kg/m^3. In tests of a 30 mm thick red oak flakeboard, ASTM E 84 FSI's of 108 per E84-79b and 122 per E 84-75 were obtained (White and Schaffer 1981). The density was 633 kg/m^3.

In the next section, we will discuss research on the heat release rate and ignition characteristics of wood products. In that context, there will be further discussion of the flame spread results for hardwoods.

Heat Release Rate

Various apparatuses have been used at FPL to measure the heat released by burning materials. The most recent apparatus is the oxygen consumption calorimeter known as the cone calorimeter (ASTM E1354) (ASTM 1977, Babrauskas and Grayson 1992). In this test, measurements of the consumption of oxygen due to the combustion of the specimen are used to calculate the heat release rate. We have tested various hardwood species (Table 2) in the cone calorimeter using a heat flux of 50 kW/m^2. The specimen was horizontal in these tests. The test data for a heat release test is a curve of heat release rate vs. time (Fig. 2). Once the material is ignited, there is an initial peak in the heat release rate. As the wood chars, the heat release rate drops to a somewhat steady-state rate until the back of the specimen heats up. Depending upon the substrate used, there is a second peak as the rest of the specimen is consumed. Various calculations have been used to reduce the curves to single numerical test results. Currently, these include the initial peak heat release rate (PHRR), the average heat release rate (AHRR) over 60, 180, and 300 s from sustained ignition and to termination of the test, and the total heat release (THR) (Table 3). For the hardwood species tested, neither the peak heat release rate nor the average heat release rate over 300 s from sustained ignition were affected by density (Figure 3). Both of these parameters have been used as an empirical predictive of the ASTM E 84 flame spread. In a study of flame-retardant beech, fire-retardant treatment was shown to reduce heat release rate (Grexa and Horváthová 1996). In earlier FPL research using a Ohio State University heat release rate apparatus modified for oxygen consumption, various hardwoods were also tested (Table 4) (Tran 1992). In these tests, the heat flux was 40 kW/m^2 and the specimen was vertical. Using the data in Table 4, Tran (1992) also found that density did not affect heat release rate.

In addition to heat release rate, the cone calorimeter also measures the mass loss over time (Table 4). The mass loss rate (MLR) curve is similar to the heat release rate curve. Limited variation in the heat contents of the hardwood species is consistent with a correlation between average heat release rate and average mass loss rate from ignition to termination of test (R^2= 0.721). By dividing the heat release by the mass loss, an effective heat of combustion can be calculated (EHOC). Since the EHOC is somewhat constant during significant mass loss (Figure 4), an average effective heat of combustion (AEHOC) is often reported (Table 5). The elevated and widely scattered data near the end of the test reflect the slow consumption of the residual char. Figure 5 includes a graph of the residual mass fraction. A 20 percent residual char layer is typical for wood in fire tests. The lignin content of wood is a factor in the amount of residual char. This is one reason why the softwoods with their higher lignin contents, compared with hardwoods, can have low heat release (Tran 1992). Fire-retardant treated wood generally has lower average effective heat of combustion (Tran 1992, Grexa 2000). Measurements are made in the exhaust duct of the transmission of a laser through the smoke. Results are reported as the average specific extinction area (ASEA).

Density strongly influences the times for sustained ignition (Figure 5). This also results in a correlation between the times for the peak heat release rate and time (R^2 = 0.594)). Flame spread is a function of the heat available to propagate the flames and the heat needed to ignite the adjacent wood. Thus, the cone data suggests that the inverse correlation of ASTM E 84 flame spread index (FSI) with density is due to the correlation between times for ignition and density. With fire-retardant treated wood with low heat release rate and wood with high volatile extractive contents with high heat release rate, the heat release rate would be a factor in differences in the FSI. With thin test material such as the 1 mm thick veneer, there is a rapid consumption of the specimen and a very high peak heat release rate (Figure 6). In the tunnel tests of thin panel products, the entire thickness will likely be consumed during the test. Since there is a correlation between mass loss and heat release, there will be a correlation between the total heat release (MJ/m^2) per unit thickness and density. This may account for the observations of a direct correlation between FSI and density in some tests of thin panel products. In tests of thick specimens, the total heat release for given time is not a function of density since the higher density reduces the thickness of wood that is charred (assuming constant AEHOC). Thus, the ignition characteristics of the material become the controlling factor in the rate of flame spread.

Table 2. Species tested in cone calorimeter

Species		Thickness	Density
Common name	Scientific name	mm	kg/m^3
Lumber			
Ash	*Fraxinus* sp.	22	603
Birch (1)	*Betula* sp.	19	618
Birch (2)	*Betula* sp.	18	679
Bubinga	*Guibourtia tessmannii*	20	918
Cherry, Black	*Prunus serotina*	20	580
Imbuia	*Phoebe porosa*	19	605
Lacewood	*Grevillea robusta*	19	543
Mahogany, Honduras	*Swietenia macrophylla*	18	570
Maple, Hard	*Acer* sp.	14	-
Meranti, Light red (2)	*Shorea* sp.	19	513
Meranti, Light red (1)	*Shorea* sp.	19	489
Oak, Red	*Quercus* sp.	25	593
Oak, White	*Quercus* sp.	19	753
Padauk	*Pterocarpus soyauxii*	25	682
Purpleheart	*Peltogyne* sp.	20	877
Teak	*Tectonia grandis*	22	552
Walnut, Black	*Juglans nigra*	19	586
Walnut, Peruvian	*Juglans neotropica*	15	513
Veneers			
Ash	*Fraxinus* sp.	1.1	596
Birch	*Betula* sp.	1.4	633
Cherry, Black	*Prunus serorina*	1.6	567
Hickory	*Carya* sp.	2.8	1021
Mahogany, African	*Khaya* sp.	1.5	447
Oak, White	*Quercus* sp.	0.7	649

The level of external heat flux affects heat release rates (Tran 1992). An example of the effect on peak heat release rate of red oak is shown in figure 7. Data on the effect of heat flux on effective heat of combustion are inconsistent. In figure 7, there was not a effect on the total heat release. Cone calorimeter tests are generally not terminated until there is no longer significant mass loss. As one would expect, the external heat affects the times for sustained ignition (Figure 10). The inverse of ignition times raised to 0.547 power versus external heat flux is an equation of Janssens (Tran and White 1992) that is generally used to express this relationship. Such data is used to derive estimates for thermal inertia (Tran and White 1992).

Room Tests

Full-scale room/comer tests are important in fire growth research since smaller scale tests have led to misleading evaluations of materials reactions to fire. As with heat release calorimeters, FPL research in this area has involved different room/comer test facilities. In recent years, our full-scale testing largely conformed to ISO 9705: 1993(E). (International Organization for Standardization 1993). In a major project with the Slovak Forest Products Research Institute, we tested 14 wood-based products in one of the modified configurations of the standard test (Dietenberger and others 1995). In this configuration, we used the European burner protocol of 100 kW for 10 minutes followed by 300 kW for 10 minutes but did not put any test materials on the ceiling. In previous work, we had also not put the materials on the ceiling but the burner protocol had been 40 kW for five minutes followed be 160 kW for 5 minutes. This protocol was in proposed ASTM standards for the room/comer test. The test material is placed on three walls and the burner located in the comer. The room is 3.6 m long and 2.4 m wide with a single door for ventilation. Observations are made of the times for flashover. One criterion for flashover is flames out the doorway. Forintek Canada Corp. was a cooperator in the testing of the two hardwood products. These were an oak veneer plywood and red oak flooring. In the 100/300 kW tests, flashovers were observed at 324 s with the red oak flooring and 174 s with the oak veneer plywood (White and others 1999). With the 40/160 kW burner protocol and no test material on the ceiling, the times were essentially the same for both the oak veneer plywood and the red oak flooring (330 s vs.

Table 3. Heat release data for various species obtained in cone calorimeter using heat flux of 50 kW/m^2 and horizontal orientation.

Species	PHRR	Peak time	AHRR60	AHRR300	THR
	kW/m^2	s	kW/m^2	kW/m^2	MJ/m^2
Lumber					
Ash	241	65	122	117	129
Birch (1)	218	81	117	141	138
Birch (2)	208	53	171	139	127
Bubinga	205	98	107	113	160
Cherry, Black	187	57	115	105	105
Imbuia	221	60	135	115	127
Lacewood	187	52	116	98	94
Mahogany, Honduran	174	41	133	89	88
Maple, Hard	218	77	128	137	109
Meranti, Light red (2)	192	48	114	93	95
Meranti, Light red (1)	187	52	114	97	105
Oak, red	214	69	113	132	146
Oak, White	219	67	137	121	129
Padauk	224	73	119	122	192
Purpleheart	182	78	99	97	137
Teak	248	63	135	130	144
Walnut, Black	215	60	115	118	108
Walnut, Peruvian	200	35	158	117	81
Veneers					
Ash	648	44	170	-	13
Birch	586	59	214	-	17
Cherry, Black	525	55	178	-	16
Hickory	585	107	168	-	35
Mahogany, African	395	47	137	-	12
Oak, White	523	39	129	-	10

366 s, respectively). In a test at the National Research Council of Canada in which the oak veneer plywood was also placed on the ceiling, flashover occurred at 78 s. Use of the 100 and 300 kW burner scenario without lining the ceiling provided the ability to differentiate between wood products with ASTM E 84 flame indexes of 70 to 125 and those with higher flame spread indexes (White and others 1999). The tests confirmed the validity of the ASTM E84

test for testing wood products.

Table 4. Average heat release rate over 300s obtained using a modified O.S.U apparatus and cone calorimeter. Specimen in vertical orientation and heat flux was 40 kW/m^2 (from Tran 1992).

Material	**Density**	**AHRR300-Cone**	**AHRR300-O.S.U.**
	kg/m^3	kW/m^2	kW/m^2
Balsa	205	84	-
Yellow poplar	410	-	73
Aspen	420	-	118
Alder	435	-	135
Red maple	495	-	110
Black ash	525	-	122
Cottonwood	565	-	131
Hackberry	575	-	122
Birch	602	118	-
Sweet gum	615	-	133
sugar maple	650	-	98
Afromosia	667	115	-
White ash	670	-	122
Rosewood	683	135	-
Hickory	695	-	120
White oak	720	-	107
Bech	730	-	114
Red oak	759	106	128
Purpleheart	867	102	-
Letterwood	1166	119	-

FIRE ENDURANCE

Fire containment is mainly the fire resistance or fire endurance of structural members and assemblies to contain a post-flashover fire. Unlike the tests for fire growth, the test for fire resistance of members and assemblies has remained essentially the same throughout the world. As a result, there is a large amount of historical data on the fire resistance of materials. The fire endurance of wood members often depends on the charring rate of the wood (White 1995). The charring rate of wood has been extensively researched (Schaffer 1967, White 1988). The challenge has been to move away from the fire exposure of the standard time-temperature curve to more realistic fire exposures. The standard test in North America is ASTM E 119 (ASTM 1998b), which is similar to ISO 834.

In a study of three species, Schaffer (1967) developed an equation for white oak. For a linear model, char rate, C (min./mm), is defined as

$$t = C\, x_c \tag{1}$$

where $\underline{t}$ is time in minutes and $\underline{x_c}$ is the char depth in mm. The equation for white oak is:

$$C = (0.001583 + 0.00318\,\mu)\,\rho + 0.594 \tag{2}$$

where μ is moisture content (faction of ovendry mass) and ρ is density, dry mass volume at moisture content μ (kg/m^3).

In the development of an empirical model for char rate, White (1988, 1992) tested four hardwood species. Species were hard maple (*Acer* sp.), yellow-poplar (*Liriodendron tulipera*), red oak (*Quercus* sp.) and basswood (*Tilia* sp.). In this study, a non-linear charring model was developed. The char rate parameter, $\underline{m}$ (min/$mm^{1.23}$), is defined as

$$t = m\, x_c^{1.23} \tag{3}$$

and $\underline{t}$ and $\underline{x_c}$ are defined above. Average results for $\underline{m}$ and $\underline{C}$ are given in Table 6.

Table 5. Related cone calorimeter data for various species.

Species	**EHOC**	**ASEA**	**AMLR**	**Tig**
	MJ/kg	m^2/kg	g/s-m^2	s
		Lumber		
Ash	11.14	44.75	10.7	30
Birch (1)	12.40	43.61	12.2	29
Birch (2)	12.17	47.73	12.2	33
Bubinga	10.48	21.96	10.7	57
Cherry, Black	10.94	12.20	9.5	26
Imbuia	12.51	86.17	9.0	29
Lacewood	10.84	22.85	8.1	19
Mahogany, Honduran	11.68	28.02	8.8	30
Maple, Hard	11.67	52.14	13.1	30
Meranti, Light red (2)	11.11	27.95	8.5	21
Meranti, Light red (1)	11.74	29.38	8.1	23
Oak, Red	11.36	25.37	9.9	28
Oak, White	11.37	19.47	10.4	33
Padauk	13.01	92.67	8.0	30
Purpleheart	10.04	8.14	9.6	40
Teak	13.61	229.20	8.4	25
Walnut, Black	10.91	61.21	11.8	25
Walnut, Peruvian	11.66	48.48	10.2	18
		Veneers		
Ash	17.12	16.63	13.3	17
Birch	16.22	67.22	12.5	22
Cherry, Black	15.77	59.29	8.4	21
Hickory	14.70	61.95	14.8	37
Mahogany, African	14.30	54.05	6.8	16
Oak, White	15.52	55.82	10.9	14

A predictive equation for $\underline{m}$ developed for both hardwood and softwood species is

$$m = -0.147 + 0.000564\,\rho + 1.21\,\mu + 0.532\,f_c \tag{4}$$

where ρ is density, ovendry mass and volume (kg/m^3), μ is moisture content (faction of ovendry mass) and f_c is a parameter called the char contraction factor. It is the thickness of the residual char layer divided by the original thickness of the wood layer that was charred (char depth). An equation for this parameter for hardwood species is (White 1992)

$$f_c = 0.529 - .0036\, d + 0.000270\, \rho \qquad (5)$$

where d is a parameter reflecting the transverse treatability of the species (3 for low treatability to 36 for highly treatable species. In the development of the model, d was the depth of penetration (in mm) of a CCA treatment of samples.

Table 6. Average char rate results for hardwood specimens exposed to the standard tire exposure of ASTM E 119.

Species	Product	Density	C (Eq. 1)	m (Eq. 3)
		kg/m^3	min./mm	min./mm $^{1.23}$
Basswood	Sawn lumber	399	1.06	0.48
Maple, Hard	Sawn lumber	691	1.46	0.66
Oak, Red	Sawn lumber	664	1.59	0.72
Poplar	Sawn lumber	504	1.36	0.61
Lapacho	Sawn lumber	920	2.00	0.96
Greenheart	Sawn lumber	1040	2.50	1.18
Aspen	LSL	674	1.58	0.67
Poplar	LSL	678	1.57	0.66
Poplar	LVL	554	1.36	0.58
Poplar	LVL	536	1.39	0.59
Poplar	PSL	628	1.57	0.67

Charring tests have been conducted on greenheart (*Ocotea rodiaei*) and lapacho (*Tubebuia* sp) (White 1988) (Table 6).

In a subsequent study, we exposed samples of the basswood and the red oak to exposures of constant heat flux in our Ohio State University calorimeter (Tran and White 1992, White and Tran 1996) and obtained results for charring rates at fluxes between 15 and 55 kw/m^2. For the red oak (C = 1.59 min/mm in the standard test), the linear charring rate, C, was 2.6 min./mm at 18 kW/m^2 and 1.4 min./mm at 53 kW/m^2.

More recently, tests have been conducted on the charring rate of composite lumber products (White 2000). Materials tested included an aspen laminated strand lumber (LSL) product, a yellow-poplar LSL, two yellow-poplar laminated veneer lumber (LVL) products and a yellow-poplar parallel strand lumber (PSL) product. Some results are shown in Table 6.

CONCLUSIONS

Like most wood properties, tire performance properties are affected by density, moisture content, and chemical composition. In general, woods of higher density and moisture content have better fire performance. The lower lignin content of hardwoods compared with softwoods reduces the residual char content. As with many fire retardants, the fire performance of wood is improved by increasing the residual char content. The limited extractive contents of hardwood species reduce their overall variability in flame spread and heat release compared with the softwoods.

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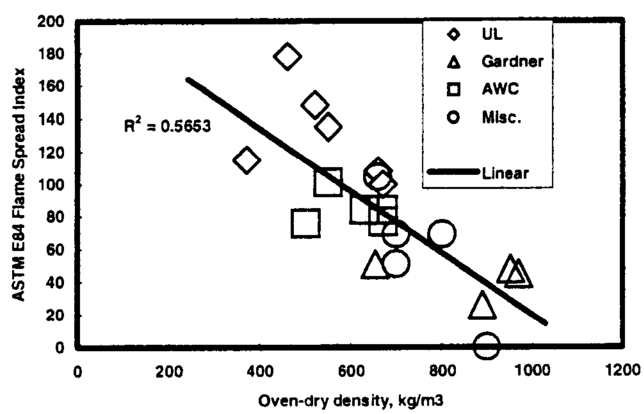

Figure 1. ASTM E 84 flame spread indices versus estimated densities of various hardwood species.

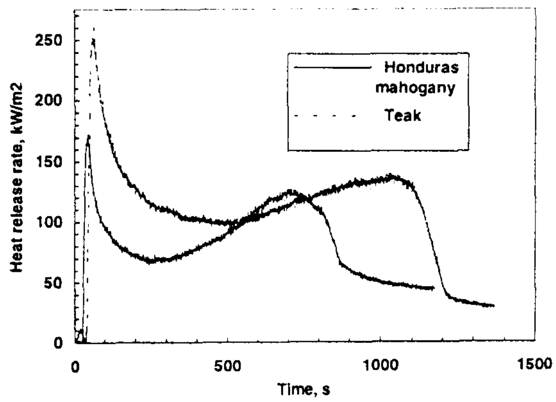

Figure 2. Rate of heat release rate curves for Honduras mahogany and teak.

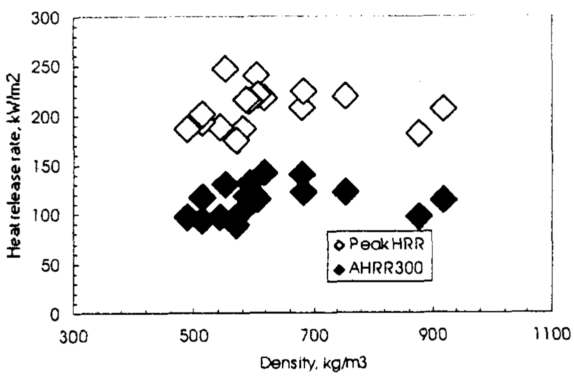

Figure 3. Peak and 300 s average heat release rates versus density for various hardwood species.

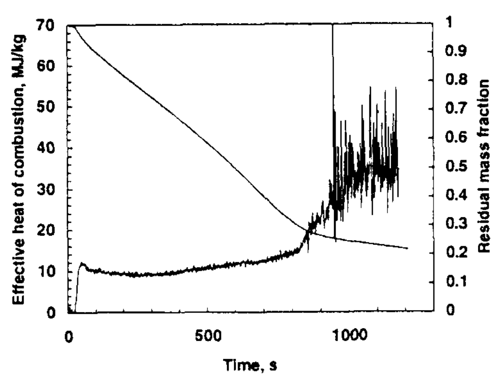

Figure 4. Effective heat of combustion and residual mass fraction versus time.

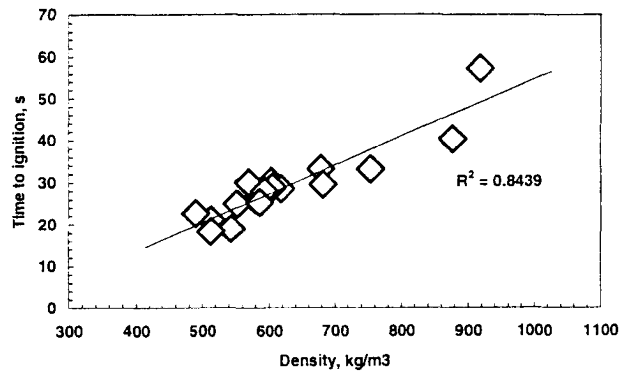

Figure 5. Times for sustained ignition versus density of various hardwood species.

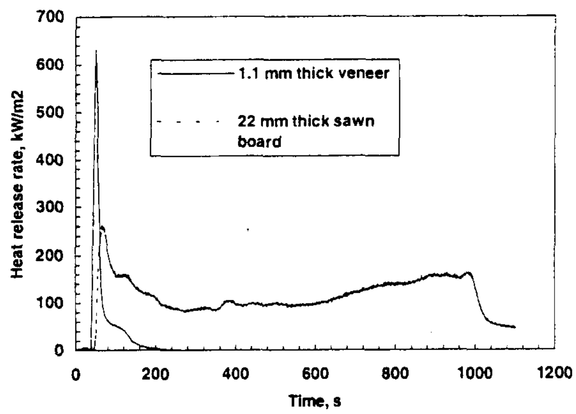

Figure 6. Heat release rate curves for thick board and thin veneer of ash.

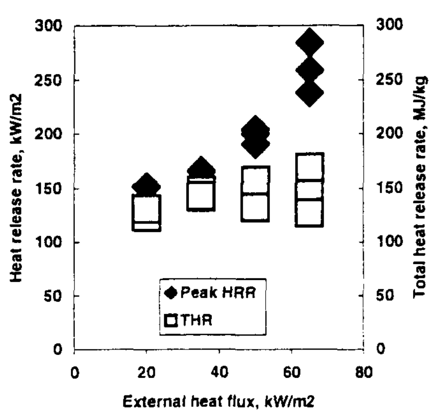

Figure 7. Effect of external heat flux on peak heat release rate and total heat release rate of red oak.