Relationship Between Density and the Ignitability and Combustibility of Wood

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ABSTRACT

To use wood as a building interior material, it is necessary to understand the fire-resistant qualities of wood. This paper describes the experiments conducted to investigate the ignitability and combustibility of wooden interior materials.

In general, wood has complicated structure and composition. Moreover, the structures and constituent elements from different types of trees differ. Therefore, the ignitability and combustibility of wood are greatly affected by the physical and chemical properties. In this paper, we focuses on density, the most important physical index of wood, because density has an extremely intricate relationship with the other physical properties of wood and is the most representative index of the ignitability and combustibility of wood. With an aim of expressing the fire-resistant qualities of wood with density, the relationship between density and the ignitability and combustibility of wood was investigated.

Assuming that when the surface temperature of the wood approached the ignition point it would ignite, ignition problems can be lumped together and dealt as thermal problems of the wood. Based on an equation of thermal conductivity, a quantitative model was prepared to represent time of ignition. Several other assumptions were made, and the model was simplified.

Cone calorimeter tests were conducted on 8 types of wood to investigate the relationship between the ignitability and combustibility of these materials on the one hand, and density on the other. From the experimental results, the model coefficients were derived. The model obtained was expressed only in terms of wood density and heat flux, allowing us to make highly accurate predictions of time of ignition.

Although the total heat release (THR) due to combustion showed a positive correlation with density, it was apparent that other factors besides density were also influential.

1. INTRODUCTION

Wood has long been used as building materials, interior materials, and furniture.

Recently, high-accuracy, high-quality man-made materials have been coming into greater use in buildings. Furthermore, due to the high esteem we have for natural wood, and its special qualities that are not found in artificial materials, demand for natural wood has been increasing.

At the same time, however, wood is a combustible material, so it is necessary to take great care to adequately reduce the risk of fire. In Japan, the use of wood as an interior material is strictly controlled by building codes, so it is necessary in the design stage to thoroughly consider the resistance of these materials to fire.

This present study focuses on density, the most widely used physical index of wood, to gain an understanding of ignitability and combustibility. Not only do the characteristics of wood from different types of trees differ, but the same type of tree can produce structurally and chemically different wood depending on the environment in which it is grown. Given this situation, it is difficult to use only the physical characteristic of density to express all the fire-resistant qualities of wood. Nonetheless, since density has an great relationship with the other physical properties of wood, and density data are extremely easy to obtain, if we can use these data to make a rough estimate of the fire-resistance of wood, it would be of immense benefit to designers of buildings that contain wooden interior materials.

Finally, 8 types of wood (i.e., 7 types which have not been treated or coated, and one type which has also been chemically treated) were subjected to ISO5660 (cone calorimeter) testing.

2. MATERIALS AND METHODS

2.1 Experimental Materials (Samples)

As Table 1 indicates, the experiments were conducted using 8 different types of wood specimens. These specimens, each with a board thickness of 25mm, consisted of 7 different types of non-treated wood, and one type which was given a urethane coating. G is cross-grain, while everything else is straight-grain. It should also be noted that the experiment was conducted after the specimens had been kept in a storage with 50% humidity at 20℃ for at least 2 weeks. Based on Kollmann et al's research[1], the water content of each of the specimens at that time was estimated to be 9%.

Table 1 Experimental Specimens

Species			Density*1 kg/m^3
A	Oak	North American broadleaf	646
B	Japanease Sen	Japanese broadleaf	420
C	Scrub oak	Japanese broadleaf	751
D	Cherry	Japanese broadleaf	671
E	Douglas fir	North American conifer	598
F	Lauan	South Seas conifer	504
G	Cedar	Japanese conifer	360
H	Oak(Urethane treated)	North American broadleaf	657

*1 Density is actual measured values Average of 6 specimens

.2 Cone Calorimeter Testing

Using ISO5660 as a basis, the time of ignition and heat release rate (HRR) were ıeasured. Heat flux was set at 2 levels, $30kW/m^2$ and $50kW/m^2$. Three of each ample was tested under each condition. In addition, slits were cut into the surfaces f the test specimens with box cutters, then 0.1mm CA thermo-couple were inserted nto the slits to measure surface temperature. Data were collected at 2-second ntervals.

:.3 Thermal Conductivity Experiment

Prior to the experiment, a shotherm QTM rapid thermal conductance gauge Showa Denko Industries) was used to take two measurements of the thermal :onductivity of each sample at room temperature.

3. IGNITABILITY

3.1 Basic Model

As is done with most ignition models[2], a rough estimate was made of the surface temperature at which the wood would ignite. This allowed us to lump ignition problems together and deal as thermal problems of the wood.

Here we will introduce the ignition model used in reference[3,4]. The basic formula for conductivity is as follows:

$$\rho C \frac{\partial T(t,x)}{\partial t} = K \frac{\partial^2 T(t,x)}{\partial X^2} \cdots\cdots\cdots (1)$$

We assumed that the initial temperature corresponded to T_0, and that there was a constant flow of heat qr" to the heating surface. We also assumed that there would be heat loss from this surface which could be represented by the equation $h(T(t,0)-T_0)$, where h is the rate of surface heat loss coefficient, T(t,0) is the surface temperature, and T_0 is the ambient air temperature.

Initial condition t=0

$T(O,X)=T_0$

Boundary condition (heated surface)

$$-K\left[\frac{\partial}{\partial X}T(t,X)\right]_{X=0} = qr'' - h(T(t,0) - T_0)$$

Note that the opposite side is infinite.

Solving the differential equation in Eq. 1 and deriving the surface temperature as X=0 gives us the following:

$$T(t,0) = T_0 + \frac{qr''}{h}\left[1 - \exp\left(\frac{h^2 t}{K\rho C}\right)\operatorname{erfc}\left(\frac{h^2 t}{K\rho C}\right)^{1/2}\right] \cdots\cdots\cdots(2)$$

Furthermore, when Eq. 2 falls within the range of the following, it closely resembles Eq. 3:

$$\frac{qr''}{h(T(t,0) - T_0)} \leq 10$$

$$1/\sqrt{at} = 1.18\{qr''/h(T(t,0) - T_0) - 1\} \cdots\cdots\cdots(3)$$

Here, $a = h^2/K\rho C$

Replacing surface temperature T(t,0) with ignition temperature Tig, time t with time of ignition tig, and heat flux qr" with ε - qe " provides us with the following ignition model when there is a slight transformation:

$$1/\sqrt{tig} = 1.18 \frac{\varepsilon}{\sqrt{K\rho C(Tig - To)}}\left(qe'' - \frac{h(Tig - To)}{\varepsilon}\right) \cdots\cdots\cdots(4)$$

Here, K is coefficient of thermal conductivity, ρ is specific gravity, C is specific heat, and ε is emissivity.

3.2 Thermal Conductivity

According to Kollmann[5], the relation $K=(0.1953\rho + 25.5) \times 10^{-8}$ apparently exists between coefficient of thermal conductivity and density. Figure 1 shows the measured values of thermal conductivity for the specimens in the present study. The line, which is a regression line, coincides relatively well with Kollmann's straight line. Ideally, the present study should have used the regression line for the relation between coefficient of thermal conductivity and density. However, Kollmann's line was used instead in the present study because of the simple nature of the equipment available.

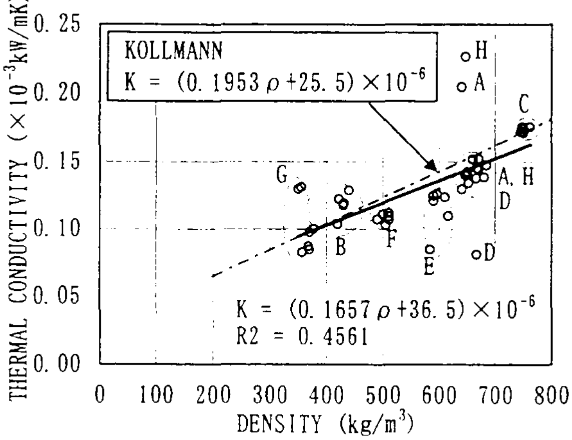

Figure 1 Relation between density and coefficient of thermal conductivity

3.3 Ignition Temperature

Figure 2 shows the relation between density and the surface temperature immediately before ignition. Even among specimens of the same tree species, this temperature varied by up to 50K. Such discrepancies were probably due to errors in the experiments. Although the experiments were conducted as faithfully as possible, the specimens were subjected to a strong heat flux, making it technologically difficult to measure the surface temperature. In addition, slight differences in the depth of the slits cut into the specimen are believed to have caused large differences in the measurements. Nevertheless, there was no correlation between density and these temperatures. So we can say that ignition temperature are roughly constant irrespective of density.

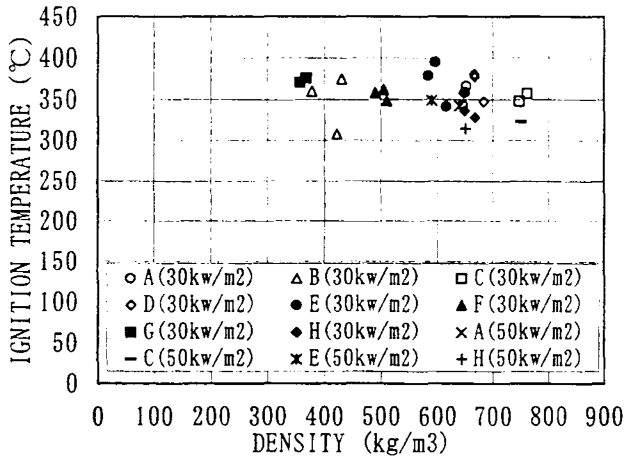

Figure 2 Ignition temperature

3.4 Predicted Time of Ignition

According to the literature[6], there is almost no fluctuation in specific heat caused by tree species or density, so we can say that C is constant. In addition, tree species had no effect on either emissivity ε, or surface heat loss coefficient h, so these can also be considered to be constant. Using the assumptions made previously, constants A and B were used to transform Eq. 4 into Eq. 5.

$$tig = \frac{A}{(qe''-B)^2}\rho(0.1953\rho + 25.5)\times 10^{-6} \cdots\cdots\cdots (5)$$

This equation represents the relation between time of ignition tig and wood density ρ when the specimens were subjected to constant heat flux qe''.

The results of the cone calorimeter experiments were used to derive A and B in Eq. 5. In this report, the experimental results were arranged by heat flux as shown in Figures 3 and 4, where the x-axis represents ρ $(0.1953\rho + 25.5)\times 10^{-6}$ and the y-axis represents time of ignition. It should be noted that H, which had been treated, was removed from the data. From the slope of the regression line when the intercept was 0, we can obtain the following relation:

$$\frac{A}{(30-B)^2} = 1103.5 \qquad \frac{A}{(50-B)^2} = 274.03$$

where A=435603 and B=10.13. Therefore, the time of ignition can be expressed by Eq. 6.

$$tig = 435603 \times 10^{-6} \frac{\rho(0.1953\rho + 25.5)}{(qe''-10.13)^2} \cdots\cdots\cdots(6)$$

where tig:in(sec), ρ :in(kg/m^3); and qe":in(kW/m^2)

This time, B=10.13 is called the critical irradiance for ignition, which prevents ignition from occurring at the low heat flux qe". This value is very close to the commonly used critical irradiance of 10kW/m^2.

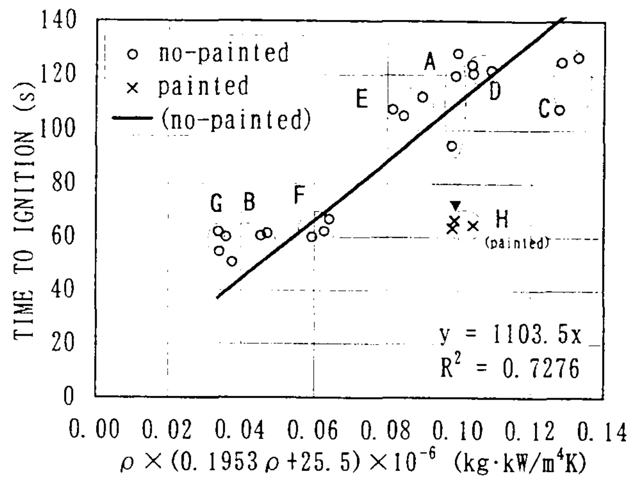

Figure 3 Relation between density and time of ignition (30kW/m^2)

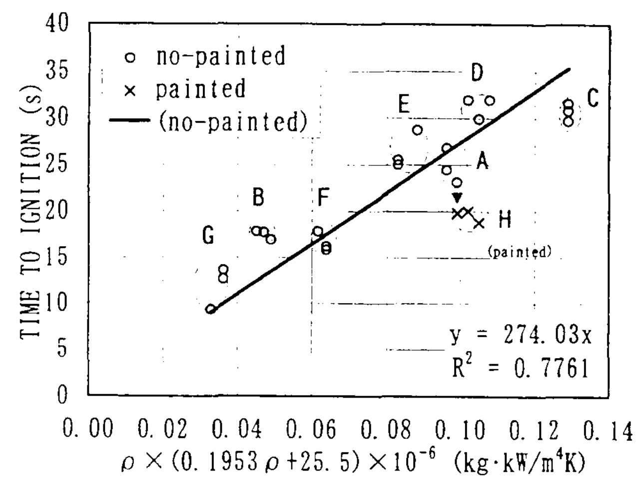

Figure 4 Relation between density and time of ignition (50kW/m^2)

3.5 Verification

Figure 5 is a plot of the value of each experimental specimen in which the x-axis is the time of ignition derived in Eq. 6 and the y-axis is the time of ignition derived in the cone calorimeter experiment. The figure indicates that relatively accurate predictions can be made.

Furthermore, plotting Yoshida[7] et al's experimental data for oak (density 300kg/m^3, heat flux of 30,40,50kW/m^2) onto Figure 5 shows an extremely high rate of correspondence.

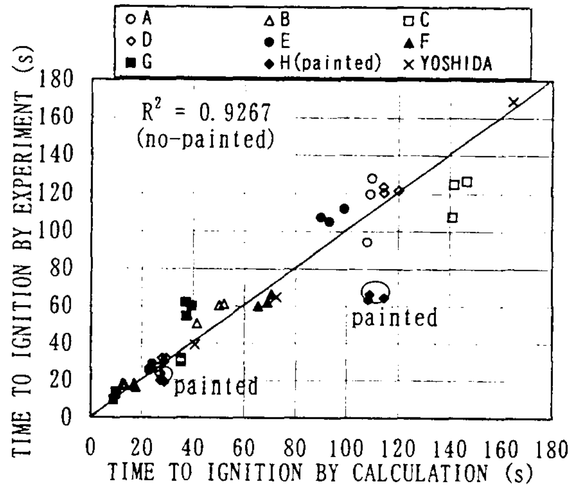

Figure 5 Comparison between calculated and experimental values

3.6 Effect of Coating Treatment

When the untreated A wood and treated (urethane coating) H wood of the same species in Figures 3 and 4 are compared, it is obvious that the time of ignition for the treated (H) wood was much shorter. Since the urethane shows properties that are completely different from other coating materials, further research is needed.

4. COMBUSTIBILITY

4.1 Heat Release Rate (HRR)

As is widely known, changes in the HRR of wood over time show 2 peaks, examples of which are shown in Figures 6-9. Such characteristics were apparent in all of the specimens used in the present experiment.

4.2 Maximum HRR

The first peak of HRR for each specimen is shown for heat flux of 30kW/m^2 and 50kW/m^2 in Figures 10 and 11, respectively. Even among the same species, there were specimens whose values were nearly 50kW/m^2 apart. This was likely because the peaks were only momentary but measurements were taken at 2-second intervals and could not be taken at the precise moment the peak was reached. In any event, no relation was seen with density. In addition, no major differences were found between

$30kW/m^2$ and $50kW/m^2$, that is, they were roughly equal.

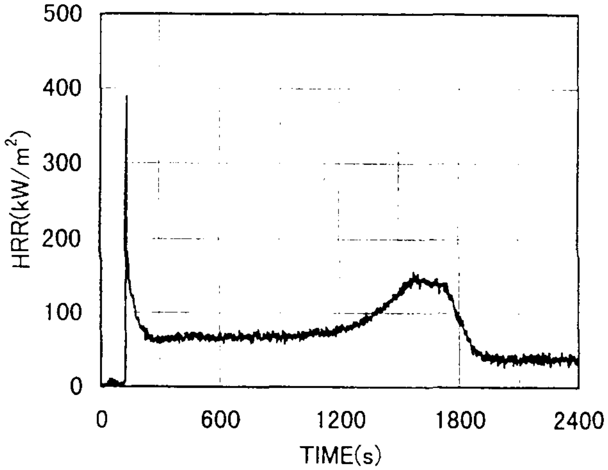

Figure 6　Examples of heat release rate (Specimen A, heat flux of $30kW/m^2$)

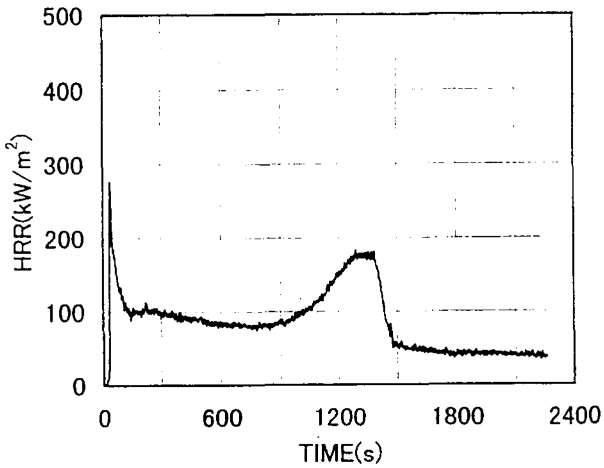

Figure 7　Examples of heat release rate (Specimen A, heat flux of $50kW/m^2$)

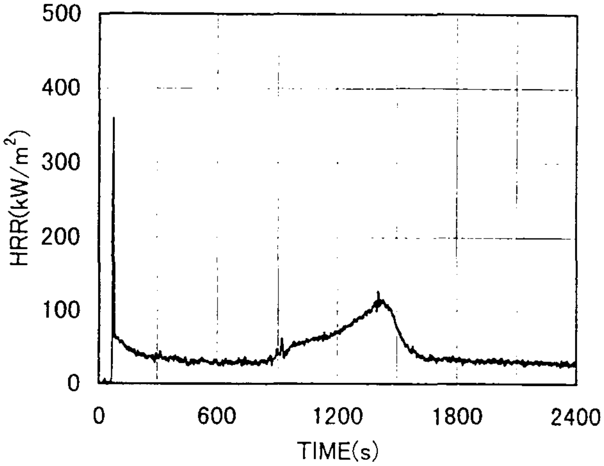

Figure 8　Examples of heat release rate (Specimen G, heat flux of $30kW/m^2$)

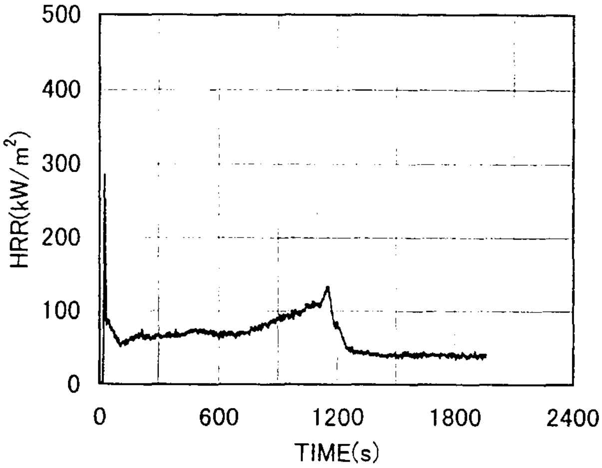

Figure 9 Examples of heat release rate (Specimen G, heat flux of $50kW/m^2$)

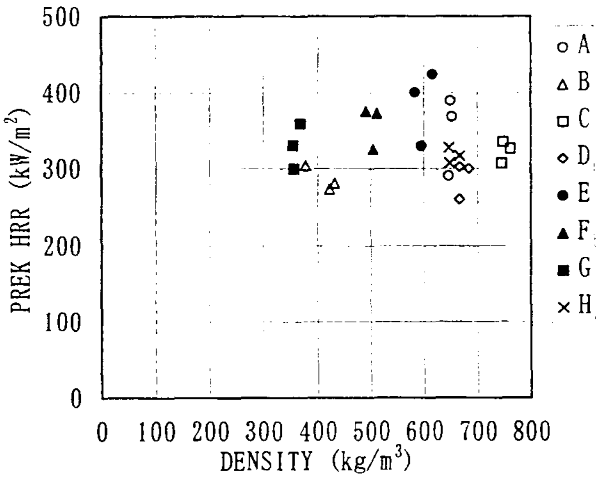

Figure 10 First HRR peak ($30kW/m^2$)

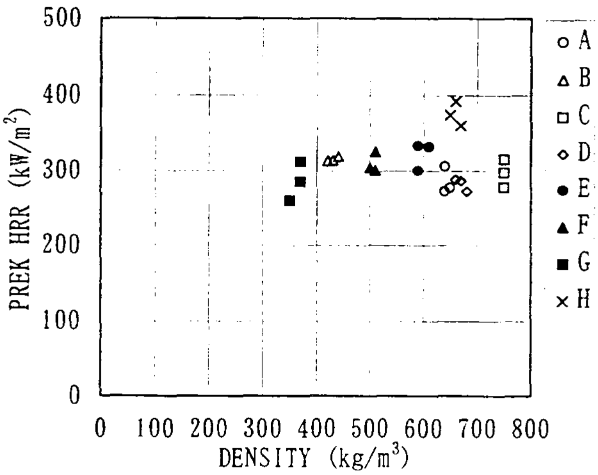

Figure 11 First HRR peak ($50kW/m^2$)

4.3 Total Heat Release (THR)

Figures 12-15 show the total heat release (THR) for heat flux of 30kW/m^2 and 50kW/m^2 at 60 seconds and 300 seconds after ignition, respectively. Although THR showed a positive correlation with density, there were wide discrepancies among species, suggesting that there was an influence from some physical property or properties independent of density. Harada[8] has pointed out that the ratio of vessels has an effet on the mass loss rate, which we can also say is involved in THR. Another likely factor influencing THR is differences in wood composition. Finally, it is quite clear that at both 60 seconds and 300 seconds, the value for 50kW/m^2 was larger than that for 30kW/m^2.

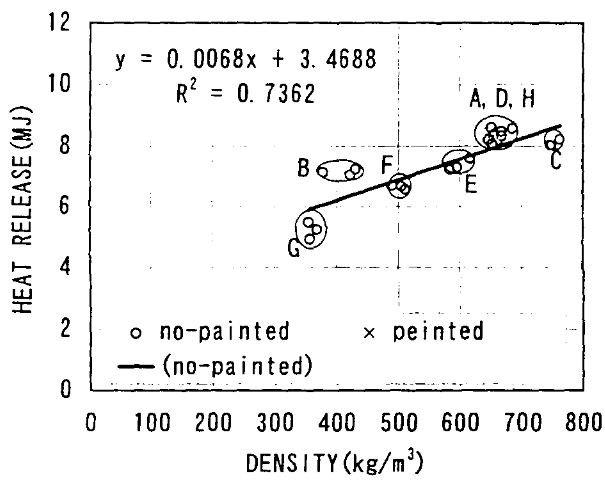

Figure 12 Total heat release 60 seconds after ignition (30kW/m^2)

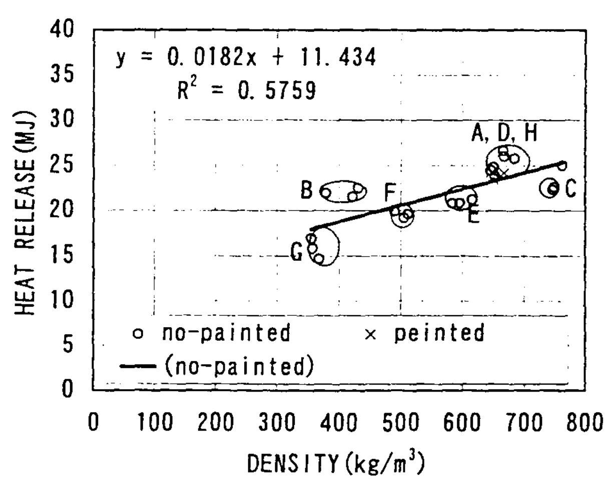

Figure 13 Total heat release 300 seconds after ignition (30kW/m^2)

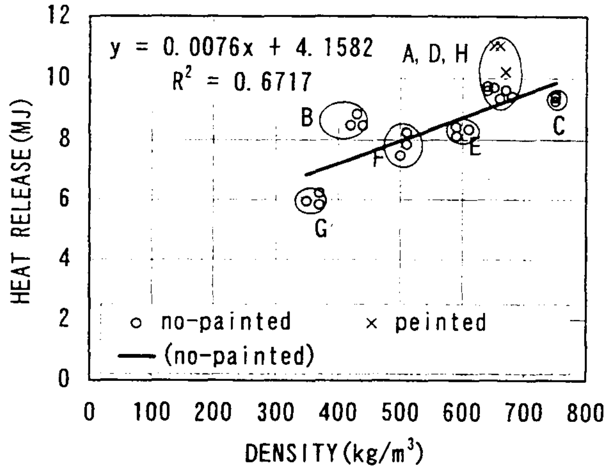

Figure 14 Total heat release 60 seconds after ignition (50kW/m^2)

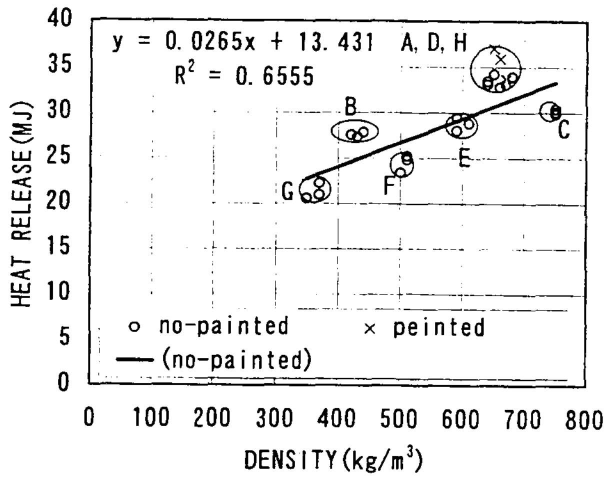

Figure 15 Total heat release 300 seconds after ignition (50kW/m^2)

4.4 Effect of Treatment

Comparing the untreated (A) and urethane-treated (H) specimens with the same tree species (i.e., oak), we can see that the coating had little effect on the total heat release. This may have been due to the extremely thin coating of the treated specimen and to the very low proportion of treated to untreated sections.

5. CONCLUSION

The cone calorimeter experiments were able to provide the following information about ignitability and combustibility:

1) The time of wood ignition could be estimated accurately from density using Equation 6. However, it should be noted that the range of heat flux used in the present study was 30-50kW/m^2

2) Although the total heat release due to combustion of the wood showed a positive

correlation with density, there seemed to be other influential factors besides density.
3) The coating treatment had a significant impact on time of ignition, but its effect on total heat release was small. Therefore, a systematic study on the effect of coating treatment must now be conducted.

ACKNOWLEDGMENT

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LIST OF SYMBOLS

K	: Coefficient of thermal conductivity	kW/m^2K
ρ	: Density	kg/m^3
C	: Specific heat	kJ/kgK
T(t,X)	: temperature	K
t	: Time	S
X	: depth	m
T_0	: Initial temperature	K
qe"	: heat flux	kW/m^2
qr"	: $= \varepsilon \cdot qe"$	kW/m^2
ε	: Emissivity	
h	: Heat loss coefficient	kW/m^2K

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