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Fire resistance of thick wood-based boards

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Abstract Thick wood-based boards are used as construction materials for walls and floors in Japan. In this study, fire resistance tests (ISO 834-1) and cone calorimeter tests (ISO 5660-1) were conducted for thick plywood, particleboard, and medium density fiberboard with sample thicknesses of about 28–30 mm, and their suitabilities for quasi-fireproof or fire-preventive structures were evaluated. In the ISO 834-1 fire resistance test, the heat-shielding performance (insulation criterion) for walls was evaluated and the results showed that the larger the apparent density of a wood-based board, the higher its insulation performance. The insulation performance of thick wood-based boards in the fire resistance test could be forecast from the results of the cone calorimeter test, especially when the second peak of heat release rate appeared. In the cone calorimeter tests, the surface layer density of the plywood, particleboard, and medium density fiberboard was the dominant parameter for the time to ignition and initial heat release rate. These results indicate that thick wood-based board is a suitable fire-preventive construction material.

Key words Fire resistance · Wood-based board · Cone calorimeter test · Fire test · Thermographic image

Introduction

In 2000, the Building Standard Law of Japan was revised to tighten the conventional specifications,[1,2] and related ordinances and notifications were also revised. This series of revisions changed the test methods and evaluation items used to assess the fire safety of building materials and structures. For the fire resistance test, the ISO 834-1 standard[3] was adopted for international harmonization.

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The heating curve in ISO 834-1 is similar to the previous fire test regulated in the Japanese Industrial Standards. Technical criteria for columns, beams, floors, and roofs for fireproof construction, quasi-fireproof construction, and fire-preventive construction were stipulated in ordinances. Through this revision, wood-based materials and structures banned in the previous code were permitted if their performance was certified to meet the new criteria. This revision may increase the demand for newly developed thick wood-based boards. In addition, the Construction Material Recycling Act encourages the reuse of wooden construction and demolition wastes, and particleboard (PB) and medium density fiberboard (MDF) are prospective products made from such recycled wastes.

Wood-based boards are used for external walls, internal walls, and floors. When wood-based boards are used as structural materials required for fire safety, the following qualities are desired:

1. The structure does not deform, melt, or break down (withstanding fire without fatal damage);
2. The unexposed side (rear surface) temperature does not exceed the burning temperature of flammable material (insulation criterion);
3. The structure does not crack or become otherwise damaged due to fire outside the building (integrity criterion).

There is much information about the fire resistance of wooden columns and beams. As for the fire resistance of wooden walls, there are some articles concerning the charring rate of softwood[4] and tropical hardwood[5] lumber and the fire resistance of timber decking.[6] As for wood lumber with thickness less than 20 mm, fire resistance in a laboratory scale exposure furnace was compared with the results of the cone calorimeter test.[7] However, there is little information about the fire resistance of thick engineered wood-based board like plywood,[8] PB, and MDF in the full-scale exposure furnace test. This is because these materials are generally used for interior materials thinner than 20 mm, and fire safety studies have focused on adding fire resistance properties to interior materials without clarifying fire resistance as a wall or floor structure.

The demand for thick wood-based board has increased since the Building Standard Law of Japan was revised and the Construction Material Recycling Act was enforced. Publishing the fire performance of thick wood-based boards would contribute to the development of fireproof, quasi-fireproof, or fire-preventive wooden construction materials. When evaluating the fire resistance test for walls or floors, the insulation criterion is an especially important factor.

In this study, the ISO 834-1 fire test and the cone calorimeter test for thick wood-based boards (plywood, PB, and MDF) were conducted. Measurements of the insulation performance, ignitability, and heat release rate of the boards were obtained and correlated, and their suitability as quasi-fireproof or fire-preventive construction materials was studied.

Materials and methods

Materials

The specimens tested were Japanese cedar plywood (*Cryptomeria japonica* D. Don, JCPW), Japanese red pine plywood (*Pinus densiflora* Sieb. and Zucc., JRPW), Japanese larch plywood (*Larix leptolepsia* Steud., JLPW), radiata pine plywood (*Pinus radiata* D. Don, RPPW), Dahurian larch plywood (*Larix dahurica* Turcz. var. *japonica* Maxim., DLPW), 13M-type PB (PB13M), 18M-type PB (PB18M), and MDF. In PB, 13 or 18 indicates the bending strength, for example, 13 is a bending strength of more than 13.0 N/mm^2. M means that the adhesive used was melamine–urea resin. The species and specifications of test samples are shown in Table 1. The symbols P and MU in the adhesive column represent phenol resin and melamine–urea resin, respectively. The test specimens were stored indoors and their moisture contents were 7.2%–10.0%.

Fire resistance test

The vertical gas-fired furnace for full-scale walls in the Building Research Institute in Tsukuba, Japan, was used. The specimens were heated according to the ISO 834-1 standard.[3] The average temperature in the furnace was controlled by the following formula:

$$T = 345 \log_{10} (8t + 1) + 20 \qquad (1)$$

where T is the average heating temperature (°C) in the furnace and t is the time (min).

The dimensions of the furnace opening to accommodate the specimens were 3200 × 3150 mm. The specimen holder illustrated in Fig. 1 was used to hold a wood-based board having dimensions of 800 × 1500 mm. This holder is made of wide-flange steel and 100-mm-thick autoclaved lightweight concrete (ALC) panels. A ceramic fiber blanket was stuffed between the test specimen and the ALC panels and both interfaces were bonded with fireproof adhesive in case the flames broke away from the specimen edge.

Insulation performance is usually evaluated by thermocouples set on the unexposed side of a specimen; however,

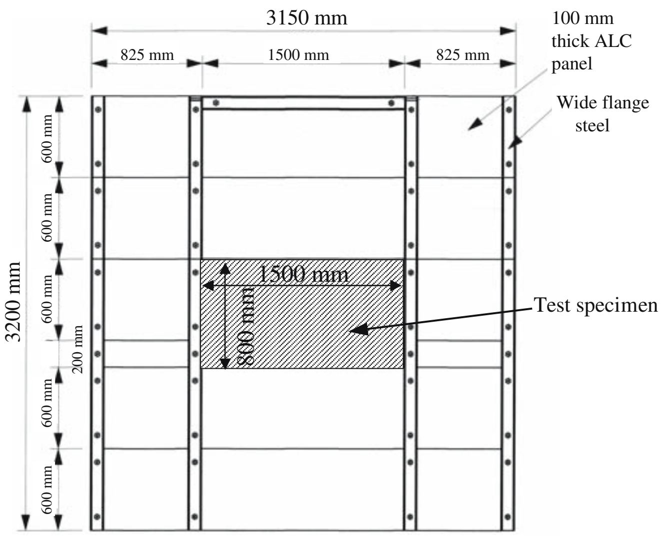

Fig. 1. Test specimen and specimen holder

Table 1. Specifications of the specimens tested in the ISO 834-1 test

Specimen	Thickness (mm)	Plies	Moisture content (%)	Density (kg/m^3)	Adhesive	Thermal conductivity (W/m K)
JCPW (plywood)	28	11	10.0	420	P	0.1203
JRPW (plywood)	28	11	9.5	550	MU	0.1391
JLPW (plywood)	28	11	8.7	550	MU	0.1425
RPPW (plywood)	28	11	9.3	510	P	0.1479
DLPW (plywood)	28	11	9.2	670	P	0.1651
PB13M (particleboard)	30	–	8.5	770	MU	0.1438
PB18M (particleboard)	30	–	8.6	770	MU	0.1388
MDF	30	–	7.2	650	MU	0.1218

JCPW, Japanese cedar plywood; JRPW, Japanese red pine plywood; JLPW, Japanese larch plywood; RPPW, radiata pine plywood; DLPW, Dahurian larch plywood; PB13M, 13M-type particleboard; PB18M, 18M-type particleboard; MDF, medium density fiberboard; P, phenol resin; MU, melamine–urea resin

Table 2. Insulation performance of thick wood-based boards in the ISO 834-1 test

No.	Specimen	Testing time (min)	$t_{160(max)}$ (min′ s″)	$t_{200(max)}$ (min′ s″)	Average temperature[a] (°C)
1	JCPW (plywood)	27	25′00″	26′00″	104.04
2	JCPW (plywood)	28.5	28′00″	–	–
3	JRPW (plywood)	31	29′45″	31′00″	149.95
4	JRPW (plywood)	32	30′15″	32′00″	156.98
5	JLPW (plywood)	34	30′45″	33′30″	165.57
6	JLPW (plywood)	32	30′15″	–	–
7	RPPW (plywood)	30	28′45″	–	–
8	RPPW (plywood)	30	27′30″	29′00″	124.65
9	DLPW (plywood)	33	31′15″	32′45″	154.26
10	PB13M (particleboard)	39	36′45″	38′30″	149.12
11	PB13M (particleboard)	39	36′30″	38′15″	148.35
12	PB18M (particleboard)	36.5	36′15″	–	–
13	PB18M (particleboard)	37.5	36′15″	–	–
14	MDF	36.5	35′15″	36′30″	138.25

$t_{160(max)}$, time when the maximum temperature of the unexposed side reached 160°C; $t_{200(max)}$, time when the maximum temperature of the unexposed side reached 200°C
[a] Average temperature of the unexposed side of the specimen at $t_{200(max)}$.

the temperature rise in inhomogeneous materials like wood is not always uniform and it is difficult to pinpoint the maximum temperature from the entire unexposed surface by a limited number of thermocouples. Su et al.[9] reported that thermographic images are useful for measuring the combustibility of fire retardant-treated wood. In this study, the temperature of the unexposed side of the specimen tested was recorded by a thermographic image system (TVS-2000MK II, Nippon Avionics) at 15-s intervals and the feasibility of using thermographic images for evaluating insulation performance was examined. The emissivity of the specimens was assumed to be 1.0.

Cone calorimeter test

The specimens were also tested by a cone calorimeter according to the procedure stipulated in ISO 5660-1.[10] The specimens were placed horizontally under a cone heater with heat flux set at 50 kW/m^2. The heated surface area of each specimen was 100 × 100 mm. A stainless steel cover with an opening of 0.0088 m^2 on the upper part was attached to prevent warping of the specimen and combustion from the edge. Measurements were recorded at 2-s intervals. Heating was conducted until the second peak of heat release rate appeared and the unexposed side of the specimen was completely charred. Heat release rate, total heat release, mass loss, and time to ignition were evaluated. The number of replications was two except for 25-mm-thick and 35-mm-thick PB13M.

The moisture content affects the combustibility of wood-based board, so fire tests to investigate the combustibility should be performed on an oven-dried specimen. However, the cone calorimeter tests were done to compare the ISO 834-1 test results in this study, and the moisture contents of engineered wood-based boards like plywood, PB, and MDF are comparatively constant. In this study we used specimens that had been conditioned in a stable atmosphere close to the actual environment of use: the specimens were conditioned at 20°C and 40% relative humidity for 1 month prior to the test.

Results and discussion

Fire resistance

The insulation performance of thick wood-based boards in the ISO 834-1 fire test is shown in Table 2. Business and service documents of the specified accreditation organization[11] state that the insulation criterion for structural walls is that the temperature rise of the unexposed side of the specimen shall be within 180°C at maximum and 140°C on average during the ISO 834-1 test. Therefore, with a room temperature of about 20°C during the test, the time when the maximum temperature of the unexposed side of the specimen reached 200°C [$t_{200(max)}$] and the time when the average temperature reached 160°C [$t_{160(avg)}$] were compared. These temperatures are regarded as the burning temperature of flammable material in ISO 834-1. In Table 2, there are some blanks for $t_{200(max)}$, because flames were observed at the edge of the specimen before the maximum temperature reached 200°C and so the fire test was ended. In such cases, the time when the maximum temperature reached 160°C [$t_{160(max)}$] was listed for reference and the values were compared. In Table 2, the average temperature is the mean value of the 30 × 55 cm center section of the specimen including the point that reached 200°C. All of the values of $t_{160(max)}$ were 25 min or higher. Figure 2 shows the temperature of the unexposed side of the specimens.

In the thermographic images, the temperature of the unexposed side was not uniform and irregularities were observed. The thermographic image system, which can measure the whole area of the unexposed side, is more suitable for evaluating the insulation performance of wall

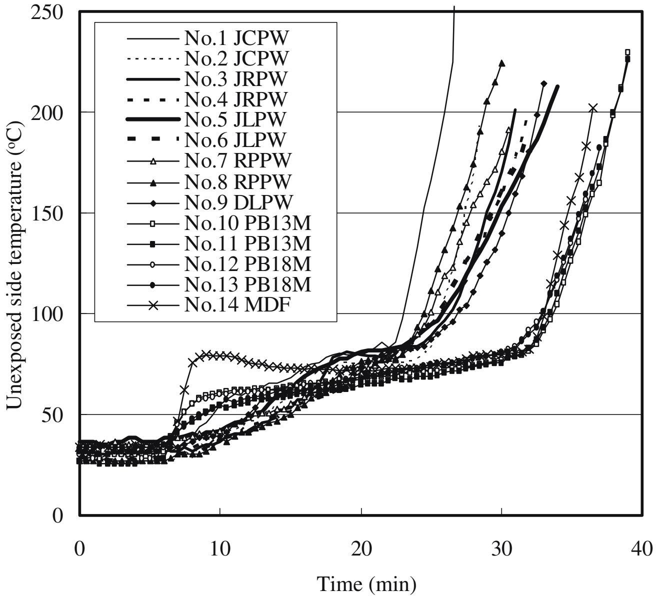

Fig. 2. Temperature of the unexposed side of the specimen. *JCPW*, Japanese cedar plywood; *JRPW*, Japanese red pine plywood; *JLPW*, Japanese larch plywood; *RPPW*, radiata pine plywood; *DLPW*, Dahurian larch plywood; *PB13M*, 13M-type particleboard; *PB18M*, 18M-type particleboard; *MDF*, medium density fiberboard

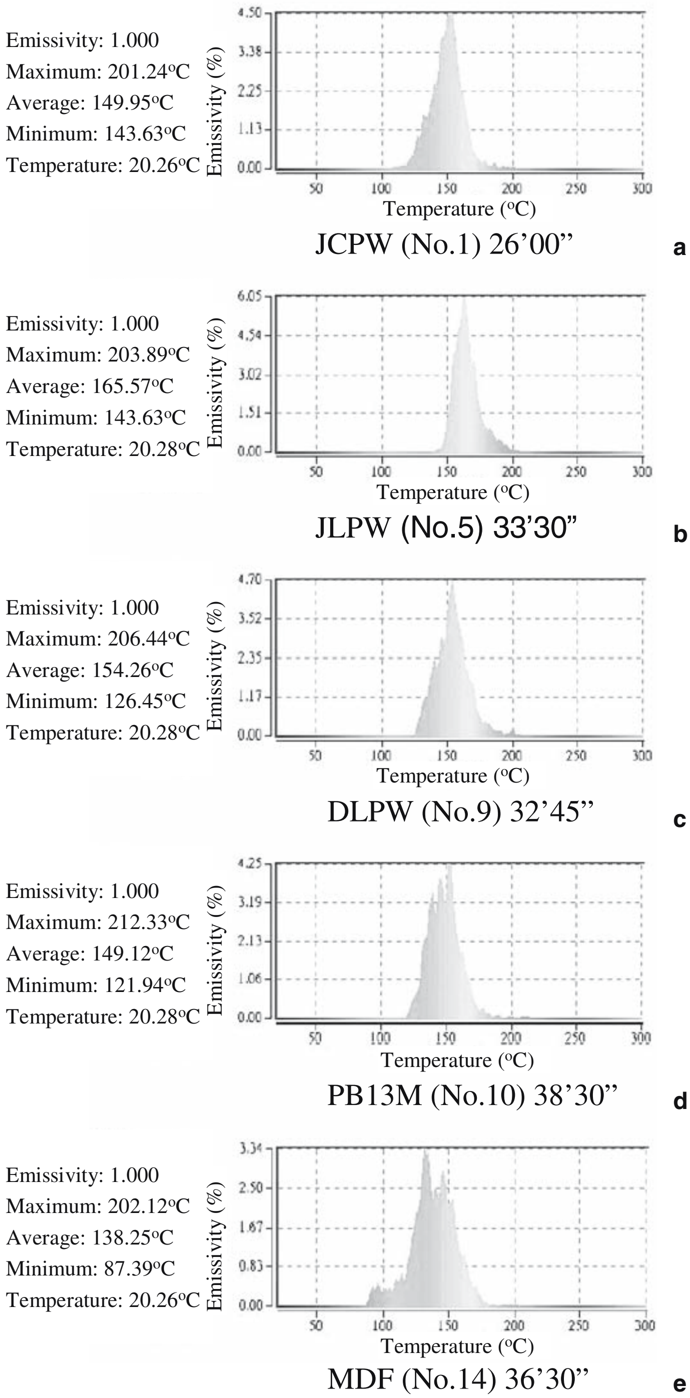

Fig. 3a–e. Temperature distribution of the unexposed side when the highest temperature reached 200°C. **a** JCPW; **b** JLPW; **c** DLPW; **d** PB13M; **e** MDF

materials than the thermocouple method in which the number of measuring points is limited. The temperature distributions of the unexposed sides of JCPW (no. 1), JLPW (no. 5), DLPW (no. 9), PB13M (no. 10) and MDF (no. 14) at $t_{200(\max)}$ are shown in Fig. 3.

In Japan, the insulation performance of walls is evaluated for room temperature at 20°C when the maximum temperature of the unexposed side reaches 200°C or its average temperature reaches 160°C, whichever comes first. The average temperature of the unexposed side was less than 160°C, except for JLPW (no. 5), when the maximum temperature reached 200°C. Consequently, $t_{200(\max)}$ is regarded as a higher priority factor than $t_{160(\mathrm{avg})}$ to evaluate the insulation property of the wall.

According to the results, the 28- to 30-mm-thick wood-based boards did not satisfy the 45-min or 1-h quasi-fireproof performance; however, the 28-mm-thick JRPW, JLPW, and DLPW, 30-mm-thick PB, and 30-mm-thick MDF did satisfy the 30-min insulation criterion required for external walls of quasi-fireproof and fire-preventive construction.

The rise of temperature of the unexposed side differs by wood species and the variety of wood-based board apparently due to differences in the respective density and thermal conductivity. In lumber, the high density of the wood delayed the time up to when the unexposed side reached the critical temperature. The insulation performances of plywood, PB, and MDF were compared with the material density to see if the same tendency could be observed. Figure 4 indicates that the higher the apparent density, the higher the value of $t_{200(\max)}$. The regression formulae for the relationships between apparent density ρ(kg/m^3) and $t_{200\ (\max)}$ (min) and $t_{160\ (\max)}$ (min) are given by:

$$t_{200\ (\max)} = 0.0330 \times \rho + 13.1 \qquad (n = 9,\ r^2 = 0.88) \tag{2}$$

$$t_{160\ (\max)} = 0.0289 \times \rho + 14.1 \qquad (n = 14,\ r^2 = 0.90) \tag{3}$$

These relations are practical for designing wooden walls and floors requiring fire resistance. The insulation performance of thick wood-based boards in the ISO 834-1 test was

Table 3. Density of the wooden board tested by the cone calorimeter

Specimen	Thickness (mm)	Moisture content (%)	Apparent density (kg/m^3)	Surface layer density[a] (kg/m^3)	Core density[b] (kg/m^3)
JCPW	28	8.8	433.6	347.7	447.6
JRPW	28	7.8	528.8	421.0	508.1
JLPW	28	6.9	573.7	497.1	582.6
RPPW	28	7.6	563.6	522.4	594.0
DLPW	28	7.3	705.3	572.4	770.3
PB13M	30	7.4	669.7	935.0	597.8
PB18M	30	7.7	718.7	925.0	653.7
PB13M	25	7.6	704.5	935.3	622.2
PB13M	35	7.4	648.1	897.3	526.0
MDF	30	6.3	645.4	816.7	568.0

[a] Average density from the surface to 1 mm depth
[b] Average density 10–15 mm from the surface

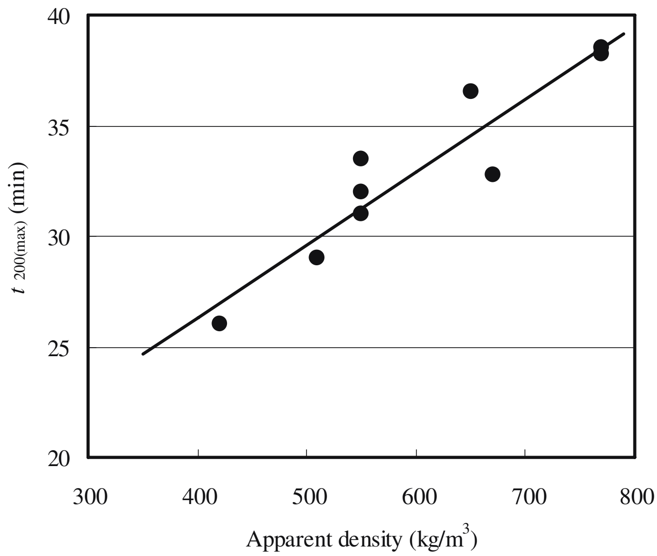

Fig. 4. Relationship between the apparent density of wood-based board and the time when the maximum temperature of the unexposed side reached 200°C [$t_{200(max)}$] in the ISO 834-1 test. *Filled circles*, observed values; *straight line*, regression line

correlated with the board density when the thickness was similar or identical.

Although the influence of the thermal conductivity on the insulation performance was examined, no correlation between them was found. The thermal conductivities of the specimens tested were measured by a thermal conductivity tester (HC-073; EKO Instruments) according to the heat flow determination method (ASTM-C518). The measurements are shown in Table 1. The influence of the specimen thickness was not examined because the thicknesses of the specimens tested were almost uniform (28–30 mm). However, the thicker specimen was assumed to be more fire resistant.

Time to ignition

Previous studies[12–15] reported that the time to ignition of sawn lumber in the cone calorimeter test was correlated with the apparent density. Although the apparent density of DLPW was 703–707 kg/m^3 which was similar to that of PB (648–725 kg/m^3), the time to ignition of DLPW was 20–22 s and was earlier than that of PB (33–43 s). In the case of PB and MDF, the surface layer density differs greatly from the core density, so the relationships between the time to ignition and the surface layer density were examined. The densities of plywood, PB, and MDF in the through-thickness direction were scanned by a density profiler (DA-X; GreCon). The specimens were taken from the same boards used for the cone calorimeter test. The apparent, surface layer and core densities of each specimen are listed in Table 3. The apparent density is the average value for the whole specimen. The surface layer density is the average density from the surface to 1 mm deep. The core density is the average value of material at a depth of 10–15 mm from the surface. The apparent density of PB was 648–725 kg/m^3, however, the surface layer density was 897–935 kg/m^3, and the core density was 526–654 kg/m^3. As for MDF, the apparent, surface layer, and core densities were 654 kg/m^3, 817 kg/m^3, and 568 kg/m^3, respectively. Some specimens had different apparent density from the specimens for the ISO 834-1 test. This is because commercial products were used for the fire tests, and the individual difference of the apparent density was large in some specimens. Figure 5 shows the density profiles of JCPW, PB18M, and MDF. In the case of plywood, the density of the adhesive layer was higher and that of the surface was lower than the apparent density. Figure 6 shows that the time to ignition of the wood-based boards was affected by the surface layer density. The regression formula of the time to ignition (t_{ig}; s) and the surface layer density (ρ_s; kg/m^3) is given by:

$$t_{ig} = 0.0421\ \rho_s - 1.46 \qquad (n = 18,\ r^2 = 0.92) \tag{4}$$

Heat release rate and total heat release

The heat release rate curves of JCPW, PB, and MDF are illustrated in Fig. 7. The tendency was the same as for sawn lumber.[15] The heat release rate of the wood-based boards underwent the following changes. The first peak value appeared just after the time to ignition, but the heat release rate gradually decreased as the charred layer grew, and then

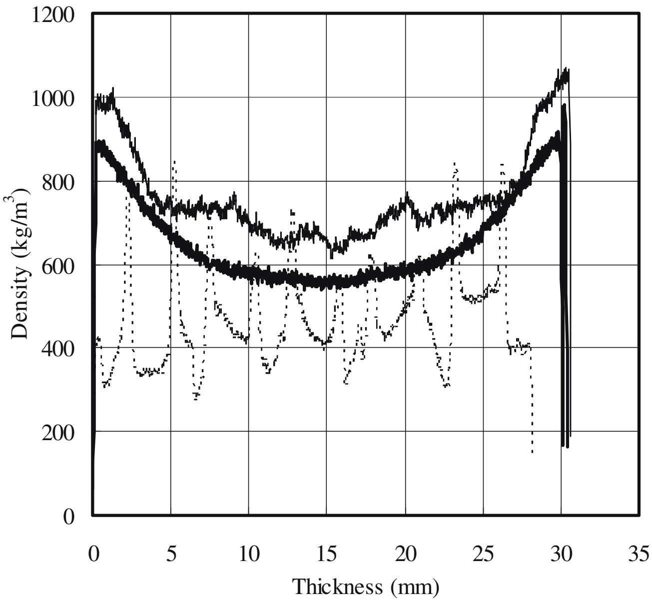

Fig. 5. Density profiles of plywood, particleboard (PB), and MDF. *Dashed line*, 28-mm-thick Japanese cedar plywood (JCPW 28 mm); *thin solid line*, 30-mm-thick 18M-type particleboard (PB18M 30 mm); *heavy solid line*, 30-mm-thick medium density fiberboard (MDF 30 mm)

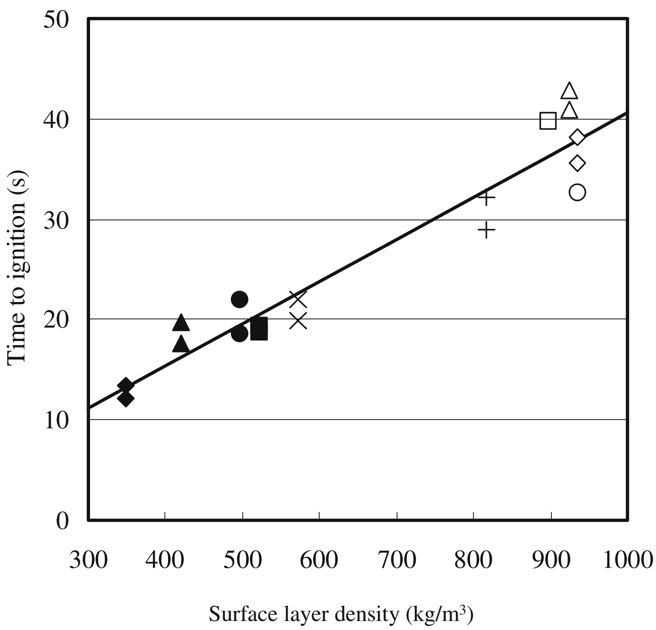

Fig. 6. Relationships between the surface layer density and the time to ignition. *Filled diamonds*, 28-mm-thick Japanese cedar plywood; *filled triangles*, 28-mm-thick Japanese red pine; *filled circles*, 28-mm-thick Japanese larch plywood; *filled squares*, 28-mm-thick radiata pine plywood; *crosses*, 28-mm-thick Dahurian larch; *open diamonds*, 30-mm-thick 13M-type particleboard; *open triangles*, 30-mm-thick 18M-type particleboard; *open circle*, 25-mm-thick 13M-type particleboard; *open square*, 35-mm-thick 13M-type particleboard; *plus signs*, 30-mm-thick medium density fiberboard; *straight line*, regression line

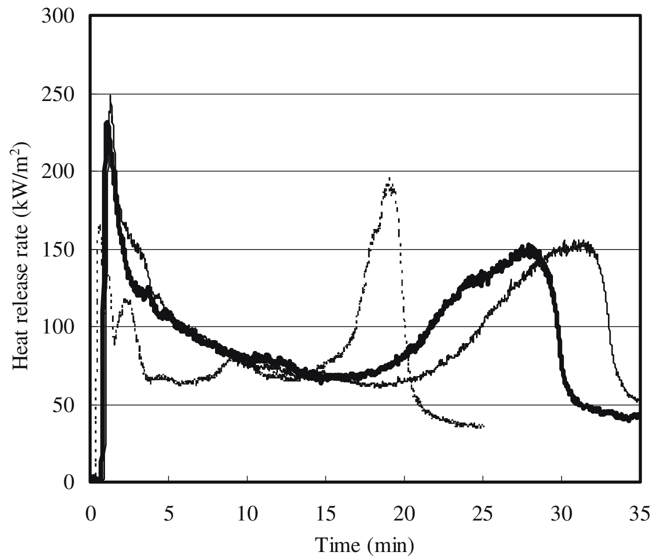

Fig. 7. Heat release rate curves of plywood, PB and MDF. *Dashed line*, JCPW 28 mm; *thin solid line*, PB18M 30 mm; *heavy solid line*, MDF 30 mm

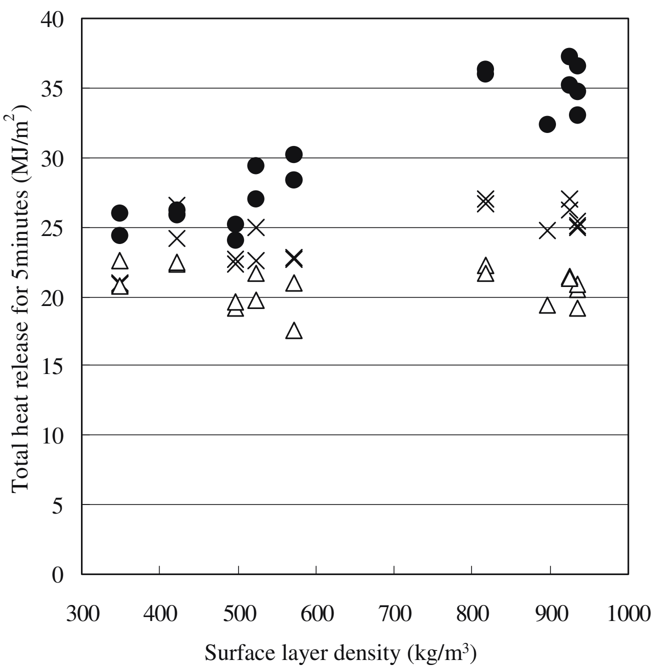

Fig. 8. Relationships between surface layer density and total heat release for 5 min. *Filled circles*, total heat release for 5 min from test start; *crosses*, total heat release for 5 min from 5 to 10 min after test start; *open triangles*, total heat release for 5 min from 10 to 15 min after test start

temporarily stabilized, and finally the second peak appeared at the end of burning.

The relationships between the total heat release values for 5 min (during the periods of 0–5, 5–10 and 10–15 min) and the surface densities are plotted in Fig. 8. The total heat release for the initial 5 min correlated with the surface layer density. However, the values for 5–10 min and 10–15 min were not affected by the type of specimen or their densities.

Further consideration will be needed to clarify the reason for this.

Prediction of insulation performance

The time to ignition and the total heat release are important factors for the combustibility of wood-based materials. However, these parameters are not of significance when predicting the insulation performance of wall materials. According to a previous study,[16] the time when the second peak of heat release rate appears ($t_{2ndPHRR}$; min) is correlated with the time when the unexposed side temperature reaches 260°C in the cone calorimeter test. The reason why the second peak heat release rate appears in the cone calorimeter test is considered to be that the wooden specimen is pyrolyzed rapidly when the temperature of the unexposed side reaches the carbonizing temperature.

In this study, $t_{2ndPHRR}$ was also correlated with the 100 × 100 mm specimen mass (Fig. 9), which means the combustible mass per unit area affects the insulation performance of wood-based wall materials. The insulation criterion for structural walls is that the temperature rise of the unexposed side of the specimen shall be within 180°C at maximum and 140°C on average during the ISO 834-1 test. When the room temperature was about 20°C, $t_{200(max)}$ and $t_{160(avg)}$ were evaluated. As described, $t_{200(max)}$ was a higher priority factor than $t_{160(avg)}$. Although these temperatures are different to 260°C, if $t_{200(max)}$ in the ISO 834-1 test is correlated with $t_{2ndPHRR}$ in the ISO 5660-1 test, the insulation performance in the ISO 834-1 test could be predicted from the results of the cone calorimeter test. Figure 10 shows the relationship between $t_{200(max)}$ in the ISO 834-1 test and the average $t_{2ndPHRR}$ value in the ISO 5660-1 test. Equation 5 is the regression formula. For comparison, the regression formula between the specimen mass (m; g) of the cone calorimeter test specimen and $t_{200(max)}$ in the ISO 834-1 test is presented in Eq. 6.

$$t_{200(max)} = 1.12 \times t_{2ndPHRR} + 3.78 \qquad (n = 7, r^2 = 0.92) \tag{5}$$

$$t_{200(max)} = 0.122 \times m + 11.8 \qquad (n = 7, r^2 = 0.74) \tag{6}$$

The value of $t_{200(max)}$ had a linear relation with $t_{2ndPHRR}$ and specimen mass in the cone calorimeter test. However, the correlation coefficient of Eq. 5 was higher than those of Eqs. 2 and 6, and so $t_{2ndPHRR}$ is a more reliable parameter to predict the insulation performance in the ISO 834-1 test.

Conclusions

The fire performances of thick wood-based boards (plywood, PB, and MDF) were evaluated by the ISO 834-1 fire resistance test for walls and the cone calorimeter test. The following findings were obtained:

1. The 28-mm-thick Japanese red pine, Japanese larch, Dahurian larch plywood, and the 30-mm-thick PB and MDF satisfied the 30-min insulation performance stipulated in the Building Standard Law of Japan.
2. The insulation property of the thick wood-based boards in the ISO 834-1 test was correlated with the board density, when the board thickness was similar or identical.

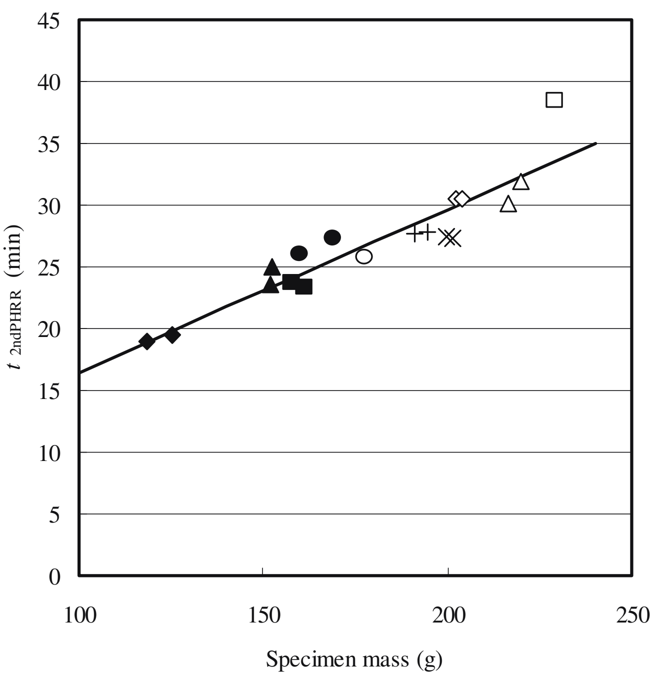

Fig. 9. Relationships between the specimen mass and the time when the second peak of heat release rate appeared. The legends are the same as in Fig. 6

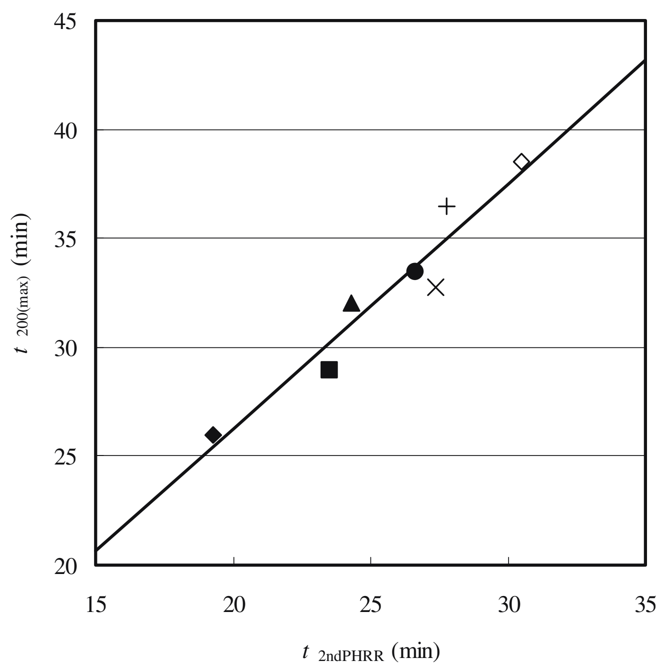

Fig. 10. Relationships between the time when the second peak of heat release rate appeared in the cone calorimeter test ($t_{2ndPHRR}$) and the time when the maximum temperature of the unexposed side reached 200°C in the ISO 834-1 test [$t_{200(max)}$]. The legends are the same as in Fig. 6

3. For evaluating the insulation property of bearing walls, the thermographic image system, which can measure the whole area of the unexposed side, was more suitable than the thermocouple method, which has a limited number of measuring points.
4. In the cone calorimeter test, the time to ignition and initial total heat release of plywood, PB, and MDF were affected by the surface layer density rather than the average density as a whole.
5. The insulation performance [$t_{200(\mathrm{max})}$] in the ISO 834-1 fire test for walls can be predicted from the results of the cone calorimeter test ($t_{2\mathrm{ndPHRR}}$).

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