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ORIGINAL ARTICLE

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Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors

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Abstract Thermal insulation and warmth-keeping properties of thick plywood-faced sandwich panels with low-density fiberboard (plywood-faced sandwich, PSW), which were developed as wood-based structural insulation materials for walls and floors, are comprehensively clarified. The properties focused on were thermal conductivity (λ), thermal resistance (R), and thermal diffusivity (D). The results for PSW panels were compared with those for commercial wood-based boards, solid wood, and commercial insulators. The λ values were measured for PSW panels and their core and face elements. As a result, the composite theory of λ was found to be appropriate for PSW composites, because the calculated/experimental λ ratios were approximately 90%. The λ values for PSW panels with densities of 340 kg/m^3 (PSW350) and 410 kg/m^3 (PSW400) were 0.070 and 0.077 W/mK, respectively. The R values for PSW350 and PSW400 were 1.4 and 1.2 m^{2}K/W, and the D values were 0.00050 and 0.00046 m^2/h, respectively. Consequently, the PSW provided thermal insulation properties superior to those of the boards and in terms of warmth-keeping properties were greatly advantageous over the insulators. These advantages were due to the moderate densities of PSW panels. The PSW panel with sufficient thickness showed remarkably improved thermal resistance compared with those of the boards.

Key words Thermal insulation property · Thermal conductivity · Wood-based sandwich panel · Low-density fiberboard · Composite theory

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Introduction

In facing the global warming trend, there is a dire need for more effective measures to sustain comfortable temperatures in living environments. To sustain an indoor temperature that is independent of outdoor temperature fluctuations, materials need to be developed that have superior thermal insulation abilities (lower thermal conductivity, λ). To provide adequate protection from severe temperature changes, materials must have good warmth-keeping properties (lower thermal diffusivity, D). Insulation materials need to demonstrate high performance in both steady and nonsteady states of heat flow. To obtain thermal resistance (R) when in use, insulation materials must be of sufficient thickness.

Commercial thermal insulators used for houses are plastic foams and mineral wools. The plastic foam is sometimes used as the core of a structural insulated panel by being sandwiched between oriented strand boards (OSBs). Mineral wools that form a mat are often inserted into the airspace in walls. The plastic foams are made from petroleum resources while the mineral wools raise some concern in that they may be harmful to health, given that they are likely to stick to skin. Switching to safer and more environmentally sensitive building materials is required.

We have developed the plywood-faced sandwich panel with low-density fiberboard core (PSW)[1] as an alternative structural insulated composite. The low-density fiberboard and veneer-faced sandwich were manufactured to improve the mechanical properties[2,3] and provide a promising insulation material made from a sustainable wood resource.

Conventionally, wood and structural plywood are not used as insulation materials for construction,[4] even though they offer relatively better insulation properties than metal or concrete.[5] Insulation board having a lower λ than wood is widely selected for non-structural use because its mechanical defects are of little importance. Recently, lowering of the density of boards[2,5–11] and wood-based sandwiching techniques have progressed[3,12–14] to improve the stiffness-to-weight ratio.[15,16]

Although much information about λ has been reported for commercial boards and insulators, the evaluation measures are usually different and the data cannot be exactly compared. Very little information about D and R for boards has been reported.[2,3,7] In these reports, the density and thickness were not often described, and consequently R and D cannot be derived. Therefore, comprehensive evaluation of thermal properties of the current variety of materials has been lacking prior to the present report.

In the present report, the thermal insulation and warmth-keeping properties of the PSW are clarified comprehensively. The results of tests with PSW are directly compared with those using commercial boards, solid wood, and commercial insulators conducted in the same manner.

Experimental

Sample preparation

Specimens of PSW

The samples used were the wood-based sandwich panel of plywood-faced low-density fiberboard core (PSW) with a thickness of 96 mm, manufactured in the previous study.[1] The core was made of fiberboard, made from lauan (*Shorea* spp.) bonded with an adhesive of commercial polymeric methylene diphenyl diisocyanate (MDI) resin at 10% resin content. The face material was commercial weatherproof and boil-proof plywood (type special)[17] of Japanese larch (*Larix gmelini* Gordon) with a thickness of 9 mm consisting of three 3-mm thick plies, and with an average density of 680 kg/m^3. Samples of with air-dried density (ρ) levels of 340 kg/m^3 (PSW350) and 410 kg/m^3 (PSW400) were prepared, and their thicknesses were 95.7 and 96.2 mm, respectively.

To examine thermal conductivity (λ) values for PSW panels, one test specimen (200 mm square × thickness) was prepared from each sample of PSW350 and PSW400. To examine the composite theory, the core and the face specimens were prepared. After the λ measurement, each PSW specimen was divided into specimens of its elements of fiberboard core and plywood faces by sawing the core part near the bonding layer between the faces. The bond layer left on the face was removed using a planer. Each core and face specimen (200 mm square × thickness) were used again for the measurement. To examine the effect of the core thickness on the measurement error, each core specimen after the λ measurement was sliced into three thinner test pieces that were 12, 20, and 35 mm in thickness and 200 mm square. Each sliced core specimen (200 mm square × 12, 20, 35 mm thick) was used again for the measurement.

Other specimens for comparison

For direct comparison of λ, other samples were prepared for measurement, such as commercial wood-based boards, solid wood, and commercial thermal insulators.

The commercial wood-based boards were structural plywoods that were 9 and 12 mm thick (PW 9, PW 12, respectively), medium density fiberboards that were also 9 and 12 mm thick (MDF 9, MDF 12), particleboard 12 mm in thickness (PB 12), and OSB 12 mm in thickness (OSB 12). From each sample, one specimen, each 200 mm square, was taken for the λ measurement. The detail of each sample was as follows; PW 9 [three plies from softwood, P type (phenol–formaldehyde resin), type I (boiled-water resistant for exterior use)],[17] PW 12 [five plies from hardwood, P type, type I], MDF 9 [from hardwood fiber, M type (melamine–urea–formaldehyde resin)], MDF 12 {from hardwood fiber, M type, type 30 [modulus of elasticity (MOE) is more than 30 GPa]},[18] PB 12 [from both hardwood and softwood particles, M type, type 18 (MOE is more than 18 GPa)],[19] and OSB 12 [from aspen strand, P type, class 3].[20] For the more details of the properties of the 12-mm-thick boards, refer to previous reports.[21,22]

The solid wood sample (*Cryptomeria japonica* D.Don) was a flat-sawn specimen (Wood 12). The sample dimensions were 200 mm square and 12 mm in thickness. The density (ρ) of the solid wood specimen (340 kg/m^3) was the same as that of PSW350.

The samples of commercial insulators were as follows: expanded polystyrene foam (EPS), two sorts of extruded polystyrene foam (XPS 1, XPS 2), phenol foam (PF), and compressed fiberglass wool (FG). The dimensions of each were 200 mm square and 24–25 mm in thickness. The data of λ for the insulators are those determined by Sekisui Plastics. The apparatus used was an AUTO-Λ HC-072 (Eko Instruments).

Measurement of thermal conductivity

All the specimens were left in an air-dried condition in a well-ventilated room for 2 weeks. After that they were conditioned at 20°C and 60% relative humidity for more than 24 h before the measurement. The λ values of the specimens were measured using the same apparatus mentioned above (AUTO-Λ HC-072; Eko Instruments), which was designed for the method using a heat-flow meter apparatus according to the Japanese Industrial Standard (JIS A1412)[23] and the American Society of Testing Materials (ASTM C518).[24] In this measuring system, each specimen was set between the heating and cooling plates in an area 200 mm square. A heat-flow meter in an area 100 mm square was attached to each plate. In the measurement, upper and lower plates were constantly heated at 35°C and cooled at 7°C, respectively. The temperature of the atmosphere around the specimen was controlled at 20°C, and the mean temperature (T) of each specimen was therefore kept around 20°C. To correct the heat relief from the cross section of specimen, the data of the two heat-flow meters were averaged by the system. The thickness during the measurement (d) was recorded for each specimen.

The λ values for the specimens of PSW350, PSW400, their cores and faces, and the sliced cores, the wood-based boards, and the solid wood were measured in the same

Table 1. Effect of core thickness on measurement errors in λ

Sample	Specimen	T (°C)	ρ (kg/m^3)	d (mm)	λ (W/mK)
PSW350	Sliced core	20.8	270	12.5	0.062
		20.8	260	19.9	0.064
		21.0	270	35.4	0.068
	Whole core	21.1	260	70.4	0.078
PSW400	Sliced core	20.8	350	12.1	0.069
		20.8	340	19.8	0.074
		20.9	350	35.5	0.077
	Whole core	21.0	350	72.5	0.087

PSW, plywood-faced sandwich panel with low-density fiberboard; T, mean temperature; ρ, air-dried density; d, thickness during the measurement; λ, thermal conductivity

manner. The solid wood sample was set with the bark side to the cold plate.

This equipment is usually used for specimens within a 30-mm thickness, and it has the capacity to handle specimens that are up to 100 mm thick. The maximum thickness of specimen was restricted by the standards individually. For example, the specimen 200 mm square was smaller than the JIS standard size (450 mm square) for testing specimens that are 100 mm thick.[23] However, it is possible to correct the λ value of PSW if composite theory can be applied to PSW.

Moisture content and density profile of PSW

The moisture contents of PSW350 and PSW400 panels were determined using five specimens (each 50 mm square × thickness) prepared from each sample. The specimens were kept in a chamber at 60°C for 48 h, and then kept in a airtight container at 20°C and 65% relative humidity conditioned using a saturated solution of magnesium acetate for 2 weeks. Moisture content was calculated from the weights of specimens in the above conditions.

The density profiles of PSW panels in the thickness direction was determined for a specimen (each 50 mm square × thickness) prepared from each sample. A scanning gamma densitometer (Raytest Isotopenmessgerate) was used. The gamma ray from americium was penetrated into the panel section.

Results and discussion

Moisture content and density profile

The average moisture contents of PSW350 and PSW400 were 8.0% and 8.1%, respectively. The moisture content had a minimal effect on λ in PSW panels. According to previous reports, the variation of λ for wood[25] with a density range of 200–500 kg/m^3 is about 0.01 W/mK in a moisture content range of 0%–10%, and the λ variation for particleboard with a density range of 400–900 kg/m^3 is negligible in the moisture content range of 0%–20%.[26,27]

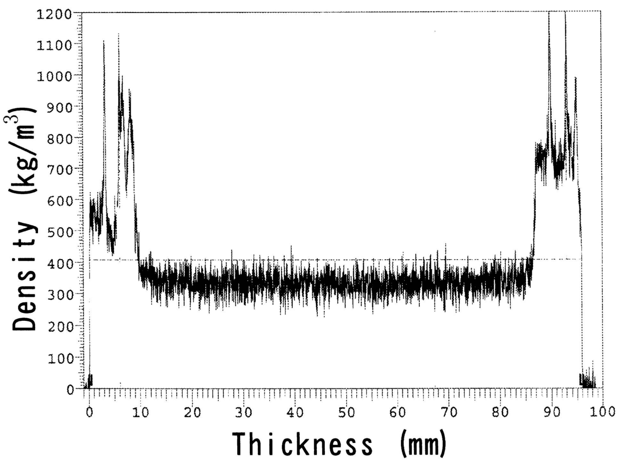

Fig. 1. Density profile of plywood-faced sandwich panel with low-density fiberboard (PSW) in the panel thickness direction. The mean density of the panel was 410 kg/m^3 (*dotted line*)

Figure 1 shows a density profile in the thickness direction of PSW400 with an average density of 410 kg/m^3. The high-density parts near both surfaces are face plywood and the flat region near the center is core fiberboard. The two sharp peaks observed in each face are assumed to be the two adhesive layers between three-ply veneers of the face. The density profile in the core was uniform throughout the thickness. A similar trend was observed in the PSW350 specimen.

Evaluation of thermal conductivity of PSW

Evaluation of thermal conductivity of core

As shown in Table 1, the λ of the core increases slightly in correlation with increase in thickness. The increase in λ was considered to reflect measurement errors. The reasons were as follows. The λ for the core was supposed to be constant throughout the thickness because its density profile was uniform. The slight increase was possibly a reflection of the heat relief from the cross section and the heat convection resulting from the continuous porosity among fiber elements.

Because of the heat relief and convection, the measurement condition became unstable for thicker specimens. The measurement time to obtain a steady-state condition was longer for thicker specimens. The area-to-thickness ratio of thicker specimens became insufficient to obtain the ideal steady-state condition. Normally, a sufficient area is required to obtain a constant heat flow, resulting in a constant temperature incline throughout the thickness. The convection effect in the fiberboard was much smaller than that in the air layer of house construction. In the air layer, the heat transfer is easily affected by convection.[28]

As a result, the values for the 12-mm-thick specimens were the most reliable as the source of λ data for the cores. The λ values for the cores with 12 mm thickness at 270 and 350 kg/m^3 densities were 0.062 and 0.069 W/mK, respectively.

Appropriateness of composite theory

The equivalent λ value for a sandwich panel composite can be calculated based on composite theory as follows:[29]

$$\lambda = \sum d_i \Big/ \sum \left(d_i / \lambda_i \right) \quad (1)$$

where d is the thickness of each layer and subscript i represents each core and face layer.

Table 2 shows measured λ values of PSW composites and their divided core and face elements. The calculated λ values of PSW composites were obtained from the λ values of the core and the upper and lower faces for each PSW specimen using Eq 1. The ratios of (calculated λ)/(experimental λ) for PSW350 and PSW400 were both 0.9. Each calculated λ value approached each experimental λ value. As a result, the composite theory could be basically applied to the λ values of PSW panels, although the calculated λ values were slightly smaller than the experimental λ values. This trend was similar to that reported in a study on sandwich panel of foam core overlaid unsymmetrically with hardboard and plywood.[29] Although the ratio occasionally exceeds 1 according to a study on several composites,[30] the composite theory was useful in any case. The panel thickness of panels without bond layers reduced by 10%, although this was negligible for the calculation of the λ ratios.

Thermal insulation performance of PSW

Thermal conductivity of PSW

The corrected value of λ for each PSW panel was calculated from the λ values for each 12-mm-thick core and for the upper and lower faces based on the composite theory (Eq. 1) as shown in Table 3. The corrected λ values of PSW350

Table 2. Measured values of λ for PSW composites and their elements

Sample		Specimen	T (°C)	ρ (kg/m^3)	d (mm)	λ (W/mK)
PSW350	Measured	Upper face	20.9	670	8.5	0.14
		Lower face	20.8	690	8.6	0.14
		Core	21.1	260	70.4	0.078
	Calculated	Composite		340	87.4	0.085
	Measured	Composite	20.9	340	95.1	0.091
	Ratio			1.0	0.9	0.9
PSW400	Measured	Upper face	20.9	660	8.9	0.13
		Lower face	20.9	690	9.1	0.14
		Core	21.0	350	72.5	0.087
	Calculated	Composite		420	90.5	0.094
	Measured	Composite	21.0	410	95.8	0.11
	Ratio			1.0	0.9	0.9

Calculated values are derived from the measured λ values for the face and core elements. Upper and lower indicate the positions of the faces in a PSW specimen during the measurement. Ratio means calculated/measured values ratio. Refer to Table 1 for parameter definitions

Table 3. Corrected values of thermal insulation properties for PSW composites and for their elements

Sample	Specimen	ρ (kg/m^3)	d (mm)	λ (W/mK)	Λ (W/m^{2}K)	r (mK/W)	R (m^{2}K/W)	$C\rho$ (kJ/Km^3)	D (m^2/h)
PSW350	Upper face	670	9	0.14	16	7.0	0.063	970	0.00053
	Lower face	690	9	0.14	16	7.1	0.064	1000	0.00050
	Core	270	78	0.062	0.79	16	1.3	390	0.00057
	Composite	340	96	0.070	0.73	14	1.4	500	0.00050
PSW400	Upper face	660	9	0.13	15	7.5	0.068	970	0.00049
	Lower face	690	9	0.14	15	7.2	0.065	1000	0.00049
	Core	350	78	0.069	0.89	14	1.1	510	0.00049
	Composite	410	96	0.077	0.81	13	1.2	600	0.00046

The measured λ values for a 12-mm thick core are used for correction. Data of PSW composites are calculated from those of the elements based on the composite theory. The specific heats (C) for PSW composites and their elements are estimated to be 1.5 kJ/kgK.[25] Λ, Thermal conductance; r, thermal resistivity; R, thermal resistance; $C\rho$, volumetric specific heat; D, thermal diffusivity

Fig. 2A–D. Thermal insulation properties of PSW panels (*diamonds*) and of the core (*squares*) and the face (*triangles*), such as **A** thermal conductivity (λ), **B** thermal conductance (Λ), **C** thermal resistivity (r), and **D** thermal resistance (R), shown in relation to density (ρ). In terms of these properties, PSW panels were compared with the commercial wood-based boards (*diagonal crosses*), solid wood (*circle*), commercial insulators (*asterisks*), veneer-faced sandwich panel (VSW, *crosses*), and low-density fiberboard (LDFB, *bars*) (see Tables 4–6)

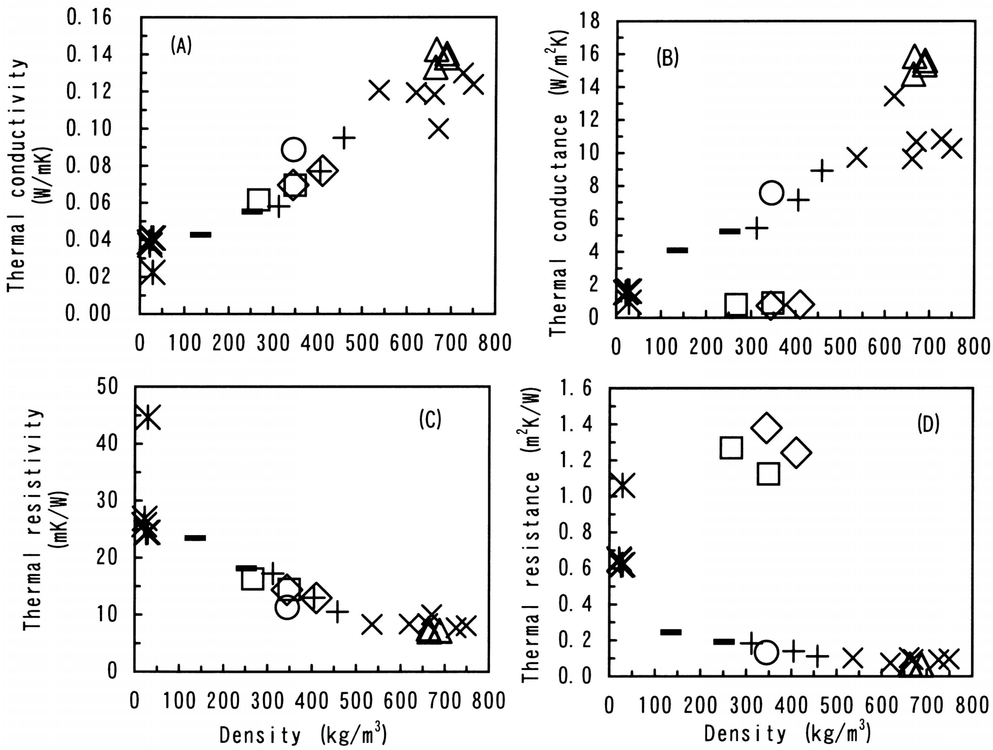

Table 4. Thermal insulation properties of commercial wood-based boards and solid wood

Specimen	T (°C)	ρ (kg/m³)	d (mm)	λ (W/mK)	Λ (W/m²K)	r (mK/W)	R (m²K/W)	$C\rho$ (kJ/Km³)	D (m²/h)
PW 9	20.9	610	8.9	0.12	13	8.4	0.074	890	0.00048
PW 12	20.6	530	12.4	0.12	9.7	8.3	0.10	780	0.00056
MDF 9	20.6	690	9.4	0.10	11	10	0.094	1000	0.00036
MDF 12	20.7	750	12.1	0.12	10	8.1	0.097	1100	0.00041
PB 12	20.6	720	12.0	0.13	11	7.7	0.092	1100	0.00044
OSB 12	20.7	660	12.3	0.12	9.6	8.5	0.10	960	0.00044
Wood 12	20.7	340	11.7	0.089	7.6	11	0.13	510	0.00063

Commercial boards include structural plywoods (PW 9, 12), medium density fiberboards (MDF 9, 12), particleboard (PB 12), oriented stand board (OSB 12). Solid wood is *Cryptomeria japonica* D.Don (Wood 12). The specific heats for the boards and wood are estimated to be 1.5 kJ/kgK[25]

and PSW400 were 0.070 and 0.077 W/mK, respectively. These λ values of PSW panels meet the requirements for thermal insulation, because a material with a λ of 0.15 W/mK or less is an appropriate insulator.[23]

A composite effect of the core and face on the insulation properties of PSW panels is shown in Table 3. The faces showed λ values (0.14 W/mK on average) that were approximately twice those of the cores. Overlaid with the face, the λ values of PSW350 and PSW400 (0.070 and 0.077 W/mK) increased by only about 10% of these values of the core (0.062 and 0.069 W/mK), respectively. The core contributed dominantly to the λ values of PSW composites, because the core thickness was approximately 80% of the total panel thickness.

Figure 2A shows the λ values of PSW panels in relation to ρ, compared with those of the commercial wood-based boards, solid wood, and the commercial insulators (see Tables 4, 5). The λ values for these materials strongly depend on ρ. In correlation with the decrease of ρ, the λ values appear to approach the λ value of air at 20°C (0.023 W/mK).[25]

The λ values of the PSW panels were about 60%–70% those of the commercial boards (0.10–0.13 W/mK), whereas the ρ values of the PSW panels were approximately half those of the boards (530–750 kg/m³). The PSW panels were advantageous for insulation over the commercial boards. The λ values of the PSW panels were approximately twice those of the insulators, such as EPS, XPS, and FG (0.037–0.041 W/mK), and were more than three times that of PF (0.022 W/mK), which was the lowest among the insulators. The ρ values of PSW panels were approximately 10–20 times those of the insulators (21–29 kg/m³).

The λ value of the solid wood (0.089 W/mK) was higher than that of PSW350 at the same ρ (340 kg/m³), although the

Table 5. Thermal insulation properties of commercial thermal insulators

Specimen	T (°C)	ρ (kg/m^3)	d (mm)	λ (W/mK)	Λ (W/m^{2}K)	r (mK/W)	R (m^{2}K/W)	$C\rho$ (kJ/Km^3)	D (m^2/h)
EPS	20.8	22.0	24.0	0.037	1.6	27	0.64	28	0.0048
XPS 1	20.7	29.2	25.4	0.041	1.6	24	0.62	37	0.0040
XPS 2	20.9	25.6	25.3	0.041	1.6	24	0.62	32	0.0046
PF	20.8	28.6	23.8	0.022	0.94	45	1.1	40	0.0020
FG	20.0	21.1	25.3	0.039	1.5	26	0.65	18	0.0079

The specific heats for the expanded (EPS) and extruded (XPS 1, 2) polystyrene foams,[5] phenol foam (PF),[32] and fiberglass wool (FG)[5] are estimated to be 1.3, 1.4, and 0.84 kJ/kgK, respectively. The data of T, ρ, d, and λ for these insulators are those determined by Sekisui Plastics Co.

Table 6. Thermal insulation properties of VSW and LDFB

Specimen	ρ (kg/m^3)	d (mm)	λ (W/mK)	Λ (W/m^{2}K)	r (mK/W)	R (m^{2}K/W)	$C\rho$ (kJ/Km^3)	D (m^2/h)
VSW	310	10.7	0.058	5.4	17	0.18	460	0.00046
	410	10.8	0.077	7.1	13	0.14	590	0.00047
	460	10.7	0.095	8.9	11	0.11	670	0.00051
LDFB	140	10.4	0.043	4.1	23	0.24	200	0.00077
	250	10.6	0.055	5.2	18	0.19	370	0.00054

The specific heats for VSW and LDFB are estimated to be 1.5 kJ/kgK[25]
VSW, the veneer-faced sandwich panel that consists of 0.55-mm-thick veneer faces and a fiberboard core (10% resin content);[3] LDFB, the same low-density fiberboard[2] as the core of VSW

wood species provided somewhat low λ among commonly used wood species due to the low density. The λ values of the face (0.14 W/mK) and core (0.062 W/mK) of PSW350 were higher and lower than that of the wood, respectively. Therefore, the core contributed to the lower λ.

The λ of the solid wood was higher than that of the fiberboard as the core of PSW400 at a similar ρ (0.069 W/mK, 350 kg/m^3). This result agreed with the general trend for wood and fiberboard.[31] The wood and the fiberboard contain the cell structures, in which the heat transmission is affected by the difference of substance (or porosity) distribution.[16] The wood consists of continuous cell walls forming cell spaces like vessels, while the fiberboard consists of fibers bonded at the contact points forming pores uniformly divided by the fibers. As a result, heat is likely to be transmitted more efficiently through the wood than through the fiberboard at the same density.

Table 6 shows previous results on the veneer-faced sandwich panel (VSW)[3] with a low-density fiberboard core (LDFB)[2] evaluated by using another test method.[2,3] As shown in Fig. 2A, the λ value of the core of PSW350 (0.062 W/mK, 270 kg/m^3) was similar to that of LDFB at a similar ρ (0.055 W/mK, 250 kg/m^3). The λ value of PSW400 was the same as that of VSW at the same λ (0.077 W/mK, 410 kg/m^3), and was not affected by the difference in construction and that the face/panel thickness ratio of PSW (20%) was twice that of VSW (10%).

Thermal resistance of PSW

The other thermal properties of PSW panels are shown in Table 3, including thermal conductance (Λ), thermal resistivity (r), and thermal resistance (R), which were calculated using the corrected λ values. These properties of PSW panels in relation to ρ are shown in Fig. 2B–D. The Λ and r values are often used for thermal evaluation of building materials. R is an important value to evaluate total resistance of heat transmission for walls, which is the summation of the R values within the wall and the facial heat transfers. A higher value of R means better thermal insulation. R is defined as thickness (in m) divided by λ. Because of the inclusion of the thickness factor, comparison using R values is useful for the field application, where the material is used with a practical thickness in building. The PSW panels and their cores, which were much thicker than other materials, showed remarkably different trends in Λ and R (Fig. 2B,D) from those in λ and r (Fig. 2A,C). The relation between Λ and R is inverse, and is the same as that between λ and r.

The R values of PSW350 and PSW400 were 1.4 and 1.2 m^{2}K/W, respectively (Table 3). The PSW panel with the lower density showed the higher R value (Fig. 2D). This was because the lower density core showed higher resistance (1.3 m^{2}K/W) than the higher density core (1.1 m^{2}K/W). The R value of each PSW panel consists of the R values of its core (90%) and each face (5%). Therefore, the core mainly contributed to the resistance of PSW panel, which was obvious as shown in Fig. 2D. The R values of the core and PSW panel were much higher than that of the face.

The R values of PSW panels were more than ten times those of the commercial boards and solid wood (approximately 0.1 m^{2}K/W), where the thicknesses of PSW panels were eight times those of the boards and wood (12 mm). The R values of PSW panels were twice those of the insulators such as EPS, XPS, and FG (0.6–0.7 m^{2}K/W), and were somewhat higher than that of PF (1.1 m^{2}K/W), where the thickness of PSW panels were four times those of the insulators (24–25 mm). This means that the PSW panels had the equivalent R values to insulators that were 50 mm or less in thickness among the commercial thickness variation (10–150 mm etc.). PSW panels with a sufficient thickness could help to compensate for this deficit compared with the insulator specimens that are 24–25 mm in thickness.

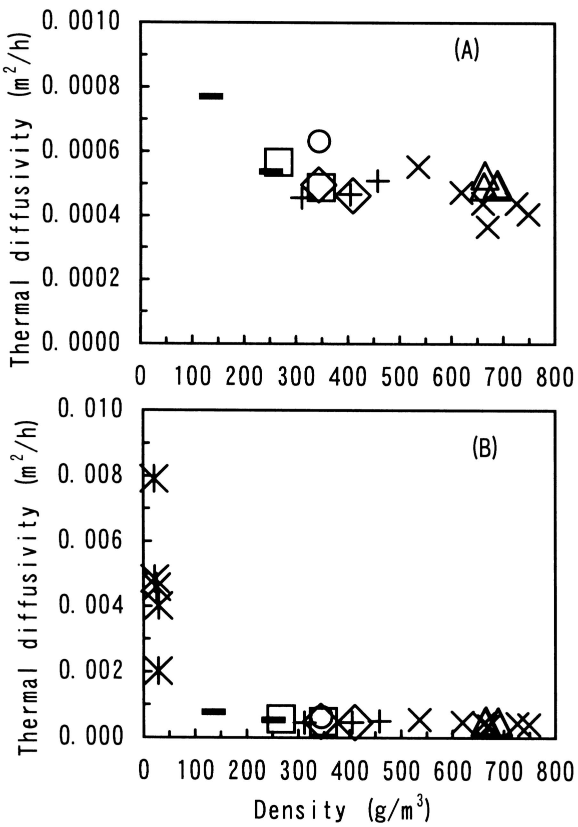

Fig. 3A,B. Thermal diffusivities (D) of PSW panels and of the cores and faces, which were compared to those of the commercial boards, solid wood, VSW, and LDFB (**A**), and to those of the commercial insulators (**B**). (*Symbols*, refer to Fig. 2. See Tables 4–6)

Warmth-keeping property of PSW

Thermal diffusivity (D) is an indicator of warmth-keeping performance, which is proportional to λ and inversely proportional to $C\rho$ (volumetric specific heat). The (specific heat) value (C) for wood with an oven-dried density range of 230–1100 kg/m^3 can be calculated according to a literature method.[25] Assuming moisture content to be 8% and $T = 20°C$, the C value for the wood was calculated to be 1.5 kJ/kgK, using a conversion unit (1 kcal = 4.18605 kJ). Therefore, the C values for PSW panels, the commercial boards, and solid wood were assumed to be 1.5 kJ/kgK. The C values of polystyrenes (EPS, XPS),[5] PF,[32] and FG[5] were estimated to be 1.3, 1.4, and 0.84 kJ/kgK, respectively.

A low D value means better warmth-keeping performance in terms of insulation in the non-steady-state condition of heat flow. As shown in Fig. 3A, the D values of wood-based specimens generally decreased in correlation with increase in ρ (or $C\rho$). A composite effect of the core and face on the D values of PSW panels is shown in Fig. 3A. When overlaid with the faces, the ρ (or $C\rho$) values of PSW composites were about 20%–30% higher than those of the cores. The ρ (or $C\rho$) values of the faces were about twice those of the cores. As a result, the D values of PSW350 and PSW400 (0.00050 and 0.00046 m^2/h, respectively, Table 3) were about 10% less than those of the cores (0.00057 and 0.00049 m^2/h respectively), which was advantageous for warmth-keeping performance.

As shown in Fig. 3A, the D values of PSW panels were similar to those of the commercial boards (0.00036–0.00056 m^2/h, Table 4). The D value of the solid wood (0.00063 m^2/h) was somewhat higher than that for PSW350 at the same ρ.

As shown in Fig. 3B, the D values of PSW panels were approximately 1/5–1/20 of those of the commercial insulators, about 1/5 of that of PF (0.0020 m^2/h, Table 5), 1/10 of those of EPS and XPS (0.0040–0.0048 m^2/h), and 1/20 of that of FG (0.0079 m^2/h). The differences in the D values between PSW panels and the insulators were mainly effected by ρ (or $C\rho$). The $C\rho$ values of PSW panels (500–600 kJ/K m^3, Table 3) were approximately 10–30 times those of the insulators (18–40 kJ/K m^3, Table 5), whereas the λ values of PSW panels were about 2–3 times those of the insulators. The ρ values of PSW panels were about 10–20 times those of the insulators, whereas their C values were similar (around 1 kJ/kg K). As a result, the warmth-keeping effect of PSW panels was 5–20 times better than that of the insulators.

Comprehensive insulation performance of PSW

Consisting of a low-density fiberboard core and plywood faces, the PSW panels obtained the characteristics of both advantages of the core and face. The steady-state insulation properties of PSW panels met the requirements for insulation, showing the λ values that were half those of the faces and higher by about 10% than those of the cores. The PSW panels obtained the ρ (or $C\rho$) values that were higher by about 20%–30% than those of the cores. Therefore, the warmth-keeping properties of PSW panels were better than those of the cores, showing D values that were 10% lower than those of the cores.

The commercial wood-based boards, having warmth-keeping potential, were insufficient for insulation purposes. The commercial insulators were suitable for steady-state insulation and disadvantageous for non-steady-state insulation. In contrast to these materials, the PSW panels provided enough insulation and warmth-keeping properties. The PSW panels were advantageous over the boards for insulation, showing λ values that were approximately 2/3 of those of the boards. The PSW panels were advantageous over the insulators for warmth-keeping properties, showing D values that were approximately 1/20–1/5 of those of the insulators. These advantages were due to the moderate densities of PSW panels, which were lighter than the boards and greater than the insulators. The PSW panels with sufficient thickness showed R values that were ten times those of the boards, which were twice those of the insulators.

Conclusions

The insulation properties of PSW panels with a thickness of 96 mm were comprehensively investigated. A composite effect of low-density fiberboard core and plywood face was examined. The results were compared with those of commercial wood-based boards, solid wood, and commercial insulators.

As a result, the λ values for PSW350 and PSW400 with the respective densities of 340 and 410 kg/m^3 were 0.070 and 0.077 W/mK, respectively. Their D values were 0.00050 and 0.00046 m^2/h, and their R values were 1.4 and 1.2 m^{2}K/W, respectively. The PSW panels showed insulation properties that were superior to those of the boards, and showed warmth-keeping properties that were superior to those of the insulators, because of the moderate densities. The thermal resistances of PSW panels were superior to those of the boards and were equivalent to those of the insulators with thicknesses of about 50 mm.

The general trend is summarized as follows. The order for better thermal insulation is insulators > PSW > wood > boards, and that for better thermal resistance is PSW > insulators > wood > boards (their ratio was about 10:5:1:1) where the thickness ratio was 8:2:1:1, and that for better warmth-keeping properties is PSW = boards > wood > insulators.

For application of PSW panels to building construction, the thermal insulation performance should be investigated on a larger scale, considering parameters such as overall heat-transfer coefficient.[33] The manufacturing system used for the PSW panels was a pilot-scale operation, which had a narrow board-pressing space that was 300 mm wide. The system should be modified for practical panel production in the future.

It can be concluded that PSW panels have the characteristics of well-balanced thermal insulation and warmth-keeping properties (steady- and non-steady-states), which are important for insulation performance in that they maintain temperature and relax severe temperature changes in residences exposed to diurnal and seasonal temperature changes.

Modern-day wood is from tree species that have survived severe climate changes in the history of earth. Because of this, wood will play a greater role in building materials for humans in the future. As a building material, wood has the characteristics of being lightweight, very strong, and with good warmth-keeping properties. Optimizing these properties of wood, PSW panels were designed for structural insulated walls and floors. Because of the well-balanced thermal insulation and warmth-keeping properties, the PSW panels are expected to improve the degree of comfort and energy efficiency of our indoor environments and activities.

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