Thermal Conductivity and Volumetric Specific Heat of Low-Density Wooden Mats

Takashi Nakaya
Mariko Yamasaki
Satoshi Fukuta
Yasutoshi Sasaki

Abstract

Using wooden waste as insulation material benefits society by using waste products, reducing building thermal load, and sequestering carbon dioxide. In this study on heat insulating materials, a novel low-density wooden mat was fabricated from wood shavings and kenaf fibers. This research addressed the influences of fabrication conditions on the thermal conductivity and volumetric specific heat of the materials used. The raw materials (wood shavings and kenaf fibers) were mixed with a binder component, and the mixture was thermoformed. The thermal conductivity and volumetric specific heat of the mats were measured, and the influence of mixing ratio, density, and heat flux was evaluated. The results demonstrated that thermal conductivity was largely affected by the mat density and mixing ratio but was largely unaffected by changes in the heat flux. The volumetric specific heat of the mats was largely unaffected by the raw material mixing ratio but was greatly affected by the mat density. The tendency of the thermal conductivity decrease was changed according to the combination ratio of the wood shavings and the kenaf. The wood shavings are flake shaped and curled, and the kenaf is fibrous. It was thought that the internal void was made smaller effectively by mixing two different shaped fibers and the thermal conductivity was minimized. As a result, the thermal performance of the subject mats, as compared with glass wool, exhibited a slightly lower thermal insulation level and higher heat capacity. The results are important in improving efficiency and the commercial design of insulation materials.

Because of current global concerns regarding energy conservation and the environment, efficiency enhancements continue to be made to help to reduce electricity use in the housing sector. According to the fifth IPCC report (Intergovernmental Panel on Climate Change 2014), annual anthropogenic greenhouse gas emissions increased by 10 Gt CO_2 eq between 2000 and 2010, and part of this increase (3%) was from the building sector. In a baseline scenario the energy demand was estimated to approximately double, and a low carbon footprint of buildings is desired. In Japan, home energy consumption is increasing. Approximately 36 percent more energy was consumed in 2005 compared with 1990 (Building Research Institute 2015). The consumed energy, on average in Japan, is divided into 23.1 percent on heating and 2.2 percent on cooling (Agency for Natural Resources and Energy 2015). Use of insulation materials is important because these materials save energy by slowing heat loss from buildings. In Japan, thermal insulation performance of buildings is regulated by the ‘‘Save Energy’’ law (Ministry of Economy, Trade, and Industry 2015). Thermal insulation performance is calculated in the design phase. The Save Energy law also recommends improving thermal insulation performance for existing buildings. As such, the growing importance of insulating materials continues to be recognized.

In Japan, insulators based on inorganic fiber and foam account for 66 and 33 percent of the insulating materials

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The authors are, respectively, Assistant Professor, Dept. of Architecture, National Inst. Technol., Gifu College, Motosu, Japan (t-nakaya@gifu-nct.ac.jp [corresponding author]); Associate Professor, Graduate School of Bioagric. Sci., Nagoya Univ., Nagoya, Japan (marikoy@agr.nagoya-u.ac.jp); Assistant Researcher, Aichi Center for Industry and Sci. Technol., Industrial Research Center, Kariya, Japan (fukuta@aichi-inst.jp); and Professor, Graduate School of Bioagric. Sci., Nagoya Univ., Nagoya, Japan (ysasaki@nagoya-u.jp).
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used in construction, respectively (Nomura Research Institute 2014). Wood-based insulating materials, such as cellulose insulation, are not yet in use in Japan. Wood is a typical material used in building construction and possesses considerable carbon storage capabilities. Therefore, the development of building materials based on wood has attracted considerable attention over the years.

In Japan, 40 percent of wood used for making columns or boards becomes wood shavings; moreover, approximately 25 percent of these wood shavings goes to landfills, and the rest is usually incinerated. However, there are currently some industrial methods for recycling wood shavings. In particular, they are effective as heat insulating materials because of the pockets of air present between the wood fibers. Wooden insulation material is significant for building heat load reduction, creating carbon storage, and reducing energy consumption in disposal. Forests absorb carbon dioxide in the atmosphere and store it as carbon. By using wood as a building material, carbon can be sequestered for the longer term. At present most of it is disposed of, and the fixed carbon is released as CO_2 into the atmosphere after a short time or, worse, released as methane from landfills. Moreover, the incineration of planar scraps uses energy. By using it as an insulation material, energy that would have been used for disposal can be conserved.

Sekino et al. (2005) and Sekino and Yamauchi (2007) fabricated binder-less insulation mats from wood shavings and measured their thermal conductivity and thermal diffusivity. Kawasaki et al. (1998, 1999) and Kawasaki and Kawai (2006) developed low-density wooden fiberboards and reported their mechanical properties and thermal conductivity. Insulating materials made from agricultural waste such as rice-straw and rice chaff (Mizunuma et al. 2007), durian peel and coconut coir (Khedari et al. 2004), solid wastes from tissue paper manufacturing and corn husks (Lertsutthiwong et al. 2008), wheat straw (Zhou et al. 2004), bulking materials (Ahn et al. 2009), and kenaf core (Xu et al. 2004) have also been reported. For example, Kawamura et al. (2004) created binder-less wood chip insulation panels, measured their thermal conductivity (0.063 to 0.079 W/m·K), and suggested that wood-based fibers and agricultural waste products could effectively be used as heat insulating materials.

Thermal conductivity is the sum of the material's interior thermal conduction and heat radiation (Hager 1967). In order to reduce thermal conductivity, reducing internal cavities and controlling heat convection within the insulation mat is effective. Ohmura and Tomiura (2002) considered the relationship between the insulation material's mat density and thermal conductivity for rock wool, which is a mineral fiber material. By changing the mat density from 10 kg/m^3 to 90 kg/m, thermal conductivity was reduced from 0.050 to 0.036 W/m·K. Moreover, thermal conductivity, in addition to the density, is affected by the fiber diameter. In glass wool, thermal conductivity was 0.050 W/m·K for the fiber diameter of 0.05 mm at 10 kg/m^3. By thinning the fiber diameter (0.03 mm) and increasing the mat density (36 kg/m^3), thermal conductivity can be improved to 0.032 W/m·K (Aclear alfa, Asahi Fiber Glass Co. 2015).

Fukuta et al. (2010, 2012, 2014) developed a method for manufacturing mats from a mixture of wood shavings and kenaf fibers and reported their mechanical, sound absorption, and fireproofing properties. Wood shavings are curled fragments where large gaps can form. Hence, the addition of fiber-form kenaf was considered in order to reduce internal cavities and thermal conductivity. The sound absorption coefficient of the mat was found to be approximately equal to that of glass wool. Fiber-based acoustic materials generally contain many cavities, which enable them to function as heat insulating materials; therefore, these mats are also expected to offer superior heat insulation properties. Factors such as density, mixing ratio, and direction of heat flux may affect the thermal characteristics of these materials. Thus, the mat density, mixing ratio, and direction of heat flux should be considered when selecting a mat for suitable use in building construction applications.

In this study, the thermal conductivity and volumetric specific heat of low-density wooden mats were evaluated for each combination of mat density and mixing ratio. The effect of heat flux direction (i.e., vertical direction facing upward, vertical direction facing downward, and horizontal direction) on thermal conductivity was also investigated.

Materials and Methods

Specimens and experimental conditions

Figure 1 shows the raw materials used to prepare the subject insulating materials. Wood shavings shown in Figure 1a (W; Japanese cedar, *Cryptomeria japonica*) and kenaf fibers shown in Figure 1b (K; *Hibiscus cannabinus*) were used as raw materials. The mat was created by thermoforming the main material and submaterial with a binder. The main material (i.e., wood shavings) is Japanese cedar, and its specific gravity when dry is 0.35 to 0.40 g/cm^3. The Japanese cedar wood shavings were created by planing a Japanese cedar board. This forms curled flakes with a thickness of approximately 0.2 mm and length of approximately 5 to 20 mm. The submaterial is kenaf, and the specific gravity when dry is 0.14 g/cm^3 (Vick 1999). The fiber length was unified at 80 mm. Curled flakes create large voids, and it was hoped that the kenaf's long fibers could fill these cavities and reduce the thermal conductivity.

The raw materials were mixed with bicomponent fibers (Fukuta et al. 2010) and placed in a formwork (310 by 310 by 25 mm). Bicomponent fibers are composite fibers (engineered structural composites [ESC]; ES Fibervisions Co. Ltd.) with a cross section composed of two resins with different properties. ESC is composed of a polypropylene core with a polyethylene sheath. The fibers are used for production of filters, hardboard, and insulation. The sheath is composed of a resin with a melting point lower than that in the core; the fibers are welded together by heating them to a temperature at which only the sheath melts. The elements are composed of a combination of polyolefin-type resins such as polyethylene, polypropylene, and polyethylene terephthalate. After the mixture was heated to 160°C, pressure was applied to the mold to form the mixture into a mat. Because the water content affects the thermal conductivity and volumetric specific heat of the materials, we subsequently covered the entire surface of the mat with acrylic tape to keep it dry.

Factors that potentially affect thermal conductivity such as mixing ratio by weight, mat density, and heat flux direction were examined in this study. Five mixing ratios of wood shavings to kenaf fibers (wt/wt) were used: 95:0, 70:25, 47.5:47.5, 25:70, and 0:95. Moreover, the mixing ratio for the bicomponent fibers was set at 5 percent, and mat densities of 0.03, 0.05, and 0.08 g/cm^3 were used. In addition, as stated previously, the three measured heat flux directions were the

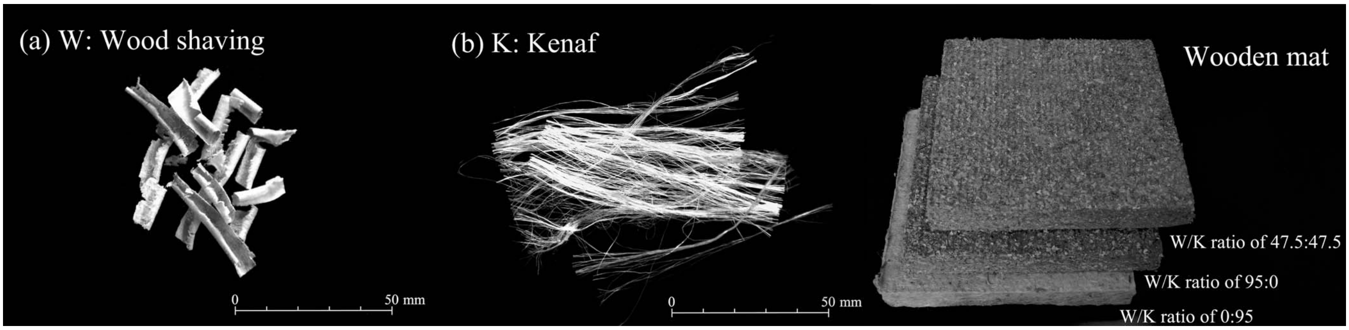

Figure 1.—Raw materials used as heat insulators: (a) wood shavings (W) and (b) kenaf fibers (K).

vertical direction facing upward, the vertical direction facing downward, and the horizontal direction.

Measurement method of thermal conductivity

Thermal conductivity (measured in watts per meter kelvin) is the rate of heat flow through a material per unit thickness per degree of temperature difference across the thickness. The measurement of thermal conductivity was based on the Japanese industrial standard (JIS 1999). The thermal conductivity was measured using a guarded hot-plate method. Figure 2a is a schematic showing the equipment used in thermal conductivity measurement. Hot and cold panels were set on each side of the specimen. An electric heater and the cold water circulation cooler were used to maintain the desired temperatures.

$$\lambda = \frac{\varphi}{A \cdot \left(\frac{\Delta T}{d}\right)}$$

where λ is the thermal conductivity (W/m·K), φ is the amount of electricity consumed (W), A is the area of the specimen (m^2), ΔT is the difference of each wide side specimen (K), and d is the thickness of the specimen (m).

The experiments were conducted in a temperature-controlled room regulated at 25°C. In addition, a low-temperature circulator (CH-202, AS ONE, Corp.) was used as the heat source on the low-temperature side, where temperature was maintained at 10°C. A sheet heating plate (Silicon rubber heater, 300 by 300 mm, AS ONE) was used as the heat source on the high-temperature side, where surface temperatures were maintained at one of three levels (20°C, 30°C, and 40°C) and were controlled by a voltage regulator (V-130-5, Yamabishi). The step-change of the surface temperature on the high-temperature side was made from 20°C to 30°C and from 30°C to 40°C. Each temperature increment was held for 8 hours to make a steady state. The measurement time at each condition was about 24 hours. For the thermal conductivity calculation, the data from

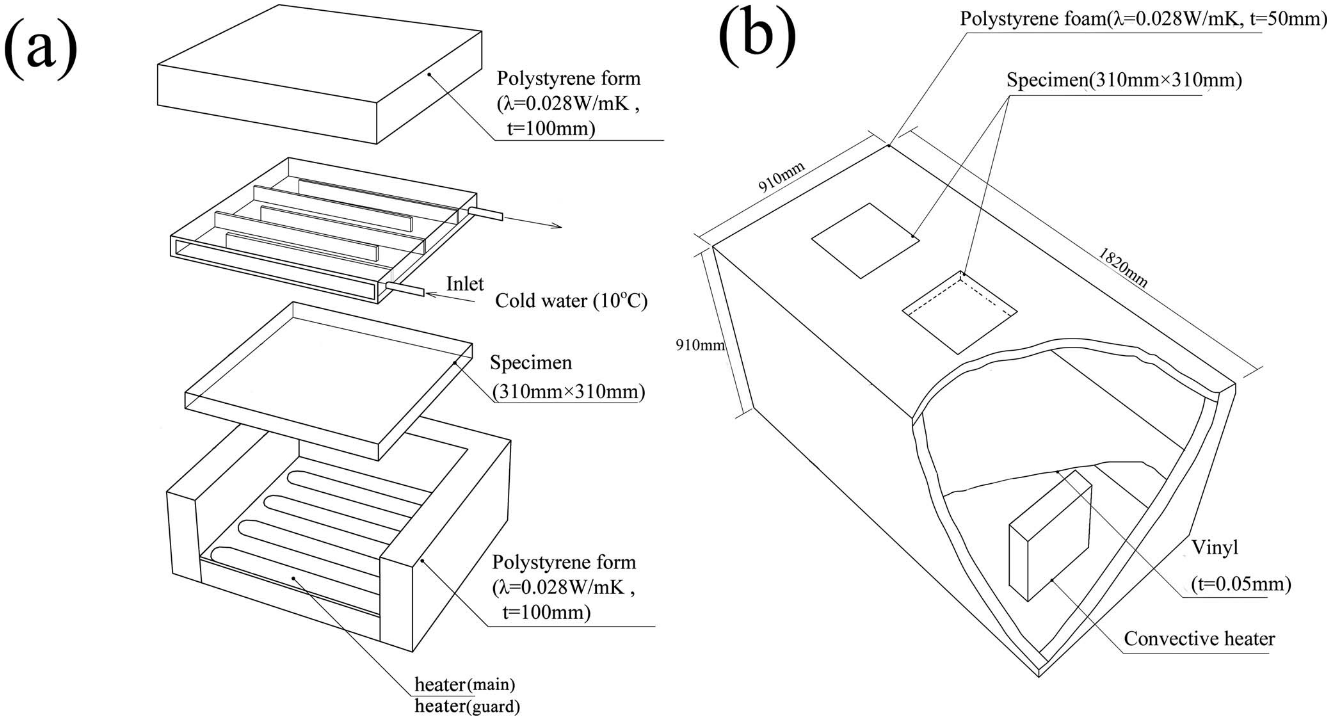

Figure 2.—Experimental equipment for measurements of (a) thermal conductivity and (b) volumetric specific heat.

the last 30 minutes at each temperature stage were used. The average thermal conductivity for temperatures of each phase within the three individual thermophases is the representative value. Two types of heaters were used: one was for direct heating, and the other was for thermal protection. The protection heater (Silicon rubber heater, AS ONE) was adjusted so that both heaters consistently maintained the same surface temperature. Furthermore, the peripheral area around the specimen was covered with heat insulating material (polystyrene foam, λ, 0.028 W/m·K; thickness, 100 mm).

The directions of heat flux were upward, downward, and horizontal as mentioned previously (Fig. 3); the directions were adjusted via rotation of the entire equipment array. For upward heat flux, the heating and cooling plates were configured on the bottom and upper sides in the vertical direction, respectively. For downward heat flux, they were configured inversely with the case of upward flow. For horizontal flow, the heating plate and a cooling plate were configured horizontally. The heat flux direction is from hot to cold. Measured parameters were temperature, amount of consumed electricity, and thickness and area of the specimen. Figure 4a shows an example of the observed time fluctuations in the electricity consumption and in surface temperature. The graph of the thermal conductivity is the comparison of the measured data between the surface temperatures on both sides of the specimens and the heat consumption of the heater. The specific heat is the analytical results of the measured data of the surface temperatures on both sides and the internal temperature of the specimen and the internal temperature.

Type ''T'' thermocouples were attached at three points on each wide side of the specimen, and the temperature was measured by using a data logger (8422-50, HIOKI). The total amount of electricity consumed by the heat source on the high-temperature side was measured by using a wattmeter (3166, HIOKI). The experiment was performed for three separate specimens for each individual condition. There were 45 experimental conditions (5 mixing ratios × 3 mat densities × 3 heat flux directions), resulting in a total of 135 data points (45 × 3).

Measurement method of volumetric specific heat

The volumetric specific heat (measured in joules per cubic meter kelvin) is the ratio of heat needed to change the

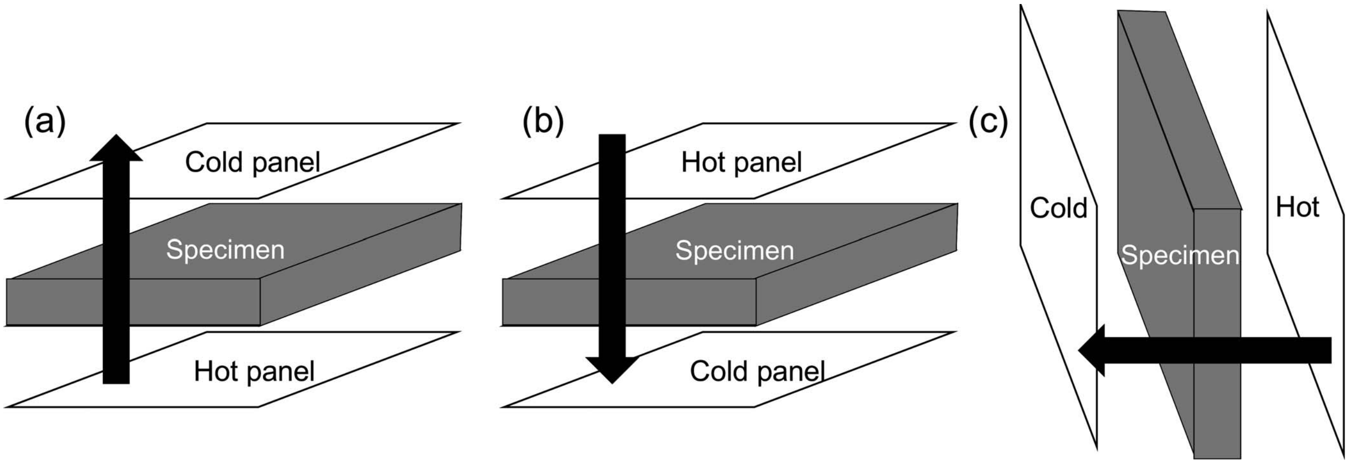

Figure 3.—The conceptual diagram of the heat flux direction in the thermal conductivity experiment: (a) up in vertical direction; (b) down in vertical direction; (c) horizontal direction. The heat flux direction is from hot to cold.

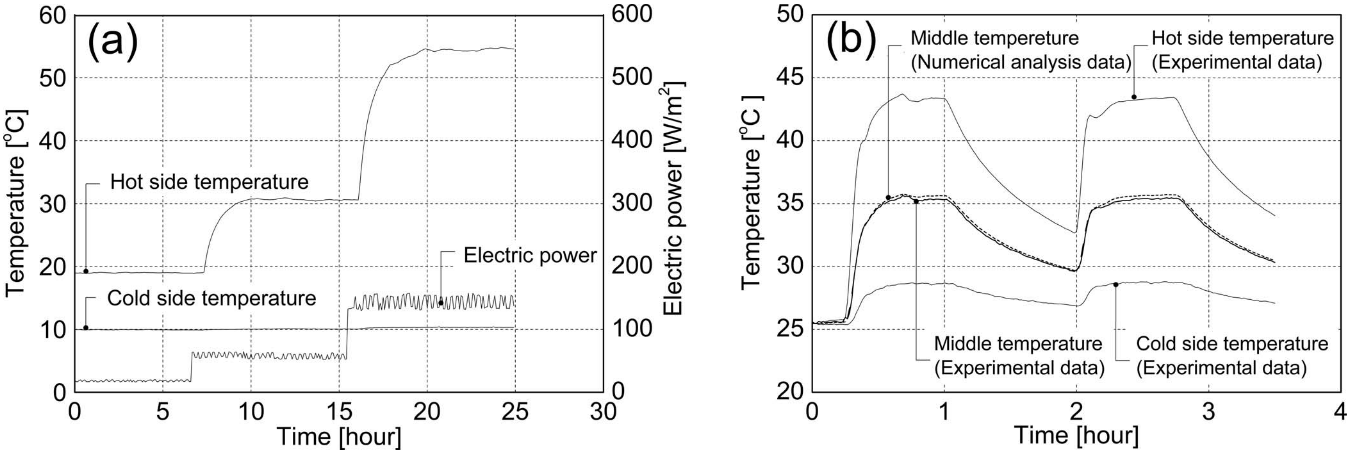

Figure 4.—The time dependence of the thermophysical property values in the experiment: (a) thermal conductivity; (b) volumetric specific heat.

temperature by 1 K per unit volume. The volumetric specific heat in the samples was also measured, because it is an important thermal characteristic; the techniques described in past research (Sekino et al. 2005, Yamasaki et al. 2008) were used to estimate this parameter (Fig. 2b). The testing equipment essentially consisted of a box, a heater, and the specimens. The box was prepared using heat insulating material (polystyrene foam, 0.028 W/m·K), and with a heater installed inside the box, temperatures were controlled using a thermostat (±0.1°C). Specimens were installed at three distinct positions on the upper part of the box. A vinyl sheet was placed between the heater and the specimens to protect the latter from direct hot-air exposure. Temperatures inside the box were varied from 25°C to 45°C. Surface temperatures of the specimens were measured on both sides, and internal temperatures were measured by an embedded thermocouple. The measured data of the surface temperature and air temperature at both sides were used in the boundary of the calculation model, and the internal temperature was calculated. Thermal diffusivity was estimated to ensure that the equations for one-dimensional thermal conduction would correspond to internal temperature distributions; these equations were therefore used by using the ''backward difference.'' Regarding the internal temperature at the nonstationary condition, the residual sum of squares was derived from the difference between the measured values and the analytical values. The time interval in the calculation was 60 seconds, and the lattice spacing was 0.001 m.

Figure 4b shows an example of the surface temperature and middle temperature measured values, as well as calculated values of the middle temperature. The measured and calculated values of the middle temperature were found to be nearly the same, indicating that it was possible to estimate thermal diffusivity with a high degree of accuracy. Volumetric specific heat, in turn, was derived by dividing the estimated thermal diffusivity by thermal conductivity. Subject experiments were performed for three specimens per individual condition. There were 15 total experimental conditions (5 mixing ratios × 3 mat densities) used, which resulted in a total of 45 separate data points.

Results and Discussion

Thermal conductivity

Table 1 lists the results for the subject thermal conductivity measurements. Figure 5a shows the relationship between the thermal conductivity and the mat density for all conditions, with the confidence interval (95%) duly emphasized. When the value of the thermal conductivity is lower, the heat flux is smaller and the thermal insulation performance is better. The mean thermal conductivity for all measurement conditions was found to be 0.069 W/m·K (SD = 0.005). When the thermal conductivity was lowest (0.061 ± 0.002 W/m·K), the mat density was 0.078 g/cm^3, and the mixing ratio was 25:70. In this study, the measurement value of the thermal conductivity was higher than Fukuta's result (Fukuta et al. 2010); this is thought to be due to the measuring environment (i.e., the test object used had the mat placed into the test box; Fukuta et al. 2010). The box used for the present study, however, had thermal insulating materials on the sides and a thin metal plate at the thermal passage surface. It contained virtually no gaps, and it could be filled evenly to realize ideal conditions. On the other hand, presuming the actual usage condition, our protocol entailed the direct measurement of the mat itself. Accordingly, the density dispersions and small cracks in the mat may have contributed to the higher measured thermal conductivity rate. For example, in the study conducted by Kawamura et al. (2004) for the thermal conductivity of wood chip panels, the thermal conductivities of mats made from Japanese cedar trees (0.12 g/cm^3) and of mats made from larch (0.135 g/cm^3) were 0.068 and 0.071 W/m·K, respectively. The thermal conductivities obtained in the present study were very similar to those reported for the wood chip panels in Kawamura et al. (2004).

The effect of convective heat transfer inside the mats on the thermal conductivity was also investigated. Characteristic linear regression lines were compared by analysis of covariance (ANCOVA) using SPSS statistical software.

Table 1.—Results of measurements of thermal conductivity (λ) and volumetric specific heat (C).[a]

Mixture ratio by weight		Measurement of λ			Measurement of *C*		
Condition	W:K:B	No. of specimens	Density (g/cm^3)	λ (W/mK)	No. of specimens	Density (g/cm^3)	*C* (kJ/m^3·K)
No. 1	0:95:5	9	0.046 (0.005)	0.075 (0.006)	3	0.034 (0.005)	148 (37)
		9	0.052 (0.006)	0.072 (0.004)	3	0.042 (0.006)	121 (24)
		9	0.062 (0.002)	0.066 (0.001)	3	0.068 (0.014)	165 (76)
No. 2	25:70:5	9	0.037 (0.005)	0.069 (0.002)	3	0.038 (0.004)	124 (60)
		9	0.055 (0.005)	0.068 (0.002)	3	0.046 (0.007)	136 (46)
		9	0.078 (0.008)	0.061 (0.002)	3	0.069 (0.004)	175 (10)
No. 3	47.5:47.5:5	9	0.035 (0.003)	0.064 (0.003)	3	0.037 (0.003)	144 (61)
		9	0.046 (0.004)	0.067 (0.003)	3	0.048 (0.004)	150 (17)
		9	0.068 (0.007)	0.064 (0.002)	3	0.069 (0.003)	229 (55)
No. 4	70:25:5	9	0.042 (0.004)	0.071 (0.005)	3	0.033 (0.002)	119 (14)
		9	0.050 (0.005)	0.072 (0.003)	3	0.039 (0.004)	126 (24)
		9	0.070 (0.006)	0.069 (0.003)	3	0.063 (0.003)	206 (60)
No. 5	95:0:5	9	0.039 (0.004)	0.076 (0.004)	3	0.032 (0.001)	124 (25)
		9	0.053 (0.004)	0.074 (0.003)	3	0.041 (0.005)	121 (9)
		9	0.071 (0.004)	0.073 (0.004)	3	0.045 (0.002)	135 (14)

[a] The values of λ, *C*, and density represent the average values of sample mats, and the values in parentheses represent the standard deviations. W = wood shavings; K = kenaf fibers; B = biocomponent fibers.

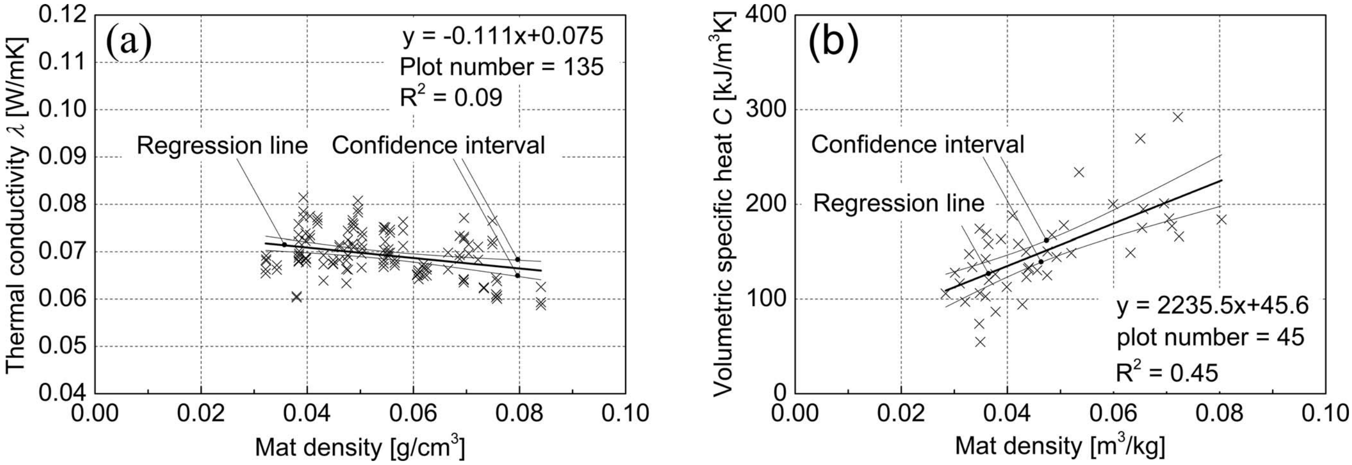

Figure 5.—Correlation between density and thermal properties: (a) thermal conductivity; (b) volumetric specific heat. Experimental data points are shown as crosses.

From the ANCOVA we found that as the mat densities covaried, the thermal conductivity was found to be independent of the direction of heat flux by the mixing ratios 95:0, 70:25, 47.5:47.5, 25:70, and 0:95 (ANCOVA, *P* = 0.878, 0.064, 0.462, 0.952, and 0.482, respectively). Therefore, the convective heat transfer inside the mat had little, if any, effect on the direction of heat flux. Thus, the additional discussion below focuses on thermal conductivity experimental data without consideration of heat flux direction.

As discussed above, the effects of mat density and mixing ratio on thermal conductivity were investigated; the estimated thermal conductivity is shown in Figure 6a. To estimate the thermal conductivity of the mat densities (0.04, 0.05, 0.06, 0.07, and 0.08 g/cm^3), the subject density values were used in linear regression equations for denoting the quantitative relationship between the mat density and thermal conductivity of each mixing ratio. These equations were, in totality, derived by using the mat densities and thermal conductivity obtained from this research study's experimental results. The results were subjected to a linear regression analysis, with a negative correlation between thermal conductivity and mat density being found. Thermal conductivity was affected by the mixing ratio of wood shavings and kenaf, even when the mat density remained the same. The insulation properties of mats produced from the mixture of kenaf fibers and wood shavings were better than those produced from wood shavings alone. For example, the thermal conductivity of pure wood shavings (W/K ratio of 95:0, 0.08 g/cm^3) was 0.071 W/m·K, whereas that of a mixture of equal amounts of wood shavings and kenaf (W/K ratio of 47.5:47.5, 0.08 g/cm^3) was noticeably lower (0.064 W/m·K). Specifically, when comparing mixing ratios in terms of the degree of reduction in thermal conductivity owing to increasing density, thermal conductivity was found to decrease in the following order of mixing ratios: (W/K ratio of 0:95) > (W/K ratio of 25:70) > (W/K ratio of 95:0) > (W/K ratio of 70:25) > (W/K ratio of 47.5:47.5). Furthermore, thermal conductivity greatly decreased when the amount of kenaf was greater than that of wood shavings.

In conclusion, thermal conductivity was largely affected by the mat density and mixing ratio but was largely unaffected by changes in the direction of heat flux. Furthermore, the insulating performance of the material consisting of wood shavings and kenaf was higher when compared with that of wood shavings alone. When the kenaf

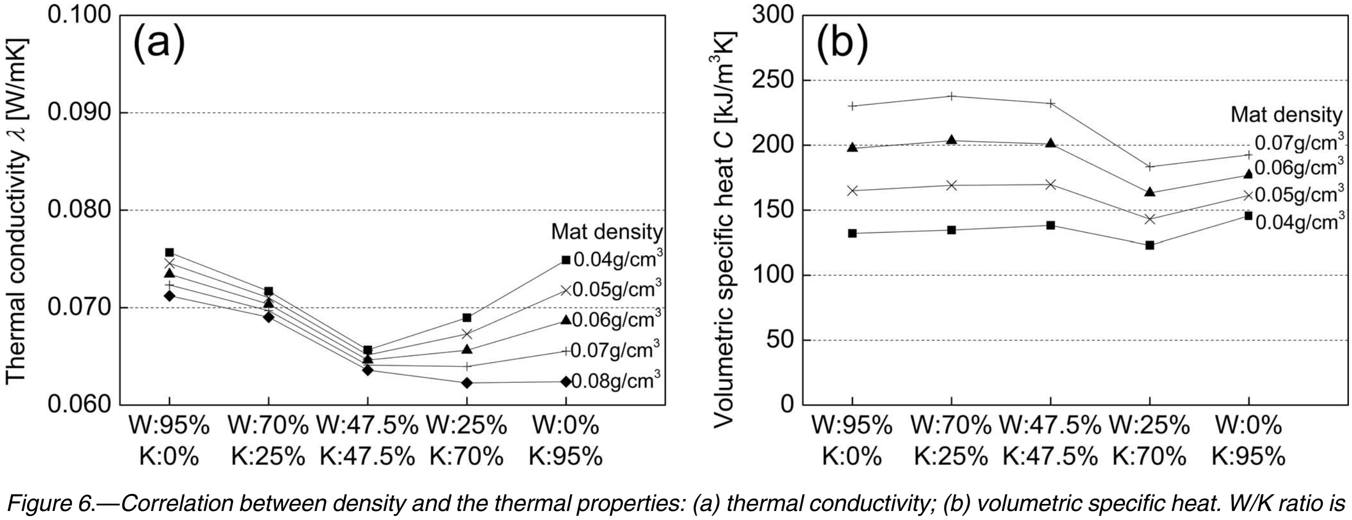

Figure 6.—Correlation between density and the thermal properties: (a) thermal conductivity; (b) volumetric specific heat. W/K ratio is the weight compounding ratio.

content was greater than that of the wood shavings, the thermal conductivity significantly fluctuated with variations in mat density.

Volumetric specific heat

Table 1 lists the volumetric specific heat for each mixing ratio and mat density, while Figure 5b shows the relationship between volumetric specific heat and mat density for all conditions, with the confidence interval (95%) duly emphasized. When the specific heat value is larger, the heat capacity is larger, the temperature change becomes smaller, and the heat reserving volume becomes larger. The mean volumetric specific heat for all measurement conditions was found to be 150 kJ/m^3·K (SD = 46 kJ/m^3·K). A positive correlation was observed between the mat density and volumetric specific heat for all mixing conditions. The highest volumetric specific heat (229 ± 55 kJ/m^3·K) was observed at a mat density of 0.069 g/cm^3 and a mixing ratio (W/K ratio) of 47.5:47.5. Sekino and Yamauchi (2007) reported that the volumetric specific heat of spruce wood (density, 0.50 g/cm^3), wooden fiberboard (density, 0.26 g/cm^3), and glass wool (density, 0.04 g/cm^3), which is an inorganic fibrous insulating material, were 734, 316, and 34 kJ/m^3·K, respectively. The measured volumetric specific heat in this present study was lower than the previously reported values because the specimens, as a whole, had lower mat densities. However, the mean volumetric specific heat of the specimens evaluated in this study was five times greater than that of glass wool.

The combined effect of mat density and mixing ratios of raw materials on volumetric specific heat was also investigated. Mat densities (0.04, 0.05, 0.06, 0.07 g/cm^3) were substituted into the linear regression equations used, and each respective volumetric specific heat value was determined. As shown in Figure 6b, the volumetric specific heat varied notably according to mat density. Moreover, the effect of mixing ratio on volumetric specific heat was investigated. Linear regression lines were compared by ANCOVA. It was found that as the mat densities covary, volumetric specific heat values are independent of the mixing ratios (ANCOVA, $P = 0.552$). Therefore, it was concluded that the volumetric specific heat of the mats was largely unaffected by the raw material mixing ratio but was greatly affected by the mat density.

Conclusions

The aim of this research was to examine the factors affecting the thermophysical properties of insulation mats made from wood shavings. Thermal conductivity and specific heat were the thermophysical properties considered. Factors considered are the mixing ratio of the main material, submaterial, and mat density. The impact of heat flux direction on the thermal conductivity was also considered.

The thermal conductivity and volumetric specific heat of low-density mats was measured. The mean thermal conductivity for all measurement conditions was found to be 0.069 W/m·K (SD = 0.005 W/m·K). The thermal conductivity was lowest (0.061 ± 0.002 W/m·K) when the mat density was 0.078 g/cm^3 (W/K ratio of 25:70). The variation of thermal conductivity as a function of mat density decreased when wood shavings were added to kenaf. Moreover, the relationship between mat density and thermal conductivity for each heat flux direction (horizontal, upward, and downward) was examined by ANCOVA. It was found that convective heat transfer within the insulating fibers had almost no effect on thermal conductivity because there was no discernible difference in thermal conductivity detected between the different directions of heat flux. Thermal conductivity was, however, noticeably affected by two factors: density and mixing ratio.

The mean volumetric specific heat of the low-density mats under all measurement conditions was 150 kJ/m^3·K (SD = 46 kJ/m^3·K), with the mat densities and volumetric specific heat found to exhibit a consistently positive correlation. The volumetric specific heat was highest (229 ± 55 kJ/m^3·K) when the mat density was 0.069 g/cm^3 (W/K ratio of 47.5:47.5). ANCOVA was used to show that as the mat densities covary, volumetric specific heat was found to be independent of mixing ratio. The volumetric specific heat of the mats was largely affected by one factor, the mat density, and was largely unaffected by the mixing ratio of the raw materials.

In this research, the effectiveness of mixing fibers with wood shavings as well as increasing the mat density in order to improve the insulation performance of the mat has been shown. These results are important for future insulation development. The thermal conductivity of the wood shaving mat found in this research was higher than the standard required in JIS and so must be improved. In order to understand the conditions that reduce the thermal conductivity, we will investigate the mat densification using thermal conductivity estimation models in future research. The mat is of higher density compared with the range in this experiment. Additional material other than kenaf fiber is also considered.

Future research to construct a model for evaluating mat thermal conductivity is planned. The causes of the compounding ratio, as well as density wielding influences on thermal insulation performance, will be examined. The necessary factors for improving overall insulation performance based on the evaluation model will also be investigated.

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