Thermal Conductivity of Low-Density Wood Composite Mats

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Abstract

In order to effectively use the waste produced during lumber sawing, the thermal conductivities of wood composite mats shaped by thermoforming and composed of wood shavings, kenaf fibers, and binders were examined by assuming a one-dimensional heat transfer process that could be described by the sum of its heat conduction and radiation components. To improve the heat-insulating properties of the mats, various types of auxiliary raw materials were examined. Mat density depended on the volumetric ratio of the air layer inside the mat to the fiber layer. In the low-density region, increasing the mat density decreased the magnitude of the radiation component and thus the thermal conductivity of the mat, whereas in the high-density region, increasing the mat density increased the value of the conduction component, which in turn enhanced the thermal conductivity of the mat. The minimum value of the thermal conductivity obtained under all experimental conditions is 0.062 W/m·K. Thus, it is difficult to decrease the thermal conductivity of the mat below 0.060 W/m·K by varying its density and mixing ratio. The utilized model predicted that mat thermal conductivity would be less than 0.060 W/m·K if the fibers with a density similar to that of Japanese cedar wood (0.40 g/cm^3) were used.

A social demand for saving energy in the construction sector has been steadily increasing due to global warming concerns (Intergovernmental Panel on Climate Change 2014). In particular, thermal insulation materials can be used to reduce energy consumption and relieve the thermal stress experienced by residents. Unlike the widely used inorganic- and mineral-based fiber composites, wood-based fiber insulation materials represent a relatively small fraction of the lumber market. However, thermal insulation for wood composites has attracted significant attention due to its excellent environment-friendly properties (such as long-term carbon dioxide storage ability) and reduced energy consumption of buildings.

Fukuta et al. (2010, 2012, 2014) have developed the thermal insulation mat using wood shavings as the main material, which was subsequently thermoformed by the addition of kenaf fibers. Nakaya et al. (2016) measured the thermal conductivities and volumetric specific heats of wood composites with low densities of 0.03 to 0.08 g/cm^3. The mean thermal conductivity calculated at different measurement conditions was 0.069 W/m·K, and its lowest value (0.061 W/m·K) was obtained at a mat density of 0.078 g/cm^3 (corresponding to a wood:kenaf [W:K] ratio of 25:70). In general, the thermal conductivity of the mats was strongly affected by their density and mixing ratio.

Generally, the heat transfer inside fiber insulation materials occurs via convection, conduction, or radiation paths (Hager and Steere 1967). Fujimoto and Niwa (1989) studied wool and polyester fibers, and Ohmura and Tomiura (2002) investigated insulation materials based on mineral fibers. Both groups found that increasing the density of fibrous insulation reduced the magnitude of the radiation component and increased heat conduction. Ohmura and Tomiura (2002) used the corrected Rayleigh number to show theoretically that the air gap inside the studied fibrous materials was very small and thus had not affected the convective heat transfer inside the mat. Nakaya (2016) investigated the thermal conductivity of wood fiber insulation materials by performing linear regression analysis of mat density and thermal conductivity at various directions of heat flow. The results of covariance analysis revealed that the heat flow direction did not affect the thermal conductivity of the mats, while the influence of the convective heat transfer process was relatively small.

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Therefore, the heat transfer inside fiber insulation materials can be modeled as the sum of its conduction and radiation components.

To estimate the heat conduction component, Hager and Steere (1967) modeled it as the sum of the thermal resistances of the fiber and air layers, while the radiation component was investigated in the works of Hager and Steere (1967) and Li et al. (1997). It was found that the thermal conductivity of fibers could be predicted from their physical properties by performing theoretical studies of the radiation heat transfer process. However, the calculation model utilized for evaluating the radiation component was very complex and required knowing individual radiation characteristics of the fibers. Since wood-based thermal insulation materials are fabricated from manufacturing waste, the dispersion of characteristic values for each individual fiber is large, making their precise estimation very difficult.

In this study, we investigated the thermal conductivities of wooden mats fabricated from scrap wood waste as the main material. The heat transfer processed inside the mat is modeled as the sum of its conduction and radiation components, assuming that the internal convection component is equal to zero. The magnitude of each component was estimated by subtracting the heat conduction and radiation components from the measured thermal conductivity, and the ratio between the heat transfer inside the mat and its thermal conductivity was determined. Finally, possible ways of improving the thermal insulating performance of the mat were examined by varying the fiber density of the secondary material.

Materials and Methods

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 is Japanese cedar, and its specific gravity when dry is 0.35 to 0.40 g/cm^3. These form 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. The raw materials were mixed with bicomponent fibers (engineered structural composites; ES Fibervisions Co. Ltd). Engineered structural composites are composed of a polypropylene core with a polyethylene sheath. 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. After the mixture was heated to 160°C, pressure was applied to the mold to form the mixture into a mat.

Factors that potentially affect thermal conductivity, such as mixing ratio by weight and mat density, 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.

Measurement method of thermal conductivity

Thermal conductivity is the rate of heat flux through a material per unit thickness per degree of temperature difference across the thickness. The measurement of thermal conductivity was based on Japanese industrial standard JIS 1412-1 (Japanese Standards Association 1999). The thermal conductivity was measured using a guarded hotplate method. 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 in surface temperature on both sides of the 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, or 40°C) and were controlled by a voltage regulator (V-130-5; Yamabishi). 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

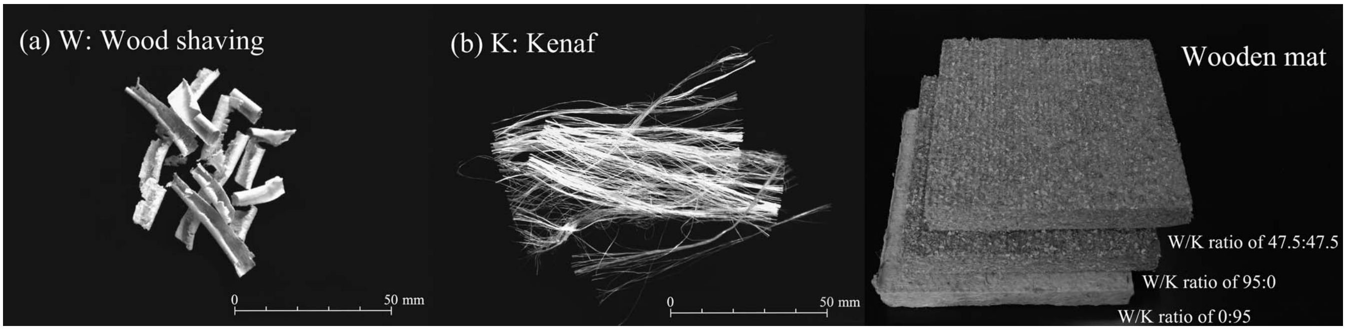

Figure 1.—Raw materials used as thermal insulators: (a) wood shavings and (b) kenaf fibers.

adjusted so that both heaters consistently maintained the same surface temperature. Furthermore, the peripheral area around the specimen was covered with thermal insulating material (polystyrene foam, $\lambda = 0.028$ W/m·K; thickness = 100 mm).

Analytical model

The model recommended by Hager and Steere (1967) was used to estimate the thermal conductivity of the mats fabricated in this study. It assumes that the solids consisting of fibers (hereafter referred to as the ''fiber layers'') and air between the fibers (hereafter referred to as the ''air layers'') inside a fibrous thermal insulating material are stacked along the direction of the heat flux and that the thermal resistance of the entire mat is the sum of the thermal resistances of the air and fiber layers. However, because the Hager and Steere model analyzes the thermal insulating materials consisting of only one type of fiber, the model was expanded to include composite materials as well. The thermal conductivity of the entire mat contains the following components:

1. The conductive heat transfer of the fiber and air layers
2. The radiative heat transfer of the air layers between the fibers
3. The convective heat transfer of the air layers between the fibers

Moreover, Nakaya (2016) examined the relationship between mat density and thermal conductivity at different heat flux directions (corresponding to the horizontal, upward, and downward ones) by performing an analysis of covariance. As a result, no statistically significant correlation between the direction of heat flux and thermal conductivity was observed. The obtained results suggest that the convective heat transfer inside the mat (C) was relatively small. Therefore, the thermal conductivity of the entire mat (λ_{mat}, W/m·K) was estimated as the sum of the conductive heat transfer of the fiber and air layers (A; λ_{con}) and radiative heat transfer (B; λ_{rad}):

$$\lambda_{mat} = \lambda_{con} + \lambda_{rad} \quad (1)$$

Hager and Steere (1967) proposed the use of the following equations for estimating λ_{con}:

$$\lambda_{con} = \frac{\lambda_{air}}{1 - f_{mat} + \left(\frac{\lambda_{air} \cdot f_{mat}}{\lambda_m}\right)} \quad (2)$$

$$f_{mat} = \frac{\rho_m}{\rho_{mat}} \quad (3)$$

where f_{mat} is the volume fraction of the fibers, λ_{air} (W/m·K) is the thermal conductivity of air, $\lambda_{con(\mathrm{W})}$ is the thermal conductivity of the wood, $\lambda_{con(\mathrm{K})}$ is the thermal conductivity of the kenaf fibers, ρ_m (g/cm^3) is the density of the wood or kenaf, and ρ_{mat} (g/cm^3) is the density of the entire mat. In this work, the thermal conductivity of air, λ_{air}, was set to 0.03164 W/m·K (Li et al. 1997). The thermal conductivities of both the Japanese cedar ($\lambda_{con(\mathrm{W})}$) and kenaf ($\lambda_{con(\mathrm{K})}$) were 0.12 W/m·K (Building Research Institute 2013). The density of the Japanese cedar, $\rho_{m(\mathrm{W})}$, was 0.38 g/cm^3, and the density of kenaf, $\rho_{m(\mathrm{K})}$, was 0.14 g/cm^3 (Webber and Dole 1999). The density of air was set to zero.

Thermal resistance (R value) was calculated according to the following equation:

$$\begin{cases} \lambda_{mat} = x/R_{mat} \\ \lambda_{con} = x/R_{con} \\ \lambda_m = x/R_m \\ \lambda_{air} = x/R_{air} \end{cases} \quad (4)$$

where x (m) is the mat thickness, R_{mat} (m^2·K/W) is the R value of the mat, and R_{con} (m^2·K/W) is the component of the conductive heat transfer process; R_m (m^2·K/W) is the R value of the fiber materials, and $R_{m(\mathrm{W})}$, $R_{m(\mathrm{K})}$, and R_{air} (m^2·K/W) are the R values of air. Equation 2 may be rewritten as follows:

$$R_{con} = f_{air} \cdot R_{air} + f_m \cdot R_m$$

$$R_{con} = (1 - f_m) \cdot R_{air} + f_m \cdot R_m \quad (5)$$

Here, Equation 5 describes the R value of a single-fiber material. In this work, it was expanded to make it suitable for composite materials:

$$f_{air} + f_{m(\mathrm{W})} + f_{m(\mathrm{K})} = 1$$

$$R_{con} = (1 - f_{m(\mathrm{W})} - f_{m(\mathrm{K})})R_{air} + f_{m(\mathrm{W})} \cdot R_{m(\mathrm{W})} + f_{m(\mathrm{K})} \cdot R_{m(\mathrm{K})} \quad (6)$$

where $f_{(\mathrm{W})}$ is the volume fraction of wood shavings and $f_{(\mathrm{K})}$ is the volume fraction of kenaf fibers. The magnitude of R_{con} calculated via Equation 6 was used to determine λ_{con}, which was substituted into Equation 1 to estimate λ_{rad}. In this study, the lower limit of λ_{rad} was set to 0.005 W/m·K.

Results and Discussion

Experimental data

In this report, an estimation model was created based on the measurement result of thermal conductivity by Nakaya et al. (2016). Table 1 shows the measurement results of thermal conductivity. 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.

Effect of fiber content

The correlations between the volume fractions of the air and fiber layers and the fiber density were determined using Equation 3 (Fig. 2). Figures 2a and 2b show the results obtained for the high (W:K ratio = 70:25) and low (W:K ratio = 25:70) amounts of wood shavings, respectively. In both cases, the volume occupied by the fibers (containing both wood shavings and kenaf fibers) increased, and the fraction of the air layer decreased with increasing mat density. The volume fraction of the fiber layer shown in Figure 2a was smaller than that depicted in Figure 2b, while the volume of air plotted in Figure 2a was higher than that shown in Figure 2b because of the larger density of wood shavings.

Heat transfer path

Figure 3 shows the relationships between the mat density and its thermal conductivity determined both experimentally

Table 1.—Results of measurements of thermal conductivity (λ).[a]

Mixture ratio by weight (%) W:K:B	Board density (g/cm^3)	Measurement of λ (W/m·K)
0:95:5	0.046 (0.005)	0.075 (0.006)
	0.052 (0.006)	0.072 (0.004)
	0.062 (0.002)	0.066 (0.001)
25:70:5	0.037 (0.005)	0.069 (0.002)
	0.055 (0.005)	0.068 (0.002)
	0.078 (0.008)	0.061 (0.002)
47.5:47.5:5	0.035 (0.003)	0.064 (0.003)
	0.046 (0.004)	0.067 (0.003)
	0.068 (0.007)	0.064 (0.002)
70:25:5	0.042 (0.004)	0.071 (0.005)
	0.050 (0.005)	0.072 (0.003)
	0.070 (0.006)	0.069 (0.003)
95:0:5	0.039 (0.004)	0.076 (0.004)
	0.053 (0.004)	0.074 (0.003)
	0.071 (0.004)	0.073 (0.004)

[a] The values of λ 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 = bicomponent fibers.

and theoretically. Figure 3a describes the results obtained for the high content of wood shavings (W:K ratio = 70:25), and Figure 3b contains the data plotted for the low amount of wood shavings (corresponding to a W:K ratio of 25:70). The thin solid lines in the figures represent the experimental mat densities, and the dotted lines depict the predicted density values. The thermal conductivities plotted in these figures include the thermal conductivity of the entire mat (λ_{mat}), the thermal conductivity component of the conductive heat transfer (λ_{con}), and the thermal conductivity component of the radiative heat transfer (λ_{rad}). Under the conditions used in this study, λ_{mat} was measured experimentally, and the magnitudes of λ_{con} and λ_{rad} were estimated using Equations 6 and 1, respectively. For the density values higher than the experimental ones (denoted with the ' symbol), the magnitude of λ'_{mat} was estimated from λ'_{con} and λ'_{rad}.

According to the results presented in Figures 3a and 3b, as the mat density increased, the values of λ_{rad} and λ_{con} decreased and increased, respectively. Because the volume fraction of air decreased with increasing mat density (see Fig. 2) and the value of λ_{air} was very small, λ_{con} increased with an increase in the mat density. However, this increase in λ_{con} was compensated for by the decrease in λ_{rad}. Since the decrease in λ_{rad} was larger than the increase in λ_{con}, the magnitude of λ_{mat} decreased as well. In addition, the value of λ_{rad} has not reached the preset lower limit of conductivity (0.005 W/m·K), as shown in Figures 3a and 3b.

The data displayed in Figures 3a and 3b were compared to examine the influence of the fiber material on the heat transfer path. Thus, the values of λ_{con} shown in Figure 3a were smaller than those presented in Figure 3b, although the opposite trend was observed for λ_{rad}. At a W:K mixing ratio of 70:25 (Fig. 3a), the volume fraction of air was higher (Fig. 2a) because of the higher content of wood shavings; as a result, the corresponding value of λ_{con} was lower. Since the wood shavings have the large void ratio, the magnitude of λ_{rad} increased with an increasing W:K ratio. When the amount of wood shavings was high (Fig. 3a), λ_{mat} decreased with increasing mat density because of the decrease in λ_{rad}. On the other hand, when the kenaf content was high (Fig. 3b), the mat density and thermal conductivity exhibited a negative correlation at mat densities of 0.09 g/cm^3 or smaller (as the mat density increased, its thermal conductivity decreased). However, as the mat density increased to higher values, the thermal conductivity started to increase as well because the magnitude of λ_{rad} reached the lower limit at a density of about 0.09 g/cm^3. Therefore, above this mat density, the influence of the λ_{con} component becomes dominant, which increases the thermal conductivity of the mat.

Figure 4a shows the experimental result on the effect of mat density and mixing ratio on thermal conductivity. For each mixing ratio, the relationship between mat density and thermal conductivity was linearly approximated. The thermal conductivity corresponding to the mat density of

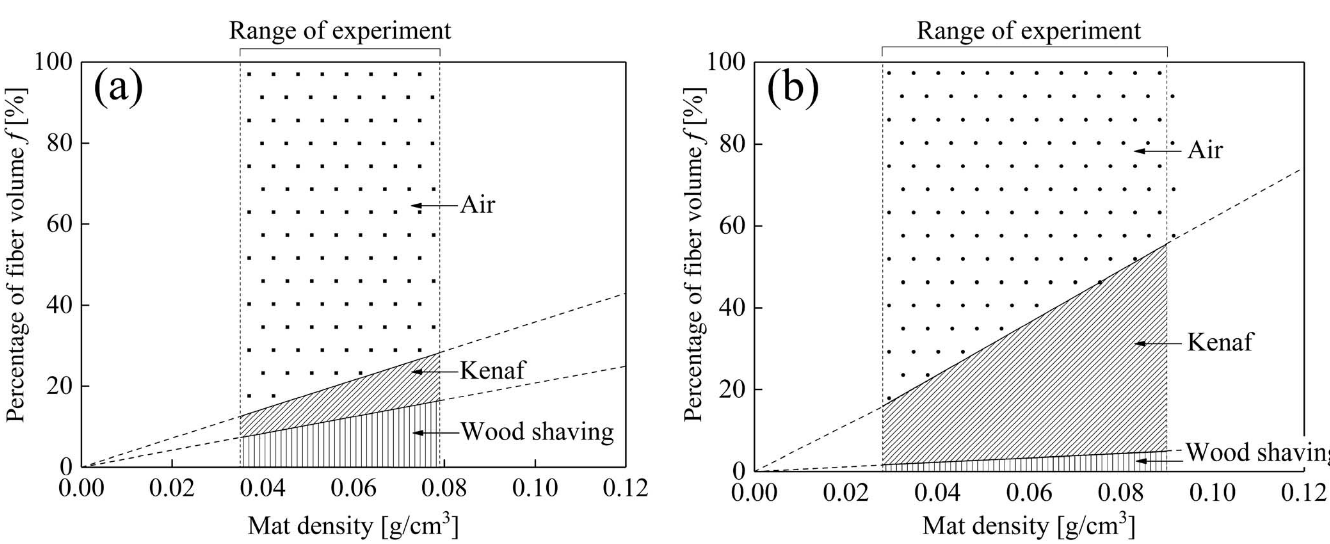

Figure 2.—Correlations between the mat density and the volume fractions of air and fibers: (a) wood shavings (W):70%, kenaf fibers (K):25%, and (b) W:25%, K:70%.

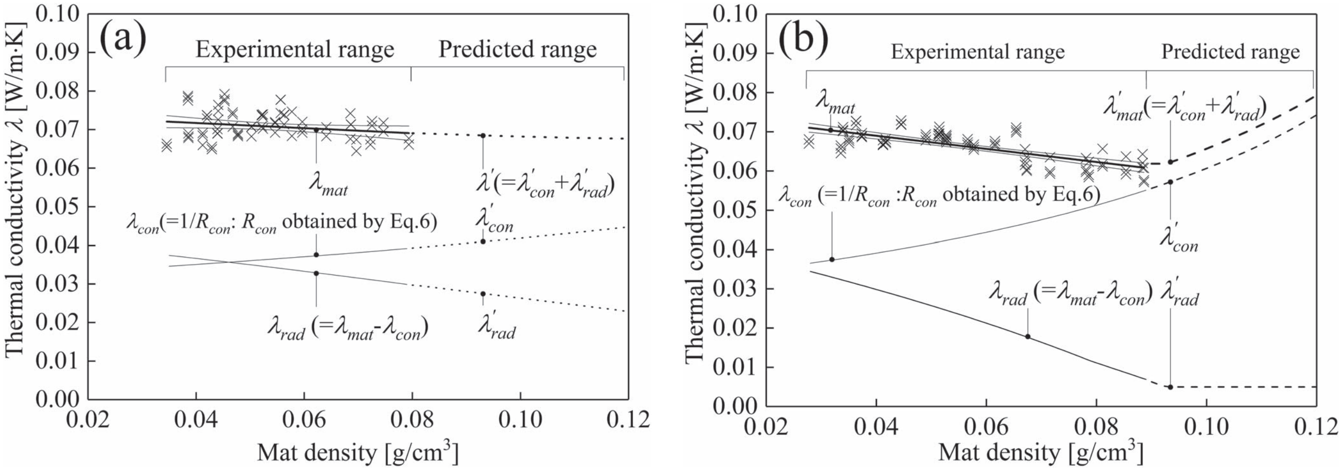

Figure 3.—Correlations between the density and thermal conductivity of the mats calculated using the theoretical model: (a) wood shavings (W):70%, kenaf fibers (K):25%, and (b) W:25%, K:70%. λ_{mat} = *measured values of the thermal conductivity of the entire mat;* λ'_{mat} = *predicted values of the thermal conductivity;* λ_{con} *and* λ'_{con} = *experimental and predicted thermal conductivities due to thermal conduction, respectively;* R_{con} = *thermal resistance; and* λ_{rad} and λ'_{rad} = *experimental and predicted thermal conductivities due to thermal radiation, respectively.*

0.04 to 0.08 g/cm^3 was determined. 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 due 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, and 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.

Figure 4b shows the estimation result of the thermal conductivity determined from the relationships between the thermal conductivity and the mat density obtained at various mixing ratios and densities exceeding the experimental ones. The measured thermal conductivity of the low-density wood chip mats with a density of 0.12 g/cm^3 fabricated from the Japanese cedar was 0.068 W/m·K (Kawamura et al. 2004). In the present study, the theoretical model used for predicting thermal conductivity values produced a value of 0.067 W/m·K at a mat density of 0.12 g/cm^3 (corresponding to a W:K ratio of 95:0), as shown in Figure 4b. This result is very similar to the data reported by Kawamura et al. (2004), suggesting that the proposed model is characterized by a sufficient level of accuracy.

Table 2 shows the relationship between mat density, components of heat transfer, and thermal conductivity. Thermal conductivity increased with an increase in mat density when the fraction of kenaf fibers was high. In particular, the largest values of thermal conductivity were

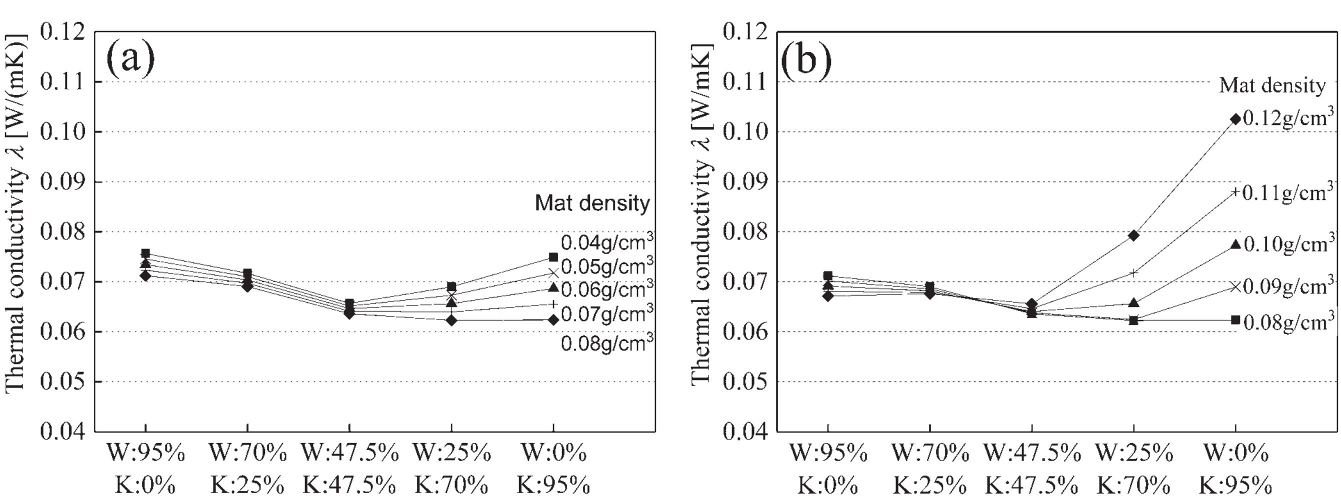

Figure 4.—Correlation between density and the thermal conductivity: (a) experimental data and (b) estimation result. W = wood shavings; K = kenaf fibers. Note: The W:K ratio is the weight compounding ratio.

Table 2.—Estimation result of relationship between mat density, heat transfer component, and thermal conductivity.[a]

Mixture ratio by weight (%) W:K:B	Mat density (g/cm^3)	Conductive heat transfer, λ_{con} (W/m·K)	Radiative heat transfer, λ_{rad} (W/m·K)	Estimation of λ_{mat} (W/m·K)
0:95:5	0.04	0.041	0.034	0.075
	0.06	0.048	0.021	0.069
	0.08	0.058	0.005	0.062
	0.10	0.073	0.005	0.077
	0.12	0.098	0.005	0.103
25:70:5	0.04	0.039	0.030	0.069
	0.06	0.044	0.021	0.066
	0.08	0.051	0.011	0.062
	0.10	0.061	0.005	0.066
	0.12	0.074	0.005	0.079
47.5:47.5:5	0.04	0.037	0.029	0.066
	0.06	0.040	0.024	0.065
	0.08	0.045	0.019	0.064
	0.10	0.050	0.015	0.064
	0.12	0.056	0.010	0.066
70:25:5	0.04	0.035	0.037	0.072
	0.06	0.037	0.033	0.070
	0.08	0.039	0.030	0.069
	0.10	0.042	0.026	0.068
	0.12	0.045	0.023	0.068
95:0:5	0.04	0.034	0.042	0.076
	0.06	0.035	0.038	0.073
	0.08	0.036	0.035	0.071
	0.10	0.038	0.032	0.069
	0.12	0.039	0.028	0.067

[a] The value of the thermal conductivity was estimated by inputting the mat density into the estimation model. W = wood shavings; K = kenaf fibers; B = bicomponent fibers.

obtained for the mats without wood shavings (at a W:K ratio of 0:95). In order to reduce the thermal conductivity of the mat, it is more effective to mix kenaf fibers with scraps rather than to construct mats containing only scraps. On the other hand, if the mat is composed of only kenaf fibers, its thermal conductivity significantly varies with density and thus becomes unstable. Therefore, to achieve maximum insulating performance and stability of the mat, it should contain both the scrap and kenaf fiber components.

The minimum value of the thermal conductivity obtained under all experimental conditions described in Table 2 is 0.062 W/m·K. Thus, it is difficult to decrease the thermal conductivity of the mat below 0.060 W/m·K by varying its density and mixing ratio. Therefore, the effectiveness of varying the density of auxiliary fibers mixed with wood shavings instead of kenaf was examined (the corresponding values are denoted by the asterisk). Figure 5 shows the relationship between the mat thermal conductivity (λ^*_{mat} in Fig. 5) and the density of the auxiliary fibers obtained at fixed densities of the mat (0.08 g/cm^3) and Japanese cedar wood ($\rho_{m(W)} = 0.38$ g/cm^3). In this experiment, the shape and thermal properties of the auxiliary fibers were assumed to be identical to those of kenaf fibers, while the densities of the mixed fibers ranged between 0.10 and 0.40 g/cm^3. As shown in Figure 5, the thermal conductivity of the mat was significantly higher when the density of the auxiliary fibers was lower than that of kenaf (0.14 g/cm^3) and smaller in the opposite case. The utilized model predicted that the mat thermal conductivity would be less than 0.060 W/m·K if the

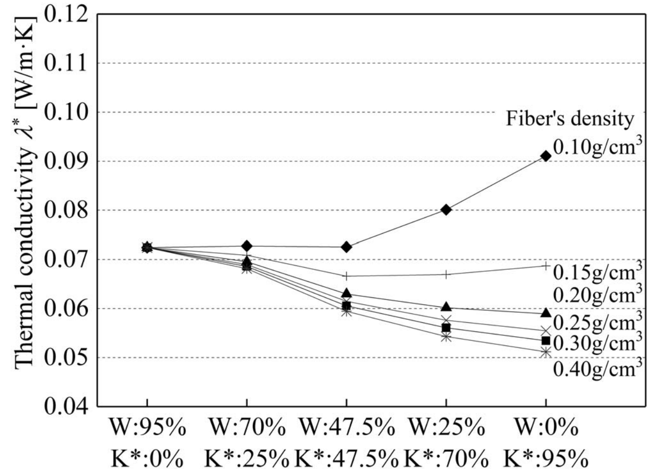

Figure 5.—Correlations between the thermal conductivity, mixing ratio, and density of the fibers mixed with wood shavings. An asterisk denotes the data obtained for the auxiliary fibers. W = wood shavings; K = kenaf fibers.

fibers with a density similar to that of the Japanese cedar wood (0.40 g/cm^3) were used. Thus, the thermal conductivity of 0.050 to 0.060 W/m·K may be achieved if the Japanese cedar is formed into a high-density mat after its processing into needle-like shapes similar to those of kenaf fibers.

Therefore, in order to reduce the thermal conductivity of the studied mats, fibers with a density higher than that of the Japanese cedar can be added. Alternatively, if wood shavings can be processed to obtain fine fibers (similar to those of kenaf), the mats with low thermal conductivity containing only wood shavings can be realized.

Conclusions

In this study, heat transfer paths inside wooden mats were examined using a theoretical model for predicting the heat conductivity of composite materials. The effects of the overall mat density and density of the added fibers on the heat conductivity of the produced mats were investigated. From the obtained results, the following conclusions were drawn:

1. The proposed theoretical model for predicting thermal conductivity can be applied to composite materials. Using the experimental and literature values of thermal conductivity, the heat conduction and radiation components of both the material and the air layer were obtained.
2. The volume fraction of the air and fiber layers varied with mat density. Since the specific gravities of kenaf fibers and wood shavings are different, the volume fraction of the air inside the mat increased with an increase in the fraction of wood shavings at a constant mat density.
3. The theoretical model for predicting thermal conductivity was used to evaluate possible heat transfer paths inside the mat. In the density range specified by the utilized experimental conditions, the heat conductivity resulting from its conductive component increased, and that due to the radiative component decreased with increasing mat density. Since the reduction of the heat conductivity by the radiative component was relatively

high, the heat conductivity of the entire mat decreased with an increase in its density.

4. The reduction of the mat heat conductivity by the radiative component was not observed when the mat density increased to a magnitude 0.10 g/cm^3 or higher. In addition, its value began to increase at higher densities because of the increased conductivity of the conductive component and reduced volume fraction of the air layer.
5. Using the results obtained for the auxiliary fibers instead of kenaf ones, it was found that the heat conductivity of the mat strongly depended on the density of the added fibers. Its value can be reduced either by using fibers with a density greater than that of the Japanese cedar or by processing wood shavings into fine fibers (similar to those of kenaf) and fabricating mats consisting only of wood shavings.

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