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ORIGINAL ARTICLE

Fuel and material utilization of a waste shiitake (*Lentinula edodes*) mushroom bed derived from hardwood chips II thermal conductivity of compression-dried waste mushroom beds

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Abstract

This study investigated using waste mushroom beds as insulation material and applied compression-drying to eliminate the coarse voids that are unfavorable for insulation. The relationship between air-dry density and thermal conductivity was investigated. The mean air-dry density of the uncompacted waste mushroom beds was approximately 200 kg/m^3, which increased to approximately 550 kg/m^3 after four levels of compression-drying. A linear relationship was recognized between the air-dry density and thermal conductivity of the waste mushroom bed. Comparing this relationship to those of wood and mat-formed wood-based panels showed that the thermal conductivity of a waste mushroom bed is similar to that of wood at low densities and mat-formed wood-based panels at high densities. Furthermore, the thermal conductivity of heat bridges was estimated using a series–parallel heat-flow model for voids and substances, and the substance thermal conductivity was in the order of wood (0.218 W/mK), waste mushroom bed (0.288 W/mK), and mycelium (0.368 W/mK). The same heat-flow model was applied to a waste mushroom bed to obtain the substance thermal conductivity along the heat-flow direction. The results show that the waste mushroom bed substance also has an anisotropic thermal conductivity.

Keywords: Waste mushroom bed, Compression-drying, Thermal conductivity, Coarse voids, Series–parallel heat-flow model, Heat bridge

Introduction

Natural growing mycelium is attracting attention as a new binder for wood-based molding materials. For example, Grown.bio [1] in the Netherlands cultivates mycelium using wood chip pieces and agricultural wastes as a medium in a molding formwork to produce interior goods and packaging, building, and construction materials. The campus benches of the University of British Columbia [2] are also made from mycelium and alder sawdust. Furthermore, the fire protection performance [3] and sound absorption properties [4] of wood-based molding materials are being explored.

However, the structure of the waste mushroom bed is similar to the wood-based molding materials above. If it can be used as a material, it will help reduce the mushroom industry's waste. This study focuses on the fuel and material usage of the waste shiitake mushroom beds using hardwood chips. This study's first report [5] discussed its suitability as a fuel for a woody biomass boiler, showing the moisture content, ash content, and calorific values.

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In the second report, we explore the possibility of using the waste mushroom beds as insulation material. For example, if the dried waste mushroom bed is installed under the floor, heat insulation from the ground surface can be expected. When the waste mushroom bed is dried, the decayed chips are bonded with the mycelia, resulting in a lightweight particleboard (PB) or insulation fiberboard (IFB) structure (Fig. 1). However, the homogeneous waste mushroom beds with small voids between decayed chips were only one-fifth of the total (Fig. 1A). The remaining have scattered or continuous coarse voids unfavorable for thermal insulation due to heat convection (Fig. 1B, C). Therefore, this study attempts compression-drying to eliminate the coarse voids and use waste mushroom beds as much as possible. The waste mushroom beds were compressed to various degrees in the height direction, and specimens with various air-dry densities were removed to evaluate the thermal conductivity. Furthermore, the thermal conductivities of wood and wood-based materials with various air-dry densities were measured, and the positioning of the thermal insulation performance of compression-dried waste mushroom beds was investigated.

The thermal insulation performance of a waste mushroom bed is affected by coarse voids and the thermal conductivity of the waste mushroom bed substance (a mixture of decayed chip and mycelium), serving as a heat bridge. Therefore, the powder mats' thermal conductivity of the waste mushroom bed was measured, and a heat-flow model was applied to estimate the thermal conductivity of the heat bridge. Similar estimates were made for raw wood and mycelium. To further investigate whether there is anisotropy in the substance thermal conductivity of the waste mushroom bed, the substance thermal conductivity along the heat-flow direction was determined using the same heat-flow model.

Materials and methods

Preparing waste mushroom beds with various densities

After being harvested five times, 100 waste shiitake mushroom beds were collected from the farm shown in the first report [5]. The waste mushroom bed's dimensions were approximately 130 mm wide, 210 mm long, and 120 mm high. They were distributed into five groups of 20 per group for equal mean weights. H_{120} was the uncompacted waste mushroom bed (120 mm high) group, dried at 105 ℃ to an oven-dry state and cured to an air-dry state. Figure 2a shows an air-dry density distribution of H_{120} from 190–220 kg/m^3. H_{60}, H_{50}, H_{30}, and H_{25} are the waste mushroom bed groups to be compacted to 60, 50, 30, and 25 mm in height, respectively. Figure 3a–d shows a 200 kN press installed with formwork bottom dimensions of 130 mm by 210 mm to compact the waste mushroom beds and the cross section of the formwork. The waste mushroom beds were heated in a microwave oven to a central temperature of approximately 90 ℃ before being placed in the formwork. After reaching the target height, the formwork's upper and lower plates were fixed with two metal rods for each plate (Fig. 3d), and the compacted

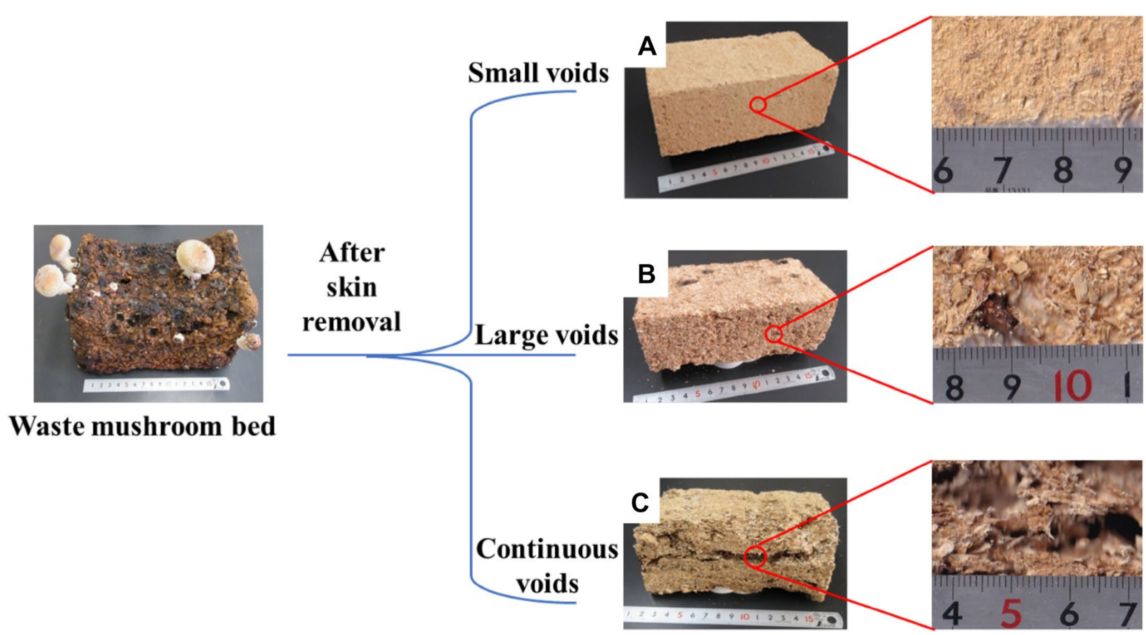

Fig. 1 Three types of voids inside the dried waste mushroom bed. **A** Small viods, **B** large viods, **C** continuous viods

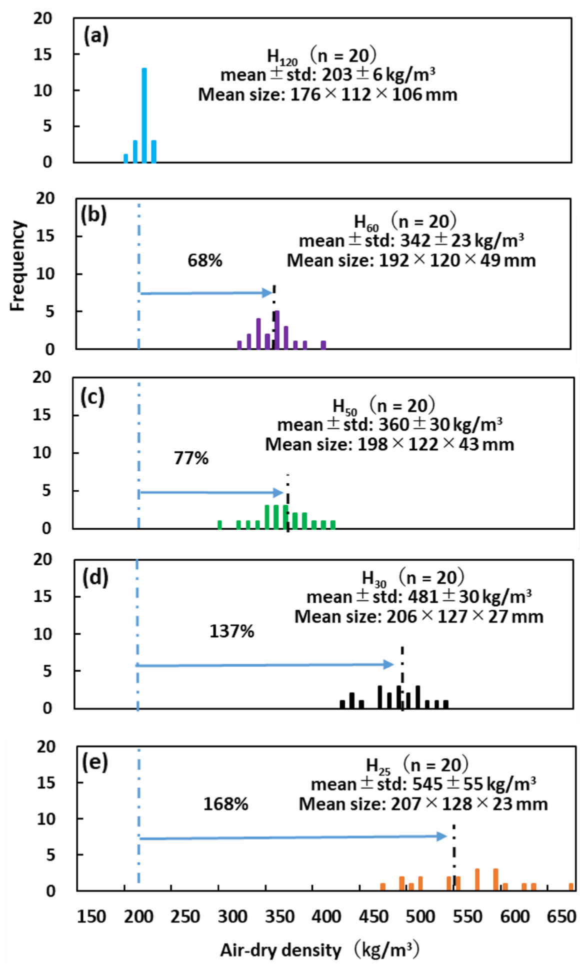

Fig. 2 Air-dry density distribution of the waste mushroom bed. **a** H_{120}, **b** H_{60}, **c** H_{50}, **d** H_{30}, **e** H_{25}

waste mushroom beds were dried at 105 ℃ to an oven-dry state. Then, they were left in an ordinary experimental room at least for 2 months until they become air-dry state (moisture content: 10–12%). Figure 2b–e shows the air-dry density distribution of H_{60}, H_{50}, H_{30}, and H_{25}, respectively. The above compaction operations were used to prepare waste mushroom beds with air-dry densities from 190–670 kg/m^3.

The inclination angle of the decayed chips with respect to the horizontal plane was measured using the waste mushroom bed before drying. The height direction of the decayed chip was almost perpendicular to the fiber. One side skin (210 mm long by 120 mm high) was cut off, and the cut surface was photographed at seven compacted heights of 120 mm (compaction rate: 0%), 110 mm (8%), 100 mm (17%), 90 mm (25%), 80 mm (33%), 70 mm (42%), and 60 mm (50%) using a universal testing machine (Fig. 4). Each photo was analyzed using imaging software (Adobe Photoshop) to obtain 200 inclination angles.

Wood and wood-based materials for comparison

The following control materials were used: balsa (*Ochroma pyramidale*), kiri (*Paulownia tomentosa*), sugi (*Cryptomeria japonica*), Douglas fir (*Pseudotsuga menziesii*), yellow cedar (*Chamaecyparis nootkatensis*), IFB, plywood, medium-density fiberboard (MDF), oriented strand board (OSB), and PB. Test specimens of 100 mm wide, 100 mm long, and 12 mm high (perpendicular to the fiber, moisture content: 10–12%) were obtained from the master board for thermal conductivity measurements. Table 1 shows the mean air-dry densities and the number of specimens.

Measuring thermal conductivity

Thermal conductivity was measured using the comparison method with a standard plate [6] (JIS A 1412–2: 1999). In this method, the test specimen and standard plate are overlapped and placed between the upper high-temperature plate and the lower low-temperature plate. When the vertical downward heat-flow reaches a steady state, the test specimen's thermal conductivity (λ) can be calculated using Eq. (1):

$$\lambda = \lambda_0 \times (\Delta\theta_0 / d_0) \times (d/\Delta\theta), \quad (1)$$

where λ_0, $\triangle\theta_0$, and d_0 are the thermal conductivity, the temperature difference between upper and lower surfaces, and the height of the standard plate, respectively. d and $\triangle\theta$ are the test specimen's height and the temperature difference between its upper and lower surfaces, respectively. The standard plate used was glass wool with a known thermal conductivity and was certified by the US National Institute of Standards and Technology (NIST, SRM1450d). Its height and air-dry density were 25.2 mm and 118 kg/m^3, respectively. The temperatures of the upper and lower plates were 40 ℃ and 20 ℃, respectively. The mean temperature of the specimens ranged from 24–26 ℃. Measurements were taken twice on one test specimen by reversing the upper and lower surfaces.

Test specimens with dimensions of 100 mm wide, 100 mm long, and 12 mm high were obtained from the waste mushroom bed groups of H_{120}, H_{60}, H_{50}, H_{30}, and H_{25} to allow for various air-dry densities (moisture content: 10–12%). Table 2 shows the number of test specimens and the mean air-dry densities. The test specimen's height direction is the same as the waste mushroom beds.

Fig. 3 Compaction equipment for the waste mushroom bed **a**: front view, **b**: side view, **c**: top view, **d**: cross section of compression formwork

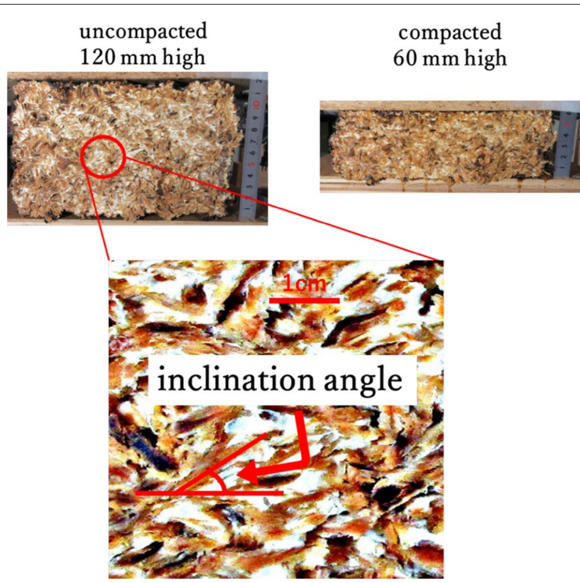

Fig. 4 Cut surface of the waste mushroom bed for chip inclination angle measurement

Table 1 Wood and wood-based panels for thermal conductivity measurement

Wood		*n*[2]	Wood-based panels		
tree species	**Mean air-dry density[1] (kg/m³)**		**Type**	**Mean air-dry density (kg/m³)**	***n***
Balsa	129	2	IFB[3]	269[4], 251[5], 244[6], 354[7]	6[4,5,6], 2[7]
Kiri	251	2	plywood	438[8], 618[9]	2[8,9]
Sugi	347	5	MDF	622	2
Douglas fir	447	9	OSB	705	2
Yellow cedar	536	2	PB	811	2

[1] Moisture content: 10–12%
[2] The number of specimens
[3] Insulation fiberboard
[4] T-Class IFB: 12 mm high
[5] T-Class IFB: 15 mm high
[6] T-Class IFB: 20 mm high
[7] Sheathing IFB
[8] Lauan plywood
[9] Softwood plywood

Table 2 Air-dry densities of the waste mushroom bed for thermal conductivity measurement

	H_{120}	H_{60}	H_{50}	H_{30}	H_{25}
Air-dry density[1] (kg/m^3) (mean ± std[2])	208 ± 42	287 ± 32	328 ± 54	408 ± 53	483 ± 65
The number of specimens (*n*)	12	11	11	13	10

[1] Moisture content: 10–12%

[2] std: standard deviation

A heat-flow model for predicting substance thermal conductivity

The series–parallel heat-flow model comprising two elements, substances (cell wall, heat bridge), and voids (intracellular pore) was applied to estimate the thermal conductivity of charcoal [7], fiber-based insulation materials [8], and PB [9] (Fig. 5). Assume that a single cell is square with a circular inner pore, and because it is symmetric, it can be divided into four equal parts. If the void's ratio is V ($0 < V < 1$), the substance's ratio is $1-\sqrt{V}$. In this model, the parallel part of the void is connected in series with the substance, where λ_s indicates the thermal conductivity of the substance. If the thermal conductivity of the parallel part is λ_p, Eq. (2) is valid because the sum of the thermal resistance of the parallel part $(1-\sqrt{V})/\lambda_s$ and that of the adjacent part $\sqrt{V}/\lambda_p$ becomes the entire thermal resistance $1/\lambda$. Equation (3) shows the mixed law based on the ratio of the void and substance and their respective thermal conductivities. Equation (4) shows the entire model's λ thermal conductivity, obtained by substituting Eq. (3) into Eq. (2):

$$\frac{1}{\lambda} = \frac{1-\sqrt{V}}{\lambda_s} + \frac{\sqrt{V}}{\lambda_p}, \quad (2)$$

$$\lambda_p = \sqrt{V}\lambda_a + \left(1-\sqrt{V}\right)\lambda_s, \quad (3)$$

$$\lambda = \frac{1}{\frac{(1-\sqrt{V})}{\lambda_s} + \frac{\sqrt{V}}{\lambda_p}} = \frac{1}{\frac{(1-\sqrt{V})}{\lambda_s} + \frac{\sqrt{V}}{\sqrt{V}\lambda_a + (1-\sqrt{V})\lambda_s}} = \frac{\lambda_s\{\sqrt{V}\lambda_a + (1-\sqrt{V})\lambda_s\}}{\lambda_s(1+V-\sqrt{V}) + \lambda_a(\sqrt{V}-V)}, \quad (4)$$

$$V = \left(1 - \frac{\rho_o}{\rho_h}\right). \quad (5)$$

The void ratio V is obtained from the oven-dry density ρ_o and the substance density ρ_h using Eq. (5)—the value in the oven-dry state. The V used in Eq. (4) is in the air-dry state, so a correction to the air-dry state is necessary (not made in this report).

Predicting the substance thermal conductivity

Powder samples were prepared to measure the substance air-dry density ρ_h and thermal conductivity λ_s using the following procedures. Approximately 500 g chip samples were prepared for the inside from several waste mushroom beds, the mycelium, and the raw wood used for the cultivation bed. Because removing only the mycelium from the waste mushroom bed was challenging, mycelium chip samples were prepared from the stem part of the shiitake fruiting body. First, these three air-dried chip samples were powdered using a Willey mill. Then, they were classified using a three-stage sieve, and the following two fractions were prepared: F1: 0.250–0.355 mm for the λ_s test, and F2: less than 0.150 mm for the ρ_h test. The

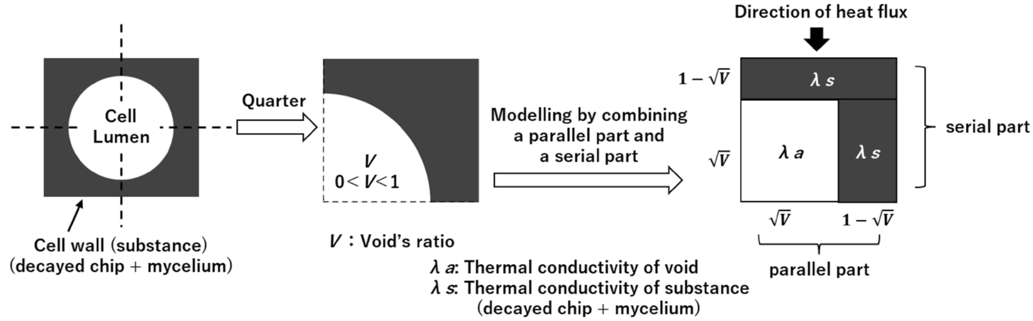

Fig. 5 A heat-flow model applied to the waste mushroom bed

Table 3 Values used in model calculations and the optimal substance thermal conductivity λ_s

Mat type	Substance density ρ_h			Powder mat			Thermal conductivity (W/mK)		
	Powder sample	*n*	Mean[1] ± std[2] (g/cm^3)	Powder sample	ρ_m [3] (kg/m^3)	V[4] (%)	λ_a [5]	λ_m [6]	λ_s
Waste mushroom bed	F2	10	1.622 [a] ± 0.046	F1	399	75.4	0.026	0.0675	0.288
Mycelium			1.550 [b] ± 0.031		330	78.7		0.0712	0.368
Raw wood			1.569 [a/b] ± 0.076		451	71.3		0.0632	0.218

[1] Means with different letters are significantly different at $P=0.05$ among the three samples

[2] std: standard deviation

[3] Air-dry density at which the voids in the mat can be treated as static air ($n=5$, moisture content: 7.9–9.0%)

[4] Values calculated using Eq. (5)

[5] Value corresponding to a specimen temperature of approximately 25 ℃

[6] Values on the regression line in Fig. 6

pycnometer method [10] was used to determine the ρ_h. Ten measurements were conducted on each sample using a 50-ml pycnometer. The test results were as follows: waste mushroom bed: 1.622 g/cm^3, mycelium: 1.550 g/cm^3, and raw wood: 1.569 g/cm^3 (Table 3).

The substance thermal conductivity λ_s was estimated by measuring the thermal conductivity of the powder mats using the comparison method with the standard plate described above. The powder mats were prepared with various air-dry densities using the F1 powder: 270–400 kg/m^3 for the waste mushroom beds ($n=28$), 290–445 kg/m^3 for the mycelium ($n=25$), and 320–460 kg/m^3 for the raw wood ($n=25$). The mats were prepared over various air-dry densities to examine whether the voids between the powders could be treated as static air. The mats were hand-formed in formwork with internal dimensions of 100 mm wide, 100 mm long, and 12 mm high. The mean mat moisture content was 8.1%, 7.9%, and 9.0% for the waste mushroom bed, the mycelium, and the raw wood, respectively.

Once the powder mat's thermal conductivity was obtained, the substance thermal conductivity λ_s was estimated from the heat-flow model shown above. Because the wood substance thermal conductivity is anisotropic and the powders in the mat are randomly oriented, the thermal conductivity obtained using this method can be the mean value of the directions parallel and perpendicular to the fiber. The powder mat of the waste mushroom bed and mycelium can be considered similarly.

Results and discussion

Thermal conductivity of the heat bridge (substance)

Typically, the thermal conductivity of fiber insulation materials, such as glass wool, takes minimum values regarding their densities [11]. At lower densities, the thermal conductivity increases due to heat convection transfer in the voids, and at higher densities, it increases due to increased heat bridges. A similar trend would apply to the results of the powder mat thermal conductivity tests (Fig. 6a–c). The thermal conductivity (λ_m) of the waste mushroom beds and raw wood decreased as the air-dry density increased. The results indicate that the mat's air voids can be treated as static air at approximately 400 kg/m^3 for the waste mushroom bed and 450 kg/m^3 for the raw wood. However, the λ_m of mycelium showed an increasing trend with the air-dry density, indicating that the air voids in the mat can be treated as static air at an air-dry density of approximately 300 kg/m^3. Therefore, the mean air-dry density ρ_m and λ_m used in the model calculations were 399 Kg/m^3 and 0.0675 W/mK, 330 Kg/m^3 and 0.0712 W/mK, 451 kg/m^3 and 0.0632 W/mK for the waste mushroom beds, the mycelium, and the raw wood, respectively. These mean air-dry densities were obtained using five data plots, and the λ_m values were obtained from the regression line in Fig. 6. The substance thermal conductivity λ_s was determined using the following procedure. First, the powder mat's thermal conductivity λ was calculated using Eq. (4), given an arbitrary value for λ_s. Then, the λ was compared to the λ_m, and the comparison was repeated for the λ calculated with 0.001 W/mK increments of the λ_s. Finally, the optimal λ_s was determined when the λ was closest to the λ_m.

Table 3 lists the values used in the model calculations and the optimal λ_s. The λ_s of the waste mushroom bed was 0.288 W/mK, 1.3 times higher than that of raw wood (0.218 W/mK). The substance of the waste mushroom bed is a mixture of decay residue of wood substance and mycelium. The λ_s of the waste mushroom bed is higher than that of raw wood because the λ_s of mycelium (0.368 W/mK) is 1.7 times higher than that of raw wood. However, further research is needed to determine the λ_s of the decayed chip substance.

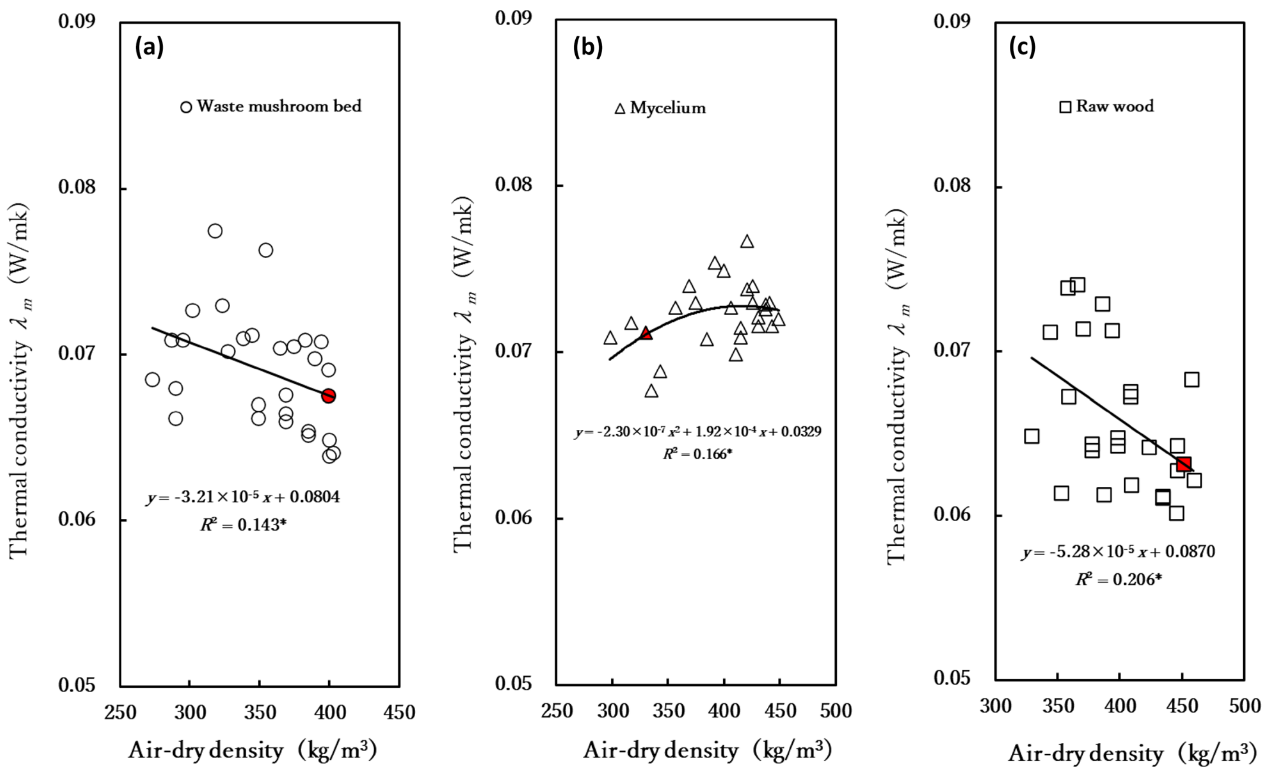

Fig. 6 Relationship between the air-dry density and thermal conductivity for the powder mat

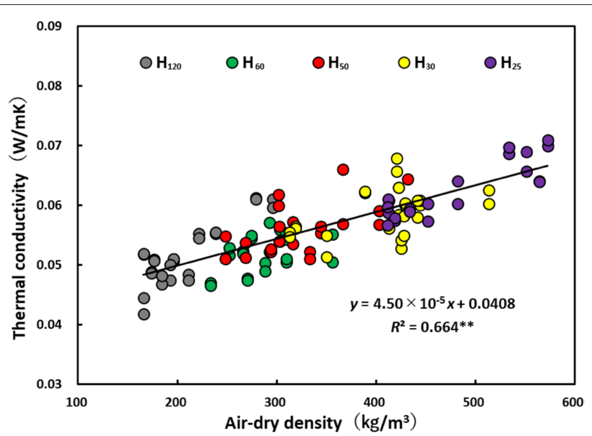

Fig. 7 Relationship between the air-dry density and thermal conductivity of the waste mushroom bed

Table 4 Comparison of the thermal conductivity of waste mushroom bed with the same air-dry density band

Waste mushroom bed	*n*	Air-dry density[1] (kg/m³) Mean	Band	Thermal conductivity (W/mK) Mean[2] ± std[3]
H_{120}	8	259	222–296	0.058[a] ± 0.003
H_{60}	10		233–275	0.051[b] ± 0.003
H_{50}	4		248–269	0.053[b] ± 0.002
H_{50}	12	327	302–367	0.057 ± 0.004
H_{30}	6		313–350	0.055 ± 0.002
H_{30}	14	426	413–441	0.060 ± 0.004
H_{25}	4		419–433	0.058 ± 0.001

[1] Moisture content: 10–12%

[2] Means with different letters are significantly different at $P = 0.05$

[3] std: standard deviation

Relationship between air-dry density and thermal conductivity

Figure 7 shows the relationship between the air-dry density and thermal conductivity of the waste mushroom bed specimens, where the mean temperatures were 24–26 ℃, and a linear relationship was recognized between the air-dry density and thermal conductivity. A closer examination was conducted in Table 4 to investigate the differences in thermal conductivity among the test specimen groups with the same air-dry density band. Focusing on the mean air-dry density of 259 kg/m³, the mean thermal conductivity of H_{60} (0.051 W/mK) and H_{50} (0.053 W/mK) was significantly lower by

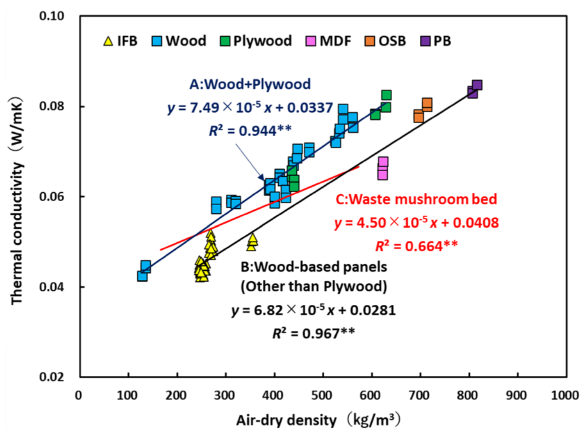

Fig. 8 Relationship between air-dry density and thermal conductivity for the waste mushroom bed and comparison materials

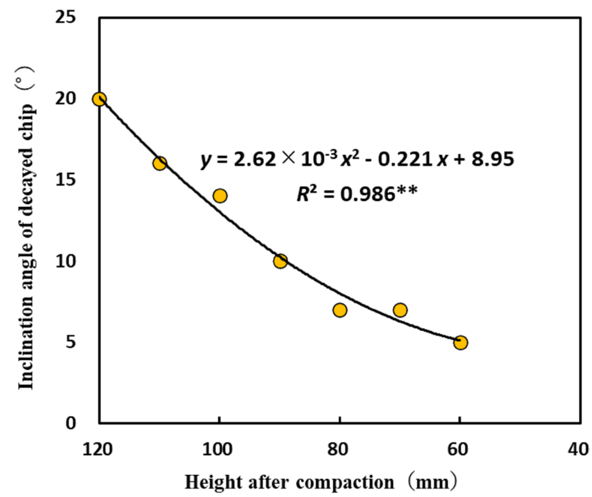

Fig. 9 Relationship between the height of the waste mushroom bed after compaction and inclination angle of the decayed chip

12% and 9%, respectively, than that of H_{120} (0.058 W/mK). Since the test specimens have the same air-dry density, the total amount of voids should be equivalent. Therefore, the decrease in thermal conductivity can be attributed to suppressing the heat convection transfer due to the compression breakup of the coarse voids. However, at the mean air-dry densities of 327 kg/m^3 and 426 kg/m^3, no significant difference occurred between H_{50} and H_{30} and between H_{30} and H_{25}, respectively. Therefore, the suppression of heat convection transfer is completed when the waste mushroom bed is compressed to these air-dry densities.

Figure 8 shows the relationship between air-dry density and thermal conductivity for the comparison materials. Regression equations were obtained from the wood plus plywood group (A) and the wood-based panel group other than plywood (B). The regression line of the waste mushroom bed (C) was between those of groups (A) and (B). Focusing on the air-dry density range of 200–300 kg/m^3, the thermal conductivity of the waste mushroom bed was greater than that of the IFB. This is because the waste mushroom bed contains coarser voids than IFB, and heat convection transfer might have affected the thermal conductivity of the waste mushroom bed. As shown in Table 3, the thermal conductivity of the heat bridge (substance) was higher for the waste mushroom bed (0.288 W/mK) than for the wood (0.218 W/mK), which could also be a reason. However, in the air-dry density range of 500–600 kg/m^3, the thermal conductivity of the waste mushroom bed was similar to that of group (B), indicating that most voids inside the waste mushroom bed were more finely divided. Furthermore, the surface of the waste mushroom beds may have a lower heat radiation rate than that of wood due to the large number of small voids inside and the surface is inhomogeneous [12]. A lower heat radiation rate would reduce radiative heat transfer, resulting in lower thermal conductivity.

Thermal conductivity of the heat bridge along the heat-flow direction

Figure 9 shows the relationship between the compaction degree along the height direction of the waste mushroom bed and the inclination angle of the decayed chips. The inclination angle decreased as the compaction degree increased. If the waste mushroom bed substance's thermal conductivity is anisotropy similar to that of the wood substance, i.e., that in the fiber parallel direction is greater than in the fiber perpendicular direction, the smaller the inclination angle, the lower the substance thermal conductivity along the heat-flow direction. The anisotropy in the thermal conductivity of the waste mushroom bed substance was examined using the heat-flow model (Eq. (4)) in the following manner.

The substance thermal conductivity along the heat-flow direction of the waste mushroom bed was determined in the same way as for λ_s described above. However, since the thermal conductivity of the coarse void λ_a depends on the air-dry density of the waste mushroom bed, the λ_a was varied (Fig. 10). For the waste mushroom bed with an air-dry density of 400 kg/m^3 or higher, λ_a was assumed to be 0.026 W/mK for static air. However, because the λ_a of the waste mushroom bed with an air-dry density of less than 400 kg/m^3 is unknown, this value was changed to increase with the decreasing density. The degree of increase was determined from literature values as follows. Sekino [12] et al. reported λ_a of 0.045 W/mK and 0.033 W/mK for wood shaving insulation panels and

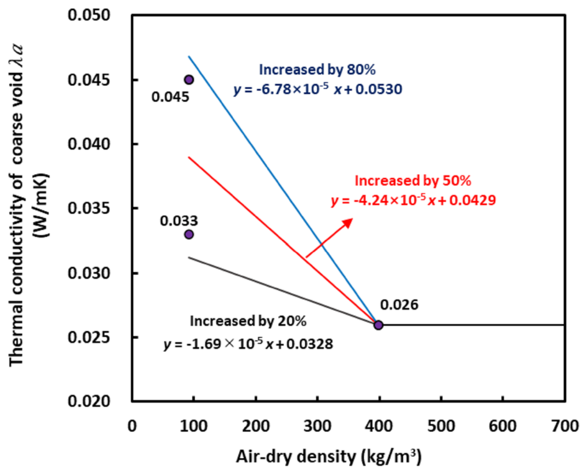

Fig. 10 Thermal conductivity of the coarse void varying with a waste mushroom bed air-dry density

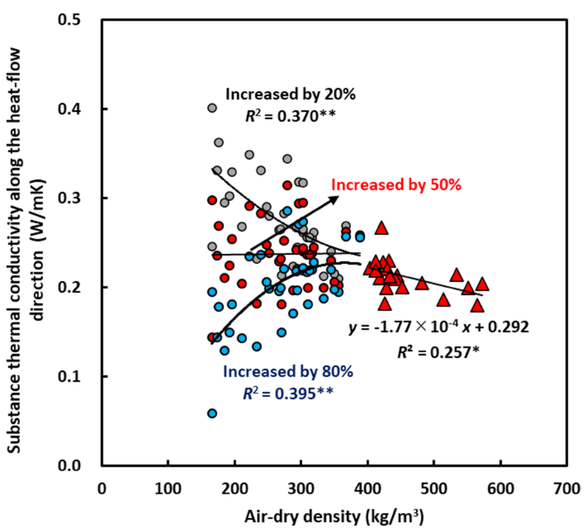

Fig. 11 Waste mushroom bed's estimated substance thermal conductivity along the heat-flow direction

carbonized wood shaving mats, respectively, with an air-dry density of approximately 90 kg/m^3. Therefore, considering that λ_a of the waste mushroom bed of the same air-dry density would be similar to these, three levels were set at an air-dry density of 90 kg/m^3 (Fig. 10): 20% increase in static air (0.031 W/mK), 50% increase (0.039 W/mK), and 80% increase (0.047 W/mK).

Figure 11 shows the waste mushroom bed's estimated thermal conductivity along the heat-flow direction. For the air-dry density of 400 kg/m^3 or higher, the substance thermal conductivity along the heat-flow direction decreased slightly with the increasing density. The values in the regression equation were 0.227 W/mK, 0.199 W/mK, and 0.196 W/mK for air-dry densities of 400 kg/m^3, 500 kg/m^3, and 600 kg/m^3, respectively. This trend is why the slope of the regression equation shown in Fig. 8 is smaller than that of wood. Now, focusing on plots with an air-dry density of less than 400 kg/m^3, when λ_a was increased by 80% of static air, many plots appeared with values smaller than 400 kg/m^3 or higher. This result contradicts the hypothesis because the substance thermal conductivity along the heat-flow direction should increase as the decayed chip inclination angle increases with decreasing density. In the case of a 50% increase, values higher than those at an air-dry density of 400 kg/m^3 or higher began to appear. Furthermore, for a 20% increase, values higher than those at an air-dry density of 400 kg/m^3 or higher appeared. These results indicate that the waste mushroom bed substance has anisotropic thermal conductivity similar to wood. However, further investigation is required to determine the specific degree of anisotropy of the substance's thermal conductivity.

Conclusions

The findings obtained from this work are summarized as follows:

1) The substance thermal conductivity λ_s of the waste mushroom bed was 0.288 W/mK, 1.3 times higher than that of raw wood (0.218 W/mK), which could be attributed to the higher λ_s of the mycelium (0.368 W/mK) contained in the waste mushroom bed substance. However, the λ_s of the decayed chip substance has not been measured in this study and should be investigated in the future.
2) A linear relationship was recognized between the air-dry density and thermal conductivity of the waste mushroom bed. A closer examination of this relationship revealed a decrease in the thermal conductivity due to compression-drying in the air-dry density range of 220–300 kg/m^3, indicating a suppression effect of heat convection transfer due to the breakup of the coarse voids. The thermal conductivity of the waste mushroom bed was greater than that of the IFB with the same density because the waste mushroom bed contained coarser voids than the IFB, resulting in higher heat convection transfer and the thermal conductivity of the heat bridge was high. However, the thermal conductivity of the waste mushroom bed at an air-dry density of 500–600 kg/m^3 was similar to the value on the regression line of the wood-based panels other than plywood.
3) Substance thermal conductivity along the heat-flow direction was determined using model calculations for waste mushroom beds of various air-dry densities. The results indicate that the waste mushroom

bed substance has anisotropic thermal conductivity similar to that of wood.

Abbreviations

λ: Thermal conductivity of the test specimen; λ_s: Substance thermal conductivity; λ_a: Thermal conductivity of the air in voids; ρ_0: Oven-dry density; ρ_h: Substance density; PB: Particleboard; IFB: Insulation fiberboard; MDF: Medium-density fiberboard; OSB: Oriented strand board.

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Author contributions

ZJ designed the study and analyzed the data, and was a major contributor in writing the manuscript. NS contributed to analyzing the data and writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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