Experimental Investigation of Thermal Conductivity Values and Density Dependence of Insulation Materials from Coir Fiber

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Abstract: This study presents the experimental results of thermal conductivity measurements for samples made from coir fibers at three different densities over the range of mean temperature from 10° to 40 °C. Data showed the dry thermal conductivity values at a mean temperature of 15 °C are 0.04 (W/m·K), 0.046 (W/m·K), and 0.0522 (W/m·K) which are lower than that of other conventional and plant-fiber materials. The dependence of λ-values of coir samples on mean temperature and density was investigated and plotted as a linear relationship with the R^2 values are higher than 0.9. Density-dependent thermal conductivity values of coir fiber reinforced phenol formaldehyde resin composite panels were also conducted. The lowest thermal conductivity was valued at the highest density indicating the highest insulation performance of the fibrous material. Overall, the experimental results demonstrate the perceived heat resistant capacity of coir fiber materials and their composites providing superior insulation properties in building applications.

Key words: Natural fiber, mean temperature, density dependence, thermal conductivity, fiber-based composite.

1. Introduction

One of the most important challenges of future building is the reduction of energy consumption and negative environmental impacts due to the use of materials obtained from petrochemicals mainly polystyrene or inorganic fibrous materials such as glass wool or rock wool. In recent decades, the presence of natural fiber as an alternative material to synthetic fibers attracts lots of researchers, engineers, businesses on the field of building application. They are renewable resources cultivated from plants which mainly available in tropical regions of developing countries, and they have become more attractive because of their high specific strength, flexibility, lightweight, biodegradability, and eco-friendly. Some outstanding benefits since replacing conventional fibers are the mechanical capabilities, material strength, low cost, low density (for example, the value normally varies from 1.2 to 1.6 g/cm³, compared to 2.4 g/cm³ of glass fiber [1]), and good thermal properties. Since plant-based fibers used as reinforcement in polymer composites, they also showed an excellent performance because of the combination of the natural fibers and matrix polymers, for example, a good damage endurance or better break elongation when the load applied.

Coir fiber is extracted from coconut husks, is cheap and locally available in many tropical countries such as Vietnam, Thailand, etc. The general advantages of coir fiber include moth-proof; resistant to fungi and rot, provide excellent insulation against temperature and sound, flame-retardant, unaffected by moisture and dampness, tough and durable, resilient, spring back to shape even after constant use. Coconut husk fibers is the highest toughness fiber (21.5 MPa) amongst common natural fibers and is capable of taking 4–6 times more strain than other fibers [2], [3]. They also contain a central hollow portion that runs along the fiber axis, so it can be used in acoustic and thermal insulation materials where its reduced bulk density and lightweight properties are advantageous. Currently, coconut fiber is widely used in cement fiber boards/panels as wall insulation, roofing materials, concrete, and other building materials [4]-[6]. The chemical compositions, mechanical and physical properties of coir fibers were tabulated in the table 1.

Table 1. Chemical, physical, and mechanical properties of coir fiber [7]-[14]

Properties	Unit	Values
Cellulose	%	36–43
Hemicellulose	%	20
Lignin	%	41–45
Diameter	µm	200±10
Density	kg/m^3	1.25–1.5
Moisture content	%	13.68±0.05
Tensile strength	MPa	105–175
Young's modulus	MPa	4–6

Thermal conductivity of coir fiber samples and the influence of operating temperature, density in the λ-values were investigated. It is reported thermal conductivity of coir fiber increased from 0.056 to 0.0576 (W/m·K) and from 0.049 to 0.05 (W/m·K) when mean temperature increased from 15.6° to 21.8 °C. Besides, in both case of mean temperature, the λ-values also decreased when density increased from 40 to 90 (kg/m^3) [15]. Reference [13] documented the decreased thermal conductivity when the density increased from 30 to 120 (kg/m^3). Since coir fiber used as reinforcement in building insulation materials, they also showed an improvement in heat conductivity, for instance, thermal conductivity values of coir fiber cement panels as wall insulation were 0.16–0.19 (W/m·K) showing a higher insulation property compared to the values of wall cladding materials varying from 1.6 to 1.8 (W/m·K) [6]. The thermal conductivity values of coir fiber boards ranged from 0.046 to 0.068 (W/m·K) which were close to those of cellulose fibers and mineral wool [16].

The aim of this current study is to investigate the dry thermal conductivity of samples made from coir fibers at a mean temperature of 15 °C. Three tested specimens were prepared and studies how the mean temperature and density influence the thermal conductivity values. Another practical experiment is the dependence of λ-values of coir fiber reinforced phenol formaldehyde on sample nominal density. Finally, the relationship between thermal conductivity values and the influencing factors was also presented from the practical data.

2. Materials and Methods

2.1. Materials

Coir fibers used in the present study were collected from coconut husk in Ben Tre province, Vietnam. The length of fibers is 12–15 mm and the diameter are about 0.89 ± 0.04 mm. The fibers were washed with water in order to eliminate the pollutant particles until the water is clean, they are being sun dried for two days and then further oven dried at 103 °C in 24 hours until reaching constant weight. For the thermal conduction experiment, 105 g coir fibers were selected from the whole raw materials.

For the fabrication of composite panels, the short fibers were ranged from 0.1 mm to 1.25 mm, whereas the long fibers were within 3 mm. The mat was mixed with the phenol formaldehyde polymeric (PF) resin in order to develop the composite panels by employing hot pressing technology.

2.2. Methods

Thermal conductivity of the samples was measured across the thickness in accordance with ASTM C518, standard test method for steady-state heat transfer by means of custom-made heat flow meter apparatus at University of Sopron. The λ-value was conducted using specimens with dimensions of 250 mm (width) × 250 mm (length) and three different thicknesses (30 mm, 40 mm, and 50 mm). The tested specimen was placed in a polystyrene holder to ensure the one-dimensional heat flux over the metered area, as shown in Fig. 1.

Fig. 1. Tested sample used for thermal conductivity test.

For temperature dependence, the specimen's thermal conductivity was measured at four different mean temperatures incremented by 10 °C from 10° to 40 °C. The time variation for this test was always 1 minute, and the measurement will be stopped when the fluctuation of the last fifty measurement steps was under 0.002 (W/m·K).

The composite panels with dimensions of 400 mm × 400 mm × 8 mm for measuring thermal conductivity were produced as shown in the Fig. 2. The investigated moisture contents were documented from 3.08% to 3.18% before starting the biocomposite fabrication [17].

Fig. 2. Tested composite panel from coir fiber reinforced with PF resin used for thermal conductivity test (this figure was adapted under BN-CC 4 open access permission [17]).

3. Results and Discussion

3.1. Thermal Conductivity Test

The dry thermal conductivity of samples for 30 mm, 40 mm, and 50 mm thickness measured at mean temperature of 15 °C are 0.04 (±0.000868) (W/m·K), 0.046 (±0.00296) (W/m·K), and 0.0522 (±0.001476) (W/m·K), respectively. According to the DIN 4108, "Thermal insulation and energy economy in buildings", materials with a λ-values lower than 0.1 (W/m·K) may be classed as thermal insulating materials. Most insulating materials with thermal conductivity ranging from 0.03 to 0.05 (W/m·K) can be regarded as good

[18], [19]. It is well known that the lower thermal conductivity demonstrate higher insulation properties. As a result, the low thermal conductivity of samples derived from coir fibers could provide superior insulation properties when used as reinforcement in building insulating materials.

Table 2. Thermal Conductivity of Coir Fibers Compared to Other Natural Fibrous Materials

Fiber name	Density (kg/m^3)	Thermal conductivity (W/m·K)	Source
Coir	33.6	0.0522	Present study
	42	0.046	
	56	0.04	
Sugarcane	70–120	0.051–0.049	[15]
Oil palm	20–120	0.095–0.058	[20]
Cotton	20–60	0.04	[19]

3.2. Effect of Mean Temperature on Thermal Conductivity

Temperature-dependent thermal conductivity of coir fibers specimens measured at three thicknesses over the range of mean temperature from 10° to 40 °C was tabulated in table 3. Data showed that the thermal conductivity of the samples increased when the mean temperature increased due to the fact that molecule movements is the basic heat conduction in the steady-state condition. It is agreed with the experimental investigation from numerous published studies which were collected and reported in the comprehensive review article [21].

Table 3. Temperature-Dependent Thermal Conductivity and the Relationship

Thickness (mm)	λ (W/m·K) T (°C)				λ (T) (W/m·K)	R^2
	10	20	30	40		
30	0.0397	0.0405	0.0415	0.0456	0.0002×T + 0.0377	0.8148
40	0.0455	0.049	0.0495	0.0539	0.0003×T + 0.0431	0.9086
50	0.0517	0.0545	0.0582	0.064	0.0004×T + 0.0469	0.9726

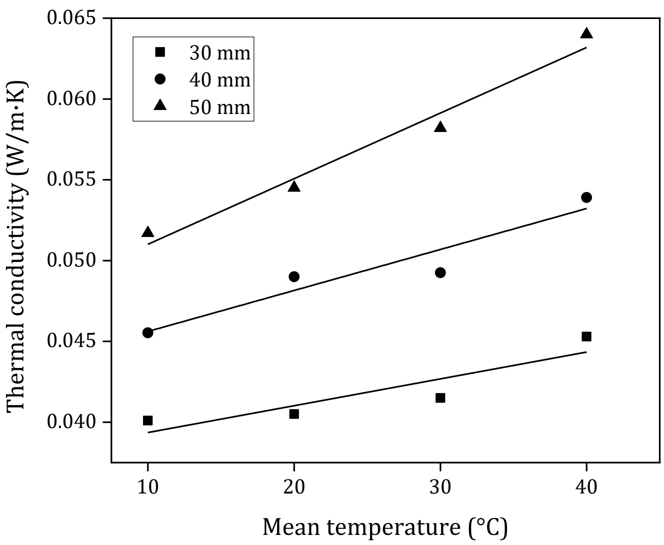

Fig. 3. Thermal conductivity as a linear function of mean temperature.

Fig. 3 shows the positive linear relationship between the thermal conductivity values and mean temperatures which were similar to that of sugarcane fiber [15], hemp, flax, and straw [22]. This is associated with the increase of heat conductivity of air flow inside the fibrous structure since the thermal conductivity of air increases from 0.0251 to 0.0274 (W/m·K) when the average temperature varies from 10° to 40 °C. Moreover, it can be observed that the increasing rate of the thermal conductivity was slightly accelerated as the sample thickness was increased. This is because its moisture content at the time of measurement was relatively high (9.77%) compared with others (6.23%).

3.3. Effect of Density on Thermal Conductivity

Table 4 presents the thermal conductivity decreased when the sample density increased at the same mean temperature. The same result reported that thermal conductivity of coir samples decreased from 0.052 to 0.035 (W/m·K) with an increase in density from 30 to 60 (kg/m^3) [13]. Generally, for neat natural fibers, the thermal conductance through the solid fibers is more crucial than both convection and radiation as if samples are high density. For this heat conduction mechanism, the thermal conductivity is decreased as the density increased. Additionally, thermal conductivity of samples having lower density increased faster in association with an increase in mean temperature. In other words, low density implies large pore volume and much more air content or moisture absorption which causes a larger effect of operating temperature on λ-values. As a result, both mean temperature and density have a strong influence on the heat resistant capacity, and therefore they are always the essential factors when investigating the insulation materials based on natural fibers in building applications.

Table 4. Density-Dependent Thermal Conductivity and the Relationship

Mean temperature (°C)	λ (W/m·K) ρ (kg/m^3)			λ (ρ) (W/m·K)	R^2
	33.6	42	56		
10	0.0517	0.0455	0.0397	-0.0005×ρ + 0.0686	0.9747
20	0.0545	0.049	0.0405	-0.0006×ρ + 0.0753	0.9996
30	0.0582	0.0492	0.0415	-0.0007×ρ + 0.0815	0.9662
40	0.064	0.053	0.0453	-0.0008×ρ + 0.09	0.9645

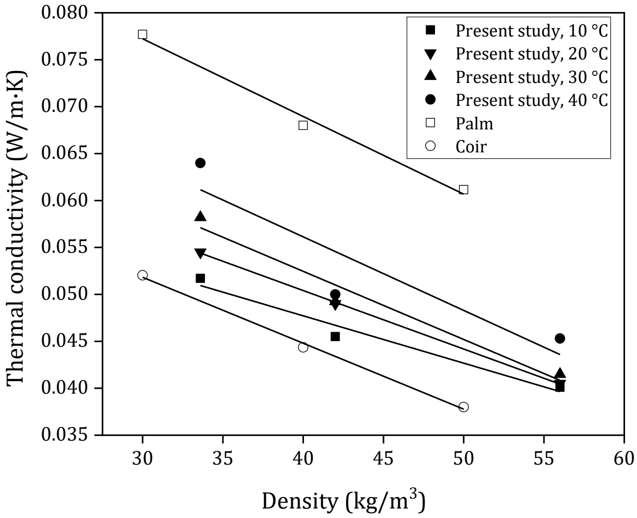

Fig. 4. Thermal conductivity as a linear function of density, compared to other studies of palm fiber [20] and coir fiber [13].

From the experimental data, the possible linear relationship between thermal conductivity and specimen density is plotted in Fig. 4. According to some previous studies, natural fibrous materials such as sugarcane, palm, coconut fibers were reported the non-linear decreased variation in which the thermal conductivity decreased to a minimum and then increased slightly as density increased from the minimum possible value upwards [13], [20]. This can be explained by three phenomena include bubble size, complexity of the frame, and the number of solid fibers. However, because of the low range of density and the thermal conductivity values are measured at only three distinct values in this current study, the data can be performed as a linear correlation with a high covariance coefficient as seen in Table 3. On the other hand, the influence of moisture content on thermal conductivity of these coir samples was also investigated [23]. It is reported that the λ-values increased with moisture content increased from dry state to saturated state of 95% relative humidity because thermal conductivity of water (0.6 (W/m·K)) is higher than the air (0.026 (W/m·K)). Nevertheless, a decrease in thermal conductivity values since the density of samples increases is due to the reduction of the voids in the fiber matrix as well as the water uptake into the cell walls of the fibers leading to a low effect of moisture content, therefore, the decreased apparent thermal conductivity.

3.4. Density-Dependent Thermal Conductivity of Coir Fiber Reinforced PF Composite

Fig. 5 shows the thermal conductivity values of coir fiber reinforced PF composites plotted against four different densities (360, 680, 800, and 1000 kg/m^3). In case of natural fiber reinforced composites, the low thermal conductivity value is normally governed by the low λ-value of fibrous materials (normally range from 0.03 to 0.06 (W/m·K) [21]), and the resin is often insulated according to Bavan and Kumar [24] (thermal conductivity of phenolic resin is 0.29 to 0.32 (W/m·K) in case of 32 to 64 (kg/m^3) density [25]). The non-linear decrease which was performed in fig. 5 may come from the reduction of wettability and absorbability due to a reduction of the voids in open structure of the natural fiber since the increased density and the effectiveness of the phenolic resin enhanced the adhesion between the cellulosic fibers and polymer matrix according to the FTIR (Fourier transform infrared spectroscopy) analysis which was already published [17]. An opposite result is observed in the thermal conductivity of binderless coir fiber boards since the values increased from 0.046 to 0.068 (W/m·K) with the density increased from 250 to 350 kg/m^3 [16].

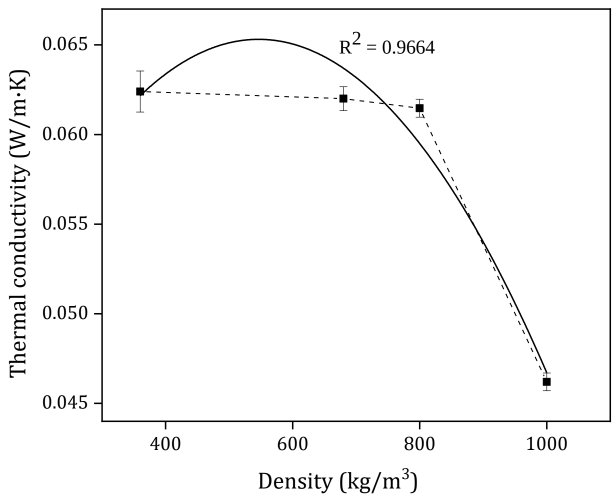

Fig. 5. Thermal conductivity of coir fiber reinforced PF composite panels as a function of nominal density.

4. Conclusions

The thermal conductivity values of coir fiber samples have been experimentally investigated. Temperature-dependent thermal conductivity at three different thicknesses was also valued. It is observed that lower thickness showed lower thermal conductivity values at the same mean temperature. A relationship between thermal conductivity values and mean temperature and density was established and the data was fit by a linear function. As a result, it can be stated that higher operating temperature is always related to higher thermal conductivity for all densities.

The thermal conductivity of the composite panels with phenolic resin reinforced with short and long coir fibers was studied. Four tested panels showed a low value of thermal conductivity, and they can be regarded as a good insulation material. The relationship between the λ-values and the nominal density was also fit by the polynomial function with a high covariance coefficient. Overall, the experimental data demonstrates the heat resistant capacity of coir fibers and their composites provided superior insulation properties in building applications.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Le Duong Hung Anh is a doctoral student in Material Sciences and Technologies at University of Sopron, who is responsible for the experiments and writing the manuscript. Dr. Pásztory Zoltán, Vice Dean of Faculty of Wood Engineering and Creative Industry, is responsible for the research project and revision. All authors had approved the final version.

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