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Experimental Study of Thermal Resistance Values of Natural Fiber Insulating Materials under Different Mean Temperatures

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ABSTRACT

The purpose of this paper is to experimentally study the thermal resistance (RSI value) of building insulation materials made mainly from natural fiber. Natural fibrous materials or renewable resources and their reinforcement composites are currently being used in building and construction as a potential solution to significantly reduce thermal load and energy consumption. The RSI value is used in describing the thermal efficiency of insulating material and in an analysis of heat transfer through the structural components of a building (such as walls, roofs, and windows) under steady-state conditions. In this study, the thermal resistance values of several samples made from coir fiber, rice straw fiber, energy reed fiber, and coconut wood were calculated from the thermal conductivity which was measured at mean temperature of 20°C, using the heat flow apparatus. The lowest RSI value was recorded in the phenol-formaldehyde polymer composites reinforced by rice straw fiber (0.115 $m^2 \cdot K \cdot W^{-1}$) and coir fiber (0.128 $m^2 \cdot K \cdot W^{-1}$) due to the relative thinness of the tested samples (8 and 12 mm). However, these samples can be used as an additional layer in multi-layered assemblies because of their low thermal conductivity value. The highest RSI value was reported on the binderless coir fiber panel (0.909 $m^2 \cdot K \cdot W^{-1}$) at the thickness of 50 mm. Another investigation examined the relationship between RSI value and mean temperature to observe the influence of variations of ambient temperature on the heat resistivity of building insulation materials. Practical data showed the decreased linear proportion between thermal resistance and specific mean temperatures increased from 0 to 40°C. It is apparent that an increase in the interior and exterior temperature of a building significantly influences the thermal resistance of its insulation materials. Based on the experimental study, once the thermal conductivity coefficient of each sample was determined, the calculated RSI value was a valuable parameter to evaluate the thermal resistant effectiveness of a multi-layered installation, which allows us to investigate practically the effect of the thickness of additional layers from different insulating materials used in building envelopes.

Keywords: coir fiber; polymer biocomposites; reed fiber; rice straw fiber; thermal conductivity; thermal resistance

INTRODUCTION

In the context of development in green technology and sustainable development, enhancing the energy efficiency in buildings and constructions, as well as reducing the global gas emissions and the dependence on traditional resources, natural fiber or plant-based fiber materials are used as a possible solution to meet these requirements. The outstanding advantages of insulation materials derived from natural resources are the qualities of being renewable, lightweight, environmentally friendly, and biodegradable. In addition, natural fiber-reinforced polymer composites have shown better mechanical capabilities, physical properties, and thermal performance. Therefore, they can be used as a potential replacement for synthetic fiber-fabricated composites.

Common cellulosic fiber used as reinforcement in building insulating materials were extracted from different parts of the plant such as stem (i.e. flax, jute, hemp), leaf (i.e. banana, pineapple), seed (i.e. coir, cotton), stalk (i.e. rice straw, oil palm), and grass (bamboo, bagasse). Natural fibrous materials are generally comprised of cellulose (30–80%), hemicellulose (5–40%), and lignin (5–20%) (Jawaid and Khalil 2011). The chemical compounds of coir, rice straw, and reed fiber are shown in Table 1. They are plant-based resources that are the raw materials used to manufacture insulating materials for building envelopes due to the low density of their fibers, high strength, and high heat retardant qualities. Besides, some products made from these fibers such as insulation boards or biocomposites were reported to have low thermal conductivity. For instance, thermal conductivity of rectangular straw-bale was found to be 0.066 $W \cdot m^{-1} \cdot K^{-1}$ at a density of 75 $kg \cdot m^{-3}$ (Conti et al. 2016), or ranged from 0.051 to 0.072 $W \cdot m^{-1} \cdot K^{-1}$ at a density of 80 $kg \cdot m^{-3}$ (Douzane et al. 2016). Thermal conductivity of giant reed particleboard was recorded from 0.059 to 0.094 $W \cdot m^{-1} \cdot K^{-1}$ at the density of 567-843 $kg \cdot m^{-3}$ (Andreu-Rodriguez et al. 2013).

The most effective approach to evaluate the heat resistance of an insulating material and the heat loss of a structure is through its thermal resistance (RSI value, $m^2 \cdot K \cdot W^{-1}$). The higher the RSI value the better ability of insulation materials is to resist the flow of heat. It is measured based on the standard ISO 8301:1991/Amd 1:2022 (ISO 1991) Thermal insulation – Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus — Amendment 1 or EN 12667:2001 (European Standardization Committee 2001) Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Generally, the RSI value depends on the type of insulation, consisting of the material, thickness, and density (Peng and Wu 2008). The earliest experiments were conducted to investigate the thermal conductivity (λ-value) of some potential insulation materials made from fibers, and their thermal resistance value was determined through the thickness of the samples. Thermal conductivity of wood waste ranged from 0.048 to 0.055 $W \cdot m^{-1} \cdot K^{-1}$, which was close to those of organic insulation materials such as jute (0.038–0.055 $W \cdot m^{-1} \cdot K^{-1}$), and the highest RSI value at a mean temperature of 30°C was 1.13 $m^2 \cdot K \cdot W^{-1}$, showing that these materials can be used as good insulating materials (Cetiner and Shea 2018). The equivalent thermal resistance values and thermal conductivity of cardboard panels were also investigated (Čekon et al. 2017). The results showed that the cardboard-based materials can be an attractive replacement to commonly used thermal insulating materials due to the lowest λ-value (0.0495 $W \cdot m^{-1} \cdot K^{-1}$) and highest RSI value (0.687 $m^2 \cdot K \cdot W^{-1}$) at a mean temperature of 20°C. Another study on binderless coconut husk and bagasse insulation boards (Panyakaew and Fotios 2011) reported thermal conductivity values ranging from 0.046 to 0.068 $W \cdot m^{-1} \cdot K^{-1}$ and from 0.049 to 0.055 $W \cdot m^{-1} \cdot K^{-1}$, respectively. Since the thickness of both samples was 25 mm, the highest calculated RSI value was 0.54 $m^2 \cdot K \cdot W^{-1}$. The thermal conductivity values of samples made from sugarcane bagasse fiber and polyvinyl alcohol as a binder ranged between 0.034 and 0.042 $W \cdot m^{-1} \cdot K^{-1}$. In that case, the highest RSI value calculated at the thickness of 20 mm was 0.59 $m^2 \cdot K \cdot W^{-1}$ (Mehrzad et al. 2022). According to the experimental data of these studies, the thermal resistance values of natural fiber-based materials were determined from their thermal conductivity values at room temperature (from 20 to 25ºC), and the data was notably reported as higher than 0.5 $m^2 \cdot K \cdot W^{-1}$. This is compatible with the EN 12667 standard which states that the insulation materials have the expected thermal resistance equals to or higher than 0.5 $m^2 \cdot K \cdot W^{-1}$ and that thermal conductivity equal to or lower than 0.06 $W \cdot m^{-1} \cdot K^{-1}$ can be considered as a good thermal insulator for building application.

The present work investigates the thermal resistance of biocomposite insulation boards reinforced with rice straw and energy reed fiber, laminated timber panels made from coconut wood, and binderless insulation panels made from coir fiber. The thermal conductivity values were primarily measured at a mean temperature of 20°C, after which the RSI value was calculated through the thickness of tested samples. The temperature dependence of thermal resistance was practically investigated as the operating temperature increased from –5 to 45°C between the hot and cold sides. Finally, the relationship between the RSI value and the mean temperatures was also examined to observe the influence of operating temperatures on the heat resistance capacity of building insulation materials.

MATERIALS AND METHODS

Materials

The raw fiber materials used in this research are coir, rice straw, and energy reed fibers currently available in many tropical countries. Coir materials (*Cocos nucifera* L.) were collected from Vietnam, rice straw from the local rice fields in Hungary, and the energy reeds (*Miscanthus* spp.)

Table 1. Chemical compositions of coir, rice straw, and energy reed fiber.

Fiber	Chemical compounds (%)				Reference
	Cellulose	Hemicellulose	Lignin	Ash	
Coir	32-43	15-25	40-45	2.22	(Pillai and Vasudev 2001)
	36.6	37	22.2	1.9	(Kochova et al. 2020)
Rice straw	38	25	12	19.2	(Yokoyama and Matsumura 2008)
	36.5	33.8	12.3	13.3	(Sun et al. 2000)
Energy reed	47.95	-	24.85	2.9	(Abou-zeid et al. 2015)
	50.3	21.7	15	4	(Wahid et al. 2015)

from a company located in Lengyeltóti, Hungary. The raw materials were pre-treated with NaOH 5% for removing impurities present in the raw plant material. Later, they were washed with water to eliminate the excess pollutant particles and then dried in the oven. Finally, they were defibrated using a defibrating machine and were sieved for ensuring homogeneous fiber dimensions before composite production. Coconut wood for manufacturing cross-laminated timber panels was collected in Thailand and the samples were prepared at the laboratory of Center of Excellence in Wood and Biomaterials at Walailak University.

Sample Preparation

Figure 1 shows the samples used for the thermal test, namely rice straw and reed fiber reinforced phenol formaldehyde (PF) biocomposites (REPF), coir fiber reinforced phenol formaldehyde polymer biocomposites (CFPF), binderless coir fiber panel (BCFP), and cross laminated timber made with coconut wood panel (CTCP). The REPF and CFPF were manufactured by mixing the pre-treated fiber with the phenolic resin, the mixture was compressed using the hot-pressing technology at different pressure (7.1 MPa, 4.7 MPa, and 3.2 MPa) and the temperature was set at 135°C (Hasan et al. 2021a, Hasan et al. 2021b). Three samples were used for thermal conductivity test.

For binderless coir fiber panel, 105 g of fibers were prepared and compressed manually in the mould with 250 × 250 mm to shape the panel. The panel was then surrounded by the polystyrene holder to ensure the one-dimensional heat flow over the metered area. Three CTCP specimens were prepared as seen in Figure 1(d). All tested samples were cured for 1 day in ambient laboratory conditions.

Thermal conductivity value (λ-value) was determined in accordance with standard test method for steady-stated heat transfer by means of heat flow meter apparatus (according to standards: EN 12667:2001 (European Standardization Committee 2001), and ISO 8301:1991 (ISO 1991)). The use of the heat flow meter (HFM) method to measure the steady-state heat transfer through flat slab specimens and the calculation of the thermal conductivity by the heat transfer (q) was measured by the heat flux sensor (size = 120 × 120 mm, an accuracy of 0.1 $W \cdot m^{-2}$) inserted at the middle of the heating plate. For the thermal test instruments, heat flow apparatus at the Laboratory of the Department for Timber Architecture at University of Sopron (for large sample sizes up to 600 × 600 mm, but not less than 250 × 250 mm) was used. Thermal conductivity coefficient (k) was calculated using the equation (1)

$$k = -\frac{q}{dT/dx} \tag{1}$$

where q is the heat flow rate ($W \cdot m^{-1}$) and dT/dx is temperature gradient ($K \cdot m^{-1}$). Thermal resistance (noted as R, in SI unit $m^2 \cdot K \cdot W^{-1}$), was calculated from the formula (2)

$$R = \frac{d}{k} \tag{2}$$

where d is the thickness of sample (m), and k is the thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

For temperature dependence, the thermal resistance values were determined through the thickness of tested samples and the coefficient of thermal conductivities which were measured at five specific mean temperatures incremented by 10°C from 0 to 40°C, specifically shown in Table 2.

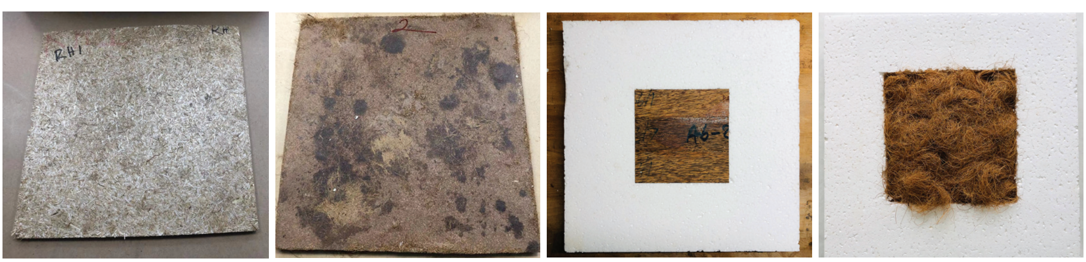
RESULTS AND DISCUSSION

Thermal Resistance

Thermal conductivity values of the tested samples measured at a mean temperature of 20°C are shown in Figure 2, and thermal resistance (RSI value) calculated regarding

Table 2. Operating temperature between cold and hot sides.

Mean temperature (°C)	Cold plate (°C)	Hot plate (°C)
0	-5	5
10	5	15
20	15	25
30	25	35
40	35	45



a) b) c) d)

Figure 1. Tested samples: **(a)** rice straw and reed fiber reinforced PF biocomposites (REPF); **(b)** coir fiber reinforced PF biocomposites (CFPF); **(c)** binderless coir fiber panel (BCFP); **(d)** cross-laminated timber made with coconut wood panel (CTCP).

the thickness is shown in Table 3. Rice straw and energy reed fiber reinforced phenol formaldehyde (PF) polymer composites (REPF) showed the lowest value (0.115 $m^2 \cdot K \cdot W^{-1}$) at the thickness of 12 mm, followed by the RSI value of coir fiber reinforced phenol formaldehyde biocomposites (CFPF) which amounted to approximately 0.128–0.130 $m^2 \cdot K \cdot W^{-1}$ at the thickness of 8 mm. The low thermal resistance came from the high thermal conductivity values measured and the high conductivity of phenolic resin used in the composites (the thermal conductivity coefficient of phenolic resins was 0.29 to 0.32 $W \cdot m^{-1} \cdot K^{-1}$ and its moisture content was nearly 34%, (Yang 2007)). While the thermal resistance of these samples was less than 0.2 $m^2 \cdot K \cdot W^{-1}$, the CFPF can be seen as a more efficient insulation material than RFPR due to the lower thermal conductivity values. Moreover, the effect of PF resin in the whole composite was not significant since the used amount was only 10% in the composite production. Additionally, these composites can be used as an additional layer in multi-layered assemblies. For example, Yuan investigated the impact of insulation type and thickness on the thermal performance of a multi-layered wall structure (Yuan 2018). Without insulation material, the total RSI value (R_{eff}) was 1.26 $m^2 \cdot K \cdot W^{-1}$ based on the following equation

$$R_{eff} = R_e + \sum (d_i/\lambda_i) + R_i \qquad (3)$$

where R_e and R_i are the external wall surface resistance and internal wall surface resistance ($m^2 \cdot K \cdot W^{-1}$), d is the thickness of materials' layer (mm), and λ is the thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$). Since the CFPF and REPF were employed as insulation layers, the total RSI value showed a slight increase, specifically, 1.4 $m^2 \cdot K \cdot W^{-1}$ and 1.395 $m^2 \cdot K \cdot W^{-1}$, respectively. Consequently, it would improve the heat resistance capacity of the building. The binderless coir fiber panels (BCFP) showed the highest thermal resistance value at 50 mm thickness, which was close to the value of sprayed polyurethane thermal insulation at 30 mm thickness (1.071 $m^2 \cdot K \cdot W^{-1}$ (Echarri et al. 2017)). The thermal conductivity of CTCP revealed the highest values since coconut wood conducted more heat than other materials, especially at higher density. Nevertheless, they showed higher thermal resistance than CFPF and REPF samples due to their greater thickness. Although thermal resistance of cross-laminated timber made with coconut wood panels (CTCP) showed a low value (lower than 0.5 $m^2 \cdot K \cdot W^{-1}$, compared to BCFB), they had a higher RSI value than the maximum value of laminated timber made with *Pinus Oocarpa* Schiede ex Schlectendahl and *Coffea Arabica* L. waste (0.115 $m^2 \cdot K \cdot W^{-1}$ at 30 mm thickness (Furtini et al. 2021)). Therefore, the CTCP may be used as insulation materials for building applications.

As it can be observed from the results, the thermal resistance value of an insulation material significantly varies depending on its type and thickness. Generally, thicker materials have higher thermal resistance values than thinner materials of the same type. However, the present study mainly investigated the thermal resistance values of four types of insulation materials with different thickness and their changes regarding the effect of mean temperatures. This can be considered in further studies that will examine the thermal performance of the multi-layered insulation materials at different thicknesses under the influence of variations of ambient temperature and relative humidity.

Relationship between Thermal Resistance Values and Mean Temperatures (R-T Relationship)

The influence of mean temperature in thermal resistance values of binderless coir fiber panels (BCFP) and cross-laminated timber coconut wood panel specimens (CTCP) is shown in Figure 3 and the specific values are shown in Table 4. As shown in the Figure 3, the RSI value of these samples decreased with increased mean temperature. It is obvious that higher temperatures always revealed higher thermal conductivity and because the thermal resistance is inversely proportional to its conductivity, increased thermal conductivity led to a decreased RSI value. On the other hand, it has been also reported that the thermal resistance values of CTCP decreased since the bulk density increased

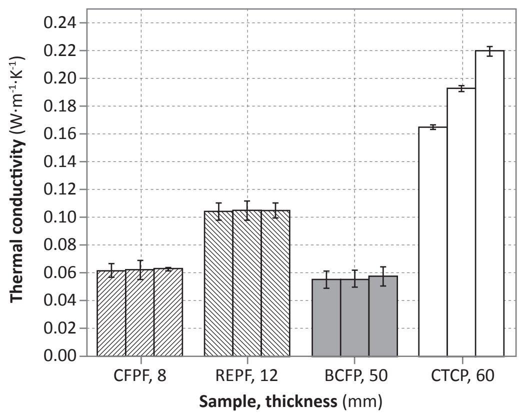


Figure 2. Thermal conductivity values and standard deviation of coir fiber reinforced phenol formaldehyde polymer biocomposites (CFPF), rice straw and reed fiber reinforced phenol formaldehyde biocomposites (REPF), binderless coir fiber panel (BCFP) and cross laminated timber made with coconut wood panel (CTCP) regarding the thickness, measured at mean temperature of 20°C.

Table 3. Thermal resistance values calculated according to equation (2).

Sample	Thickness (mm)	Thermal resistance ($m^2 \cdot K \cdot W^{-1}$)
CFPF	8	0.128
		0.129
		0.130
REPF	12	0.116
		0.115
		0.115
BCFP	50	0.909
		0.898
		0.873
CTCP	60	0.365
		0.311
		0.273

from 678 to 828 kg·m^{-3}. Having the same thickness, high-density wood conducts more heat than low-density wood due to the high heat conduction at a higher solid substance and the reduction of porosity at high density. As a result, the thermal resistance capacity of CTCP decreased relatively. For BCFP samples, it has been also shown that the RSI value decreased significantly regarding the increased density. This result was similar to the relationship between thermal resistance value of sugarcane bagasse waste fibers specimens (calculated from Eq. (2)) and the bulk density (Mehrzad et al. 2022). Specifically, the RSI value of bagasse fiber samples decreased from 0.588 to 0.476 m^2·K·W^{-1}, while density increased from 100 to 200 kg·m^{-3} at a thickness of 20 mm.

It is essential to examine the heat resistance of any insulation materials due to their crucial role in determining the thermal performance of building envelopes. Undoubtedly, the thermal resistance value is the main key to evaluating the efficiency of insulation material to resist heat flow. It is calculated from the thickness divided by the thermal conductivity of the insulation. Because the λ-value is affected strongly by mean temperature and relative humidity (Le and Pásztory 2021), then so is the RSI value. According to the experimental data, the changes in thermal resistance values regarding the increased mean temperature were presented as a linear reduction with a high R^2 value (see Table 4), demonstrating the great influence of temperature on the thermal resistant capacity. In fact, the molecule transfer will become faster with the increase of the operating temperatures, leading to an increase in heat flux across the thickness of insulation materials, and therefore decreasing the RSI value. The linear relationship can be explained by the sole heat conduction mechanism in the steady-state condition of the experiments.

CONCLUSIONS

This paper investigated the thermal resistance values of samples made from natural fiber materials. The main goal of the experiments was to determine thermal resistance values in different thicknesses at room temperature and the dependence of the R-value on operating temperatures. According to the thermal conductivity results, most of these samples are potential thermal insulation materials used in building envelopes. Only cross-laminated timber made with coconut wood was not suitable. The calculated R-values of CFPF and REPF showed that they can be used in the multi-

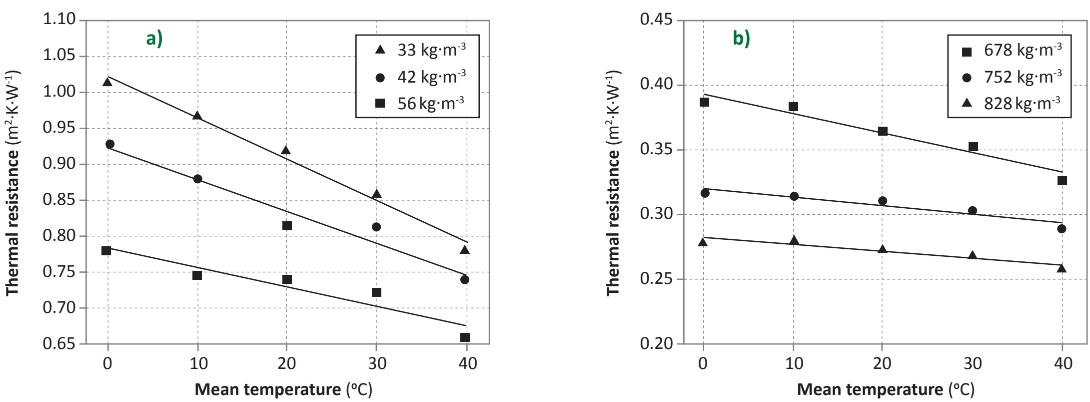


Figure 3. Relationship between thermal resistance values and R^2 value: **(a)** binderless coir fiber panels (BCFP) (regarding density); **(b)** cross-laminated timber coconut wood panels (CTCP) (regarding density).

Table 4. The thermal resistance of binderless coir fiber panels (BCFP) and cross-laminated timber coconut wood panels (CTCP) regarding the increased mean temperatures.

Sample	Thermal resistance (m^2·K·W^{-1}) Temperature (°C)					R-T relationship	R^2
	0	10	20	30	40		
BCFP	0.7796	0.7481	0.7407	0.7229	0.6579	-0.0027 X *T* + 0.7836	0.89
	0.9281	0.8785	0.8163	0.8122	0.7421	-0.0044 X *T* + 0.9231	0.96
	1.0142	0.9671	0.9174	0.8591	0.7813	-0.0057 X *T* + 1.0226	0.99
CTCP	0.3859	0.3839	0.4130	0.3517	0.3272	-0.0015 X *T* + 0.3926	0.94
	0.3176	0.3146	0.3650	0.3041	0.2897	-0.0007 X *T* + 0.3207	0.92
	0.2801	0.2808	0.2733	0.2683	0.2592	-0.0005 X *T* + 0.2832	0.92

layered installation. The thickness factor made a significant difference in the thermal resistance values. The research has also shown that the thermal resistance values decreased with increased mean temperature, and their relationship is presented as a possible linear correlation.

These findings contribute in several ways to our understanding of thermal resistance values of natural fiber-based insulation materials and provide a basis for further investigation on multi-layered insulation materials. As expected, natural fiber has proved to be an effective resource used as raw material in reinforcement polymer composites and has been valued as an essential replacement for traditional insulation materials in the future.

Author Contributions

DHAL generated the idea, carried out the sample preparation; conducted the experiment, analysed the data, prepared the first draft of the manuscript. ZP is responsible for the research project and revision.

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Conflicts of Interest

The authors declare no conflict of interest.

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