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FAIPARI MÉRNÖKI ÉS KREATÍVIPARI KAR

AZ ALKALMAZOTT MŰVÉSZET LÉTMÓDJAI ÉS A KREATÍV IPAR KIHÍVÁSAI NAPJAINKBAN

Faipari Mérnöki és Kreatívipari Kar Tudományos Kiadványa

Szerkesztette: Márfai Molnár László és Pásztory Zoltán

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Tartalom

Bevezetés.. 5

Művészeti szekció

Posztmodern performansz.. 7

Szabó Tibor

Az alkalmazott és az autonóm művészet szakrális alkotásokban. 15

Karikó Sándor

Szépség és öröm. Gondolatok a hazai kortárs transzcendens művészetről............................. 21

Kovács-Gombos Gábor

A képi világ üzenetei. Két leány folyóirat margójára 30

Fáyné dr. Dombi Alice

Ökoművészet és ökodesign mint új paradigma?.. 40

Zalavári József

Fenntartható létharmónia, esztétikum és a feminin reprezentációja 48

Major Gyöngyi

Tér(más)kép(pen) - adalékok a kortárs építészeti ábrázolás eszköztárának áttekintéséhez..... 61

Kósa Balázs, Markó Balázs

Képírás – képolvasás (illúzió és gyakorlat) 70

Gáspárdy Tibor

A kortárs (alkalmazott) művészet értelmezhetősége... 80

Márfai Molnár László

Bepillantás művészet és természettudomány közös metszetébe... 87

Nagy Máté

„Ut pictura poesis” Az intermedialitás megjelenési formái Tandori Dezső költészetében 95

Zámbó Bianka

A soproni műemlék épületek dokumentálásának bemutatása egy helyi példán keresztül..... 102

Kósa Balázs, Markó Balázs, Tárkányi Sándor

A makett, mint szemléltető eszköz.. 113

Horváth Péter György, Markó Balázs, Tárkányi Sándor,Antal Mária Réka, Kósa Balázs

A fa élettani hatása 123

Boros Eszter

Művészet és innováció az információ korában 130

Szécsi Gábor, Szilágyi Tamás

A térészlelés és térhasználat kognitív működése 145

Mucsi Zsuzsanna Mária, Horváth Péter György

A design hét megjelenési szintje 152

Reményi Andrea

Műszaki szekció

Kézi és gépi intarziakészítés összehasonlító elemzése 162
Antal Mária Réka, Horváth Péter György

Vászontól kompozitig – Anyaghasználat a repülőgépgyártásban 178
Zsákai Balázs, Alpár Tibor, Horváth Péter György

Ütemezési feladat eredményeinek nemparametrikus statisztikai elemzése 185
Tóth Zsolt, Hegyháti Máté, Kulcsár Ernő, Ősz Olivér

Fenyő rönk és fűrészáru behozatal környezeti terhei 193
Börcsök Zoltán, Pásztory Zoltán

A faenergetika racionális, környezetkímélő lehetőségei (kutatási összefoglaló) 204
Németh Gábor; Kocsis Zoltán

Faipari projektek szakirodalmi elemzése 212
Novotni Adrienn

Faipari por-forgács elszívó hálózatok és a munkahelyi légtér fapor tartalmának kérdései ... 222
Németh Gábor, Németh Szabolcs, Kocsis Zoltán, Magoss Endre

Természetes anyagok szigetelőképessége 230
Szendi Dorina; Pásztory Zoltán

Foregin languages section

Thermal resistance values of natural fiber-based insulation panels and the impact of their thickness on the thermal transmittance values of an external wall structure 240
Le Duong Hung Anh, Zoltán Pásztory

Developing Info-Droplets to model the dark flight phase of meteorite fall 252
Agota Lang, Matyas Bejo, Benke Hargitai, Barnabas Molnar, Aron Sztojka

Social Network and Text Mining Analysis of Publications Related to Remote Sensing and R Programming 260
Zsolt Tóth

Small and medium-sized enterprises (smes) in Hungary: industry 4.0 trends and challenges 272
Ádám Fazekas, Endre Magoss, Veronika Suriné Lengyel

The effect of natural-based additive on paper 284
Zsófia Kóczán, Katalin Halász, Edina Preklet, Zoltán Pásztory

Comparative social network analysis (SNA) of FP7 and Horizon 2020 projects on remote sensing 293
Zsolt Tóth

Advancements in Sustainable Wood Furniture: A Comprehensive Review of Bonding Techniques and Adhesives 302
Seda Baş, Levente Dénes, Csilla Csiha

Thermal resistance values of natural fiber-based insulation panels and the impact of their thickness on the thermal transmittance values of an external wall structure

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Abstract
The purpose of this paper is to experimentally study the thermal resistance values (R-value) of insulation panels made mainly from natural fibers. Another investigation is to study the impact of the panel's thickness on the values of thermal transmittance (U-value) of a multi-layered installation for external wall systems to determine the optimal thickness of insulation panels used for building envelopes. 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. In this study, the thermal resistance values of several samples made from rice straw, energy reed, and coir fiber are calculated from the thermal conductivity which was measured at room temperature (20 °C) using the mean of heat plate method. The lowest R-value was recorded from the polymeric composites reinforced by coir fiber and rice straw fiber (0.11 to 0.19 m^2·K/W). Although these samples showed the least heat insulation capacity, however, they can be used as an additional layer in multi-layered wall structures because of their low thermal conductivity coefficient. Besides, the R-value per mm was also scored to highlight a strong dependence of thermal resistant performance on the thickness of the samples. On the other hand, the simulated data showed that increased thickness resulted in decreased U-value and the optimal thickness can be determined when the thickness is larger than 120 mm according to the standard of low energy house. Overall, the calculated R-values is a valuable parameter to evaluate the thermal resistant effectiveness of a multi-layered installation, which allows us to investigate the effect of additional layers from different insulating materials used in building envelopes.

Keywords: building insulation materials; natural fiber; polymeric composite; thermal conductivity; thermal resistance; thickness.

1. Introduction

Nowadays, buildings sector has been identified as the largest energy consumer as well as over 1/3 of greenhouse gas emissions worldwide. More especially, buildings account for 35-36% of global energy demand and 38,37% of greenhouse gas emissions in the year 2019 and 2020 according to the global status report by the UN Environment Programme in 2021, while in the EU, these numbers are 40% and 36%. 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 the possible solution to meet these requirements. The outstanding advantages of natural resources are renewable, lightweight, environmentally friendly, and biodegradability. In addition, natural fiber-reinforced polymeric 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.

Many studies up to now have been investigated the potential of natural fibers which are extracted from plant-based materials or agricultural waste on improving the energy efficiency of the construction sector at the building level. The common natural fibers used as reinforcement in building insulating materials were found such as flax, hemp, coconut husk, rice straw, bagasse, bamboo. They are generally comprised of 5–20% lignin, 30–80% cellulose, 5–40% hemicellulose (Jawaid and Khalil, 2011). Coir, rice straw, reed fiber are plant-based resources that are the raw materials used to manufacture thermal insulating materials due to the low density of their fibers, high strength, and high heat retardant because of the low thermal conductivity as shown in Table 1 (Panyakaew and Fotios, 2011, Naidu et al., 2017, Hasan et al., 2021b, Bui et al., 2020, Suardana et al., 2011, Xie et al., 2015, Wahid et al., 2015, Pfundstein et al., 2012, El-Haddad et al., 2014, Costes et al., 2017, Prasad and Rao, 2007, MA Ismail, 2007, Balaji et al., 2014, Nunes et al., 2020, Hattalli et al., 2002, Devadiga et al., 2020, Prabakaran, 2017).

Components/ Properties	**Unit**	**Fiber**		
		Coir	**Rice straw**	**Reed**
Cellulose	%	36–43	35.6	50.3
Hemicellulose	%	20	20.5	21.7
Lignin	%	41–45	16.8	15
Density	kg/m^3	70–120	50	490
Tensile strength	MPa	105–175	69.72	70–140
Young’s modulus	GPa	4–6	2.427	37
Moisture content	%	13.68	12.1	-
Thermal conductivity	W/m·K	0.04–0.05	0.048–0.061	0.055–0.09

Table 1. Chemical compositions, physical, mechanical, thermal properties of coir, rice straw, and energy reed fiber

Several previous studies were conducted to investigate the thermal conductivity (λ-value) of some potential insulation materials made from fibers, and their thermal resistance value (R-values) was determined through the thickness of the tested specimens. Thermal conductivity of wood waste ranged from 0.048 to 0.055 (W/m·K) which was close to those of organic insulation materials such as jute (0.038–0.055 (W/m·K)) or bagasse (0.046–0.055 (W/m·K)), and the highest R-values at a mean temperature of 30 °C was 1.13 (m^2·K/W) 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/m·K)) and highest RSI value (0.687 (m^2·K/W)) at a mean temperature of 20 °C. Another study on binderless coconut husk and bagasse insulation boards reported the thermal conductivity values ranging from 0.046 to 0.068 (W/m·K), then the highest calculated R-value was 0.54 (m^2·K/W) (Panyakaew and Fotios, 2011). Therefore, these natural fiber-based boards can be considered as a good thermal insulation material.

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 value. The higher the R-value the better ability of insulation materials is to resist heat flow. According to the previous studies, the thermal resistance values of natural fiber-based composites were determined from their thermal conductivity values at room temperature (from 20 to 25 °C), and the data was reported from 0.5 to 1 (m^2·K/W). Insulation materials with R-value lower than 0.5 (m^2·K/W) can be used as an additional layer for multi-layered installation, whereas materials with R-value from 1 to 2 (m^2·K/W) were usually used for a wall structure of a building.

The aim of this study is to investigate the thermal resistance values of samples made from natural fibrous material. Another investigation is the simulation by COMSOL Multiphysics program of the impact of insulation panels' thickness on the values of thermal transmittance to determine the critical/optimal thickness of the panels when used as an additional layer in an external wall structure.

2. Materials and Methods

2.1. Materials

The raw fiber materials used in this research are coir, rice straw, energy reed, and sugarcane bagasse fibers currently available in many tropical countries. Fig. 1 shows the samples were manufactured in published studies, namely coir fibers reinforced phenol formaldehyde polymeric composites (CFPF) (Hasan et al., 2021a), rice straw and reed fibers reinforced phenol formaldehyde bio-composites (REPF) (Hasan et al., 2021c).

2.2. Sample preparation

The biocomposites made from short and long coir fiber, rice straw/energy reed fiber were manufactured by reinforcing the pre-treated fibers (NaOH 5%) with the phenolic resin using the hot-pressing technology. All the specimens were conditioned in the normal atmosphere conditions (20 °C and 60% relative humidity) before doing the measurement.

(a) (b)

Fig. 1. Tested samples. (a) REPF, (b) CFPF

2.3. Thermal conductivity and thermal resistance value

The thermal conductivity value (λ-value) of dry specimens was determined at a mean temperature of 20 °C in accordance with standard test for steady-stated heat transfer by means of heat plate method (according to standards: EN 12667 (Committee, 2001), and ISO 8301 (ISO, 1991)). The thermal resistance value (noted as R) 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 window), calculated from Eq. 1.

Thermal resistance ($m^2 \cdot K/W$), $R = \frac{d}{\lambda}$ (1)

where d is the thickness of tested sample (mm), λ is thermal conductivity (W/m·K).

2.4. Model definition of simulation

2.4.1. Steady state heat transfer in multilayer wall structure

The first simulation is to study the temperature distribution, the thermal transmittance and the heat losses of an external wall system using the manufactured panels as an additional layer in 1-dimensional stationary. Heat transfer through the building walls can be modelled as steady-state and one dimensional because wall area is large enough compared to the wall thickness so that we consider that wall temperatures varies only in one direction (x-direction), normal on the wall surface (Paraschiv et al., 2020). For a multilayers wall with different structures and without internal heat source, the heat flow rate is expressed as Eq. 2.

Heat flow rate (W/m²), $q = \frac{\Delta T}{\sum R_i} = \frac{T_i - T_e}{R_{total}}$ (2)

where ΔT is temperature difference (K), R_{total} is the total thermal resistance of wall ($m^2 \cdot K/W$)

The thermal transmittance value (noted as U-value), also called the overall heat transfer coefficient refers to how well an element conducts heat from one side to another side. For a multilayer wall due to layers of different materials with different physical and thermal proprieties (thickness and thermal conductivity) it is often used the overall heat transfer coefficient, given as Eq. (3)

The overall heat transfer coefficient (W/ m²·K), $U = \frac{1}{R_{total}} = \frac{1}{R_{conv,i} + R_{ins} + R_{conv,o}}$ (3)

where $R_{conv,i}/R_{conv,e}$ is the thermal resistance of internal heat convection/external heat convection on the surface of wall, and R_{ins} is the thermal resistance of insulation materials.

The general heat loss is determined by the U-value of the materials and the difference in temperature between inside and outside surfaces of wall structure, given as Eq. 4.

Heat loss (W), $Q = U \times A \times \Delta T$ (4)

where A is the area of wall (m^2)

2.4.2. Model definition of one-dimensional heat transfer: stationary study

The specific model is defined with three layers, in order from indoor to outdoor: 150 mm of concrete, L mm of insulation layer, and 12 mm of plaster as shown in Fig. 3. The thermophysical properties of each material are displayed in Table 2. To calculate the heat loss, supposing that the wall area is 6 m^2. The temperature distribution, the thermal transmittance value, and the heat losses were calculated in two seasons with boundary conditions are set as follows: from 26 to 70 °C in summertime and 20 to −20 °C in wintertime.

As the total wall thickness is about 188 to 192 mm which is much smaller than the wall area, therefore, the heat flow transfers only in one direction and the study is considered as stationary.

Physical properties	Concrete	Insulation layer		Plaster
		Coir	Rice straw/Reed	
Thickness, *d* [mm]	150	8	12	30
Density, ρ [kg/m^3]	2300	450	680	1250
Specific heat capacity, c_p [J/(kg·K)]	880	2000	2500	1050
Thermal conductivity, λ [W/(m·K)]	0.9	0.0624	0.0935	0.43

Table 2. Physical properties of each material of wall structure

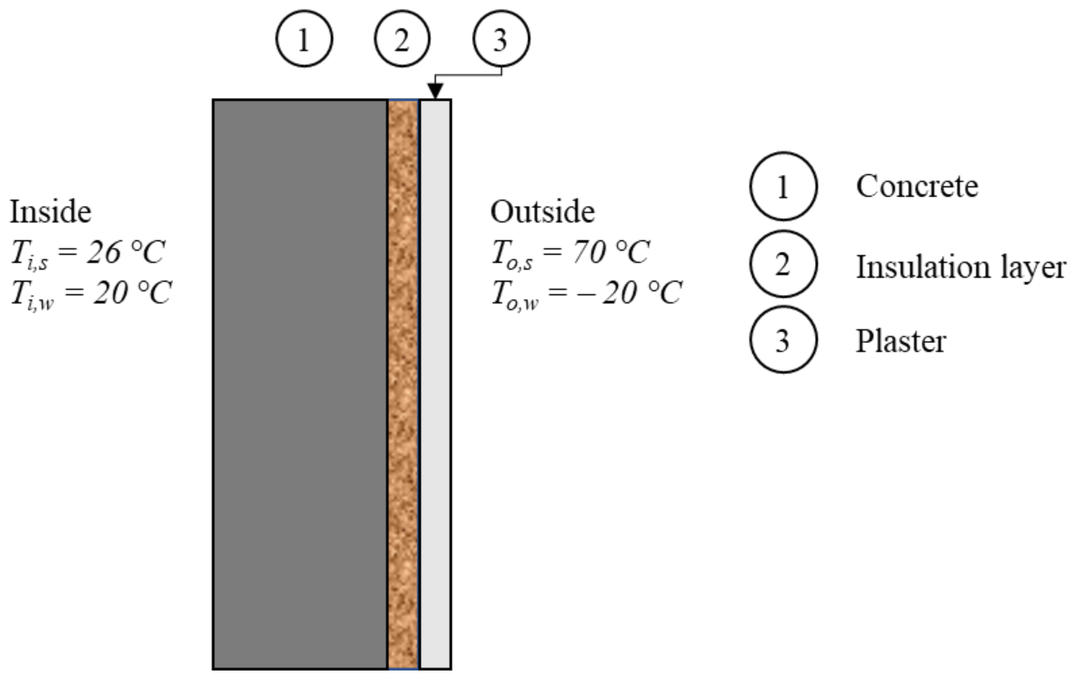


Fig. 2. Schematic view of external wall structure

2.4.3. Model definition of heat transfer in 2-floor building: stationary study

The model definition of stationary heat transfer in 2-floor building using manufactured panels as an additional insulation layer is shown as Fig. 3. Additionally, the heat losses were presented as the increased thickness of insulation layer varied from 50 to 100 mm.

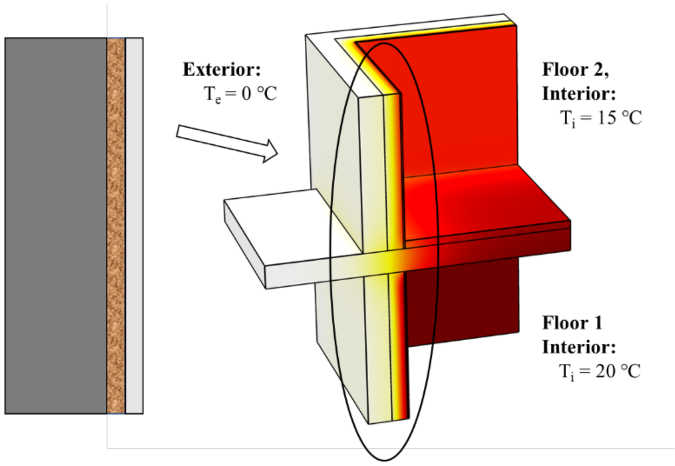


Fig. 3. Schematic view and initial conditions of stationary heat transfer in 2-floor building

2.4.4. Model definition of the impact of thickness on U-value in multilayer wall structure

In this case, we used the parameters of the coir and rice straw/reed fiber reinforced composites which was manufactured but changing the thickness and using the same simulated model (in section 2.3.2) to observe how the influence of thickness factor on the thermal transmittance values of the external wall structure.

3. Results and Discussion

3.1. Thermal resistance values

Thermal resistance values (R-value) of samples tested at a mean temperature of 20 °C are shown in Table 3. Although the thermal resistance values of these samples were less than 0.2 $m^2 \cdot K/W$, they can be seen as efficient insulation material due to the lower thermal conductivity values. More specifically, these composites can be used as an additional layer in multi-layered assemblies. For example, if they insulated with 80 mm thick foil-faced polyisocyanurate (with thermal conductivity of 0.022 W/(m·K) and calculated R-value of 3.64 $(m^2 \cdot K)/W$, it would have a total R-value for the insulated wall of 3.81 $(m^2 \cdot K)/W$. Consequently, it would improve the thermal resistance by more than 22 times and can be employed for insulating ceilings or roofs.

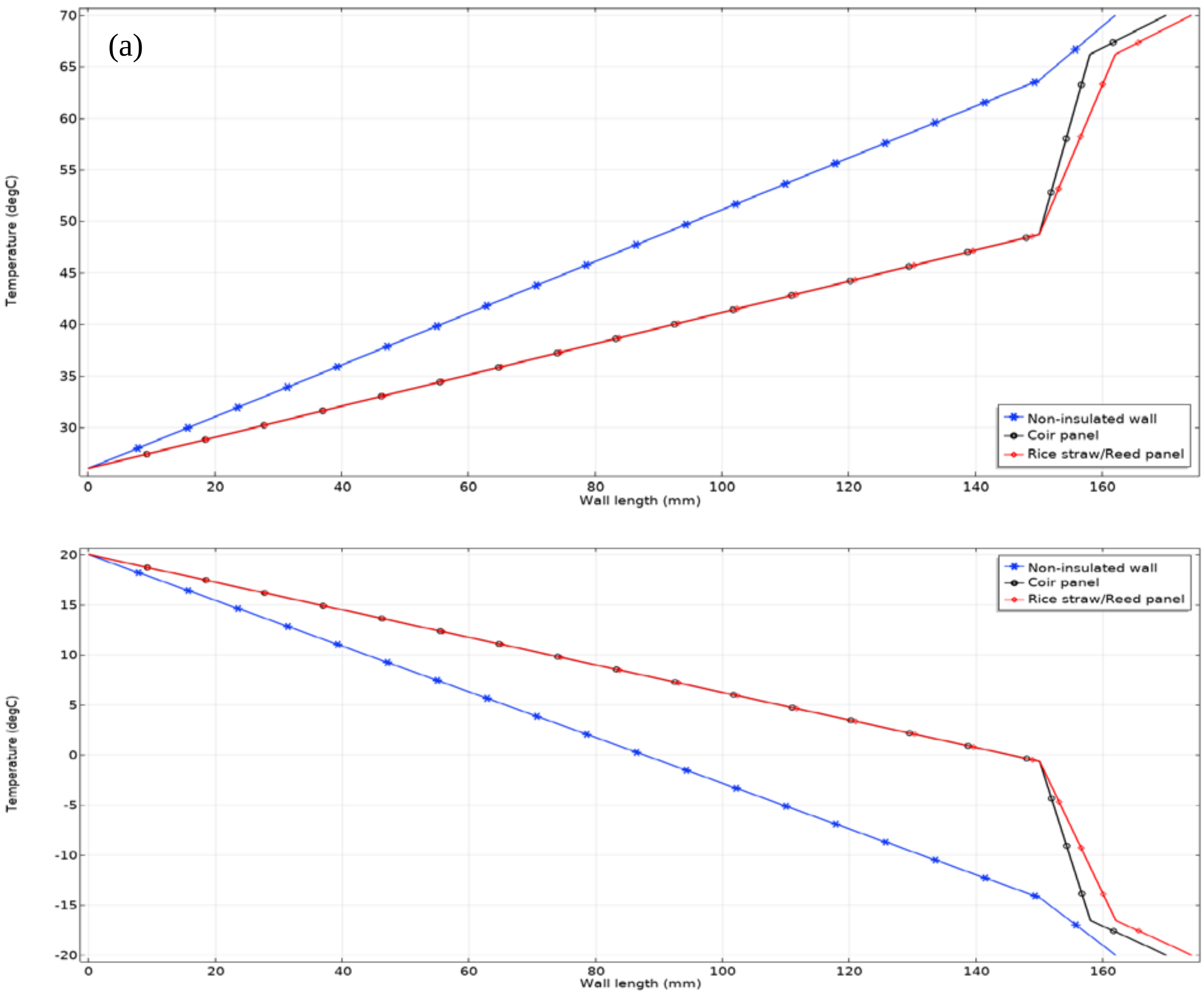
Samples	**Thickness** (mm)	**Thermal conductivity** (W/m·K)	**Thermal resistance** ($m^2 \cdot K/W$)	**RSI per mm** ($m^2 \cdot K/W/mm$)
CFPF	8	0.0624	0.1282	0.0160
REPF	12	0.0935	0.1283	0.0107

Table 3. Thermal resistance values and R-value per mm at room temperature

3.2. Simulation

3.2.1. Heat conduction in stationary multilayer wall structure

The temperature distribution of each fiber-based insulation panel under the most unfavorable temperature in summer and winter is shown in Fig. 4. In the summer condition, the temperature increased sharply leading to a large heat flux due to the high temperature difference, with insulated protection, the surface of the base layer temperature only rose to 43 °C and the temperature change is mainly in the insulation layer showing that the heat insulation capacity was obvious. Under winter conditions, the surface temperature of uninsulated layer dropped dramatically to −14.8 °C while there was only 20 °C of temperature difference since the insulation layers were employed. In general, the temperature variation between the inside and outside the wall of a building was enhanced since the thermal insulation materials were manipulated.



(b)

Fig. 4. Temperature distribution: (a) summertime, (b) wintertime

The usage of natural fiber-based insulation panel showing the reduction of heat consumption in both seasons as seen in Table 4. Since the insulation panels were operated, the total heat losses were reduced by 26% compared to the uninsulated wall. Apparently, adding a thermal insulator causes a significant decrease in heat consumption. This is an effective method to improve the energy performance of building since near zero-energy is expected to play a vital part in EU's strategy to cut greenhouse gas emissions by 2050.

	Heat loss (W)			
	Summertime	Energy saving (%)	Wintertime	Energy saving (%)
Uninsulated wall	734.22	-	667.44	-
Coir panel	541.23	26.2	492.02	26.2
Rice straw/Reed panel	541.07	26.3	491.88	26.3

Table 4. Heat losses in summertime and wintertime

3.2.2. Heat conduction in stationary 2-floor building

As seen in Table 5, the heat losses of both floors at thickness of 50 mm when they have no insulation part are higher double times than using the insulation. Moreover, since the thickness increased to 100 mm, the heat losses decreased remarkably showing the thickness influences significantly in the energy consumption in buildings. Additionally, the minimum temperature on both floors in wintertime (Fig. 5) also showed a slight increase at different thicknesses. It is clear that the manipulation of insulation layer in the wall insulation system can enhance the thermal comfort of inhabitants in a building.

	Heat loss (W) **Thickness** (mm)						
	Uninsulated wall	**50**	**60**	**70**	**80**	**90**	**100**
Floor 1	134.73	63.7	58.95	55.07	51.82	49.03	46.59
Floor 2	75.82	26.11	23	20.51	18.48	18.48	15.32

Table 5. Heat losses under different thicknesses of insulation layer

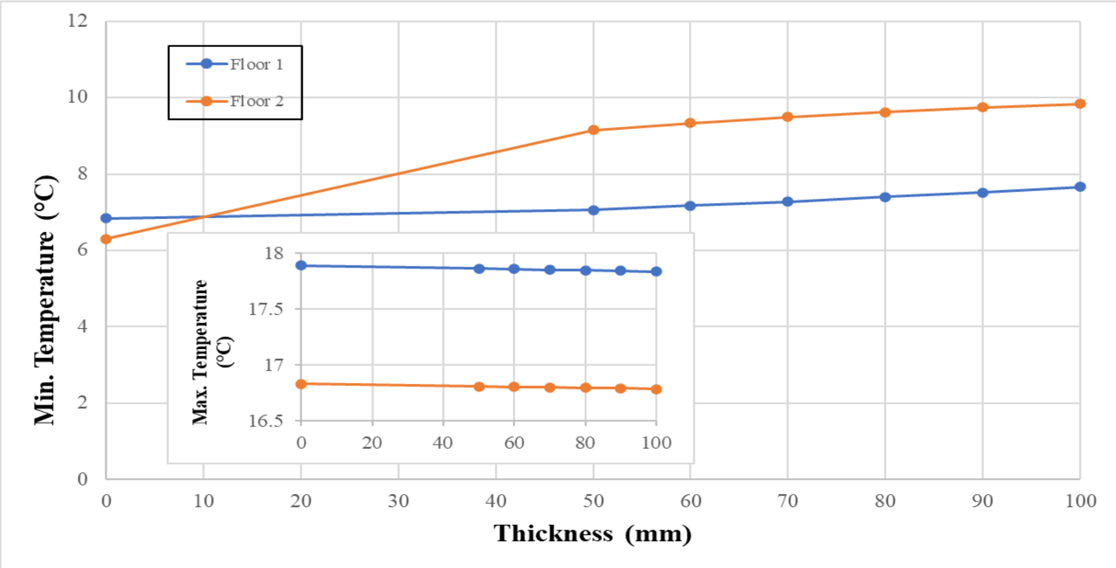


Fig. 5. Thermal comfort of 2 floors under variation of thickness of insulation layer

3.2.3. Influence of thickness in the thermal transmittance values (U-value)

The influence of thickness of insulation layer in the U-value of a multilayer external wall was presented in Fig. 6. As seen in the graph, the thermal transmittance decreased sharply since the thickness increases to 120 mm, and slight decreases since the thickness increases to 200 mm. Based on the simulated results, the critical or optimal thickness can be valued based on the actual standard of low energy house. For example, the thermal transmittance values of exterior wall according to German legally prescribed standard for new constructions (EnEV 2014, (Horst-P. Schettler-Köhler, 2016)) is 0.28 W/m^2·K for 12–16 cm of thickness. Based on this standard, the optimal thickness of coir composite and rice straw/reed composite can be valued at around 13 cm and 20 cm, respectively.

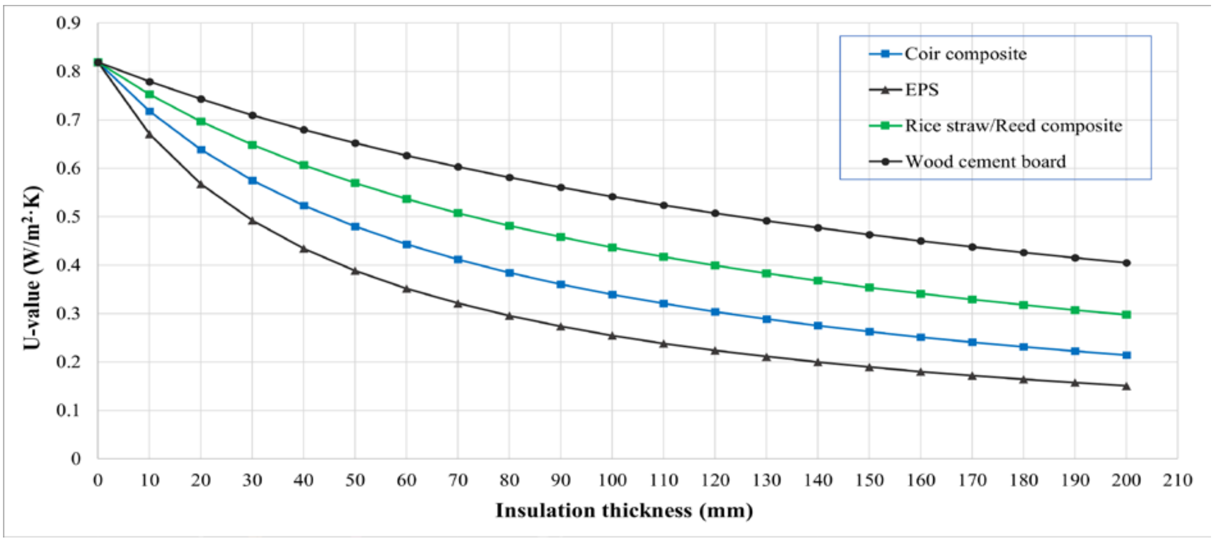


Fig. 6. Thermal transmittance values under variation of thickness of insulation layer

4. 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 impact of thickness of insulation layer on heat conduction of external wall structure of a building. According to the thermal conductivity results, most of these samples are potential thermal insulation materials used in building envelopes. The calculated R-value of CFPF and REPF showed that they can be used in the multi-layered installation. The thickness factor made a significant difference in the thermal resistance values. The simulation has also shown that the thermal transmittance values decreased with increased thickness and therefore, the critical/optimal thickness of insulation layer can be determined. 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 shown an effective resource used as raw materials in reinforcement polymeric composites and has been valued as an essential replacement for traditional insulation materials in the future.

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