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The study of thermal conductivity of composite panels for buildings using recycled materials

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Abstract: Alongside technological advancement, there is a growing need for materials that are easier to obtain and process, and that offer multiple uses, thereby reducing environmental impact. Such materials are generally subject to mechanical, resistance and fatigue studies, often without considering their thermal properties, which could potentially expand the range of applications for the studied compound. The current study aims to analyze possible fluctuations and deviations from linearity in temperature flow curves, as well as their impact on the conductivity coefficient. These studies are conducted on a new type of panel made of fiber glass, a low-cost material with significant recycling potential, used foam elements recycled from packaging insulations, and a cement biding mixture. The study considers the time variation of the different thermal coefficients, and the temperature curves obtained from the experimental measurements. These data are analyzed and used to simulate heat variation, in order to observe the heat flux fluctuations within the plate. The results suggest that the proposed composite plate can serve as an alternative to classical insulating panels.

Keywords: Thermal conductivity, Fiber glass panels, Foam insertion panels, Insulation, Reusable materials

1. Introduction

In the recent years, the main focus of the building industry has been the development and use of new materials that can improve building comfort levels and lower energy costs. Technological advancement is driven by the technical and visual requirements of manufacturers. Therefore, there is a growing need to build composite structures with reinforced fibers that have a high resistance module. The building sector has significantly changed since 1953, as composite materials became a viable alternative to conventional ones. These new materials offered desirable proprieties such as light weight, high resistance, and good thermal proprieties. Despite the initial challenges of high costs and longer production times associated with these materials, they have proven to exhibit better long-term performance due to their lower transfer rate. Fiber reinforced composites are characterized by their lightweight nature, resistance and durability, characteristics that play a crucial role in the building sector, by satisfying many requirements related to energy waste reduction [1-6].

As one of the main polluters is plastic, we created for this study a panel that incorporates recycled plastic foam elements to serve as air-pockets that can increase the insulating properties of the plate. This panel also incorporates recycled fiber glass consolidated by using epoxy resin. This study is focused on presenting an experimental approach used to determine the conductivity coefficient and heat variation inside the experimental panel.

2. Materials and Methods

The thermal conductivity coefficient is influenced by the type of layered materials used in a composite panel, therefore depending on the nature and properties of the studied material. One factor that influences thermal conductivity is moisture. The tests were made in a controlled environment with low moisture content and constant temperature.

The experimental plates were subjected to thermal conductivity coefficient (λ) measurements using the hot plate technique according to ISO 8301 :1991 and DIN EN 12667 :2001. The HFM436 Lambda apparatus (Netzsch, Selb, Germany) was used for the test (Figure 1). The method is based on the determination of the heat that passes from the hot plate to the cold plate through the tested material or structure. The temperatures of the two plates and the thermal conductivity coefficient, which is calculated based on Fourier's Law are automatically recorded by the software of the apparatus.

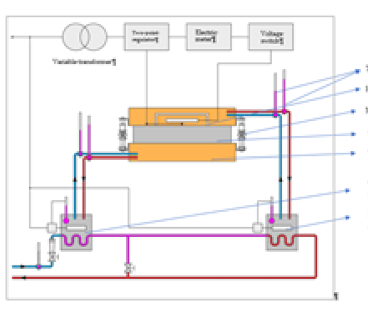


Figure 1. Hot plate system set-up

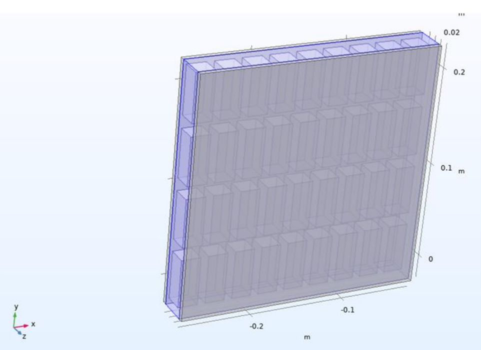


Figure 2. Composite plate with foam insertions, 3D view

The installation used for determining the coefficient of thermal conductivity for the composite panel is presented in the Figure 1. It consists of a bench on which a control panel is mounted and a system of metal plates. Between the two plates, hot and cold, the specimens are mounted for testing. The installation for determining the coefficient of thermal conductivity is connected to the electricity and the water network.

The determination of the thermal conductivity coefficient is based on the hot plate method with a single sample body having the following dimensions for the surface: A and B which vary between 200 and 250 mm, and C, the sample thickness, which can have different values with a maximum of 70mm, by measuring temperature variation with 0,01°C sensibility.

In order to obtain the optimum values for the temperatures, the machine has to enter a stationary heat regime; the fluctuations in the upper and lower plate temperatures have to be almost constant. The determinations were made at different time intervals by reading the electric consumption meter, the temperatures of the plates, the room temperature, the cooling water temperature, and also the thickness of the sample.

Before conducting the measurements for the selected composite panels, the device was calibrated using a standardized reference plate for which the conductivity coefficient is known [32]. In Table 1, are presented the measured values for the reference plate.

After performing the computations for the reference plate, we obtained a value of 0.10972 W/mK and a relative error in the thermal conductivity coefficient value of 2.034% by comparing with the known value of the reference plate.

Table 1. Reference plate conductivity measurements-calibration

	Value	Unit
Average thickness	0.021494	m
Total Energy consumption	0.1255	kWh
Time frame	0.83	hour
Heat flow	0.1506	kW
Heat flow rate	55.62712	W/m²
Average temperature (heating plate)	30.91	°C
Average temperature (cooling plate)	19.95	°C
Temperature drop	10.96	°C
Average temperature	25.43	°C
Thermal conductivity coefficient measured	**0.109722**	W/mK
Room temperature	24.5	°C
Thermal conductivity coefficient – reference plate[32]	**0.112**	W/mK
Error	**2.034**	%

2.1. Thermal conductivity coefficient method

The thermal conductivity coefficient was computed using the equation (1) which uses the measured heat flow in each time frame and temperature drop across a composite plate [33-35]:

$$\lambda = \frac{q \cdot \delta}{\Delta t - q \cdot r_a} \tag{1}$$

where:

λ is the thermal conductivity coefficient [W/m.K];

q is the heat flow rate [W/m²], which is measured;

δ is the average thickness of the plate [m], which is measured;

Δt is the average drop of temperature in the plate [°C], which is measured;

r_a is the hot plate testing device constant, r_a=0.001118 m²K/W;

The constant for the testing device, r_a, is based on the all-thermal resistances considered at the passing of the heat flow between the thermostatic fluids and the contact surface of the material sample.

2.2. Material: Cement plate with foam insertions

The fiberglass cement plate was made using second hand foam elements to induce air pockets that will improve the thermal insulating properties of the plate. The use of second had elements is important, as it is a significant step toward a cleaner environment and waste reduction. The plate's surface area is 0.2x0.2 m² (see Figure 2).

We used a layer of MAT fiberglass with a specific mass of 450g/on each side of the panel. An important factor that we had to consider was the variation in the panel's thickness. The median variation could not surpass 2% of its median value to ensure uniform surface contact on the plates of the testing device.

The foam elements (50 x 20 x 20 mm) are made of recycled material used in packing in the delivery industry. Before selection, the elements were thoroughly inspected, the selected ones maintaining their geometry even after the first use. Due to the foam's elasticity, most of the elements were usable, therefore having a high re-usage percentage. The total number of foam elements was 36 per plate.

For the inner panel, instead of polymer resin, we used cement mixed with 30% sawdust from softwood as binding agent. The sawdust was collected from a wood processing facility and categorized as waste from the wood cutting process. The reason of using wood was to increase the thermal insulation properties of the plate.

3. Experimental results

After processing the data from the experimental measurements (Table 2), we obtained the following values (presented in Table 3) for the unitary heat flow and for the thermal conductivity coefficient.

The values for the conductivity coefficient decrease as the thermal flow crossing the material sample from the upper surface to the lower one lessens. This is due to the heating plate transferring heat to the cooling plate, thus increasing its temperature. Consequently, the energy consumption increases to maintain the selected hot plate temperature. Both samples have a conductivity coefficient within the range of values for insulating materials, making them suitable for use in construction panels.

Table 2. Measured values for the hot and cold plate temperatures using corrections for the composite panel

	Value	Unit
Total Energy consumption	0.053	kWh
Time frame	1	hour
Average temperature (heating plate)	30.59	°C
Average temperature (cooling plate)	23.23	°C
Temperature drop	7.36	°C
Average temperature	26.90	°C
Room temperature	22	°C

Table 3. Computed values for new geometry

	Value	UM
Heat flow	53	W
Heat flow rate	19.58	W/m²
Thermal conductivity	0.13357	W/mK

4. Thermal conductivity coefficient resulted by simulation

From the proposed new geometry composite panel, we selected the model definition presented in the Figure 3 for simulation. The panel dimensions are 250 x 250 x 50 mm, featuring a 3D array of 36 foam elements (50 x 20 x 20 mm) in its inner layout, encapsulated within the cement mixture mass.

The thermal boundary conditions are also shown in Figure 8. The physics for the thermal field are solved using finite element modelling discretization using FEM Multiphysics software. The global definitions of thermophysical property values are assigned using the material database.

The mesh was generated using the extremely fine option, resulting 311204 tetrahedral elements, 74394 triangular elements, 6673 edge elements and 600 vertex elements, The average element quality is 0.6563, which is considered a good value for mesh.

The simulation results are presented in the Table 4. The values for heat flow rate and temperature gradient are averaged over the normal surface area.

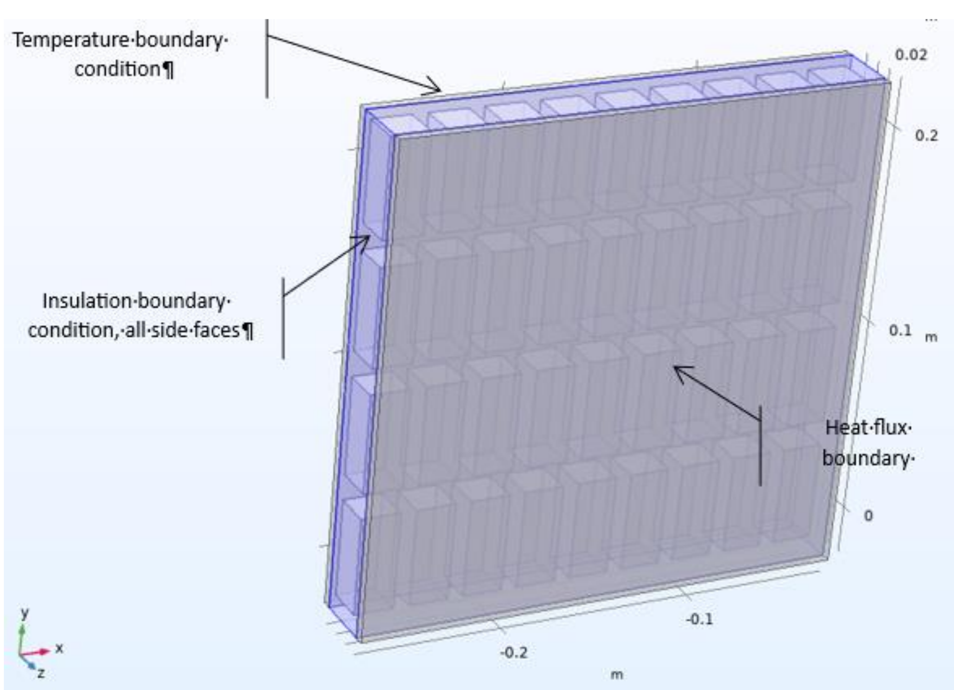


Figure 3. Model geometry definition of all the boundaries and domain conditions

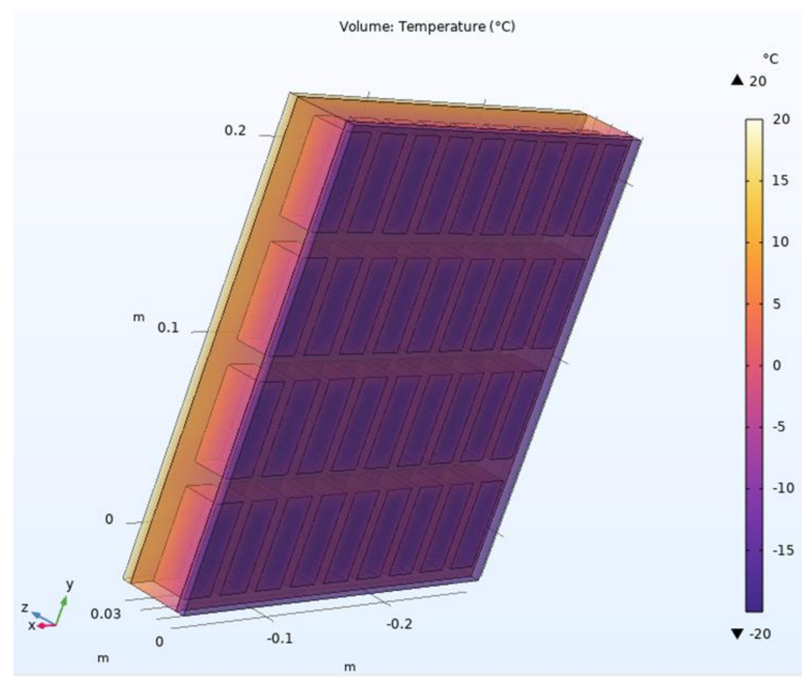
Table 4. Resulted values from simulation for the composite panel

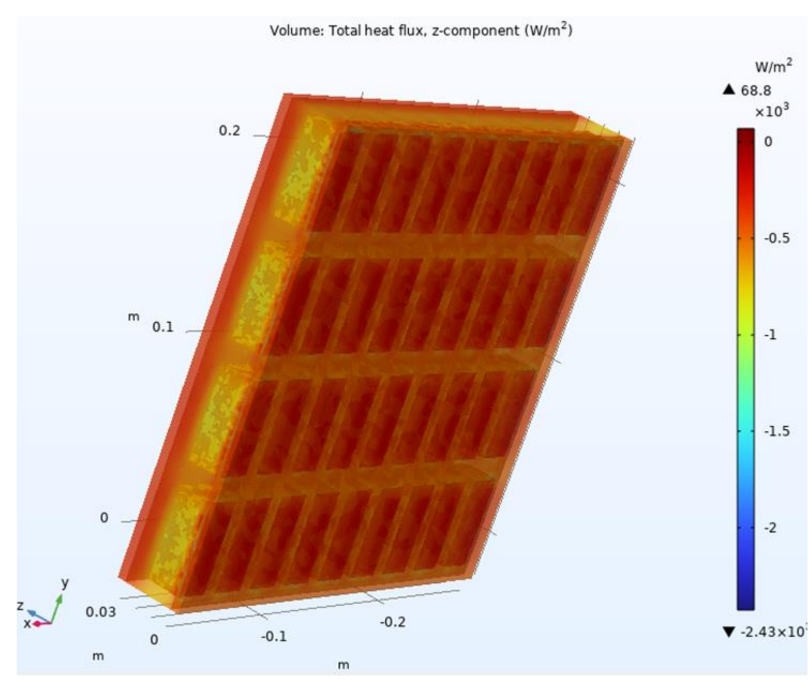
Simulation					
Cold plate Temperature t_1[°C]	Hot plate Temperature t_2[°C]	Temperature Difference [°C]	Average Heat flow rate [W/m²]	Average Temperature gradient [W/m]	Effective Thermal Conductivity [W/mK]
-20	20	40	320.21	2463.2	0.1299
-10	20	30	240.16	1847.4	0.1299
0	20	20	160.11	1231.6	0.1298
10	20	10	80.05	615.79	0.1299
30	20	-10	80.26	-617.36	0.1296
*30.59	23.23	7.36	19.58	-150.51	0.130
35	20	-15	120.49	-926.87	0.130
* this simulation was made with the values used in experimental measurement (temperatures and heat flow rate)					

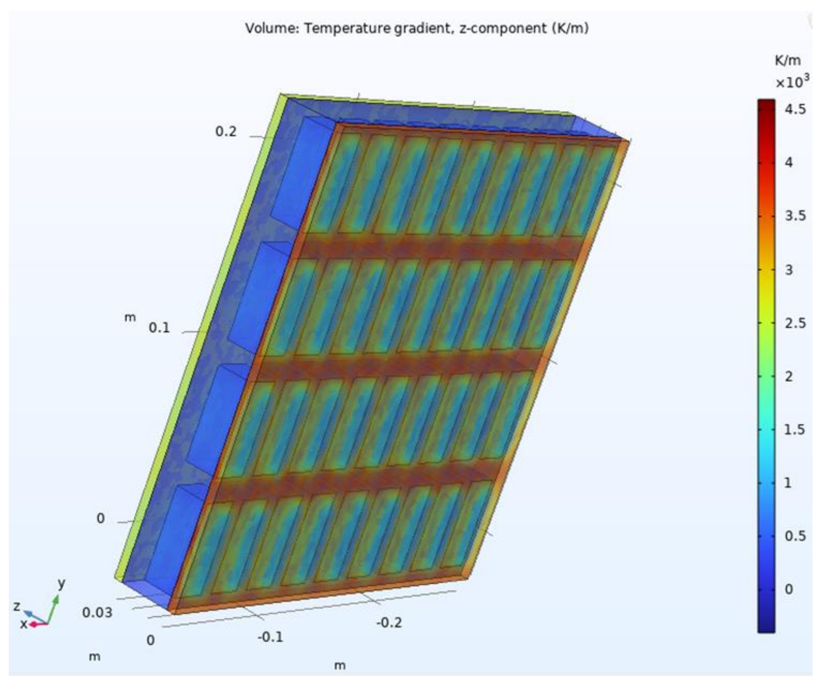
Thus, the resulting temperature field on the experimental panel for temperature conditions ranging from -20 °C on the cold side to +20 °C on the warm side is presented in Figure 4. Under the same temperature conditions, the total heat flux in z direction is presented in Figure 5, and the temperature gradient in Figure 6.

As Figure 5 shows, the heat flow variation within the inner foam elements can be determined. These elements play an important role in increasing the thermal properties of the panel, acting similarly to air pockets within the panel structure. In the presented simulation, we considered a wider range of temperatures applied to the surfaces of the panel, starting from negative 20 to positive 20 Celsius degrees. By analyzing the temperature scale and the heat flux variation on the mentioned elements, the inner foam elements act as insulation, as shown in Figure 5, when the outer face of the panel is subjected to -20°C.

The effective thermal conductivity calculated using Fourier's law is λ = 0.1299 W/m.K for the proposed panel geometry. Simulation 6 was performed to compare the effective thermal conductivity value with experimental obtained value. The simulated value is λ = 0.130 W/m.K, while the measured experimental value is λ = 0.133567 W/m.K, resulting in a relative error of 2.67%.







5. Discussions and Conclusions

The proposed composite panel was studied to highlight the possibility of using a different arrangement of foam within a building wall structure to achieve increased thermal resistance, decreasing the effective thermal conductivity of the panel by ten times compared with the thermal conductivity of the concrete, which is about 1.33 W/(mK). The source of relative error of 2.67% between simulated and experimental thermal conductivity values can be the difference in concrete thermal conductivity. In simulation the material library uses properties for dry-concrete, and in experiments the plate was at ambient laboratory conditions. Future work will consider the effect of humidity of the wall and ambient.

The foam we used for this study has a defined shape, but one can use any type of foam insertions as a solution to prevent waste and give another life to already produced materials. Our study shows that the proposed foam insertion panel has a similar average conductivity to thermo-insulating bricks and, as an advantage, a lower mass per panel.

This research points out the influence of thermal behavior on samples made of composites materials. It highlights the possibilities that new types of materials bring to the development of a future in which conventional, single-use materials are cast aside. Another important aspect is that studying the thermal behavior of layered materials will lead to further research for their unique aspects that were not encountered in classic materials due to the need for a binding agent.

A further study direction that will be considered is the investigation of mechanical properties of the proposed panel, since the thermal insulation of the panel has been analyzed and demonstrated as valuable solution.