ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 18 N° 4 2022
pp. 26-35

THERMAL INSULATION PERFORMANCE OF WALL STRUCTURES MADE OF RECYCLED MATERIALS

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Abstract:
One of the most important actions to reduce the energy consumption in a building is to use the thermal insulation materials. These are used to prevent the transfer of heat and they should have the lowest thermal conductivity. Traditional insulation materials include mineral wool, glass fiber, polystyrene, and polyurethane foams. They are efficient but, they are made from non-renewable resource, and some of them are based on chemicals which can deteriorate the indoor air quality. The paper aims to evaluate the thermal performance of different insulation structures of wall made of recyclable materials. The insulation structures include a core made of sheep wool and cardboard tubes and faces based on particleboard and oriented strand board. Other insulation structures included white expanded polystyrene as core being considered reference to compare the thermal insulation performance. The insulation structure with sheep wool registered the lowest coefficient of thermal conductivity (0.051 W/mK) comparable with that of the reference structures. The corrugated tubes didn't ensure thermal insulation, the values of the thermal conductivity coefficient being over 0.16 W/mK. The best thermal insulation performance of structure with sheep wool was also demonstrated by other parameters like thermal resistance and thermal transmittance.

Key words: *cardboard tube; insulation structure; sheep wool; thermal properties.*

INTRODUCTION

The energy efficiency improving plays a key role to the construction industry, considering the impact and future prospects of the energy sector. Thus, many countries have developed their standards and certifications for buildings with lower environmental impact, including low energy consumption.

Energy efficiency can be defined as approaches and technologies that require less energy to produce the same amount of services. In buildings, for example, energy is consumed directly from delivered energy sources such as electricity and natural gas, which is commonly known as operational energy, and indirectly through the use of building materials, known as embodied energy (EE) (Cabral and Blanchet 2021).

The impact of climatic conditions on building design is affected by construction conditions such as outside air temperature, humidity, solar radiation and wind speed. The heating demand of buildings is associated with the temperature difference inside and outside.

In terms of energy efficiency, the envelope is one of the basic elements of the building. It represents the physical barrier between the external and internal environment of a building, providing resistance to air, heat, noise, light and water (Aslani *et al.* 2019). The thermal envelope of a building represents all the perimeter construction elements that delimit the interior (heated) volume of a building from the outside environment or unheated spaces inside the building. The envelope of a building is made up of a series of surfaces through which the heat transfer phenomenon takes place. Building materials are an important factor in the energy performance of the building. These typically include walls, roof, windows and foundation insulation. It is estimated that construction materials consume about 40% of different raw materials (stone, gravel, sand) and about 25% of harvested wood (Hussain and Kamal 2015). In addition, construction is responsible for generating approximately 25% of all waste worldwide (Yeheyis *et al*. 2013) and is the largest energy consumer (about 40%) generating approximately 36% of total emissions worldwide (Chau *et al*. 2015).

According to Directive 2010/31/EU of the European Parliament, the long-term goal for 2050 is to reduce greenhouse gas emissions in the Union by 80-95% compared to 1990, and to ensure a high energy efficiency for buildings, so that to reach nearly zero-energy buildings in the future. The major energy consumers in a building are given by heating, ventilation, and air conditioning which represent about 35% of total building energy (QTR 2015).

One of the solutions to decrease the energy demand in buildings and to reduce the energy bills is the insertion of an insulation layer in the building envelope. Thermal insulation materials are used to reduce the rate of heat transfer through the walls and roof. On the market different insulation materials could be found, among which the most used are: polystyrene foam, mineral wool, polyurethane foam and fiberglass. The thermal conductivity coefficient is one of the most important parameter that describes a thermal insulation material. As the lower the value of this coefficient, the better the thermal insulation is ensured.

The choice of insulation materials is important, if we take into consideration that organic-based synthetic materials have low fire resistance, inorganic-based synthetic materials are strongly hygroscopic (Ozer and Ozgunler 2019), and others are not environment friendly or are very expensive.

OBJECTIVE

The aim of this research is to design some experimental structures for wall insulation and to analyze their thermal insulation performance. The potential of some recyclable materials as core for the insulating structures was evaluated in order to minimize the impact with the environment. It is known that the production of some insulating materials is fossil-fuel intensive, or are organic compound-based chemicals which can deteriorate the indoor air quality.

MATERIAL, METHOD AND EQUIPMENT

A. Raw material for insulating structures

The raw material used for the wall insulating structures was the following:

a. Sheep wool (SW); (for core)
b. Cardboard tubes (CT) (for core)
c. Oriented strand board (OSB); (for faces)
d. Particleboard (PB); (for faces)
e. Expanded Polystyrene foam (EPS); (for core)

a) Sheep Wool

The Sheep's wool has a great potential to be used as insulating material because is an abundant renewable raw material resource, it is made from the waste of the wool which is not used in the textile industry and has high durability and low flammability (Hegyi *et al*. 2021).

Fig. 1.
Cleaned sheep wool.

Inferior quality wool is not accepted in the textile industry (about 2–2.5 kg of wool/sheep’s head) as a result, it can be considered an important resource for insulating structures, taking into account the fact that Romania holds the 3rd place in sheep and goat number, among the member states, after Spain and Greece (INS 2022). Sheep wool soft mat has a thermal conductivity coefficient of 0,040 W/mK at 100 mm thickness of panel (Pennacchio *et al*. 2017). Sheep wool has the quality to regulate humidity. Wool is hygroscopic, having the ability to absorb water between 33% and 40% of its own weight, without affecting its insulation properties and without changing its dry fiber appearance (Bucişcanu 2014). This makes it very suitable for areas where condensation can form. It is also very suitable for insulating wooden houses. Wool fibers are resistant at burning. In case of fire, sheep wool does not contribute to the flame propagation since it carbonizes and does not burn. Wool is a self-extinguishable material thanks to the high presence of nitrogen (Dénes *et al.* 2019). The sheep wool was cleaned and naturally dried (Fig.1), before using in the structure.

b) Cardboard tubes

Tubes recovered from toilet paper (tubes A- thin tubes with dimeters of 47.34 mm and 46.48 mm) and kitchen towels (tubes B- thick tubes with diameter of 60.44 mm) were used (Fig. 2). These are made of cardboard in 2 or more layers and were cut to the dimensions required for the cores necessary to the experimental structures.

Fig. 2.
Cardboard tubes.

Cardboard tubes consist of layers of paper or cardboard wrapped together to form strong, hollow and usually cylindrical shapes. Paper layers are laminated or glued together with adhesives. The wall thickness of the tube may vary depending on the number of layers wound during production. Cardboard tubes have densities between 1.1 and 1.2 g/cm^3 (https://www.labara.cz/en/isolants/solid/tubes).The characteristics of tubes used for the core of the experimental structures are presented in Table 1.

Table 1

Cardboard tubes characteristics

Tube type		Dimensiuni, mm					
		Thickness, mm	Height, mm	External diameter, mm	Inside diameter, mm	Mass, g	Density, kg/m³
Thick cardboard tube type B	1	5.43	87.92	60.58	55.15	60.39	1392.39
	2	5.56	89	59.9	54.34	60.32	1359.27
	3	5.46	87.76	60.85	55.39	60.4	1381.40
	average	**5.48**	**88.22**	**60.44**	**54.96**	**60.37**	**1377.69**
Thin cardboard tube type A1	1	0.57	88.52	47.39	46.82	4.41	1165.74
	2	0.58	88.08	47.2	46.62	4.47	1160.38
	3	0.59	88.14	47.44	46.85	4.52	1148.66
	average	**0.58**	**89.24**	**47.34**	**46.76**	**4.46**	**1158.26**
Thin cardboard tube type A2	1	0.66	96.45	46.72	46.06	6.29	1356.68
	2	0.66	96.27	46.2	45.54	6.35	1387.74
	3	0.67	96.68	46.54	45.87	6.32	1344.98
	average	**0.66**	**96.46**	**46.48**	**45.82**	**6.32**	**1363.14**

c) Oriented strand board (OSB) and particleboard (PB).

The panels were purchased from a warehouse on the Romanian market (Fig.3)

a. **b.**

Fig. 3.
The faces of insulation structures: a – Oriented strand board of 6 mm thickness; b - Particleboard of 16 mm thickness.

Studies show that for the particleboard (PB) thickness range from 10 mm to 20 mm, the panels can be considered a good insulating material with thermal conductivity coefficient (λ) values ranging from 0.066 W/mK to 0.125 W/mK. Low thermal conductivity is due to the low conductivity of the air trapped in the pores

(Theasy *et al*. 2017). Other authors give a thermal conductivity of 0.1081 W/mK at a density of 637 kg/m^3 (Sonderegger and Niemz 2009).

Thermal conductivity of oriented strand board (OSB) with an average density of 660 kg/m^3 at temperature of 20^{0}C, is considered 0.12 W/m K (Kawasaki and Kawai 2006) and 0.111 W/mK at a moisture content of 8% and density of 594 kg/m^3 (Igaz *et al*. 2017).

d) Expanded Polystyrene (EPS)

Polystyrene is a very popular and very advantageous insulating material, it ensures good thermal insulation and is easy to handle, cut and install. EPS is commonly produced in blocks, can easily be cut into necessary panels for insulating. Polystyrene foam is characterized by very low water absorption, thus can be used to insulate facades, terraces, basement walls or floors on the ground, and also for interior walls or roofs.

On the other side this panels are flammable and break down gradually when exposed directly to the sunlight. (https://www.fao.org/3/y5013e/y5013e08.htm).

Three types of expanded polystyrene are usually used: EPS 50 used for insulating sandwich walls, EPS 70 or 80 used for façades and EPS 100 for floors.

Fig. 4.
White expanded polystyrene (EPS).

The EPS white panel provides a thermal conductivity coefficient 0.030 W/mK to 0.038 W/mK (Simpson *et al.* 2020).

For all materials used in the research, the moisture content and density were determined according to EN 322:1993 and EN 323:1993, respectively.

B. Designing the insulating structures

The experimental structures were designed in a sandwich system with faces made of composite materials such as particleboard (PB) and oriented strand board (OSB). All structures have the dimensions of 300 x 300 mm and thickness of100 mm. For the core was used the recycled materials, such as cardboard tubes and sheep wool, so that we fit into the concept of sustainable development, reduced embedded energy in product and low emissions. As reference structure, those with the expanded polystyrene core (EPS) were used.

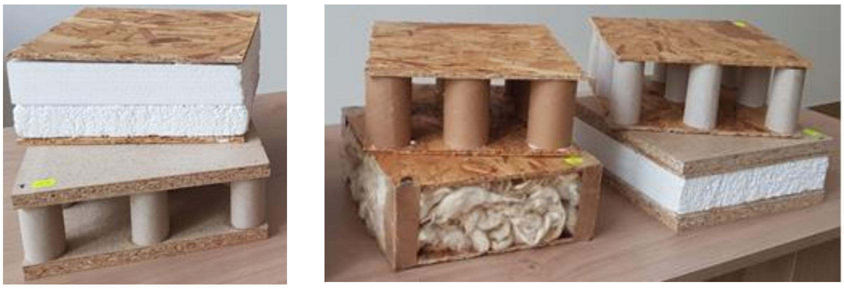

Fig. 5.
The experimental insulating structures for wall.

Polyvinyl acetate (PVAc) water-resistant, type D3 adhesive was used to apply the faces to the core by brushing. All structures are shown in Fig 5 and their components are presented in Table 2.

Table 2

The experimental structures

Type of structure	Materials			Thickness, mm
	Faces/ thickness, mm		Core/ thickness, mm	
Structure 1 	OSB 6.3	OSB 6.3	Sheep wool (bulk) 87.4	101,87
Structure 2  	OSB 6	OSB 6	Cardboard tubes B 88,22 It consists of 9 thick tubes B with an outer diameter of 60.44 mm, and a height of 88.22 mm.	101,88
Structure 3  	PB 16.6	PB 16.6	Cardboard tubes A2 66.47 It consists of 9 thin tubes A2 with an outer diameter of 46.48 mm, and a height of 96.46 mm. These were cut to the necessary height of 66.47 mm	101,67
Structure 4  	OSB 6	OSB 6	Cardboard tubes A1 88.24 It consists of 9 thin tubes A1 with an outer diameter of 46.48 mm, and a height of 88,24 mm	102,94
Structure 5 	OSB 6	OSB 6	EPS 50+40 2 boards of EPS	102,87

Structure 6 	PB 16,6	OSB 6,3 A face is made of a board of PB and one of OSB	EPS 50 1 board of 50 mm thickness	100.11

C. Methodology of testing

The testing of the experimental structures included the determination of some physical properties (density, moisture content) and evaluation of thermal performance (coefficient of thermal conductivity, thermal resistance and thermal transmittance).

a. Thermal conductivity (λ, in W/mK)

This represents the ability of the material to transmit heat by conduction and determines the insulating capacity of a material. The lower this coefficient, the better heat-insulating parameters of the material are obtained. Materials with low thermal conductivity coefficient are considered good heat-insulating materials, and include materials that have a large pore volume and low apparent density.

b. Thermal resistance (R, in m^2K/W)

The thermal resistance (R-value) can be defined in simple way as the resistance that any specific material offers to the heat flow. A good insulation material will have a high R-value.

The value of the coefficient of thermal conductivity (λ) and the thermal resistance are taken directly from the measurements made with the HFM Lambda 436/6 equipment.

c. Thermal transmittance (U, in W/m^2K)

The thermal transmittance (U) represents heat transfer through the material (C107 1.2.3. 2005). The lower the transmittance of a wall structure, the better the insulation of the structure. The thermal transmittance of a structure is the inverse of the total thermal resistance.

Thermal transmittance through a simplified method is determined with relation (1) (EN ISO 6946).

$$U = 1/R_{tot},\ [W/m^2K] \quad (1)$$

where: R_{tot} – is total resistance of the structure, in m^2K/W

The method of determining the coefficient of thermal conductivity is that of heat transfer in stationary mode from a hot plate with temperature T2 to a cold plate with temperature T1. The method is standardized (SR EN 12667, 2009, SR EN 12939, 2002) and is applied using the HFM Lambda 436/6 equipment (NETZSCH, Germany).

The temperature difference between the upper and lower plates (ΔT) was set to the values of 5°C, 10°C, 15°C, 20°C, 25°C, 30°C (test no. 1/ 2/ 3 / 4/ 5/ 6) and the temperatures T1 and T2 of the lower and upper plates, respectively, are shown in Table 3.

The temperature of the upper plate was maintained at an approximately constant value of 20°C, simulating the temperature of the indoor environment, and the temperature of the lower plate varied between -10°C and + 15°C, thus simulating the temperature of the outdoor environment. Through this testing protocol, the variation of the thermal conductivity coefficient was followed, depending on the temperature variation.

ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 18 N° 4 2022
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Table 3

Testing protocol for determining the coefficient of thermal conductivity (λ)

No of test	Temperature T1, °C	Temperature T2, °C	Temperature difference (**Δ**T), °C	Average temperature
	Inferior plate	Superior plate	T2-T1	(T1+T2)/2
1	-10	20	30	5
2	-5	20	25	7.5
3	0	20	20	10
4	5	20	15	12.5
5	10	20	10	15
6	15	20	5	17.5

RESULTS AND DISCUSSION

A. Physical characteristics of the materials used in the experimental structures

The density, moisture content and the coefficient of thermal conductivity of the materials included in the experimental insulating structures are presented in Table 4.

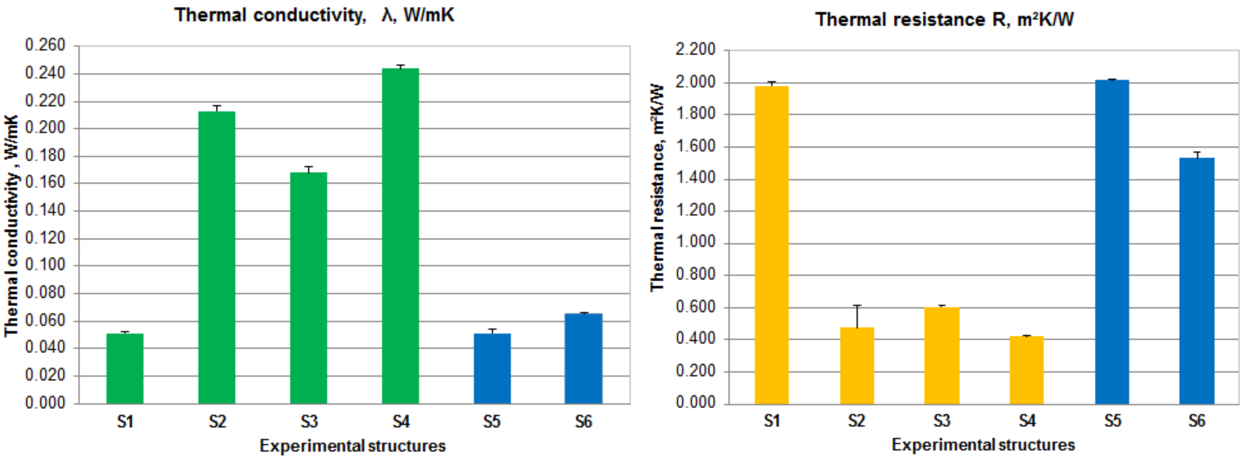
Table 4

Characteristics of the materials used in the experimental structures

Material	Density, kg/m^3	Moisture content, %	Thermal conductivity coefficient, W/mK	Dimensions, mm		
				Length/ Øext	Width/ Øint	Thickness/ heigh
Oriented strand board (OSB) 6	668	9.96	0.12	300	300	6-6.4
Particleboard (PB) 16	590	7.54	0.108	300	300	16-16.6
Expanded polystyren (EPS)	13.55	-	0.03	300	300	40-50
Sheep wool	23	-	0.042	-	-	-
Cardboard tubes type B	1377	5.75	-	60.44	54.96	88
Cardboard tubes type A1	1158	6.69	-	47.34	46.76	89
Cardboard tubes type A2	1363	4.88	-	46.48	45.82	96

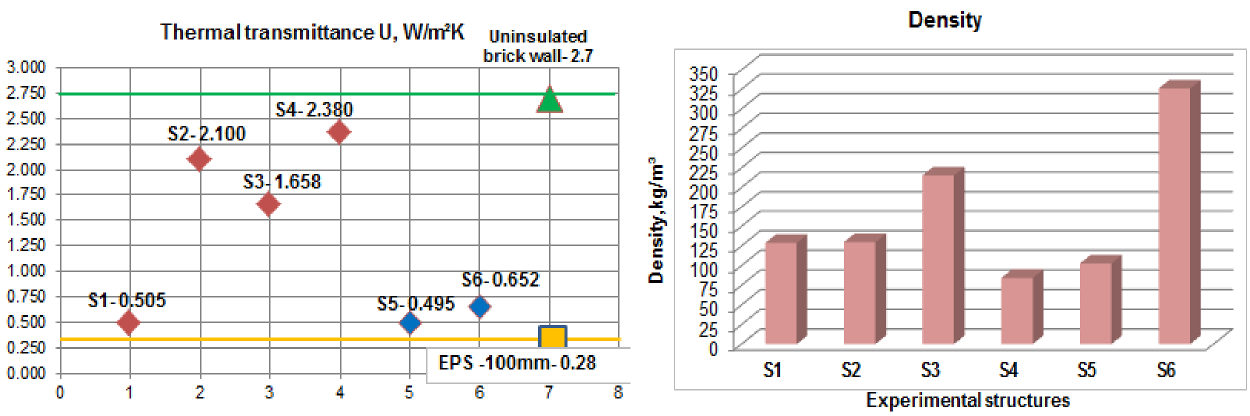
Thermal conductivity, resistance and transmittance variation in the experimental insulating structures are presented in figures 5 and 6.

The best structures in terms of thermal insulation parameters (thermal conductivity coefficient, resistance and thermal transmittance) were S1, S5 and S6. The structures S5 and S6 were considered reference samples due to the fact that expanded polystyrene is well-known insulating material with low thermal conductivity.



a. ***b.***

Fig. 5.
Performance of the experimental insulating structures: a - variation of thermal conductivity; b – variation of thermal resistance.



a. ***b.***

Fig. 6.
Performance of the experimental insulating structures: a - variation of thermal transmittance; b – density.

The lowest value for the thermal conductivity coefficient recorded was at S1 - 0.051W/mK equal with that obtained for reference structure S5 and lower than S6 with 0.0653 W/mK. As can be observed, wool is a very good thermal insulator comparable to expanded polystyrene. These core materials have the lowest densities (13.5 kg/m³-polystyrene and about 23 kg/m³ -wool) and the lowest coefficients of thermal conductivity, being the best thermal insulators.

The structures with cardboard tubes (S2, S3, S4) had the highest thermal conductivity coefficient values (0.16-0.24 W/mK) and thermal transmittance values U between 1.6-2.3 W/m²K. The higher values of thermal conductivity coefficient of S2, S3, S4 structures with tubes, can be explained by a more intense circulation of moist air through the gaps created (free zones) in these structures. It was observed also an increasing trend of the coefficient with the increase in temperature of the lower plate

Particleboard panels (PB) have a slightly better thermal conductivity coefficient (λ -0.1081 W/m K) than oriented strand board (OSB) panels (λ- 0.13 W/mK) (Sonderegger and Niemz 2009), which determined a better thermal insulation performance of S3 (PB faces) compared to S4 and S5 (OSB faces). A dependence of the conductivity coefficient on the density of the structure was not observed.

According to Normative C107/2 (2005) a layer from the structure of a building element is considered thermally insulating if it is made of a material with a thermal conductivity lower than 0.065 W/mK and with a thickness for which the specific resistance to thermal permeability to be greater than 0.5 m^2K/W. These conditions are met by the structures S1, S5 and S6, so they prove that they are good thermal insulators with values lower than 0.06 W/mK and resistance higher than 1.5 m^2K/W. Structures 2, 3, 4, due to the core formed by the tubes and the gaps created, allowed the formation of condensation due to temperature variations and the increase of thermal conductivity.

For the temperate continental zone specific to Romania, the thermal transmittance (U) recommended for external walls is between 0.3 and 0.5 W/m^{2}K according to the passive house criteria (PHP 2022) and 0.56 W/m^{2}K according Order 2641 (2017) issued by the Ministry of Transport and Construction. The minimum thermal resistance also recommended by this Order is 1.80 m^{2}K/W. According to DIN 4108-2 (2017) materials with a λ value less than 0.1 W/ mK can be classified as thermal insulation materials. Considering the values obtained for a wall thickness of 100 mm represented by experimental structures, it can be said that the structures S1 and S5 fall within the recommendations of the Order for thermal resistance. Further investigation should be done to find the optimal structure of the core to lead to the lowest thermal conductivity coefficient.

CONCLUSIONS

Based on the theoretical and experimental study it can be concluded:

- it is necessary to use insulation materials for better energy conservation knowing that the construction sector has been identified as the largest energy consumer, generating up to 1/3 of the annual global greenhouse gas emissions;

- according to the passive house criteria, for the temperate continental zone specific to Romania, the thermal transmittance (U) recommended for external walls is between 0.3-0.5 W/m^{2}K, corresponding to a thermal conductivity coefficient between 0.03 and 0.056 W/mk;

- the experimental structures that fulfilled the above conditions are S1 and S5;

- corrugated tubes as core layer in insulation structures had the lowest insulation properties;

-sheep wool as recyclable material from industrial wool production can be used for the production of thermal insulation material having a very good thermal properties.

ACKNOWLEDGEMENTS

The author would like to thank Brenci Luminita Ph.D., coordinator of the Research Center C14, from the Research and Development Institute of Transilvania University of Brasov, for the equipment provided, and to Sergiu Georgescu for his contribution to this research.

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