Thermal Conductivity of Wood with ABS Waste Core Sandwich Composites Subject to Various Core Modifications

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Five types of alternative sandwich composite structures designed for building walls were investigated in this study using various core materials such as wood shavings, recycled acrylonitrile butadiene styrene panels, and rock wool. The sandwich structures were designed for exterior walls with a thickness of 175 mm. The experiment simulated the conditions for inside and outside temperatures during winter and summer seasons. The thermal conductivity coefficient associated with winter was lower by about 55% than those registered for summer. Wood shavings and one ABS panel as core components led to the most thermally stable structure. The best insulation solutions were the rock wool core structures with a mean thermal conductivity coefficient between 0.0564 W/mK and 0.0605 W/mK for the entire testing cycle. The two ABS panels from the core configurations had a negative impact on the thermal performance. The lowest thermal performance was recorded by the pure wood shavings core structure, with a maximum value of thermal conductivity coefficient of 0.150 W/mK. Compressed wood shaving core structures can compete with rock wool as thermal insulation solution.

Keywords: Wood frame; Wall structure; Sandwich composites; Thermal conductivity coefficient

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INTRODUCTION

The thermal conductivity of an insulating material is an important thermal property to be considered when rating the materials for building construction. A high resistance to heat flow and a low thermal conductivity coefficient is recommended for materials that are utilized as thermal insulators. The most commonly used building insulation materials are polystyrene (extruded and expanded), rock wool and glass wool, polyurethane, and foam glass. The possibility of high CO_2 emissions during production and their short life cycle make them less desirable as building materials (Su *et al.* 2016). Carbon reduction is an important advantage of wood buildings because only one cubic meter of structural lumber stores 0.9 tons of CO_2 from the atmosphere (Asdrubali *et al.* 2017).

New raw materials, such as cellulose loose-fill (Nicolajsen 2005), wood wastes (Agoua *et al.* 2013), hemp (Benfratello *et al.* 2013; Zach *et al.* 2013; Latif *et al.* 2014), bark wastes (Kain *et al.* 2013), olive seeds (Binici and Aksogan 2016), cork (Limam *et al.* 2016), and palm tree surface fibers (Ali and Alabdulkarem 2017) have been investigated in recent years, especially with regard to their thermal insulating properties.

These innovative insulation materials are currently studied as alternative solutions to traditional insulators. Some modern cellulose insulation materials are made from recycled newspaper, such as soft fiber pulp spray-applied product and cellulose loose-fill insulation material, which have thermal conductivity values of 0.040 W/mK (Roberts *et al.* 2015) and 0.050 W/mK (Nicolajsen 2005), respectively. Straw bales with a thickness of 50 cm have also been investigated (Ashour *et al.* 2011). These experimental samples show a low thermal conductivity of 0.067 W/mK. Panels made from olive seeds, wood shavings, PVC grounds, and epoxy resin, at various rates and with densities around 1000 kg/m^3 have a thermal conductivity coefficient in the range of 0.0742 W/mK to 0.145 W/mK. A low density in samples results in lower heat transfer coefficients (Binici and Aksogan 2016). Natural insulation materials made only from pure untreated wood fibers have low thermal conductivity coefficients (0.04363 W/mK dried-up samples) (Zach *et al*. 2013).

Most studies dealing with insulation materials (cork, bark, rice straw, hemp, *etc*.) report low densities between 170 kg/m^3 and 260 kg/m^3 and low thermal conductivity coefficients between 0.0475 W/mK and 0.0697 W/mK (Kain *et al.* 2013; Wei *et al.* 2015; Ali and Alabdulkarem 2017). In contrast, a low-density board of 212 kg/m^3 made from corn cob had a higher thermal conductivity coefficient of 0.139 W/mK (Pinto *et al.* 2012).

Sandwich structures are more and more used for their various applications, having the advantage of light weight without affecting the level of performance and their mechanical responses change with the variation of thermal conductivity and density. (Mehar *et al*. 2017). Wood frame wall systems are considered better alternatives for fire resistant and hygro-thermal performant walls. In these cases, the heat transfer coefficient ranges between 0.204 W/m^{2}K and 0.30 W/m^{2}K for structural wood-paper frame wall of 185 mm thick (Pásztory *et al.* 2015) and for a wood frame with hemp and stone wool insulations 100 mm thick (Latif *et al.* 2014), respectively. A similar heat transfer coefficient of about 0.200 W/m^{2}K was obtained for a wall system made of 5 cm-thick reinforced concrete and 80 cm-thick glulam studs filled with polystyrene foam with a 3-cm air gap (Destro *et al.* 2015). Bark fill material at a density of 250 kg/m^3 for bark loose bulks was used in a wood frame wall system (Kain *et al.* 2013) and showed low thermal conductivity values in the range of 0.062 W/mK and 0.096 W/mK. The performance of the bark fill was not as good as light insulation materials such as polystyrene or rock wool because of the relatively high density of bark loose bulks. The methods for measuring thermal parameters are generally based on sensors and monitors placed in the wall structure to hourly record the temperature, moisture content, and relative humidity in order to assess the influence of these parameters on the heat transfer (Kain *et al.* 2013; Wang *et al.* 2013; Latif *et al.* 2014; Pásztory *et al.* 2015). Besides density, an increase in temperature and moisture content in wall panels causes an increase of thermal conductivity influenced by the porous structure and the different intermolecular distances of matter at different states (Latif *et al.* 2014; Wei *et al.* 2015). The use of wooden elements in wall structures improves their thermal performances compared with masonry and concrete systems (Destro *et al.* 2015).

This study focused on creating wooden sandwich composite structures for walls with different cores design at the laboratory level. The thermal conductivity coefficient was measured on five types of structures. Spruce wood (*Picea abies*) was used for frame and wood shavings, and rock wool and hot pressed acrylonitrile butadiene styrene (ABS) panels constituted the core. The thermal conductivity was automatically measured based on thickness, density, temperature gradient, and mean temperatures.

EXPERIMENTAL

Materials

The experimental walls included acrylonitrile butadiene styrene (ABS) wastes as manufactured panels, and wood shavings (WS) and rock wool (RW) as loose bulk for the core. The wastes used for the core (ABS and WS) were provided by the small scale furniture production site at Faculty of Wood Engineering in Romania. The oriented strand board (OSB) and commercial gypsum board (GB) were used for the face sheets. OSB panels had a density of 660 kg/m^3 and a thermal conductivity coefficient (λ) of 0.125 W/mK, whilst the GB's density was 650 kg/m^3 and measured λ was 0.225 W/mK. The polyethylene foil (P) with a specific weight of 195 g/m^2 was used as a vapor barrier in the sandwich structure.

Mixed spruce (80% share in the mat) and beech (20% share in the mat) wood shavings (WS) collected from milling machines and planer were used in the sandwich composite cores. The initial moisture content of wood shavings (before forming the structures) ranged between 8.2% and 8.7% (greater for the softwood). Few days after, the structures were constituted and they were conditioned to stable conditions at a relative humidity of 65% and temperature of 20 ºC, before installation and starting the tests. WS are relatively thin and wide and occupy a large unit of space, so it constituted the porous structure of the wall. The loose bulk density for the WS was approximately 135 kg/m^3 (for S2), whilst the compacted bulk density was 160 kg/m^3 (for a compaction ratio of 1.2 for structures S1 and S3). The shavings length varied from 12 mm to 38.7 mm for flakes and from 1.2 mm to 12 mm for particles, with a thickness between 0.2 mm and 0.5 mm. The shares of flakes and particles into the WS were 25% and 75% respectively (Fig. 1a). Curled flakes create large voids, which could be filled by mixing them with particles from milling, thus intending to improve the thermal insulation of WS. Even so, a definitive pattern of variation of thermal coefficient with particle sizes it is difficult to be established, because of the heterogeneous structure of wood (Oluyamo and Bello 2014).

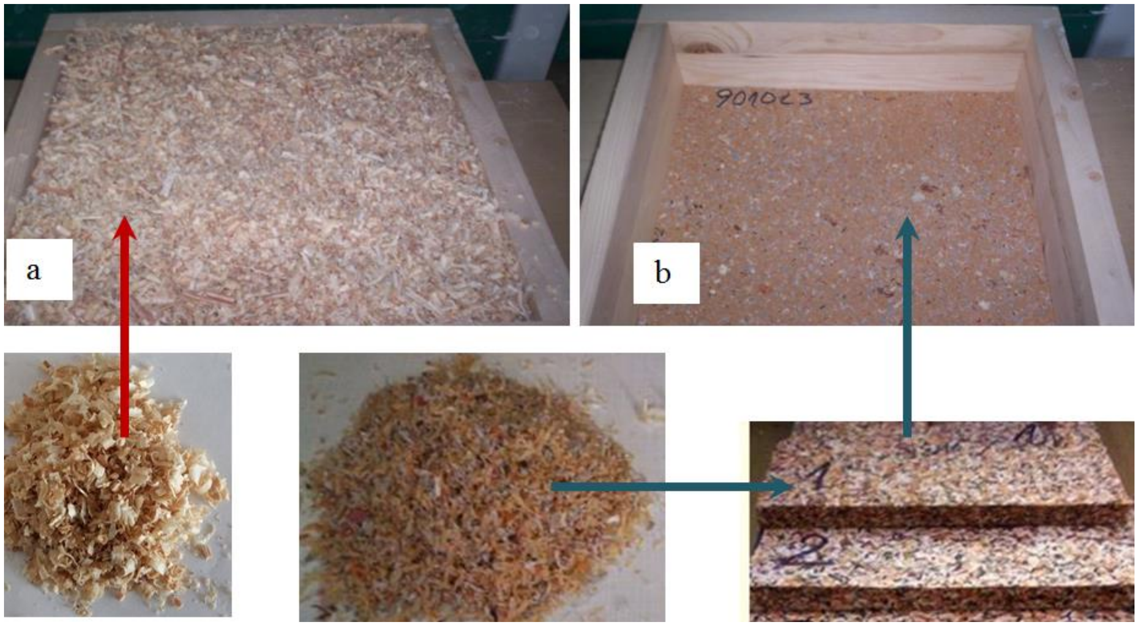
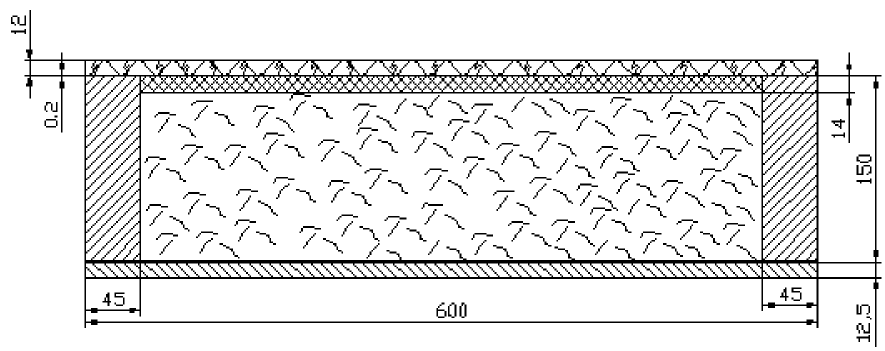
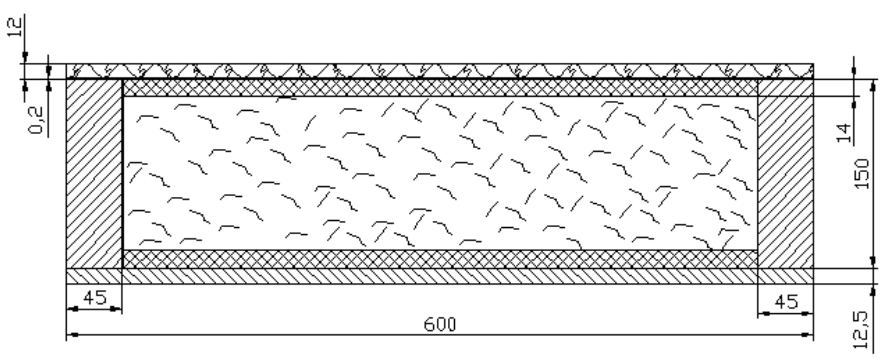


Fig. 1. Wood shavings (a) and ABS panel (b) used for the core experimental wall structures



Structure 1

a.



Structure 2

b.

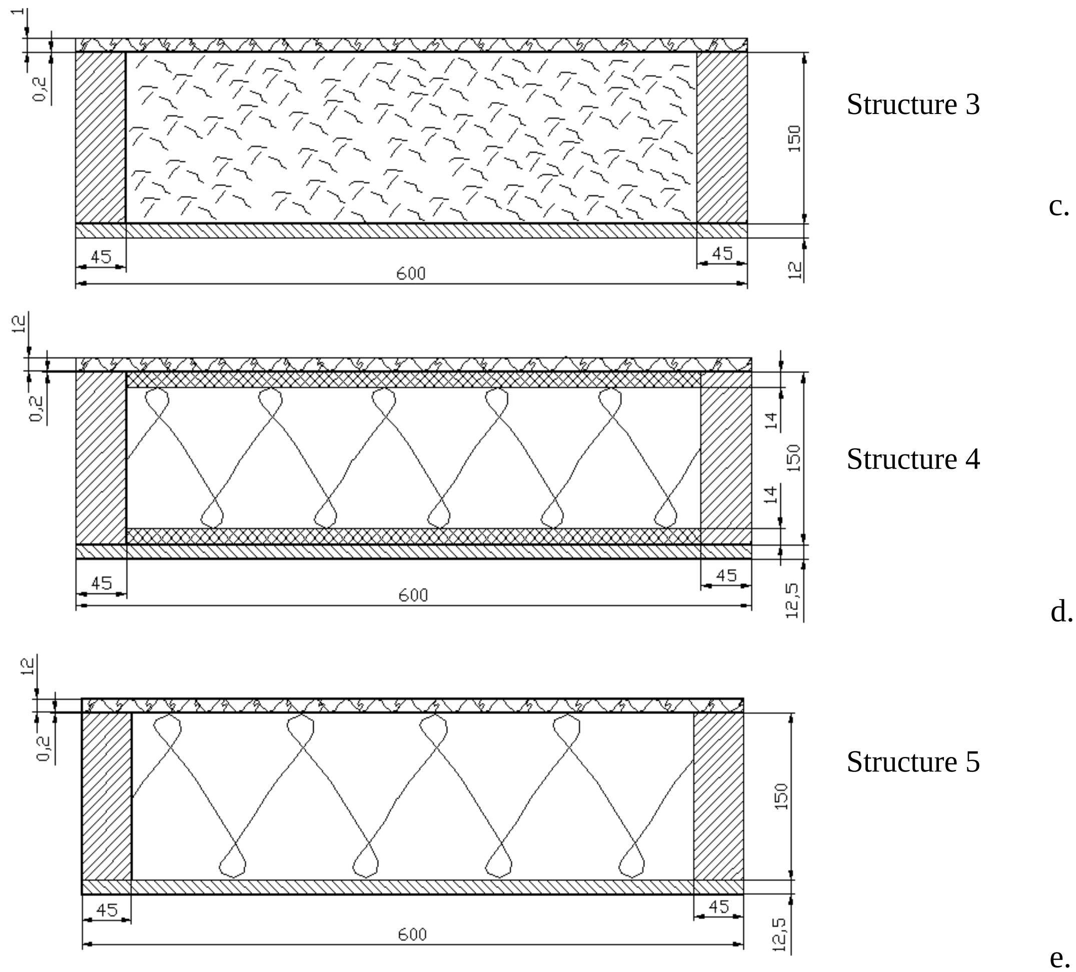


Fig. 2. Designed sandwich composite structures of the experimental walls

ABS was collected as waste and removed from the edge of the banding operation. The wastes were collected in a special bag attached to the machine exhaust outlet. ABS particles with lengths between 2 mm and 20 mm, widths between 0.5 mm and 3 mm, and with a 0.2 mm thickness formed a mat, which was hot pressed for 20 min at a temperature of 130 °C and a pressure of 20 bar (Cosereanu and Lica 2014). ABS panels (Fig. 1b) with the dimensions 600 mm x 600 mm and density of 240 kg/m^3 were obtained. They were then sized to the final dimensions of 510 mm x 510 mm x 14 mm and used for the core of the experimental walls.

Experimental Walls

Five experimental wall structures with a length of 600 mm, a width of 600 mm, and a thickness of 175 mm were designed and built for thermal conductivity measurements. The designed structures of the walls are presented in Fig. 2. The walls were designed as sandwich structures (Table 1), composed of wooden frames, cores, and two face sheets. The wood frames were made from spruce wood (*Picea abies*) with a thickness of 45 mm. Each wood frame was planked with a 12.5 mm gypsum board (GB) on one side and a 12 mm OSB panel on the other side. The experimental walls were designed with various core compositions, as specified in Table 1.

Structure S5 was considered a reference sample because of the low thermal conductivity coefficient of rock wool core, which had a measured thermal conductivity coefficient of 0.037 W/mK at a density of 30 kg/m^3, and it is a material generally used for insulations.

Table 1. Components of Designed Walls

Structures and Materials	Inside Face Sheet		Core				Outside Face Sheet
	GB	P	ABS	WS	RW	ABS	OSB
Structure 1 (S1)	x	x	-	x	-	x	x
Structure 2 (S2)	x	x	x	x	-	x	x
Structure 3 (S3)	x	x	-	x	-	-	x
Structure 4 (S4)	x	x	x	-	x	x	x
Structure 5 (S5)	x	x	-	-	x	-	x
x – raw material used in the structure							

Methods

The five structures of the experimental walls were subjected to thermal conductivity coefficient (*λ*) measurements. The tests were performed on HFM436 Lambda equipment (Netzsch, Selb, Germany), according to ISO 8301 (1991) and DIN EN 12667 (2001). This testing method is based on the determination of the quantity of heat that is passed from a hot plate to a cold plate through the sandwich composite structure.

The temperature difference between the two plates is registered, and the thermal conductivity coefficient is automatically calculated based on Fourier's Law. Before the samples were tested, the equipment was calibrated depending on the temperature differences (ΔT) and mean temperatures (T_m). Table 2 presents the values set for temperature configuration.

Table 2. Temperatures Configuration Set Up

$\Delta T = T_1 - T_2$ in °C	$T_m = \frac{T_1+T_2}{2}$ in °C													
	-5		0		5		10		15		20		25	
	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
10	0	-10	5	-5	7.5	2.5	15	5	20	10	25	15	30	20
15	2.5	-12.5	7.5	-7.5	12.5	-2.5	17.5	2.5	22.5	7.5	27.5	12.5	32.5	17.5
20	5	-15	10	-10	15	-5	20	0	25	5	30	10	35	15
25	7.5	-17.5	12.5	-12.5	17.5	-7.5	22.5	-2.5	27.5	2.5	32.5	7.5	37.5	12.5
30	10	-20	15	-15	20	-10	25	-5	30	0	35	5	40	10
(T_1) upper plate temperature (T_2) bottom plate temperature														

Density was introduced as input data in the equipment software. The density was calculated as the ratio between mass and volume of the tested structure. Two specimens of each structure were built and tested, and the results presented are the mean values.

RESULTS AND DISCUSSION

The experiment simulates the outdoor temperatures (T_2), indoor temperatures (T_1), and differences between them (ΔT). Thermal conductivity coefficients were determined for each ΔT and each mean temperature T_m. The results are presented in the histograms in Fig. 3.

The mean temperature values used in the experimental measurements were characterized by two intervals: T_m of -5 ºC, 0 ºC, and 5 ºC for the winter season, and T_m of 15 ºC, 20 ºC, and 25 ºC for the summer season.

The structures are not homogeneous, so they did not have a predictable behavior (increase or decrease), of thermal coefficient considering the variation of the experimental setup conditions. The impact of negative temperatures on the structures caused the probable occurrence of condensation inside the structures.

The sudden rise in temperature (in the case of ΔT = 10 ºC) in structures 3 and 5 (the simplest ones), for T_m between 5 ºC and 10 ºC favored the humidity circulation inside the structure, which led to a sudden increase of thermal coefficient. Inside the structures, pure thermal conductivity along with other phenomena associated with moisture and heat transfer occurs. Moreover, heat transfer by convection and capillarity takes place. These phenomena lead to an increase in the thermal coefficient value, observed mainly with the structures having loose bulk wood shavings as core.

For all structures, as can be observed in Fig. 4, when ΔT increases (from ΔT = 10 ºC to ΔT = 30 ºC), the negative temperature field of T_2 (blue area) extends from T_m = 5 ºC to 15 ºC. The conditions at which the structures are subjected, are more stable (negative temperatures) for a longer period of time, between ΔT = 20 ºC and ΔT = 30 ºC. This may have favored the conditions of thermal and humidity transfer determining a slower reaction of the structures components, resulting in a less variation of thermal conductivity coefficient.

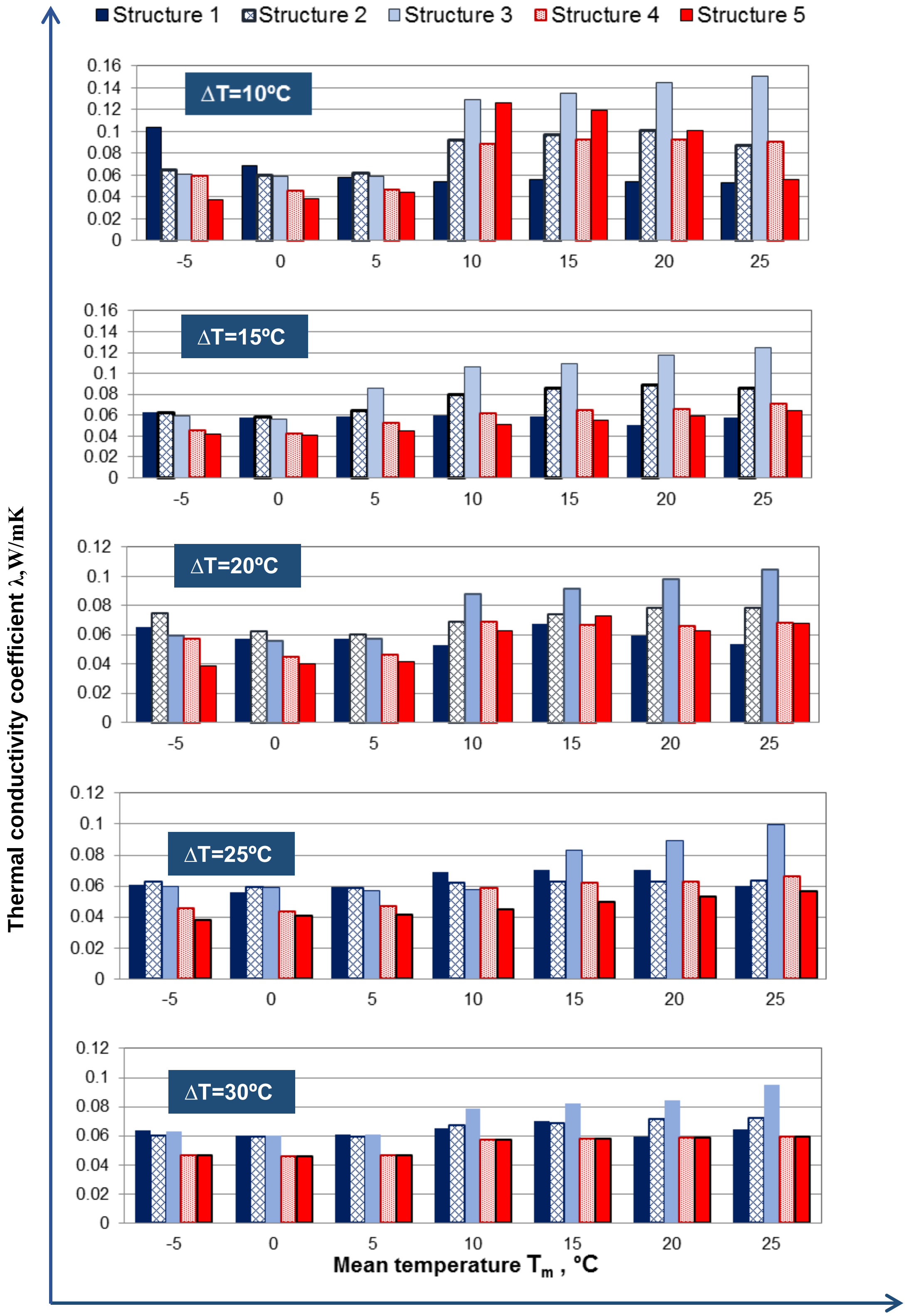


Fig. 3. Thermal conductivity coefficient values at various temperature differences between equipment hot plate and cold plate (ΔT) and at different mean temperatures T_m

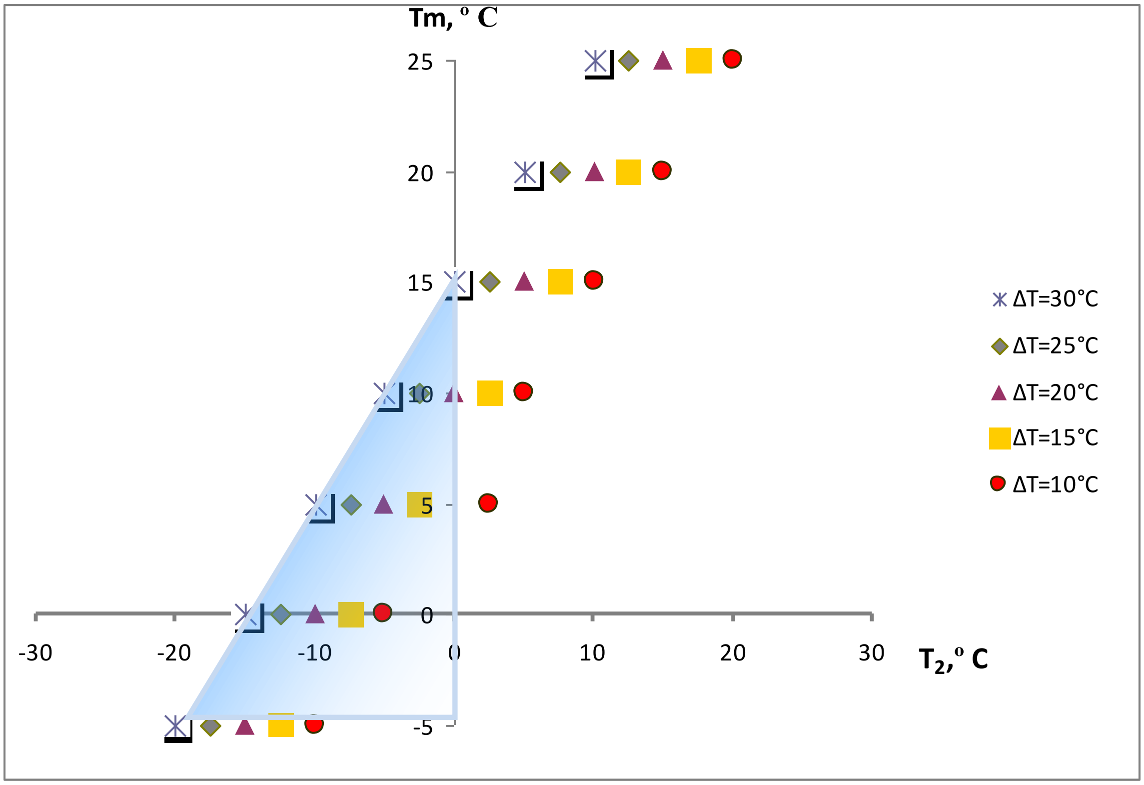


Fig. 4. The evolution of negative and positive temperature zones according to variation of Δ*T*

For each structure, the same measurement protocol was used. The test consisted of a continuous passage of structures from negative to positive values of temperature T_2. The structures had undergone through successive cooling and heating, which influenced the core thermal behavior, leading to oscillatory variation of thermal conductivity coefficient λ (*i.e.* S5 at ΔT = 10 ºC and ΔT = 15 ºC). During the testing time the structures were not removed from the equipment, passing an entire cycle testing period.

The structures are defined in two categories based on the core components: one filled with wood shavings (S1, S2, and S3) and the other one with rock wool (S4 and S5). Analyzing the behavior of the first category, it can be observed that the structure S3 (the simplest one) does not provide the required thermal resistance to reduce convection heat losses due to the local temperature differences appeared in the structure during the summer. In summer time, accumulated heat was higher than in winter, S3 recording the highest thermal coefficient of 0.150 W/mK.

The same trend can be observed in structures S1 and S2, but the phenomenon is less amplified due to the presence of the ABS layer acting as a moisture barrier. Generally, structure S1 had the lowest λ coefficient compared to S3 and S2 in both seasons (below 0.063 W/mK) (Fig. 5), showing a smaller variation related to T_m and ΔT. On the other hand, reducing voids by compaction of shavings, the convective loops are eliminated and convection heat losses are diminished.

The gaps between flakes for S2 with loose bulk core shavings favor the heat flow, resulting in convective heat transfer and a higher λ.

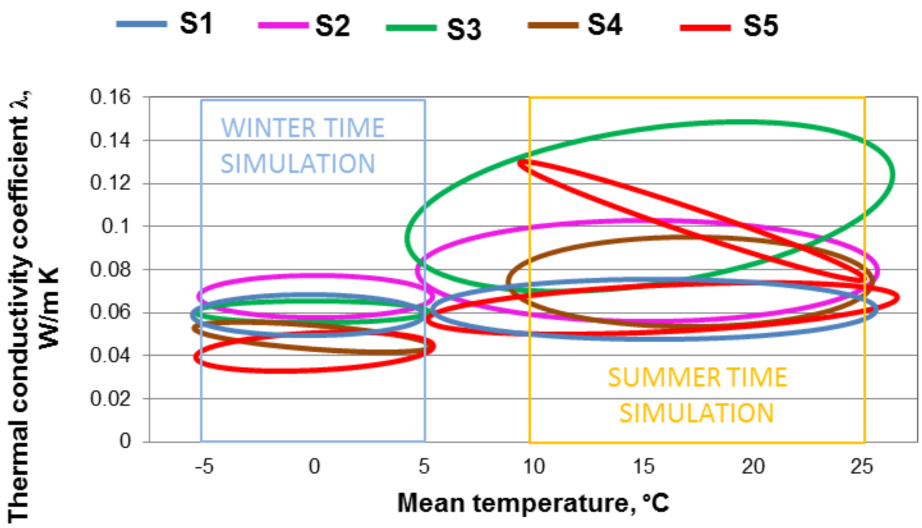


Fig. 5. Comparison between thermal conductivity coefficient limits of investigated structures in the conditions of both winter and summer season simulation

Structure S5 had a lower thermal conductivity compared to S4 (both with rock wool core). The mean values for the entire testing cycle were 0.0564 W/mK for S5 and 0.0605 W/mK for S4 (Fig. 6). The differences between these structures are attributed to core structure, S4 including ASB layers on both sides. The upper layer (from the exterior) might control the interior humidity to lower level during cold periods, thermal coefficient reaching values below 0.06 W/mK. During summer time the ABS bottom layer (from the interior) favored the increasing of λ to values ranging from 0.090 W/mK (ΔT=10 ºC) to 0.071 W/mK (ΔT=15 ºC) and 0.059 W/mK (ΔT=30 ºC).

From the analyzed structures, it can be seen that S5 and S1 had a better performance compared to the other structures with the lowest values of λ throughout the test cycle (0.0564 W/mK for S5 and 0.0614 W/mK for S1) (Fig 6).

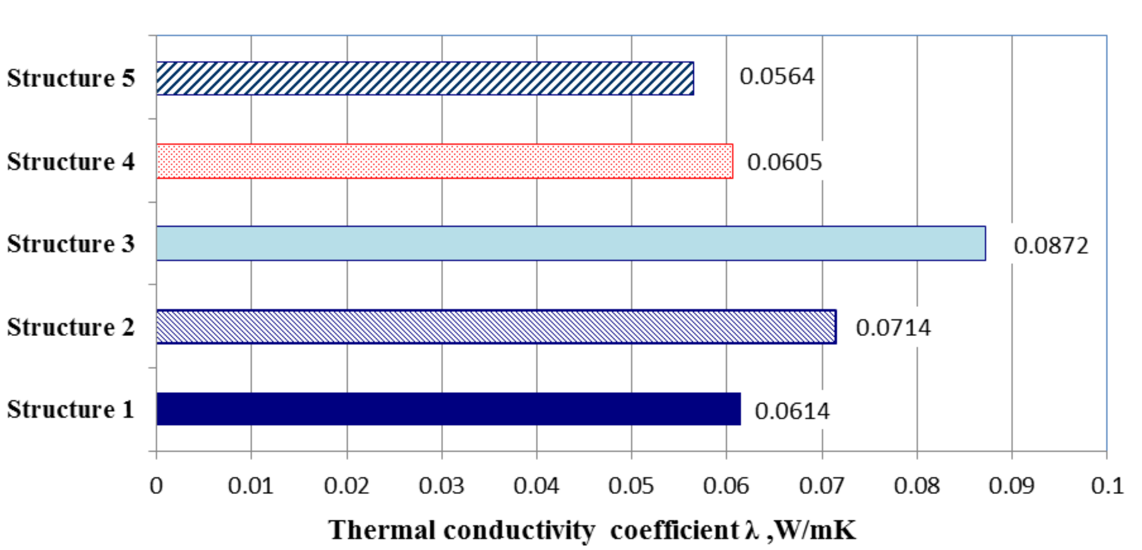


Fig. 6. Mean values of thermal conductivity coefficient for the entire test cycle

The densities of the experimental wall structures and standard deviations are shown in Fig. 7. The highest density (299 kg/m^3) was recorded for S2, having a core composition of wood shavings and two panels made from ABS wastes.

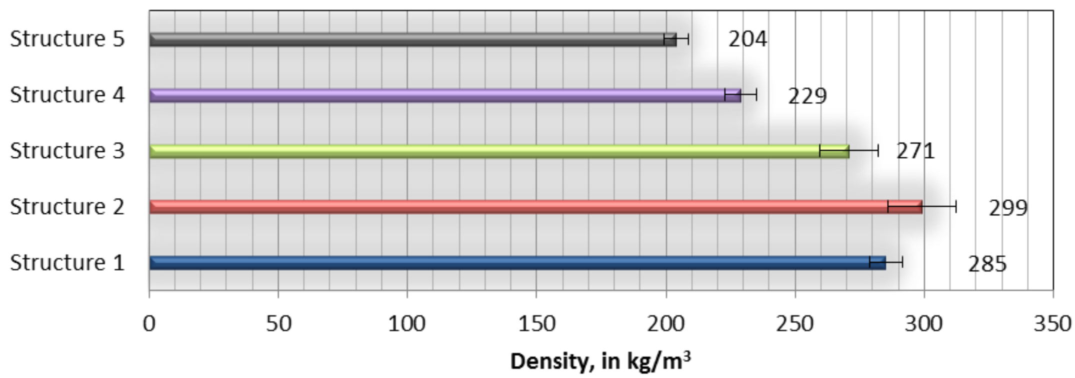


Fig. 7. Histogram of densities of the experimental wall structures

The lowest density value (204 kg/m^3) was in S5 (reference) witch was composed only of rock wool core and OSB/ GB faces. The spread values of the λ at different densities and the ΔT limits are shown in the left panel in Fig. 8. The mean values of λ and standard deviations of all structures are shown in the right panel in Fig. 8.

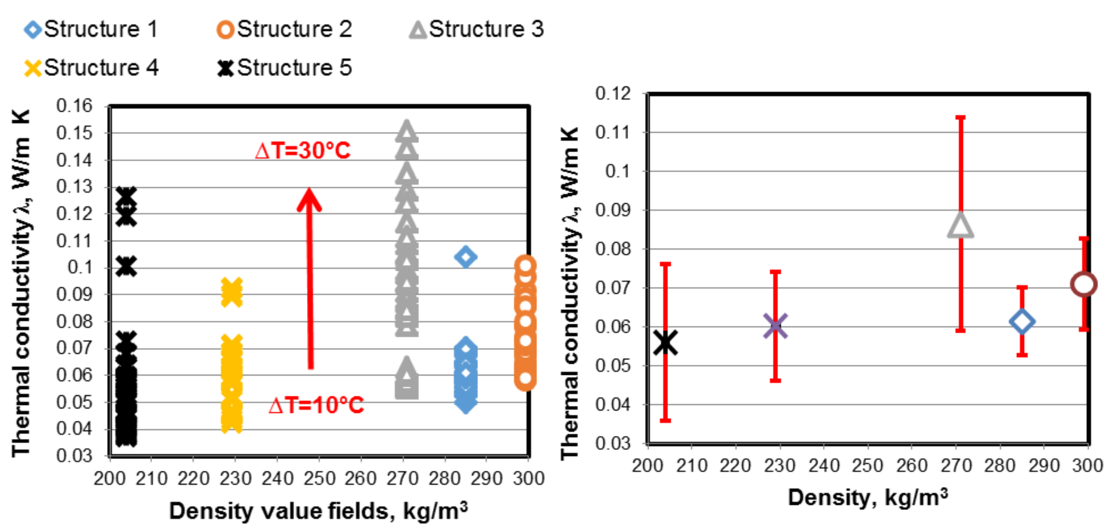


Fig. 8. Histogram of thermal conductivity against structure density for all ΔT (left) and mean values of thermal conductivity coefficient (right)

The influence of the interaction of factors on the thermal conductivity coefficient was performed using the statistical ANOVA single-factor variance analysis. Differences were considered statistically significant at $p \leq 0.05$. Factors that significantly affect the thermal conductivity were determined using the reported p-values. After performing the statistical analysis of the mean values obtained in the experiment, ΔT and density were found to have a highly significant influence on the measured thermal conductivity at a 95% confidence level ($p \leq 0.05$), whilst the mean temperature was not statistically significant.

CONCLUSIONS

1. The best thermal performance was recorded for S5 followed by S4, rock wool core as low density fibrous insulation layer reaching the lowest thermal conductivity coefficient compared to wood shaving core structures.
2. Less variation of thermal conductivity coefficient during the entire testing cycle was reached by S1. This structure registered a better thermal behavior compared to structures containing in their core wood shavings (S2 and S3).
3. The successive cooling and heating phases during the testing cycle influenced the thermal behavior of structures, perceived as oscillatory variation of thermal conductivity. Inside the structures there is not only pure thermal conductivity, others phenomena associated to moisture and heat transfer occurred.
4. The ABS layer applied above the gypsum board didn't improve the insulation behaviour of S2 and S4 structures.
5. Both density and ΔT influenced to a greater extend the thermal conductivity coefficient than the mean temperature T_m
6. Wood shavings compressed to a lower density, as an ecological and inexpensive material could represent a viable solution for thermal insulation compared with rock wool.

ACKNOWLEDGMENTS

The authors acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, No. 11/2009) for providing the infrastructure used.

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Article submitted: August 17, 2017; Peer review completed: October 22, 2107; Revised version received: November 17, 2017; Accepted: November 18, 2017; Published: November 22, 2017.
DOI: 10.15376/biores.13.1.555-568