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COMPARISON OF THERMAL PERFORMANCES OF PLYWOOD SHEAR WALLS PRODUCED WITH DIFFERENT THERMAL INSULATION MATERIALS

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ABSTRACT

Shear walls are one of the envelopes of light-frame wooden buildings where thermal insulation is most required. The thermal performance of shear walls can vary according to the type, properties and thickness of the wood and insulation materials used in their production. This study, it was aimed to compare the thermal performances of plywood shear walls produced with different thermal insulation materials. For this aim, the archetype walls with properties similar to commonly used plywood shear walls were designed and produced for each thermal insulation material type and wood specie. The shear wall groups were formed by using Scots pine (*Pinus sylvestris*), black pine (*Pinus nigra*) and spruce (*Picea orientalis*) as wood species and cellulose, flax, felt, XPS, EPS, sheep's, rock and glass wool as thermal insulation materials. The thermal conductivity of the shear wall groups was determined according standard. Thermal resistance and other thermal performance parameters were calculated using the thermal conductivity values. As a result of the study, rock wool was the best thermal insulation material among the Scots pine shear wall groups while glass wool was the best thermal insulation material among the black pine and spruce shear wall groups. The shear walls produced with EPS foam boards indicated the worst thermal performance among all groups

Keywords: Plywood, shear wall, thermal conductivity, thermal insulation materials, thermal performance.

INTRODUCTION

Building construction and operations caused 35 % of global total energy consumption and 38 % of energy related CO_2 emissions in 2019 (United Nations Environment Programme 2020). In addition, it has been reported that the global energy consumption in buildings will grow by 1,3 % per year on average from 2018 to 2050 (IEA 2020). These data indicate that energy efficiency and reduction of emissions are extremely important in the building industry. Building walls, which form a major part of the building envelope, interact thermally with the changing environment during the day (Jannat *et al*. 2020). Therefore, they are the building envelopes with the highest heat losses that cause the increase in energy consumption (Balaras *et al*. 2000). The thermal performance of the walls is an important factor in increasing the energy efficiency of the building industry and reducing greenhouse gas emissions. Thermal insulation is one of the most effective measures to increase energy efficiency by improving the thermal properties of building walls (Cetiner and Shea 2018). Energy savings up to 77 % can be achieved with the insulation of the wall and roof in the building (Çomaklı

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and Yüksel 2003). Bio-based, petrochemical and mineral-based materials such as extruded polystyrene (XPS), expanded polystyrene (EPS), polyisocyanurate, polyurethane foam, cork, cotton, wood fibre, flax, hemp, coconut, cellulose, rice, sheep's wool, glass wool, rock wool can be used for thermal insulation in the building industry (Cetiner and Shea 2018, Asdrubali *et al*. 2015).

Wooden structures can provide a better living environment compared to other building types with superior advantages such as environmentally friendly, energy efficiency, earthquake resistant, structural safety, health and comfort (Liu *et al*. 2018). Light-frame wood structures among the wood building types are widely preferred in low-rise residences, commercial and industrial buildings, especially in Northern Europe and North America because of its similar advantages (Liu *et al*. 2021). They are conventionally formed of framing, sheathing materials, fasteners, and anchorage (Peng *et al*. 2020). Shear walls are the most important components affecting the structural and thermal performance of these structures. Thermal properties of the shear walls can be further improved by using suitable insulation materials besides the good thermal performance of sheathing materials. However, when choosing an insulation material, it is important to consider other important aspects such as acoustic performance, environmental impacts, impacts on human health and production costs (Asdrubali *et al*. 2016, Schiavoni *et al*. 2016).

Thermal conductivity is a significant parameter used in both building and industrial processes in determining the heat transfer rate, developing drying models and adhesive curing rate (Hassanin *et al*. 2018, Kol and Altun 2009). In addition, when choosing insulation materials that are not affected by fluctuations in outdoor temperature and maintain indoor temperature, it is necessary to know the thermal conductivity values. Wood and wood-based materials give lower thermal conductivity values compared to other building materials due to their porous structure (Gu and Zink-Sharp 2005, Krüger and Adriazola 2010). The thermal conductivity of wood materials has varied according to wood species, wood fibre direction, resin type and additive members used in the manufacture of wood-based materials (Kamke and Zylkowoski 1989, Hassanin *et al*. 2018). Thermal conductivity values in the wooden shear walls can vary according to properties of the sheathing materials, wall thickness, space of frame and properties of the thermal insulation materials used in the cavities (Kosny *et al.* 2014).

The main purpose of this study is to compare the thermal performance of plywood shear walls produced with different thermal insulation materials. For this purpose, the archetype walls with properties similar to commonly used plywood shear walls were designed and produced for each thermal insulation material type and wood species.

MATERIALS AND METHODS

Materials and manufacturing of plywood

In this study, three species of coniferous wood, which are widely preferred in the building industry, were used: scots pine (*Pinus sylvestris*), black pine (*Pinus nigra*) and spruce (*Picea orientalis* L.). The logs for veneer manufacturing, with an average 40 cm, were obtained from Trabzon, located at the northern point of the Black Sea Region of Turkey. In addition, 40 mm thick cellulose, flax, felt, XPS, EPS, sheep's, rock and glass wool were commercially supplied as thermal insulation materials within the scope of the study. Cellulose, one of the insulation materials used in the study, was produced from 80 % recycled newsprint and 20 % boric acid which was a non-toxic fire retardant. Flax was produced from recycled flax and hemp fibres whilst felt was produced from fibres obtained from the recycling of polyethylene terephthalate. Rock wool consisted of 97 % of natural fibres obtained from melting basalt stone while glass wool consisted of fibres produced by melting silica sand. Moreover, XPS boards was produced by extrusion of polystyrene raw material whilst EPS foams were produced by inflating polystyrene particles and sticking to each other and 98 % was composed of still dry air. Technical information about these thermal insulation materials was obtained from the suppliers. Furthermore, some technical specifications of these materials were given in Table 1.

Table 1: Some technical specifications of the thermal insulation materials.

Thermal Insulation Material Types	Density (kg/m^3)	Specific Heat Capacity (J/g ºC)	Vapor Diffusion Resistance Factor	Thermal Conductivity (W/mK)	Measured* Thermal Conductivity at 30 ºC (W/mK)
Cellulose	40	1,4	2,1	0,040	0,042
Flax	36	1,6	2,4	0,040	0,043
Felt	70	1,3	1,9	0,040	0,040
Sheep's Wool	18	1,3	4,2	0,039	0,041
Rock Wool	45	0,9	1,2	0,033	0,038
Glass Wool	15	0,8	1,2	0,030	0,038
XPS	32	1,5	90	0,034	0,042
EPS	10	1,3	40	0,042	0,052

*These were the values measured in the laboratory within the scope of the study. Other specifications were obtained from the suppliers.

In literature, the limit values of some specifications of building insulation materials were given in the study by Kumar *et al.* (2020). In this study, it was determined that some specifications values of the thermal insulation materials in Table 1 were in the range of these limit values. In addition, it was recalculated in the laboratory according to ASTM C518-04 (2004) standard to compare the insulation materials more accurately within the scope of the study. Before the measurement, the thermal insulation materials were kept at 20 ºC and 65 % relative humidity until they reached approximately 8 % moisture content.

The logs were steamed for 12 hours - 16 hours at a temperature of 80 ºC before the peeling process and veneer sheets with dimensions of 300 mm by 300 mm by 2 mm were clipped. The vertical opening was 0,5 mm and the horizontal opening was 85 % of the veneer thickness in the veneer manufacturing process. After rotary peeling, the veneers were dried at 110 ºC in a veneer dryer until to reach 6 % - 7 % moisture content.

The Eurocode 8 states that the minimum thickness of the plywood boards to be used in shear walls should be 9 mm (Bisch *et al*. 2012). Therefore, five-ply plywood panels, 10 mm thick, were manufactured by using phenol formaldehyde (PF) glue resin with 47 % solid content. The glue was applied at a rate of 160 g/m^2 to the single surface of veneer by using a four-roller spreader. The assembled samples were pressed in a hot press at a pressure of 0,785 MPa and at 140 ºC for 10 min. The plywood panels were conditioned to achieve equilibrium moisture content at 20 ºC temperature and 65 % relative humidity prior to testing.

Some physical specifications such as density, equilibrium moisture content (EMC) and thermal conductivity values of plywood used in the shear walls and the veneers used in plywood production were given in Table 2 according to tree species. The density, EMC and thermal conductivity measurements were performed after drying in the veneers and after conditioning in the plywood according to ISO 9427 (2003a), ISO 16979 (2003b) and ASTM C518-04 (2004) standards, respectively.

Table 2: Some physical specifications of the veneers and plywood.

Material Type	Specifications	Wood Species		
		Scots Pine	Black Pine	Spruce
Veneer	Density (kg/m^3)	498	523	462
	EMC (%)	6,21	6,28	6,17
	Thermal Conductivity (W/mK)	0,027	0,029	0,026
Plywood	Density (kg/m^3)	587	596	512
	EMC (%)	8,42	8,64	8,21
	Thermal Conductivity (W/mK)	0,105	0,118	0,097

Manufacturing of archetype plywood shear wall

The sheathed shear walls used in light-frame wooden structures are generally manufactured in the dimensions of 2,4 m x 2,4 m according to the dimensions given in ASTM E72-13a (2014) Standard. In the building industry, the thermal properties of the shear walls are increased by filling the spaces between the frame and the sheathing materials with thermal insulation materials. Typical plywood shear walls and spaces where thermal insulation materials are used are shown in Figure 1.

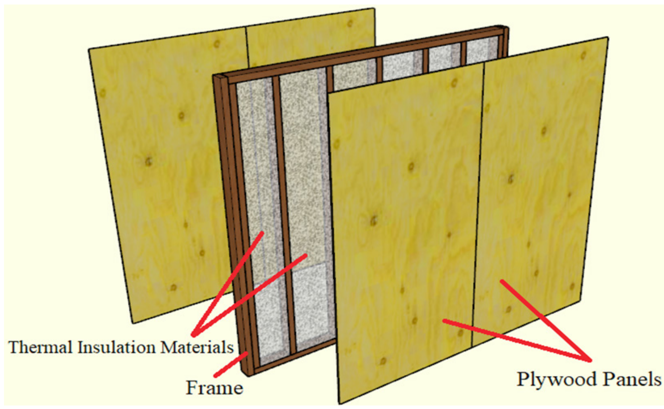


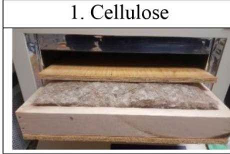
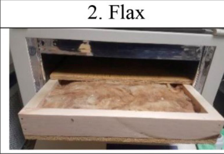
Figure 1: Typical plywood shear walls and use of thermal insulation materials.

Within the scope of the study, the archetype specimens of 300 mm x 300 mm were produced for each shear wall group formed according to the determined variables. They were used because both the specimen measurement dimensions of the test apparatus and the purpose of the study were to compare only the thermal insulation materials. The spruce timbers were used as frames in all the archetypal shear wall groups. The density of the timbers was 451 kg/m^3, the moisture content was 12 % and the thermal conductivity was 0,124 W/mK. The frame was produced with dimensions of 300 mm x 300 mm by nailing from 4 pieces of spruce timber with a thickness of 40 mm and a width of 18 mm.

The control groups were formed to reveal the percentage differences of the thermal conductivity coefficients of the thermal insulation materials from the shear walls consisting of only the plywood panels and the frame filled with still air.

The descriptive information about the shear wall groups created to achieve the aim of the study and the views of the test specimens are given in Table 3.

Table 3: The descriptive information and views of the archetype specimen groups.

Wood Species	Scots Pine	Black Pine	Spruce
Thermal Insulation Material Types			
	1. Cellulose	2. Flax	3. Felt
			
	4. Sheep's Wool	5. Rock Wool	6. Glass Wool
			
	7. XPS	8. EPS	9.Control

Thermal performance test

The thermal conductivity, thermal resistance and other parameters that can be calculated with these are considered as important measurements in the selection of thermal insulation materials (Hassanin *et al.* 2018). In this study, the thermal conductivity coefficients of archetype specimens were determined according to ASTM C518-04 (2004) at average 30 ºC and FOX 314 Steady-State Heat Flow Meter apparatus (HFM) was used for these measurements (Figure 2). The thermal conductivity coefficient measurements were carried out with 6 repetitions for each group. Before the tests, the standard calibration of the HFM test machine was made and during the test, the 300 mm × 300 mm specimen was placed between the cold and hot plates. During the measurements, the temperature of the cold (upper) plate was set to 20 ºC and the temperature of the hot (lower) plate to 40 ºC. Moreover, all measurements were carried out in the laboratory at 20 °C and 65 % relative humidity. These plates have a guard area and a 100 mm x 100 mm dimensions metering area where the heat flow is measured (Figure 2).

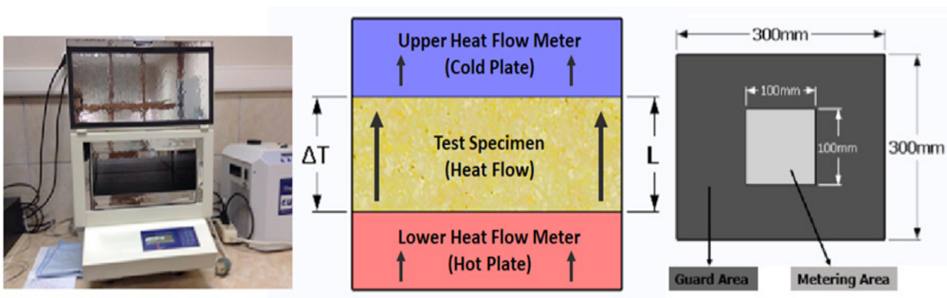


Figure 2: Photo and schematic of the HFM apparatus.

The thickness of the test specimens was measured with four optical encoders, one on each corner of the plate, and the temperature drop across the specimen was measured with thermocouples placed on the plates. The temperature and voltage values were recorded for the upper and lower layers every 0,5 seconds, and these records were organized in groups of 512 called data blocks, one of which consists of approximately 4 minutes of data. The software of the apparatus determined the average thermal conductivity with equation 1 by calculating the average temperatures and voltages of the plates for each data block. For the apparatus to measure the average thermal conductivity, the last three data blocks must reach the steady state condition. This was achieved when the average temperature differences of the plates were within the limits of ± 0,2 ºC and the average voltage value for a data block did not differ by more than 2 % of the previous data block, Equation 1.

$$k = \frac{q^{"}L}{\Delta T} \quad (1)$$

Where:

K - average thermal conductivity coefficient (W/mK)

q” - heat flux (W/m^2)

ΔT - temperature difference across the specimen (K)

Using Equation 2, the percent differences of heat flow between the upper and lower plates of the device were determined.

$$\%Difference = \frac{q^{"}_{U} - q^{"}_{L}}{q"} \quad (2)$$

Where:

q''_U - upper heat flux (W/m^2)

q''_L - lower heat flux (W/m^2)

q'' - average q''_U and q''_L (W/m^2)

The capacity of a material to prevent heat flow in a certain area and under a certain temperature is called absolute thermal resistance (R) and the higher the absolute thermal resistance, the better the material's thermal insulation. R (absolute thermal resistance) and R-value, which is the thermal resistance of a material per unit area, were calculated with Equation 3 and Equation 4.

$$R = \frac{L}{k\,A} \quad (3)$$

$$\text{R-value} = \frac{L}{k} \quad (4)$$

Where

R - absolute thermal resistance (K/W)

R-value - thermal resistance (m^{2}K/W)

L - total thickness of the shear wall (m)

K - measured average thermal conductivity coefficient (W/mK)

A - metering area in (m^2)

Moreover, thermal resistivity (r) and thermal conductance (C) values of the specimens in Km/W and W/m^{2}K were calculated based on Equation 5 and Equation 6.

$$r = \frac{1}{k} \quad (5)$$

$$C = \frac{k}{L} \quad (6)$$

RESULTS AND DISCUSSION

The thermal conductivity coefficient average values and percent differences of the shear wall groups formed within the scope of the study were given in Table 4 according to the wood species and thermal insulation material types. In addition, the thermal conductivity coefficient changes and percentage reduction in the thermal conductivity of these groups were graphically shown in Figure 3.

Table 4: Thermal conductivity average values and percentage differences of the shear walls groups.

Wall Numbers	Wood Species	Thermal Insulation Material Types	Thickness (L-mm)	Thermal Conductivity (k-W/mK)	Percent Difference (%)
1	Scots Pine	Cellulose	59,11	0,059	12,58
2		Flax	59,30	0,059	3,32
3		Felt	59,17	0,057	2,06
4		Sheep's Wool	59,46	0,057	2,40
5		Rock Wool	59,25	0,055	1,46
6		Glass Wool	59,16	0,056	4,98
7		XPS	59,16	0,058	1,63
8		EPS	59,12	0,076	0,73
9		Control	59,10	0,200	5,05
10	Black Pine	Cellulose	60,60	0,059	3,44
11		Flax	60,67	0,061	2,67
12		Felt	60,62	0,058	2,13
13		Sheep's Wool	60,87	0,060	2,92
14		Rock Wool	60,69	0,057	2,33
15		Glass Wool	60,65	0,057	3,84
16		XPS	60,64	0,061	10,05
17		EPS	60,55	0,080	0,12
18		Control	60,61	0,213	6,55
19	Spruce	Cellulose	59,00	0,057	3,08
20		Flax	59,09	0,059	5,65
21		Felt	59,02	0,057	2,56
22		Sheep's Wool	59,23	0,058	2,72
23		Rock Wool	59,19	0,057	0,28
24		Glass Wool	59,00	0,056	1,61
25		XPS	59,01	0,057	0,37
26		EPS	58,94	0,075	0,27
27		Control	58,95	0,187	5,97

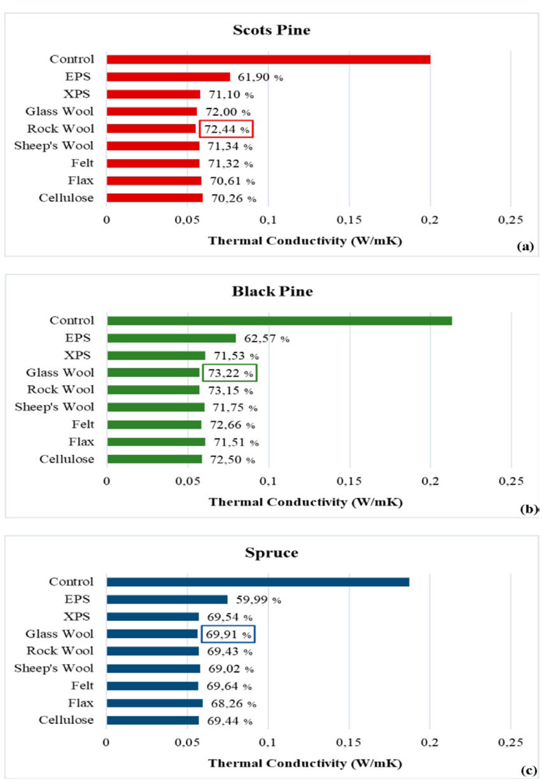


Figure 3: Thermal conductivity values changes of the shear wall groups (a) Scots pine, (b) Black pine and (c) Spruce.

In the comparison of the control groups with each other, it was determined that the highest thermal conductivity value was obtained from the shear walls formed with black pine plywood. The lowest value was found in the control group of shear walls formed with spruce plywood. It was stated in the literature that the most important factors on the thermal conductivity values of solid wood and wood-based panels were density and moisture content (Sonderegger 2011). Sonderegger and Niemz (2009) determined that the thermal conductivity of wood materials increased as the density and moisture content increased. In Table 2, the density and EMC of the veneer sheets and plywood panels used in the control groups of shear walls were given. It was observed that both density and EMC values of larch veneer and plywood were higher than the other two wood species. Likewise, the lowest of these values were obtained from spruce wood species. In addition, it could be seen from Table 2 and Table 4 that there was a linear relationship between the thermal conductivity values of the veneers and plywood and the values of the control groups of shear walls. Therefore, it was an expected result that the thermal insulation properties of spruce shear walls were better among the control groups.

When the data in Table 4 and the graphs in Figure 3 are examined, the thermal conductivity coefficient values of the black pine and spruce plywood shear walls produced with glass wool were found to be the lowest in percentage compared to the control groups. The lowest thermal conductivity coefficient was obtained from rock wool in the scots pine plywood shear walls. The reason for these results could be shown that the thermal conductivity coefficient values of glass and rock wool (0,038 W/mK and 0,038 W/mK) were the lowest compared to other the thermal insulation materials (Table 1). Ducoulombier and Lafhaj (2017) compared hygrothermal properties of glass wool, rock wool, EPS, wood fibreboard and polyester fibrefill and found similarly that the thermal conductivity values of glass wool were the lowest. Domínguez-Muñoz *et al.* (2010) investigated that thermal conductivity of inorganic (cellular glass, glass and rock wool), organic (XPS, EPS, Polyurethane foam) and natural (sheep, cellulose and cotton) insulation materials. They observed that the inorganic materials have the lowest thermal conductivity values while the highest values were obtained from the organic materials. In this study, it was seen that similar results with the literature were obtained.

The percentage reduction in the thermal conductivity coefficient values was the least for all three species of wood in the shear wall groups produced with EPS panels. It was determined that the thermal conductivity of EPS foam (0,052 W/mK) was the highest among the thermal insulation materials (Table 1). Therefore, it was expected that the thermal conductivity values of plywood shear walls produced with EPS were also high. The glass wool is more porous material and have larger cavities than polystyrene materials (Berge and Johansson 2012). Heat flow occurs through the air in the cavities of the solids and the thermal conductivity of the air in the cavity is much lower than that of the solid material. This situation causes the whole material to have lower thermal conductivity (Zhou *et al.* 2010). Therefore, it was thought the plywood shear walls produced with glass wool gave the lowest thermal conductivity values according to polystyrene materials. Liu *et al.* (2020) determined the thermal conductivity of the wooden-frame walls that they formed with XPS and EPS in different configurations and observed that the thermal conductivity of the walls using EPS foam boards were higher than that of XPS. In order for an envelope of building to be considered as an insulating layer, it must have a thermal conductivity lower than 0,065 (W/mK) (Florea and Manea 2019). According to the thermal conductivity results obtained from the study, the shear wall groups except EPS can be used as an insulation layer in light-frame wooden buildings.

According to the percent difference values between the heat flux measured by the upper and lower HFM, EPS foam boards gave the lowest values among the thermal insulation materials for all of wood species. Hassanin *et al.* (2018) found that that the lowest percent difference values were obtained from the materials giving the highest thermal conductivity. A similar relationship was observed in this study. In the thermal conductivity coefficient measurements of the shear wall groups, the frames made of spruce timbers with similar density, moisture content and thermal conductivity values were used. In this way, the differences arising from the frame elements in the comparison of the thermal conductivity of the groups were minimized. Moreover, the metering area in the device was 100 mm x 100 mm as can be seen in Figure 2. The frame element was not included in the thermal conductivity metering area. The differences in the groups measured at the same temperature and relative humidity were entirely due to the plywood and thermal insulation material properties. The thermal conductivity values rather than density values of thermal insulation materials produced from materials with different properties (Table 1) showed a close relationship with the values of the shear wall groups. Similar thermal insulation materials used in all groups were the same properties.

In this study, after determining the thermal conductivity coefficient values of the shear wall groups, the absolute thermal resistance, thermal resistance, thermal resistivity and thermal conductance which are the most important parameters showing the thermal performance of the materials, were calculated and the results were given in Table 5.

Table 5: Thermal performance parameters of the shear wall groups.

Wall Numbers	Wood Species	Thermal Insulation Material Types	Absolute Thermal Resistance (R - K/W)	Thermal Resistance (R-value- m^{2}K/W)	Thermal Resistivity (r-Km/W)	Thermal Conductance (C-W/m^{2}K)
1	Scots Pine	Cellulose	99,365	0,994	16,810	1,006
2		Flax	100,878	1,009	17,013	0,991
3		Felt	103,136	1,031	17,431	0,970
4		Sheep's Wool	103,736	1,037	17,446	0,964
5		Rock Wool	107,496	1,075	18,142	0,930
6		Glass Wool	105,629	1,056	17,854	0,947
7		XPS	102,358	1,024	17,301	0,977
8		EPS	77,583	0,776	13,123	1,289
9		Control	29,550	0,295	5,000	3,384
10	Black Pine	Cellulose	103,420	1,034	17,065	0,967
11		Flax	99,931	0,999	16,472	1,001
12		Felt	104,039	1,040	17,161	0,961
13		Sheep's Wool	101,115	1,011	16,611	0,989
14		Rock Wool	106,089	1,061	17,479	0,943
15		Glass Wool	106,290	1,063	17,525	0,941
16		XPS	99,944	0,999	16,483	1,001
17		EPS	75,920	0,759	12,538	1,317
18		Control	28,442	0,284	4,693	3,516
19	Spruce	Cellulose	103,089	1,031	17,473	0,970
20		Flax	99,416	0,994	16,824	1,006
21		Felt	103,775	1,038	17,584	0,964
22		Sheep's Wool	102,062	1,021	17,232	0,980
23		Rock Wool	103,397	1,034	17,467	0,967
24		Glass Wool	104,692	1,047	17,743	0,955
25		XPS	103,419	1,034	17,525	0,967
26		EPS	78,661	0,787	13,346	1,271
27		Control	31,475	0,315	5,339	3,177

The changes in thermal resistance values of the shear wall groups whose thermal conductivity coefficient values were determined experimentally were found similarly. Liu *et al.* (2018) measured the thermal resistance of the wooden-frame walls that they formed with glass wool, XPS and EPS in different configurations and found that EPS foam boards have the lowest thermal resistance values while the lowest values were obtained from glass wool. The other thermal performance parameters also varied in parallel with both thermal resistance and thermal conductivity coefficient values. Kumar *et al.* (2020) compared the properties and thermal performances of some building insulation materials and determined thermal conductivity coefficient value ranges for these materials. These ranges were 0,037 W/mK - 0,042 W/mK for cellulose, 0,033 W/mK - 0,090 W/mK for flax, 0,030 W/mK - 0,054 W/mK for sheeps's wool, 0,033 W/mK - 0,040 W/mK for rock wool and 0,030 W/mK - 0,050 W/mK for glass wool. Similarly, Wang *et al.* (2018) found that the thermal conductivity of rock wool ranges from 0,035 W/mK to 0,039 W/mK. In this study, it was determined that the measured thermal conductivity values of the thermal insulation materials were between these ranges. Moreover, the density values of all the materials used in the study except EPS were among the value ranges determined in the literature (Kumar *et al.* 2020, Anh and Pásztory 2021). According to FAO (2022), EPS densities vary between 10 kg/m^3 and 33 kg/m^3, and the thermal conductivity value of EPS foam with a density of 10 kg/m^3 is 0,057 W/mK. Duijve (2012) found the thermal resistance of rock wool and glass wool used as wall insulation material from 1 m^{2}K/W to 1,5 m^{2}K/W and also found the thermal resistance of the empty cavity wall as 0,35 m^{2}K/W. These thermal resistance values were found to be close to the values found in the study. However, the results of the study could not be compared with the literature due to the absence of studies in which plywood sheathed shear walls were filled with thermal insulation materials.

CONCLUSIONS

In this study, thermal performances of plywood shear walls, where thermal insulation is extremely important in light-frame wooden buildings, were compared according to the type of insulation materials used. In determining the thermal performances, different parameters such as thermal conductivity coefficients and thermal resistance values were used. When the measured thermal conductivity values and other calculated thermal parameters are examined, the shear walls produced with EPS foam boards have been identified as the groups with the worst thermal performance. Rock wool was the best thermal insulation material among the scots pine shear wall groups while glass wool was the best thermal insulation material among the black pine and spruce shear wall groups. The shear walls produced with spruce plywood indicated better thermal performance than other wood species. The thermal conductivity values obtained as a result of the study remained below the value of 0,065 W/mK, excluding EPS foam board. This case proved the shear wall groups formed in this study can be used for thermal insulation in light-frame wooden buildings.

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