THERMAL CONDUCTIVITY OF EXPERIMENTAL WALL CONSTRUCTIONS OF RENEWABLE INSULATING MATERIALS

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Abstract
Global scale environmental problems and economic issues are the main aspects what point out exigency to do research in the construction of renewable building materials. Renewable building materials are those materials that can be regenerated quickly enough and in theory, their production could be carbon-neutral. In order to evaluate the thermal efficiency of renewable materials in the framework systems of building envelope structures, test samples were made with the filling of renewable materials. The aim of the work is to find out the thermal conductivity coefficient of these natural composites and to compare them. Different size test samples were created for determination of thermal conductivity coefficient: 1.type as reference value: (width x height x depth) 290 x 290 x 30 mm; 2.type as experimental construction value (imitation of real wall construction): (width x height x depth) 980 x 980 x (165; 250; 345) mm. In this research as renewable insulating materials were used: maple leaves, legume (*Galega orientalis*), the composition of hemp shives (*Bialobrzeskie*) and sapropel with lime. A renewable insulating materials (also known as eco-thermal insulating) as alternative building materials discussed in this research work meets the requirements of the normative documents of the Republic of Latvia on sustainable construction principles. The analysis of results indicates significant difference among investigated materials – 0.040 W $m^{-1}K^{-1}$ lowest obtained value of thermal conductivity coefficient.
Key words: renewable insulating materials, thermal conductivity coefficient.

Introduction

Each eco-thermal insulating material has different properties but it shares the ecological origin of the inhabitants of heat-insulated premises providing a healthy environment for their health (RB&B EKOmateriāli, 2012).

Renewable materials contain natural fibres (e.g., jute, flax, hemp, cotton, cellulose), and have many positive properties: low thermal conductivity, low density, good specific tensile strength (Korjenic *et al*., 2011; Zach *et al*., 2013; Ku *et al*., 2011). The natural fibre materials have less impact on the nature (Korjenic *et al*., 2011; Papadopoulos, 2005; Visockis *et al*., 2016). Also, renewable building materiāls have lower embodied energy than conventional building materials (Myers, Fuller, & Crawford, 2012).

The publication compares the eco-insulation properties of monolithic and bulk maple tree leafs, hemp shives with sapropel binder, bulk legume (*Galega orientalis*) (Kolosovs & Rizkovs, 2016). These eco-source materials in the territory of Latvia can be obtained in huge quantities by providing ecosystem insulation manufacturers with work for many years and allowing economically justified industrialization of innovative ecosystem insulation production. Innovative eco-thermal insulation materials studied in the publication can be reused for different purposes. Eco-thermal insulation material originally purposed for the insulation of buildings, but after it served as a substrate for the cultivation of ecologically pure plants and finally was used as a fertilizer for increasing soil fertility by a completely recycling it in the environment. Production of innovative eco-thermal insulation materials consumes a minimum amount of materials, equipment and energy for the production technological process (Organiskais mēslojums dārzam, 2017).

Concept of evaluation of the thermal efficiency of renewable materials in the framework systems of building envelope structures was based on thermal conductivity coefficient comparison of 1.type (reference) and 2.type (experimental construction) samples. Proposed assumption: the concept must highlight the difference between methods of determination of thermal conductivity coefficient and scale factor influence on results. The method of determination of the thermal conductivity coefficient for the reference sample equates to the ideal working conditions, without any side influences contrariwise 2.type sample, there were turbulent cold air flow, heat flux and scale factor at the same time (building site conditions).The assumption for a scale factor influence: as the size of the test sample increases, also different deviation increases, so the thermal conductivity coefficient must alternate.

From previously defined conditions, the aim of the work is to find out the thermal conductivity coefficient of these natural composites at different sample types and working conditions and to compare them.

Materials and Methods

The following basic materials as fillers were used for preparation of testing samples: hempshives variety *Bialobrzeskie*, lime, maple leaves, legume (*Galega orientalis*).Testing sampleswere created for thermal conductivity coefficient determination in two different dimensions: 290x290x30 mm (for testing with device NETZSCH HFM 436 Lambda – as a reference value);

large scale samples (for testing in climate chamber Welltech YTH-1000Z/07-394B) 980x980 mm and with different thicknesses –345 mm for hemp shives mix with limeand sapropel, 165 mm for maple leaves; 250 mm for legume (*Galega orientalis*). The sample moisture measurements were carried out using Greisinger GMH-3830 Material moisture meter for general moisture assessment. The measurements were made in an ambient air temperature of ~ 25 °C.

Sample preparation of hemp shives mix with limeand sapropel: natural raw materials were obtained from different local companies. Sapropel was obtained from Ubagova Lake in Makoņkalns rural territory of Rezekne municipality, where LATPOWER Ltd is operating. Hemp shives were obtained from Latgale Agricultural Science Centre Ltd and processed in flax pre-treatment workshop in Preili (Pleiksnis *et al*., 2016). Hemp shives, sapropel, lime and water were mixed in a mixer to reach a plastic homogeneous mass. The mixture was packed in a wooden frame and sealed to obtain an optimum density of about 152 kg m^{-3}. The thickness of the sample was selected on the basic theoretical calculations and according to the Latvian Building code LBN 002-15. In previous studies, the optimal mass ratio of sapropel and hemp shives was determined 3:1. Binder mass is sapropel with additional water. Wooden frame was used as a mould and was filled with wet mixture of hemp shives and lime. Lime was added 5% of expected dry mass of mixture of hemp shives and lime. Wooden mould was kept vertically at filling process and mixture was filled at several steps. Sample was dried 168 hours in a natural way and 336 hours forced drying at 50 °C. The moisture of sample was measured at different depths – from 20 mm until 140 mm.

Sample preparation of maple leaves were harvested in Ludza Town Park. They were stored in bags to make sure for their long life. Experimental sample construction: a particle board box was created in size: width x height x depth 980 x 980 x 165 mm.

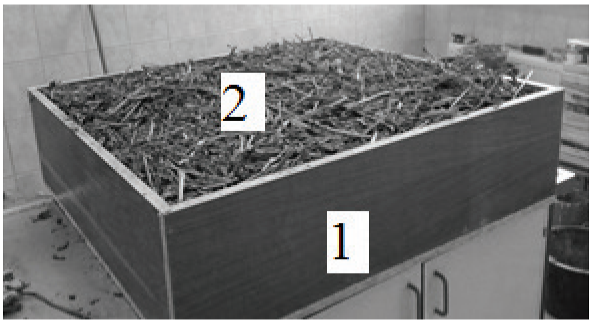

Figure 1. Test sample of 2.type as experimental construction. 1 – a particle board frame in size: width x height x depth 980 x 980 x 200 mm; 2 – renewable insulating material.

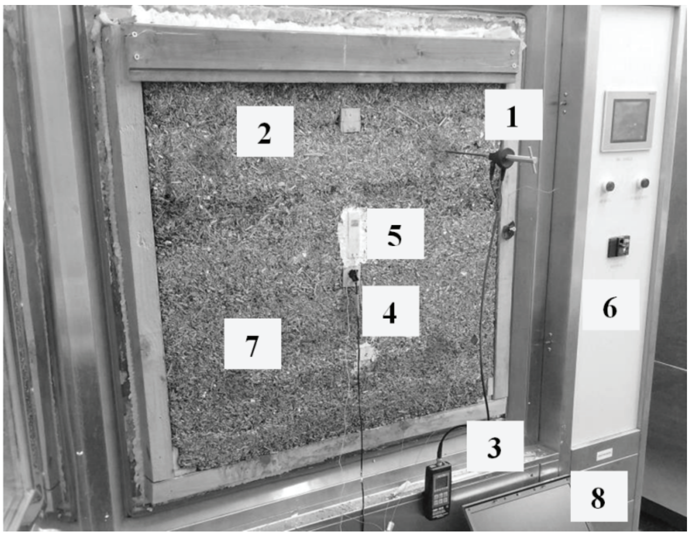

Figure 2. The testing process of thermal conductivity coefficient determination of experimental construction. 1 – moisture measurement device (injection probe Greisinger GSF 40); 2 – location of measurement points where the probe was injected in different depths; 3 – Greisinger GMH-3830 Material moisture meter; 4 and 5 – heat flux and temperature sensors; 6 – environmental chamber; 7 – test sample of 2.type (experimental construction);8 – data logger.

The particle board box was kept vertically at the filling process and filled with maple leaves at several steps. Mass of maple leaves was previously calculated for box volume to reach exact material density (ρ=30 to 40 kg m^{-3}). No additives were used for leaves. Sample was dried before filling 168 hours in a natural way and 336 hours forced drying at 50 °C. The moisture of sample was measured at different depths – from 20 mm until 140 mm.

Sample preparation of legume (*Galega orientalis*) – a particle board box was created in size: width x height x depth 980 x 980 x 250 mm. The particle board box creates a mould that was filled with legume at several steps. The particle board box was kept horizontally at the filling process. No additives were used to the legume. The sample was dried before filling 168 hours in a natural way and 336 hours forced drying at 50 °C. The moisture of sample was measured at different depths – from 20 mm until 140 mm. Apparent density of mixture about 45 kg m^{-3} was obtained. The moisture of sample was measured at different depths – from 20 mm until 140 mm.

The sample moisture measurements for all types of samples were carried out using Greisinger GMH-3830 Material moisture meter combined with an injection probe GSF 40.

The reference value of the thermal conductivity coefficient of samples was determined by using the NETZSCH HFM 436 Lambda device for 1.type (290 x 290 x 30 mm) samples, but for large samples – heat flux, temperature sensors and a mathematical calculation were applied. Equation of heat conductivity coefficient:

$$\lambda = \frac{qd}{T_1 - T_2} \qquad (1)$$

where:

λ – heat conductivity coefficient, $Wm^{-1}K^{-1}$

q – heat flux, Wm^{-2}

d – thickness of sample, m

T_1 – temperature of room (positive),°C

T_2 – temperature of climate chamber (negative),°C

For thermal conductivity coefficient calculations assumption was used: the horizontal line (as general direction trend of the line) of temperatures and heat flux characterizes a stable period at the appropriate temperature difference.

Results and Discussion

A common feature for all graphs: all measurements were started when the experimental sample was installed and climate chamber was switched on; graphs are divided into periods of time which represent the status of the process; oblique position lines (as a general direction trend of the line) represent an alteration in the process; data of horizontal line (also as a general direction trend of the line) of temperatures and heat flux were used for thermal conductivity coefficient calculations. Slight positive temperature increase can be explained by the room temperature increasing because the climate chamber releases heat

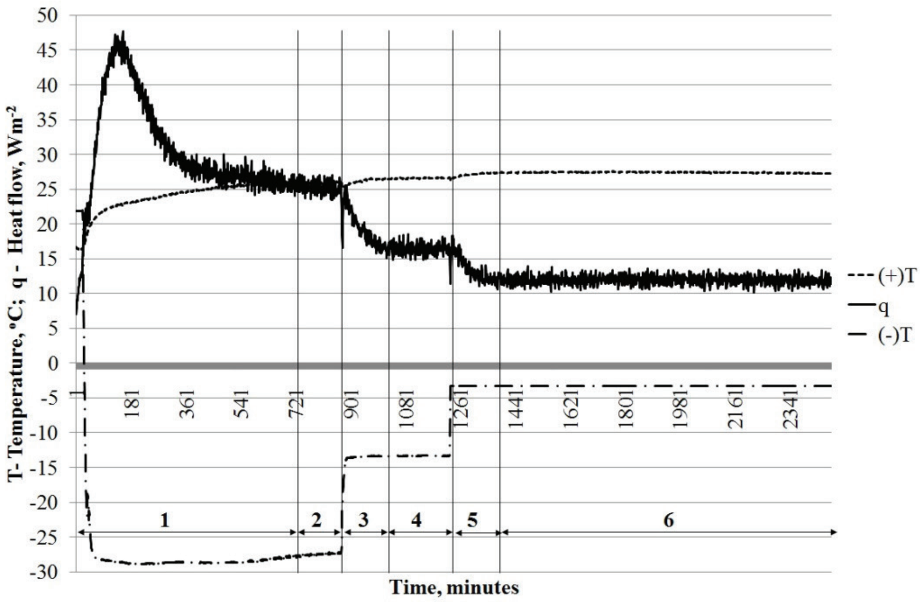

Figure 3. Maple leave sample, thickness 165 mm. Value of heat flux depending on differences of temperatures. Horizontal axis: Time – minutes, sampling rate – 1 sample each minute. Vertical axis: (+)T – positive room temperature, °C; (-)T – negative chamber temperature, °C; q – heat flux, W m^{-2} (only positive values). Temperature and heat flux values have the same scale. 1, 2, 3, 4, 5, 6 – time periods of change and stability for temperature and heat flux.

in the room. The negative temperature line represents the operation of the climate chamber.

Test results of maple leaves eco heat insulation, were used sample thickness 165 mm (Figure 3). Moisture content was measured before heat conductivity coefficient determination was carried out. Moisture of leaves from 7.4 to 9% was obtained. Measurements and calculation have been executed at different negative temperatures (-27 °C, -13 °C, -3.5 °C).

Description of Figure 3: 1 – period 0 to 770 minutes, period duration 770 minutes; switching on the climate chamber, adaptation of the heat flux sensor at specific temperatures; the rapid increase in heat flux would be explained by the initial state of the sample. 2 – period 770 to 900 minutes, period duration 130 minutes; (+)T and (-)T temperatures and q – heat flux period may be considered as stable and valid for calculations; calculated thermal conductivity coefficient 0.079 W m^{-1} K^{-1} at DT=52 K, (+)T 25 °C, (-)T -27 °C, q=25 W m^{-2}; 3 – period 900 to 1050 minutes, equalization period duration 150 minutes; switching negative temperatures in the climate chamber (increasing to -13 °C); 4 – period 1050 to 1240 minutes, period duration 190 minutes; (+)T and (-)T temperatures and q – heat flux period may be considered as stable and valid for calculations, calculated thermal conductivity coefficient 0.072 W m^{-1} K^{-1} at DT=39 K, (+)T 26 °C, (-)T -13 °C, q=17 W m^{-2}; 5 – period 1240 to 1420 minutes, equalization period duration 220 minutes; switching the negative temperature in the climate chamber to -3.5 °C; 6 – period 1420 to 2340 minutes, period duration 920 minutes; (+)T and (-) T temperatures and q – heat flux period may be considered as stable and valid for calculations, calculated thermal conductivity coefficient 0.070 W m^{-1} K^{-1} at DT=30.5 K, (+)T 27 °C, (-)T -3.5 °C, q=13 W m^{-2}. Thermal conductivity coefficient reference value of maple leave sample was 0.046 W m^{-1} K^{-1}.

General observation of maple leaf samples tests results: As the difference in temperatures decreases, the heat flux and the calculated thermal conductivity coefficient also decreases. An average time of 185 minutes (3 hours and 5 minutes) is needed to equalize the heat flux in a sample of 165 mm thick leaves (0.89 mm per minute).

Test results of legume (*Galega orientalis*), showed sample thickness 250 mm (Figure 4). Moisture content was measured before the thermal conductivity coefficient determination was carried out. Moisture of leaves from 6.5 to 8.5% was obtained. Measurements and calculations have been executed at different negative temperatures (-23 °C, -15 °C, -9 °C). Description of Figure 4: 1 – period 0 to 150 minutes, period duration 150 minutes; switching on the climate chamber, adaptation of the heat flux sensor at specific temperatures; 2 – period 150 to 370 minutes, period duration 220 minutes; (+)T and (-)T temperatures and q – heat flux period may be considered as stable and valid for calculations; calculated thermal conductivity coefficient 0.063 W m^{-1} K^{-1} at DT=40 K,

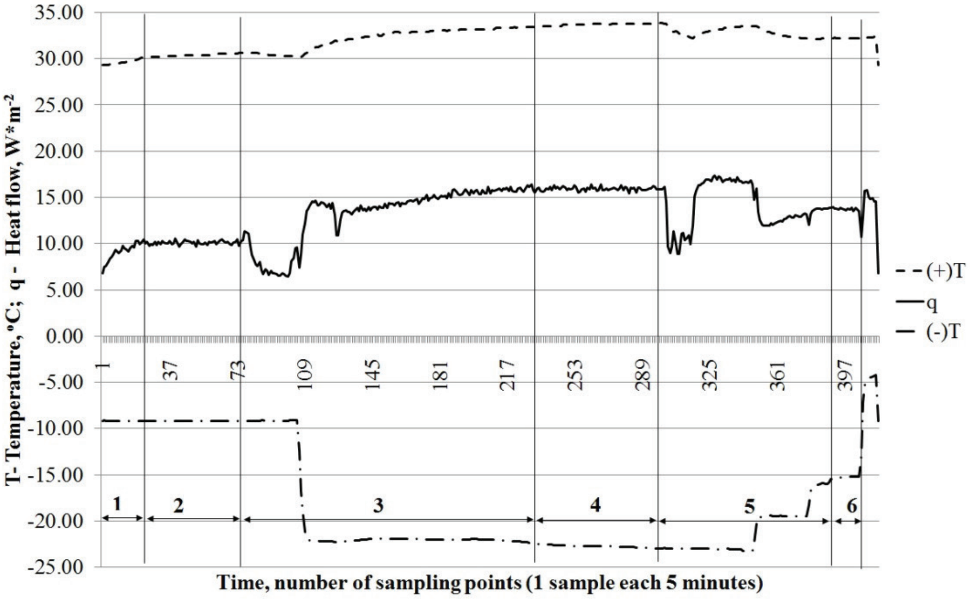

Figure 4. Legume (*Galega orientalis*) sample, thickness 250 mm. Value of heat flux depending on differences of temperatures. Horizontal axis: Time – minutes, sampling rate – 1 sample each minute. Vertical axis: (+)T – positive room temperature, °C; (-)T – negative chamber temperature, °C; q – heat flux, W m^{-2} (only positive values). Temperature and heat flux values have the same scale. 1, 2, 3, 4, 5, 6 time periods of change and stability for temperature and heat flux.

Table 1

Thermal conductivity of renewable materials

Materials	Thermal conductivity value, W m^{-1} K^{-1}		Density, kg $^{m\text{-}}3$
	1.type – reference	2.type (average value)	
Maple leaves	0.046	0.074	30.0 to 40.0
Legume (Galega orientalis)	0.040	0.069	45.0
Sapropel and hemp shives mixture	0.052	0.145	152.0 to 183.0
NatuHemp – hemp fibre (Black, 2019)	0.039	-	30.0
Thermafleece CosyWool – sheep's wool (Eden, 2019)	0.039	-	31.0
Straw bale (Costes *et al*., 2017)	-	0.062 to 0.079	60.0 to 125.0

(+)T 31 °C, (-)T -9 °C, q=10 W m^{-2}; 3 – period 370 to 1165 minutes, equalization period duration 795 minutes; switching negative temperatures in the climate chamber (decreasing to -23 °C); 4 – period 1165 to 1485 minutes, period duration 320 minutes; (+)T and (-)T temperatures and q – heat flux period may be considered as stable and valid for calculations, calculated thermal conductivity coefficient 0.073 W m^{-1} K^{-1} at DT=57 K, (+)T 33 °C, (-)T -23 °C, q=16.5 W m^{-2}; 5 – period 1485 to 1950 minutes, equalization period duration 465 minutes; switching the negative temperature in the climate chamber to -15.5 °C; 6 – period 1950 to 2030 minutes, period duration 80 minutes; (+)T and (-)T temperatures and q -heat flux period may be considered as stable and valid for calculations, calculated thermal conductivity coefficient 0.071 W m^{-1} K^{-1} at DT=47.5 K, (+)T 32 °C, (-)T -15.5 °C, q=13.5 W m^{-2}. Data sampling rate were: 1 sample every 5 minutes.

Thermal conductivity coefficient reference value of legume sample was 0.040 W m^{-1} K^{-1}.

Description of sapropel and hemp shives mixture results (not shown in the figure): 1 – period 0 to 815 minutes, period duration 815 minutes; switching on the climate chamber, adaptation of the heat flux sensor at specific temperatures; 2 – period 815 to 965 minutes, period duration 150 minutes; (+)T and (-)T temperatures and q – heat flux period may be considered as stable and valid for calculations; calculated thermal conductivity coefficient 0.145 W m^{-1} K^{-1} at DT=54.5 K, (+)T 27.5 °C, (-)T -27 °C, q=23 W m^{-2}. Thermal conductivity coefficient reference value of sapropel and hemp shives mixture was 0.049 to 0.054 W m^{-1} K^{-1}.

The value of the thermal conductivity coefficient obtained from the 2.type sample differs significantly from the reference value indicating the influence of the side effects. It points out the need to further investigate this issue. The data in Table 1 clearly show the difference between small samples (1.type samples, reference values) and large scale experimental samples (2.type samples). As mentioned in the literature (Costes *et al*., 2017) a quite significant influence on thermal conductivity has material density and fibre orientation (perpendicular or parallel to heat flux). As it was mentioned at the introduction and expected the testing conditions, scale factor via sample manufacturing technology and also a difference in density among samples, lead to the dissimilarity of thermal conductivity coefficient even for the sample of the same material. It is unexplored which of these factors do the most impact on obtained values. Also, for further investigations, the following variables must be included into account – density, humidity, fibre orientation and method of sample preparation.

Conclusions

1. Obtained results of thermal conductivity coefficient from reference samples (290 x 290 x 30 mm) are always better than large scale sample value. These points out the need to do further study of large-scale samples. It also points out the need to assess the variation of this nature in the design.
2. Experimental samples show the following trend: reference samples have lower values of bulk density and lower thermal conductivity coefficient, large samples have larger bulk density and also higher thermal conductivity coefficient values (leaves ρ=30 to 40 kg m^{-3}; leaves λ=0.046 to 0.074 W m^{-1} K^{-1}; legume ρ=45 to 50 kg m^{-3}; legume λ=0.040 to 0.069 W m^{-1} K^{-1}).
3. The values of the thermal conductivity coefficient obtained from renewable materials show a relatively sufficient competitive potential for materials on the market of building materials.

Considering that the actual working conditions of building envelope structures are going to be close to the 2.type test and based on the obtained values, the renewable materials mentioned in the article are not recommended to be used as thermal insulation materials without changing the application technology. Otherwise, it leads to the disproportionate thickness of building envelope structures (depends on local normative).

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