ANALYSIS OF THE EFFICIENCY OF NON-TRADITIONAL THERMAL INSULATION MATERIALS

Dr Staņislavs Gendelis

Dr Andris Jakovičs

Faculty of physics and mathematics, University of Latvia, **Latvia**

ABSTRACT

The aim of this research is to analyse the thermal properties of different non-traditional insulation materials with low thermal conductivity and light weight that are made from Latvian local raw materials and are "green" or are innovative and advanced materials. The studied materials are grouped depending on the production type and possible applications as follows:

- multi-layer combination of insulation materials, incl. low-emission surfaces;
- straw, cane, hemp, and birch wood fibreboard made from local raw materials;
- mixture of two disperse insulation materials with variable proportions.

The thermal conductivity measurements depending on the mean temperature and set temperature differences were carried out using the hot plate measuring technique. The research results are compared with theoretical calculations and available manufacturer data. As a result, a pros and cons list is created for the studied non-traditional materials.

Keywords: non-traditional insulation materials, reflective insulation, hot plate, hemp.

INTRODUCTION

In recent years, the EU has adopted several directives related to energy efficiency, e.g., the Energy Performance of Buildings Directive 2010/31/EU (EPBD recast) [1] and the Energy Efficiency Directive 2012/27/EU [2], which require significant reduction of buildings' energy consumption, i.e. introducing near–zero energy buildings (nZEB). To meet these requirements, the industry will have to improve the efficiency of existing materials and optimize their use as building structures as well as develop novel, sustainable, and ecological construction materials [3]. In the frame of this work, three rarely used materials and solutions are reviewed and analysed in detail:

1. Reflective thermal insulation materials consisting of a lightweight material layer (e.g., foam polyethylene) laminated on one or both sides with polished low-emittance aluminium foil, which almost excludes the radiative heat transfer on its surfaces [4]. It is important to note that this technology works only when combined with an airspace adjacent to the low-emittance surface. As it is not a bulk material but is used in composite structures with airspaces of different dimensions, the convective part of heat transfer in air gaps is very important.
2. Another type of non-traditional insulation material is ecological or "green" materials produced from straw, reeds, hemp, or wood fibre. Such materials were historically used in the construction of houses and farm buildings. The easiest and cheapest way is to make them into blocks by just pressing the raw materials

(without any additives). A more complicated method is combination of the green materials with denser base materials like lime mortar. Thereby, this construction mixture simultaneously provides good thermal insulation and sufficient load-carrying capacity necessary for wall construction. Those materials in total have ensured a negative CO_2 emission by locking more carbon dioxide in the material than is unlocked during the production process [5]. Other factors that are important for these unconventional materials but are not analysed in this research are sustainability, acoustic performance, life cycle assessment of sustainability, etc. [6].

3. As the last sample of non-traditional insulation materials, a mixture of two different disperse materials—granular polystyrene (insulation beads) and thermowool flakes as a filler—is reviewed. The main idea of adding the flakes is to reduce the radiation and convection heat transfer between the individual granules. The effective thermal conductivity of such mixture may be lower than that of the raw materials [7].

In parallel to the mentioned thermal insulation properties that will be analysed in this paper, other material characteristics like water vapour permeability, water absorption, sound reduction index, etc. are also very important when choosing materials for insulation or refurbishment.

MATERIALS AND METHODS

Efficiency of thermal insulation materials can be described by the thermal conductivity λ (W/(m·K)). One of the approaches for the measurement of thermal conductivity in steady-state conditions is the guarded hot-plate method [8]. Although this method is basically used to measure homogeneous materials, it can also be used for thermal resistance R ($m^2 \cdot K/W$) determination for heterogeneous constructions with flat parallel surfaces. The measurement principle is simple: A specimen is placed between two surfaces kept at constant temperatures, and the heat flow passing through the plates is registered after stationary conditions are reached; a so-called compensations zone with the same temperatures surrounds the flow meters to avoid heat losses in other directions. Dependence on mean temperature can be estimated by conducting the measurements with different surface temperatures while maintaining or changing the temperature difference.

The measurements for this research were carried out at the University of Latvia using the *Taurus TCA 500-P* measuring instrument (Fig. 1) with the sample dimensions of 50×50 cm. The heater and cooling plate temperature is adjusted by means of a Peltier cryostat. Five thermocouples of each measurement plane are embedded in the surface of the heating and cooling plate for the direct measurement of the temperature difference. When measuring samples with hard surfaces, special sponge rubber mats with known thermal conductivity are used as compensating layers. The device is equipped with electric lifting equipment used for the movement of the upper cold plate, as well as with force (resolution 1 N) and thickness (resolution 0.1 mm) sensors.

Measurements for the constructions including reflective thermal insulation material were made also with changed direction of heat flow, i.e., the temperature of the heating plate (Fig. 1) was set to lower values than the cooling plate. This was done to evaluate the changes in thermal resistance due to different convection conditions in the enclosed air cavities.

Insulation materials made from agricultural and plant products like straw, reeds, hemp, and birch fibre are mostly soft and easily compressible; therefore, it is very important to choose the optimal pressure on a specimen in the hot plate device—the highest compression pressure will squeeze out the air, which will lead to incorrect results due to increasing thermal conductivity. 100 N of force is experimentally approved as good for measurement of such materials.

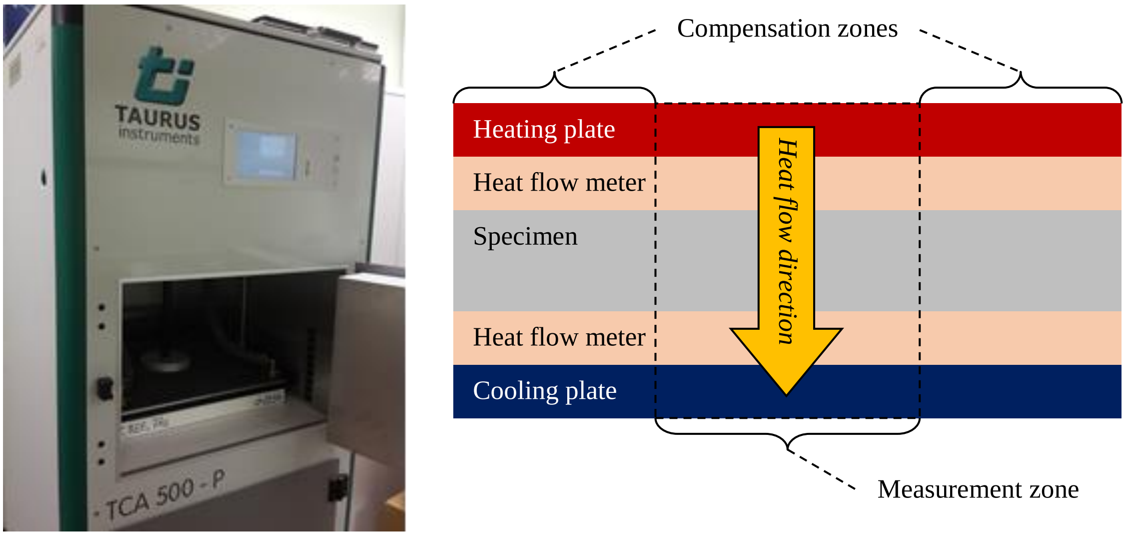

Fig. 1. Thermal conductivity measurement device and measurement principle.

RESULTS

Results obtained for different unconventional and rarely used building insulation materials are grouped based on the material type:

1. **Reflective insulation material.** A special wooden box was constructed for the thermal properties research of the reflective material, which was installed in the middle part (Fig. 2). The specimen is based on multiple foam polyethylene layers, laminated on both sides with polished aluminium foil, with total thickness of 10 mm. The influence of the emission for the second airspace surface on total thermal resistance was investigated too by gluing an aluminium foil coating there. Measurements were carried out at the same mean temperature of 20°C, but temperature difference was changed for some experiments. Data of experimental setups and the obtained results are summarized in Table 1.

   One of the important measurement findings is a quantitative evaluation of low-emission coating's effect on thermal resistance. As can be calculated from setups 1, 4, and 5, the additional thermal resistance for only one surface coated with low-emission foil is 0.14 $m^2 \cdot K/W$, while two-surface low-emission coating gives an extra R value of 0.19 $m^2 \cdot K/W$, thereby increasing the initial resistance of 0.40 by almost 50%. Measurements with variable temperature difference (setups 2–4 and 6–8) clearly show decreasing thermal resistance, which is explained by an increase in the radiative heat transfer rate, which rises as the fourth power of the absolute temperature, as expressed by the Stefan–Boltzmann law [9].

By analysing the measurement data from setup 8 (material in the box with airspaces) and setup 9 (only the material placed between heating/cooling plates without airspaces), the role of the reflective aluminium coating in combination with an airspace on both sides of the insulation material can be easily quantified. Thermal resistance is increased from 0.33 to 0.65 $m^2 \cdot K/W$, meaning that the radiative part along with surface thermal resistances are about the same as only the conduction part of the installed material. The effective thermal conductivity λ_{eff} for such material in the case without airspaces therefore can be calculated as 0.030 W/(m·K), and it reduces twice down to 0.015 W/(m·K) in the case when the material is installed between small airspaces, meaning that the reflective coating is working as expected. It is important to note that this material is completely impermeable to water vapour and does not absorb it.

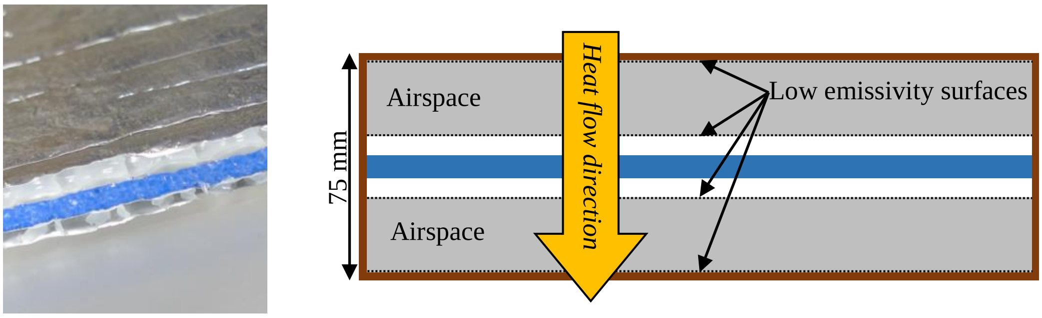

Fig. 2. Reflective insulation material and cross-section of an experimental box.

Table 1. General measurement and calculation results for reflective material.

Setup	Comment	Surface emissivity ε (-)	Temperature difference (°C)	Total thermal resistance *R* ($m^2 \cdot K/W$)
1	Empty box	0.9; 0.9	20	0.40
2	Empty box with upper surface aluminium foil coating	0.05; 0.9	10	0.60
3			15	0.57
4			20	0.54
5	Empty box with full aluminium foil coating	0.05; 0.05	20	0.59
6	Box with full aluminium foil coating and installed reflective material in the middle (Fig. 2)	0.05; 0.05; 0.05; 0.05	10	1.42
7			15	1.32
8			20	1.24
9	Reflective material (without coating effect)	N/A	20	0.33
10	Reflective material* (with coating effect)	0.05; 0.05	20	0.65

** calculated from setups 5 and 8*

2. **Ecological or “green” insulation materials**. Different insulation materials made from agricultural products and wood veneer waste are being studied in terms of their thermal insulation properties. The measurement results are summarized in Table 2. The first group of materials is simply mechanically pressed raw materials without any additives (Fig. 3). Thermal conductivity for those materials is very similar and is within the range 0.08…0.1 W/(m·K); the key roles here are played by the fibre orientation and compression (which affects the thermal resistance of the air inclusions), not the basic material.

   The second measurement group includes three hemp-based products: simply pressed hemp shives (included also in group 1), industrially produced hemp batt, and hemp-lime concrete (Fig. 4), which can be used in load-bearing vertical constructions. The best insulation properties were measured for hemp batt, which is very lightweight with a density of only 35 kg/m^3. The pressed hemp consists mainly of unbounded fibres, meaning a leading role for the conductivity heat transfer mechanism, which increases the effective thermal conductivity. The highest λ value was determined for hemp-lime concrete (also called *hempcrete* [10]), which is a combination of chopped hemp shiv and binder comprising natural hydraulic lime and cement. As the main use of hemp-lime concrete is in bearing structures, mechanical properties (e.g., hardness) are more important.

Fig. 3. Fibres of pressed rye (left), reed straw (centre), and hemp shives (right).

Fig. 4. Hemp batts (left), hemp-lime concrete (centre), and wood fibre (right).

Table 2. General measurement and calculation results for green materials.

Group	Material	Thermal conductivity λ_{10} (W/(m·K))
1	Pressed rye straw	0.09
	Pressed reed straw	0.10
	Pressed hemp shives	0.08
2	Industrially produced hemp batts	0.04
	Hemp-lime concrete	0.20
3	Birch wood fibre board	0.04

Finally, birch wood fibre board with thickness of 5 cm and density of 55 kg/m^3 made from birch veneer waste was tested. The thermal conductivity for this type of renewable insulation material was measured as 0.04 W/(m·K), which is practically the same as for industrially produced hemp batts and conventional fibre-based insulation materials.

In contrast to the first studied reflective material, most of the ecological materials have remarkable water vapour absorption, who depends on the material density; this property helps to stabilize humidity changes in a room. One the other hand, increased material moisture content also causes increased thermal conductivity.

4. **Mixture of two disperse materials**. As the last example of infrequently used building insulation materials, a mixture of two different disperse materials was studied. One of the materials — EPS insulation beads (polystyrene granules, Fig. 5) — is widely used for cavity wall insulation; they are blown into the cavity at high pressure. As the bead is simply a tiny sphere containing 98% air, they have good insulation properties, and the weakest place is the heat transfer in air gaps between the granules. The radiation part here may be reduced when the granules are coated with low-emission material like graphite, which brings down the thermal conductivity to less than 0.030W/(m·K). Also, to reduce the convective heat transfer part between granules, porous thermowool in the form of flakes may be used as a filler.

   Several mixtures of the above-mentioned materials with different volumes of fraction were prepared and tested using a special case made from a diffusion membrane (Fig. 5). Thermal conductivity for pure beads and thermowool materials was also measured. Table 3 summarizes the measured data for pure materials and their mixtures; the results are visualised in Fig. 4. As is seen, there is a minimal λ value for material mixtures compared to the pure materials, meaning that the combination of both components reduces the heat transfer, mainly due to radiation and convection reduction between granules. Another possible reason is increased contact resistance between granules and flakes. The lowest thermal conductivity value is found for mixture No. 5, where the volume fraction of the EPS beads is 58% and the λ value the value is 5% less than for the pure beads. It should be noted that although a reduction of λ was found, it is very small, and it is comparable to the measurement uncertainty.

Fig. 5. Graphite EPS beads (left), beads and thermowool flakes mixture (centre) and a special case with beads/thermowool mixture ready for measurement (right).

Table 3. Measured data summary for pure materials and their mixtures.

Mixture No.	1	2	3	4	5	6	7
Beads, %	100	88	78	64	58	48	0
Thermowool, %	0	12	22	36	42	52	100
λ_{10}, mW/(m·K)	31.5	31.4	30.9	30.3	30.1	30.3	30.9

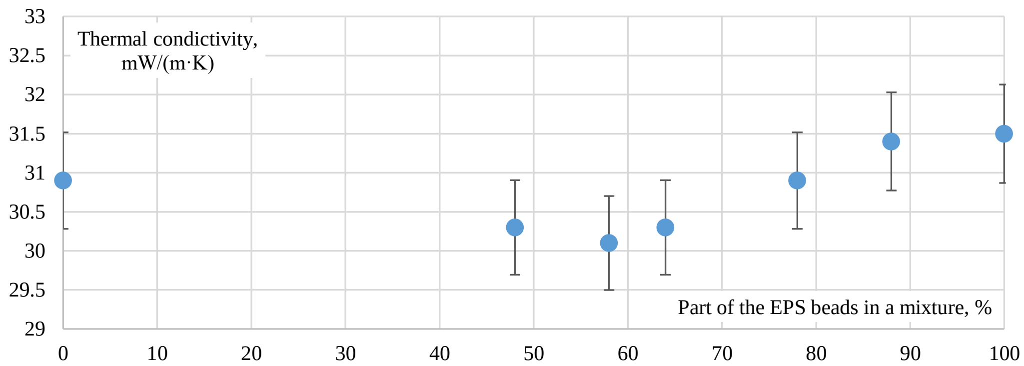

Fig. 6. Thermal conductivity of different mixtures at 10ºC (see Table 3).

Like the materials from the previous group, disperse materials can significantly absorb water vapour, and due to their relatively high porosity, they also have a high water vapour transmission rate.

CONCLUSIONS

This paper reports an analysis of the thermal efficiency of different non-traditional building insulation materials. The measurements carried out show that is it possible to achieve good thermal characteristics not only using commonly used materials but also with different types of unconventional materials and advanced solutions. Thus, use of cheap, lightweight, and easy-to-install reflective materials with low-emission surfaces for insulation indoors makes it possible to achieve effective thermal conductivity that is almost two times less than that of the best glass wool insulation. But it must be taken into account that this technology will not work if there is no required airspace at the reflective surface; furthermore, airspaces must be hermetic and airtight.

Also observed were renewable and green materials: straw, cane, hemp, and wood can be used as insulation materials. However, the main advantage of these materials is sustainability, which is linked to their availability—they should be used preferably where they are harvested, produced, or manufactured. Another advantage of these materials is ability to absorb and retain water vapour, thereby improving thermal comfort indoors.

Measurement results show that a properly selected mixture of two disperse insulation materials can give better thermal insulation than each pure material; nevertheless, this reduction is relatively small—less than 5%. This decrease is connected with reduction of radiation and convection heat transfer in the void spaces between granules; another possible reason is increased contact resistance. The greatest advantage of such materials is the possibility to effectively fill in hard-to-reach locations and small airgaps by blowing this insulation material through small holes in the construction.

ACKNOWLEDGEMENTS

This work was supported by the European Regional Development Fund project "Development, optimization and sustainability evaluation of smart solutions for nearly zero energy buildings in real climate conditions" [1.1.1.1/16/A/192].

REFERENCES

[1] European Union, European Parliament and Council. (2010). *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*. Official Journal of the European Union, L153, 13–35.

[2] European Union, European Parliament and Council. (2012). *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*. Official Journal of the European Union, L 315, 1–56.

[3] Pacheco-Torgal, F. (2014). Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. *Construction and building materials, 51*, 151-162.

[4] Lee, S. W., & Lim, C. H. (2016). Reflective thermal insulation systems in building: A review on radiant barrier and reflective insulation. *Renewable and Sustainable Energy Reviews, 65*, 643-661.

[5] Sinka, M., Sahmenko, G., Korjakins, A., Radina, L., & Bajare, D. (2015). Hemp Thermal Insulation Concrete with Alternative Binders, Analysis of their Thermal and Mechanical Properties. In *IOP Conference Series: Materials Science and Engineering* (Vol. 96, No. 1, p. 012029). IOP Publishing.

[6] Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies, 4*, 1-17.

[7] Geža, V., Jakovičs, A., Gendelis, S., Usiļonoks, I., & Timofejevs, J. (2017, October). Thermal conductivity of disperse insulation materials and their mixtures. In *IOP Conference Series: Materials Science and Engineering* (Vol. 251, No. 1, p. 012012). IOP Publishing.

[8] International Organization for Standardization (1991). ISO 8302: Thermal Insulation—Determination of Steady-state Thermal Resistance and Related Properties—Guarded Hot Plate Apparatus.

[9] Çengel, Y. A., Ghajar, A. J., & Kanoğlu, M. (2014). *Heat and mass transfer: Fundamentals & applications.* New York: McGraw-Hill Education.

[10] Elfordy, S., Lucas, F., Tancret, F., Scudeller, Y., & Goudet, L. (2008). Mechanical and thermal properties of lime and hemp concrete ("hempcrete") manufactured by a projection process. *Construction and Building Materials, 22*(10), 2116-2123.