

# Thermal conductivity of insulations approached from a new aspect

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**Abstract** In the literature, several definitions can be found for the thermal conductivity; however, many of them are not clearly explained. The easiest explanation is the following: the property of a material to conduct heat. It is evaluated primarily in terms of Fourier's Law for heat conduction. Nowadays, the examination of the thermal conductivity of building materials is very important both for the manufacturers and for the consumers. Nonetheless in real, confusing definitions and interpretations can be found regarding the exact meaning of the thermal conductivity of the materials. In physics and in engineering practice, the following appellations are used as heat conductivity, thermal conduction coefficient, design and declared values of the thermal conductivities as well as the effective thermal conductivity. In this article we would give an overview about the correct explanations of the above-mentioned values. At first thermal conductivity measurements of four different types of expanded polystyrene materials (EPS, 80, 100, 150, 200) will be presented by using Holometrix Lambda 2000 type Heat Flow Meter after drying them in a Venticell 111 type laboratory oven to changeless mass.

**Keywords** Heat transfer in building walls · Thermal conductivity · Insulation materials

## Introduction

As the energy use in the building sector accounts for a significant part of the world's total energy use and greenhouse gas emissions, there is a demand to improve the energy efficiency of buildings. This situation forces countries that have limited resources to study more efficient use of energy. The reduction both of the energy consumption and the emission of the green house gases can be easily achieved by thermal insulation. Expanded polystyrene is proved to be an excellent insulating medium which exhibits consistent thermal performance over the range of temperatures normally encountered in buildings. It is also used in a wide range of other areas including, packaging, buoyancy, panel cores, bean bags and civil engineering. Thermal conductivity is a key thermal transport property of materials [1–5]. Thermal conductivity is the primary property of an insulation material. The most accurate way to determine its value for a specific sample is to measure it accordingly to a standard method. The guarded hot plate and the heat flow meter hot plate are steady-state methods that can provide excellent results, with uncertainties as low as 3% for measurements in the dry state [6]. The main key property of a thermal building insulation material or solution is the thermal conductivity, where the normal strategy or goal is to achieve as low thermal conductivity as possible. The importance of the measurements of the thermal conductivity was reported by several authors [7–19].

The measurements were executed as the rules of the EN ISO 12664:2001 standard (Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Dry and moist products of medium and low thermal resistance). The thermal conductivity measurements were carried out after drying the samples in a

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laboratory oven as above mentioned to constant mass. In this article, besides the measured values, declared values of the thermal conductivity will be given at different temperatures. Expanded polystyrene (EPS) is usually obtained by evaporating the pentane added into polystyrene grains. This process allows the realization of a white, rigid and open-cell foam characterized by thermal conductivity from 0.031 to 0.037 W m<sup>-1</sup> K<sup>-1</sup>, density from 15 to 75 kg m<sup>-3</sup> and specific heat about 1.25 kJ kg<sup>-1</sup>K<sup>-1</sup>; the higher the density, the higher the insulation performance [4, 20]. It is caused by the reduction of the convective part in the effective thermal conductivity caused by the decreasing size of the pores with the increasing density. This will be further discussed. EPS shows no significant acoustic property, because of the open porosity and low density. Since the material is easily flammable and burning releases dangerous gases, a fire retardant is often added in the manufacturing process. The recycling process of these kinds of materials is performed by specialized industries. The detailed properties of the expanded polystyrene are presented in our previous papers [3, 4]. In contrast to our previous papers see references [3, 4] where only measurement results carried out on different types of expanded polystyrene was presented, this article would give a presentation about the thermal conductivities and declared values reached from the measurements of new expanded polystyrene materials produced by another manufacturer. Firstly, new results on the dependency of the density and thermal conductivities will be given; secondly uncertainties in the declared thermal conductivity will be presented too. This paper estimates the uncertainty that can be expected in the thermal conductivity of insulation materials in the lack of specific experimental measurements. Results are presented for different levels of specification, in order to consider the common situation in which the definition of the material is imprecise (e.g., at early stages of a project). This means that the uncertainty in the conductivity of a sample of known material and density (e.g., EPS of 30 kg m<sup>-3</sup>) should be less than the uncertainty in the conductivity of a sample just described by the kind of material (EPS), or by the family of insulation materials it belongs to (organic foams). As our knowledge evolves, uncertainties must decrease. Similar investigations can be found in reference 6, but focusing on other properties.

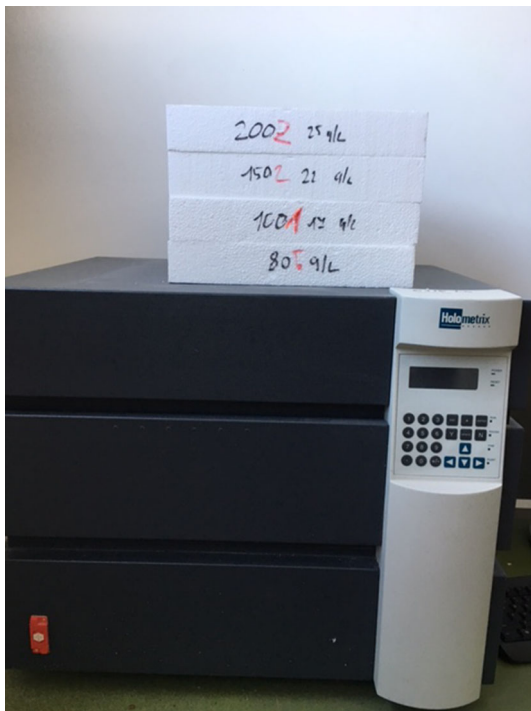
## Materials and methods

The thermal conductivity measurements were carried out after drying the samples in a VentiCell drying instrument to changeless mass at 70 °C. In Fig. 1 one can see an image about the Venticell apparatus. Drying of the samples



**Fig. 1** Image from the Venticell drying apparatus

was derived according to standard ISO 12570: Hygrothermal performance of building materials and products—Determination of moisture content by drying at elevated temperature. Constant mass is reached if the change of mass between three consecutive weighings made 24 h apart is less than 0.1% of the total mass. With this device materials can be dried setting different air temperatures (up to 523 K). It works with hot air circulation using an inbuilt ventilator, after the drying of the samples was conditioned at 30 °C. For measuring the thermal conductivity of each polystyrene samples, Lambda 2000 Heat flow meter (HFM) was used. In Fig. 2 an image can be seen from both the Holometrix equipment and from 1 to 1 pieces of the EPS samples. This equipment is designed to determine the thermal conductivity of insulation materials in accordance with standard ASTM C518 and ISO 8301 protocols. Five different samples from each type with 30 cm × 30 cm × 5 cm geometry were placed in the test section between two plates which are maintained at different temperatures ( $T_1 = 42$  °C and  $T_2 = 22$  °C, with  $T_{\text{mean}} = 30$  °C) during the test. After achieving thermal equilibrium and establishing a uniform temperature gradient throughout the sample, thermal conductivity is determined. To determine the thermal conductivity of a sample, five independent measurements were carried out. The thermal conductivity of analyzed material was the mean value of the five measured results.



**Fig. 2** Image from the Holometrix Lambda Instrument and 1–1 pieces from the EPS samples

For understanding the measurement method of Holometrix Lambda equipment, the following comments are indispensable.

The magnitude of the heat flow ( $q$ ) depends on several factors:

- Thermal conductivity of samples ( $\lambda = k$ ),
- The thickness of the specimen ( $\Delta x$ ),
- The temperature difference across the specimen ( $\Delta T$ ),
- Area through which the heat flows ( $A$ ).

The Fourier heat flow equation (Eq. 1.) gives the relationship between these parameters when the test section reaches thermal equilibrium [3, 4, 21].

$$q = \lambda A \frac{\Delta T}{\Delta x} \quad (1)$$

One or two heat flow transducers measure the heat flow through the specimen. The signal of a heat flow transducer (in Volts (V)) is proportional to the heat flow through the transducer. In the Lambda 2000 HFM instrument, the area of the heat flow transducer represents the area through which the heat conduction is realized and it is the same for all specimens; therefore, the heat flow will be (Eq. 2):

$$q = NV \quad (2)$$

where  $N$  is the calibration factor that relates the voltage signal of the heat flow transducer to the heat flux through

the specimen. For calibration of apparatus, a fibrous glass board standard sample with  $30 \text{ cm} \times 30 \text{ cm} \times 3 \text{ cm}$  geometries and  $130 \text{ kg m}^{-3}$  density, moreover with  $\lambda = 0.05 \text{ W m}^{-1} \text{ K}^{-1}$  thermal conductivity was used. Using Eqs. 1 and 2 the thermal conductivity can be determined (Eq. 3):

$$\lambda = k = N \frac{V \Delta x}{\Delta T} \quad (3)$$

The term reproducibility indicates the variation of the test results of one specimen from test to test. Factors such as how well the specimen makes contact with the plates and the temperature stability affect the reproducibility. If the thermal resistance of the test specimen is commensurable with the reference standards,  $\pm 5\%$  or better accuracy can be obtained.

Five different samples were tested from each type of EPS, and five measurements were carried out on each sample. From the measured values, the averages and the standard deviation were calculated too [3, 4].

### The effective thermal conductivity

We cannot apply the above-mentioned theory for bulk, regular insulation materials with  $10^1$ – $10^{-2}$  m thicknesses, because we cannot speak about homogenous materials in those cases, resulted by this new definition for thermal conductivity should be given:

$$\lambda_{\text{eff}} = \lambda_{c,s} + \lambda_{c,g} + \lambda_r + \lambda_{\text{conv}} + \lambda_{\text{coupling}} + \lambda_{\text{leak}} \quad (4)$$

where ( $\lambda_{c,g}$ ), ( $\lambda_r$ ), ( $\lambda_{c,s}$ ) and ( $\lambda_{\text{conv}}$ ) are the conductive part of the gas filling, and the solid material, the radiation part and the convective part of the gas filling (if there is enough place). If the density of the EPS is increasing the ( $\lambda_{\text{conv}}$ ) will decrease, resulting lower effective thermal conductivity. Moreover, the  $\lambda_{\text{coupling}}$  and  $\lambda_{\text{leak}}$  can be defined as the followings:  $\lambda_{\text{coupling}}$  = thermal conductivity term accounting for second-order effects between the various thermal conductivities in Eq. (4),  $\lambda_{\text{leak}}$  = leakage thermal conductivity. In order to reach a thermal conductivity as low as possible, each of the above thermal contributions have to be minimized. Normally, the leakage thermal conductivity  $\lambda_{\text{leak}}$ , representing an air and moisture leakage driven by a pressure difference, is not considered as insulation materials and solutions are supposed to be without any holes enabling such a thermal leakage transport. The coupling term  $\lambda_{\text{coupling}}$  can be included to account for second-order effects between the various thermal conductivities in Eq. (4). This coupling effect can be quite complex and will be neglected in the rest of this article. This  $\lambda_{\text{eff}}$  is called to effective thermal conductivity [5, 21].

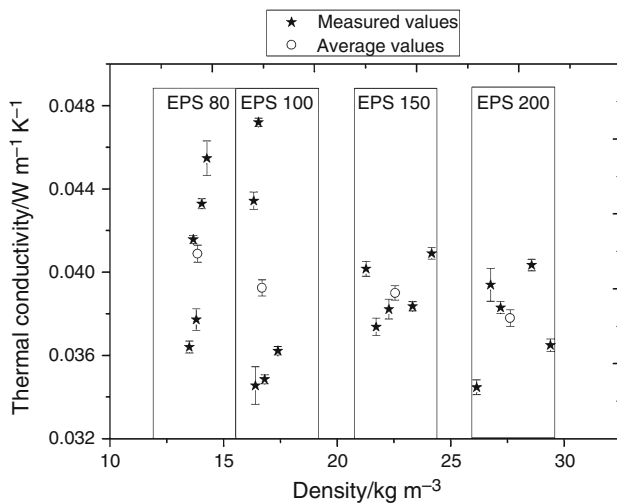
## The calculation method

At microscopic level, the apparent thermal conductivity depends on numerous factors such as cell size, diameter and arrangement of fibers or particles, transparency to thermal radiation, type and pressure of the gas, bonding materials, etc. A specific combination of these factors produces the minimum apparent thermal conductivity [8]. At macroscopic level, the apparent thermal conductivity largely depends on four factors, namely density, moisture content, temperature, and age. The effect of pressure (i.e., compression of the insulation) will not be considered in this paper.

Therefore:

$$\lambda = f(\rho, \omega, T, \text{age}) \quad (5)$$

According to the standard ISO 10456, the effects of moisture, temperature and age are independent, and can be written as (Eq. 5). In this article, only the temperature and density dependency were taken into account, because dried and perfectly new samples were tested.



**Fig. 3** The measured and average thermal conductivities in function of the densities

**Table 1** The measured thermal conductivities

Measured thermal conductivity/W m <sup>-1</sup> K <sup>-1</sup>							
EPS 80	St. dev.	EPS 100	St. dev.	EPS 150	St. dev.	EPS 200	St. dev.
0.0364	2.89E-04	0.04343	4.14E-04	0.04016	3.56E-04	0.03447	3.59E-04
0.04157	1.88E-04	0.03455	9.03E-04	0.03737	4.16E-04	0.03939	7.90E-04
0.03772	5.16E-04	0.0472	2.02E-04	0.03822	4.76E-04	0.0383	2.84E-04
0.04329	2.38E-04	0.03485	2.22E-04	0.03836	2.17E-04	0.04034	2.74E-04
0.04548	8.27E-04	0.03622	2.03E-04	0.0409	2.76E-04	0.03649	3.01E-04
<i>Average</i>							
0.040892	0.000412	0.03925	0.000389	0.039002	0.000348	0.037798	0.000402

The calculation method for the declared values is clearly written in the standard and in reference [6], now just a brief presentation will be given. Firstly, the mean value and the standard deviations (s) should be calculated:

$$x = \frac{\sum_i x_i}{n} \quad (6)$$

where  $x$  is the average value of the measurements,  $n$  is the number of the measurements and  $x_i$  = thermal conductivity results of each measurements.

$$s = \sqrt{\frac{\sum_i (x_i - x)^2}{n - 1}} \quad (7)$$

$$L_S = f(x; k_2(n, p, 1 - \alpha); s) \quad (8)$$

then the declared thermal conductivity can be given in the function of  $F_T$  what is the exponential temperature factor in function of  $T_1$  and  $T_2$ , where  $T_1$  is the temperature where the thermal conductivity measurements were carried out and  $T_2$  is the temperature where one would declare the value.

$$\lambda_D = (L_S, F_T) \quad (9)$$

The definition of the declared value: Expected value of a thermal property of a building material or product assessed from measured data at reference conditions of temperature and humidity; given for a stated fraction of confidence level; corresponding to a reasonable expected service lifetime under normal conditions. See reference [6].

## Results and discussion

### Thermal conductivity measurements results with Holometrix apparatus, and statistical analyses

In Fig. 3 and in Tables 1 and 2, the measurement results with the standard deviations can be found for all types of

**Table 2** The measured densities

Measured density/kg m <sup>-3</sup>			
EPS 80	EPS 100	EPS 150	EPS 200
13.49	16.33	21.27	26.15
13.67	16.40	21.72	26.76
13.80	16.53	22.28	27.20
14.04	16.81	23.33	28.57
14.26	17.39	24.17	29.40
<i>Average</i>			
13.85	16.69	22.55	27.61

EPS (80, 100, 150, 200) materials. One can see the uncertainties in the density function of the thermal conductivities. On this graph for each type of EPS materials, besides the measurement results, each average value is indicated too. The greatest uncertainty can be found for the samples of EPS 100. While the deviance in their density values is small, their measured thermal conductivities are very scattered. The smallest differences can be found for the EPS 150 samples. To be much more picturesque box chart analysis of each material was executed too. In Fig. 4a and b, one can see the mean values and the upper and lower quartiles both for the densities and for the measured thermal conductivities of the tested EPS's. The lowest deviance in the densities can be found for the EPS 80 and EPS 100; however, the greatest difference in the thermal conductivities can be found for the EPS 150 and EPS 200. These results justify the above-mentioned statements. That upon these measurements the best results can be obtained for the EPS 150. From Fig. 4a and b, an inverse relationship between the uncertainty in the thermal conductivity and in the material type was detected.

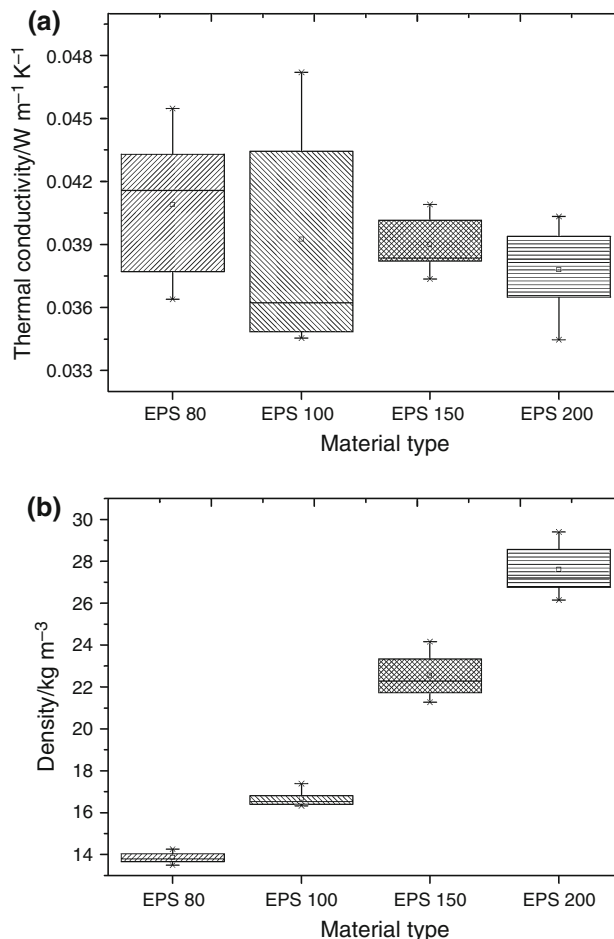
**Further development of the thermal diffusion**

It was previously discussed that thermal diffusion coefficient of the insulation materials is key thermal property from the insulation capability point of view. Thermal diffusivity or thermal diffusion coefficient (m<sup>2</sup> s<sup>-1</sup>) can be defined from the measured thermal conductivity coefficients ( $\lambda$ ) by using (Eq. 10):

$$D_T = \frac{\lambda_{\text{eff}}}{\rho \times c} \tag{10}$$

where  $\rho$  (kg m<sup>-3</sup>) is the mass density, and  $c$  (kJ kg<sup>-1</sup> K<sup>-1</sup>) is the specific heat (for expanded polystyrene  $c = 1250$  kJ kg<sup>-1</sup> K<sup>-1</sup> see reference [20]).

Here has to be mentioned that the literature for example as reference 20 does not take difference in the specific heat capacity of the different types of expanded polystyrene, it



**Fig. 4** a The box chart analysis of the measured thermal conductivities. b The box chart analysis of the measured densities

is defined only to a constant number (1250). This why a new insulation capability for the density factor ( $f_{\rho, \lambda}$ ) can be defined as:

$$f_{\rho, \lambda} = D_T \times c = \frac{\lambda_{\text{eff}}}{\rho} \tag{11}$$

The lower density factor represents higher thermal insulation capability. Let me mention here, if the thickness is increasing in the direction of the heat flow, the thermal performance of the insulations is decreasing. Regarding to this new material property (see Fig. 5) with histograms was created in order to represent the insulation capabilities of the materials. From Fig. 5 one can see that the best insulation capabilities belong to the EPS 150 and 200.

**The declared values of the thermal conductivities at different temperatures**

From the Eqs. 6–10, one can easily calculate the declared values of thermal conductivities of the insulation materials

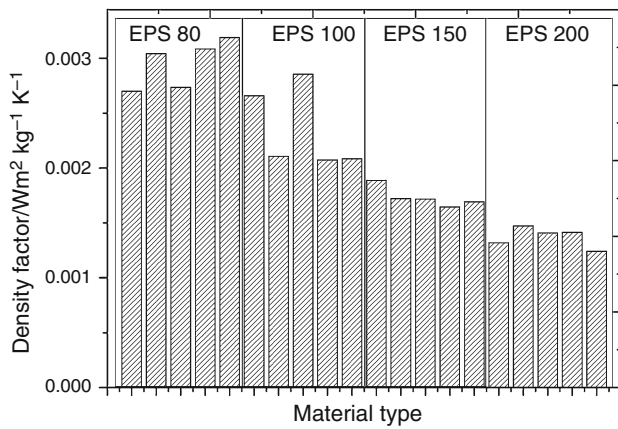


Fig. 5 The histograms of the density factors

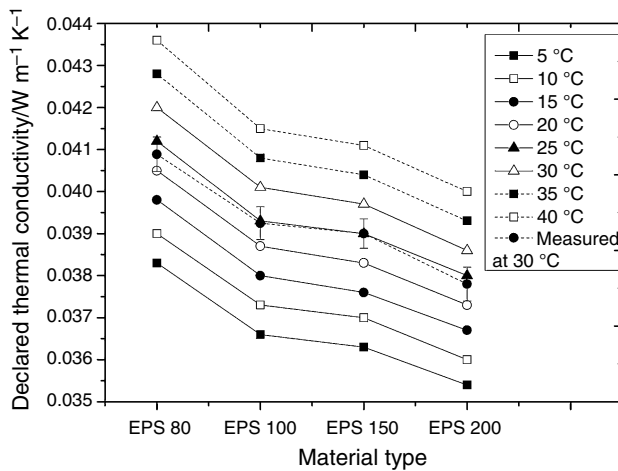


Fig. 6 The declared thermal conductivities at different temperatures

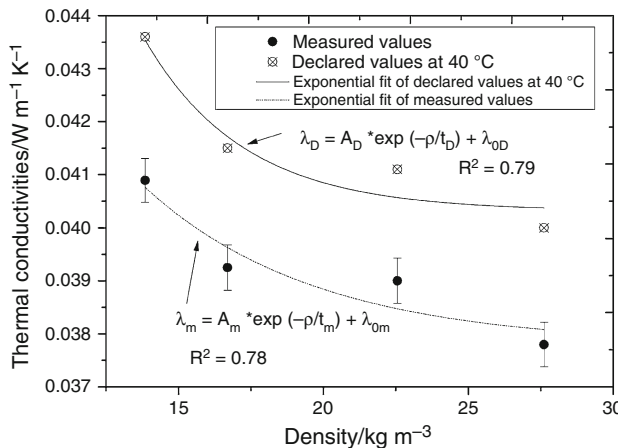


Fig. 7 The exponential fits of the measured and declared values at 40 °C of the thermal conductivities in function of the density

from the measured ones in accordance with the above-mentioned standard. Declared thermal conductivity values are given and presented in Fig. 6 for the insulation

materials at 5–40 °C temperature in 5 °C steps. From the figure, one can see that average of the measured values at 30 °C average temperature are going together with the declared values at 25 °C temperature. Furthermore, in Fig. 6, the similar shape of the trends is also observable. From Fig. 7 new equation is given to represent the function between the density, temperature and thermal conductivity:

$$\lambda_x = A_x \times \exp\left(-\frac{\rho}{t_x}\right) + \lambda_{0x} \tag{12}$$

where  $A$  and  $t$  are constants and depend from the density and temperature, while  $\lambda_0$  is the intercept, moreover  $x$  represents the type (declared or measured).

### Conclusions

Nowadays, the proper use of insulation is becoming more important than ever. There are many different ways to insulate buildings with materials.

In this study, the effects of temperature and density variations in open-cell thermal insulation materials on their thermal conductivity are investigated. Thermal conductivity has been measured by a Holometrix 2000 lambda HFM compliant with EN 12664, 12667 standards. Declared values were given regarding to ISO 10456 standard.

In our previous papers references [3, 4] regarding the correlation of the mass density and thermal conductivity the following remark were taken: The thermal conductivities are decreasing with increasing density. In this article we made some corrections and further developments. The main contributions of this study are summarized below:

- About 100 thermal conductivity measurements were carried out.
- Reciprocal relationship between the uncertainties of the measured thermal conductivities and the measured densities was shown, where the smaller deviance in the density is the greater uncertainty in the thermal conductivity can be found.
- New material constant, as the density factor was defined and given for the materials.
- New equation for the temperature and density dependency is given for the declared values of the thermal conductivity.
- The suggested empirical relationship (12) can be applied in practice for temperature conversion of thermal conductivity.

Until recently, the density was seen as the only factor affecting the product properties of the expanded polystyrene foam insulation boards. However, today, it is reported that product properties are also affected by the production process parameters. This can be the answer for

the inverse relationship between the uncertainty in the density and thermal conductivity. The results of this study also indicate the importance of energy saving and the correct selection of insulation material, as well as energy production.

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## References

1. Pe´rez-Lombard L, Ortiz J, Pout CA. Review on buildings energy consumption information. *Energy Build.* 2008;40:394–8.
2. Kalmár F, Kalmár T. Energy class, building structure and solar gains. *J Harbin Inst Technol (New Ser).* 2007;14:81–4.
3. Lakatos A, Kalmar F. Analysis of water sorption and thermal conductivity of expanded polystyrene insulation materials. *Build Serv Eng Res Technol.* 2013;34:4407–16.
4. Lakatos A, Kalmar F. Investigation of thickness and density dependence of thermal conductivity of expanded polystyrene insulation materials. *Mater Struct.* 2013;46(7):1101–5.
5. Jelle BP. Traditional, state-of-the-art and future thermal building insulation materials and solutions—properties, requirements and possibilities. *Energy Build.* 2011;43:2549–63.
6. Muñoz DF, Anderson B, Cejudo-López JM, Carrillo-Andrés A. Uncertainty in the thermal conductivity of insulation materials. *Energy Build.* 2010;42(11):2159–68.
7. Cha J, Seo J, Kim S. Building materials thermal conductivity measurement and correlation with heat flow meter, laser flash analysis and TCi. *J Therm Anal Calorim.* 2012;109:295–300.
8. Fukushima H, Drzal LT, Rook BP, Rich MJ. Thermal conductivity of exfoliated graphite nanocomposites. *J Therm Anal Calorim.* 2006;85:235–8.
9. Chen M, Wan S, Lingchao G, Zhao LP, Gong C. Effect of matrix components with low thermal conductivity and density on performances of cement-EPS/VM insulation mortar. *J Therm Anal Calorim.* 2016;126:1123–32.
10. Wilinska I, Pacewska B. Calorimetric and thermal analysis studies on the influence of waste aluminosilicate catalyst on the hydration of fly ash–cement paste. *J Therm Anal Calorim.* 2014;16(2):689–97.
11. Lakatos Á. Measurements of thermal properties of different building materials. *Adv Mater Res.* 2014;1016:733–7.
12. Lakatos A, Csáky I, Kalmár F. Thermal conductivity measurements with different methods: a procedure for the estimation of the retardation time. *Mater Struct.* 2015;48(5):1343–53.
13. Lakatos A. Measurement of the decrement factor of different wall structures. *WSEAS Trans Heat Mass Transf.* 2016;11:1–5.
14. Moga L, Moga I. Masonry thermal conductivity influence on thermal performance of a thermally insulate wall. *J Appl Eng Sci.* 2011;1143:51–8.
15. Shanshan C, Cremaschi L, Afshin JG. Pipe insulation thermal conductivity under dry and wet condensing conditions with moisture ingress: a critical review. *HVAC&R Res.* 2014;20:4.
16. Koru M. Determination of thermal conductivity of closed-cell insulation materials that depend on temperature and density. *Arab J Sci Eng.* 2016;41:4337–46.
17. Moga L, Moga I. Heat loss coefficient influence on the energy performance of buildings, In: *Indoor Air 2014—proceedings of the 13th international conference on indoor air quality and climate.* (2014); ISBN 978-1-64339-731-5, pp 299–306.
18. Davraz M, Kiliñarslan S, Koru M, Tuzlak F. Investigation of relationships between ultrasonic pulse velocity and thermal conductivity coefficient in foam concretes. *Acta Phys Pol A.* 2016;130(1):469–70.
19. Kirilovs E, Kukle S, Beļakova D, Borodiņecs A, Ruciņš Ā, Stramkale V. Thermal conductivity of hemp based boards. *Tehnologija Resursi Environ Technol.* 2015;1:61–6.
20. Schiavoni S, D’Alessandro F, Bianchi F, Asdrubali F. Insulation materials for the building sector: a review and comparative analysis. *Renew Sustain Energy Rev.* 2016;62:988–1011.
21. Lakatos Á. Thermophysical investigations of nanotechnological insulation materials. *AIP Conf Proc.* 2017;1866:030003. doi:10.1063/1.4994479.