Experimental and Numerical Approach of the Thermal Conductivity of Building Façade Materials

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Abstract: - An experimental research has been conducted to assess the thermo-physical properties of five building materials in both dry and moist state: beech wood, autoclaved aerated concrete and brick, and in dry state for expanded and extruded polystyrene. The objectives of the paper envisage the measurement of the thermal conductivity of these materials through an unsteady state method. The experimental method used in determining the thermal conductivity is based on the principle of temperatures at the interface of two homogeneous semi-infinite bodies of previously altogether different temperatures. The advantage that this method provides lies mainly in the short measuring time and the small temperature rise across the samples. The experimental tests have been accomplished by numerical modeling by means of a computational program based on the finite element method (FEM). The latter have been conducted bidimensionally, under transient state conditions for different lengths of the five materials in dry state. The numerical and experimental results have shown a good agreement for the temperature of the contact area.

Key-Words: - Thermal conductivity, Contact temperature, Building materials, Finite element, Determining method, Numerical modeling

1 Introduction

The physical properties of the building materials play a major role in the energy conservation of the building as well its thermal load. With growing awareness of the problems associated with indoor air quality and the energy consumed in the building, there is now a strong impetus for manufacturing and selecting building materials which are friendly to the environment as well as thermally efficient.

Continuous exposure of building facades to high levels of driving rain keeps the level of moisture contents high. This leads to moisture penetration inside the building façade which can modify the thermal properties of building materials. Thermal conductivity is one of the fundamental properties of materials, and is necessary when the thermal transfer through building façade materials and elements is studied. Thus, appropriate measuring methods that lie to simplicity, accuracy and quickness determination of the thermal conductivity of moist and dry materials are needed.

The ability to accurately determine the thermal conductivity of a material plays an important role when considering its suitability for energy saving insulation, whether it be for building use or for more general heating or cooling processes.

Two groups of testing methods are used in practice for the measurement of heat conductivity as materials property: stationary and non-stationary methods. The stationary methods (hot plate method, cylinder method, sphere method) are in existence in various forms since 1898. They are quite accurate but are time-consuming (no possibility for measuring of materials with moisture content) and the application of these method is possible only in the case of samples with exactly determined dimensions and they are very demanding concerning sample preparation.

Since 1970 there have been developed methods that have successfully been applied to measure the thermal properties of isotropic and homogeneous materials. These are known as the transient hot wire

[1], transient line source [2], transient hot strip [3] and transient plane source techniques [4]. Variations of the transient line source (LST) techniques have been developed to measure the thermal conductivities of building materials [5]. Many efforts have been made to measure the thermal conductivity of weakly [6] and highly [7] porous building materials using the transient plane source (TPS) technique.

The thermodynamic processes in testing moist materials are very complicated, and the concept of thermal conductivity of moist materials may be interpreted in different ways. Extensive works have been made in determining thermal conductivity of many buildings materials in dry state but very few studies have been carried out on wet porous materials. Using the “line source method” Laurent and Guerre - Chaley studied the evolution of the thermal conductivity with water content and temperature for aerated autoclaved concrete (AAC) blocks [8]. The temperature range studied was 0–60°C in steps of 10°C. A series of water contents from completely saturated to completely dry was established by progressive drying in a microwave oven.

Using the box method, an experimental study was carried out by Meukam *et al.,* on the thermal properties of bricks made from lateritic soil [9]. In order to limit water absorption and to increase durability cement has been added to the earth blocks. It was obtaining that the thermal properties as a function of water content give non-linear relations.

We can quote and other studies carried out by Azizi *et al.* [10], by Becker and Katz [11], by Batty *et al.* [12], by Kostic and K.C. Simham [13], by Suleiman [14, 15], and by A. Saljnikov *et al.* [16] witch reveal that the coefficients of thermal conductivity were strongly influenced by the material’s water content.

This paper aims at determining the thermal conductivity of moist and dry building façade materials by means of an experimental method and numerical modeling.

2 Experimental setup

The method used in measuring the thermal conductivity of materials is based on the heating and cooling by contact (considered perfect) of two homogeneous and semi-infinite bodies. This method was developed at the middle of the last century by Campan [17]. The tests were conducted only for mortar and sand, but the method was not used, because of the lack of instrumentation and computer software.

The principle is based on the fact that through the contact surface of two solid bodies, each of them having a different but uniform temperature occurs a heat transfer under unsteady state conditions.

The experimental setup consists of a cube - shaped standard specimen, made of white marble, with the following characteristics measured in laboratory:

- square base of 10.37 x 10.33 cm and 10.10 cm high;
- weight: 2905 g;
- volume: 1081.93 cm^3;
- density: 2685 kg.m^{-3};
- thermal conductivity: 2.99 W.m^{-1}.K^{-1};
- specific heat: 920 J.kg^{-1}.K^{-1}.

The use of the marble block specimen is justified by the fact that this material is not permeable to air or water and cannot get moist at the contact with the humid specimens which have to be tested experimentally. Also, the marble cube is not transparent, has a thermal conductivity close to that of the brick, concrete type building materials, etc, and it cools down over a long period of time because of its bulkiness and of lateral envelopes, which is important in making the contact with the investigated materials.

To avoid heat losses from the lateral sides and the top side, the marble cube is thermally insulated by means of expanded polystyrene. The marble cube and the expanded polystyrene envelope are introduced into a metallic box provided with screws and handles which enable an easy handling and transport of the setup.

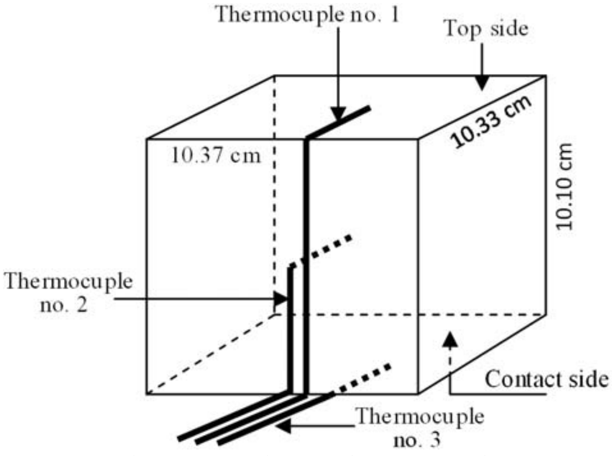

Fig. 1. Location of thermocouples in the marble cube

The marble cube, sketched in Figure 1, was equipped with three Cu – Constantan thermocouples, as follows:

- one thermocouple introduced in an orifice made in the middle of the cube (thermocouple no. 2) and another one fixed at its top side for the checking of uniform heating within the entire mass (thermocouple no.1);

- one thermocouple for determining the contact temperature between the two bodies (thermocouple no. 3), fixed on the bottom side of the cube.

In order to carry out the experimental tests, several pieces of equipment were used, such as: a device for the humidifying of the specimens at various degrees of moisture, a numerical voltmeter for the measuring of the temperatures indicated by thermocouples (precision 0.5 %, measuring range 0-1000 μV, sensitivity 1μV), a digital thermohygrometer for measure humidity and temperature in laboratory (RH range: 0 – 98 %, accuracy ±2 %; temperature range: -20...+50°C, accuracy ±0.3°C), a heat chamber for the uniform heating of the standard specimen (temperature range 40 – 220°C, temperature accuracy ± 0.8°C) and a semi-automatic weighing scale (capacity 10 kg, readability 5 g).

The temperature of the marble cube is considered uniform when the measured temperatures values are equalized by means of the three thermocouples, moment when the standard body is placed fast and tight over the specimen under test. The temperatures of the tested specimens, whose thermal conductivity is going to be measured, kept in the constant ambient laboratory conditions, are checked by means of another thermocouple, introduced in the middle of the tested specimen. The reading of the contact temperature is done after approximately 4 minutes from specimens superposing, thus waiting for the heat flux to get equalized through the interface area and, therefore, for this surface temperature to become steady. After this length of time, the effect of the lateral heat losses will become evident in the central area of the system, as well, resulting in a slow decrease of the contact temperature. The thermal conductivity of the tested specimens is found using the formula [17]:

$$\lambda_{ts} = \left(\frac{T_{ss} - T_c}{T_c - T_{ts}} \right)^2 \cdot \frac{\lambda_{ss} \cdot c_{ss} \cdot \rho_{ss}}{c_{ts} \cdot \rho_{ts}} \tag{1}$$

Besides ensuring a perfect contact, the use of relation (1) assumes knowing the thermophysical properties (specific heat and density) of the two bodies, as well as the thermal conductivity of the marble cube. The specific heat of the moist materials (u % of weight) was found by averaging the specific heat of the dry material (c_o) and the specific heat of water (c_w), with the relation:

$$c = \frac{c_o(100 - u) + c_w \cdot u}{100} \tag{2}$$

The specimens' densities were found using their mass/volume ratio. In order to determine the thermal conductivity of the marble cube, this was previously calibrated using an immobile fluid (water), whose thermal conductivity is known. The following relation was used [17]:

$$\lambda_{ss} = \left(\frac{T_c - T_w}{T_{ss} - T_c} \right)^2 \cdot \frac{\lambda_w \cdot c_w \cdot \rho_w}{c_{ss} \cdot \rho_{ss}} \tag{3}$$

The marble cube thermal conductivity found by calibration is λ_{ss} = 2.99 W.m^{-1}.K^{-1}. The error in the measurement of the thermal conductivity was estimated to be within ± 5%. The major sources of errors in the measurement arise from the uneven surfaces of the samples and imperfect contact between the sensors and the surroundings.

3 Experimental results

Based on the principle of contact heating and cooling of bodies, a measurement of the thermal conductivity of several thermo-insulating materials, frequently used in constructions, was carried out. These materials are:

- a beech wood specimen (tested normally on its fibres), 24.37 x 24.3 cm in size, 3.95 cm thick and 613.5 kg.m^{-3} density in dry state;
- a autoclaved aerated concrete specimen 24.89 x 25 cm in size, 5.03 cm thick and 589.5 kg.m^{-3} density in dry state;
- a brick specimen 25.2 x 25.14 cm in size, 3.26 cm thick and 1576 kg.m^{-3} density in dry state;
- a expanded polystyrene specimen 24.6 x 24.7 cm in size, 9.71 cm thick and 13.4 kg.m^{-3} density in dry state;
- a extruded polystyrene specimen 24.55 x 24.47 cm in size, 1.94 cm thick and 33.6 kg.m^{-3} density in dry state.

The first three specimens were tested both in dry state and at different degrees of relative moisture, and the polystyrene specimens were tested in dry state. The tests were conducted in normal laboratory conditions, in an undisturbed environment, at temperatures between 18 and 23°C (Table 10) and a humidity of 40–50 %.

For the beech wood, autoclaved aerated concrete and brick specimens, the first set of tests were carried out on materials having an equilibrium moisture content after keeping the specimens under controlled laboratory temperatures and moistures, for over 4 months. In order to do the next sets of tests, the specimens were placed in the moisturizing enclosure for water absorption. By subsequently introducing the specimens in sealed plastics sheets, it was possible to preserve the absorbed water content inside the materials and to allow it to spread evenly over long periods of time (2 – 3 months). At the same time, a set of tests were conducted on the specimens previously dried in the oven at temperatures of 105 … 110°C. In these conditions the water from the specimen was eliminated by evaporation, until its mass remained the same.

Taking into account the necessity of ensuring a perfectly tight contact between the marble cube and the materials being tested, the top areas of the autoclaved aerated concrete and brick specimens were polished with grinding materials. The resulting dust was left on the specimen, so as to eliminate the risk of possible air voids. The stages of the experimental testings consisted in: uniform heating of the standard marble cube, measuring the specimen temperature before testing, placing the materials in tight contact and following the evolution of contact temperature over time. Figure 2 shows the testing done on the autoclaved aerated concrete. One can see the contact between the marble cube and the specimen, the measuring of contact temperature by the numerical voltmeter and the environment conditions measured by the thermo-hygrometer.

Fig. 2. Contact temperature measuring at the surface of autoclaved aerated concrete specimen with a relative moisture content of 6.35%

Figures 3, 4, 5 and 6 show the evolutions of contact temperatures against time, for beech wood, autoclaved aerated concrete, brick, expanded and extruded polystyrene. One can see that from the moment of getting the marble cube out of the oven to its contact with the materials under test, for several seconds, there was a temperature drop of 0.4 – 1°C for beech wood, of 0.2 – 0.5°C for autoclaved aerated concrete, of 0.5 – 3.5°C for brick and of 0.1°C for expanded and extruded polystyrene. Then, during the first several minutes, the contact temperature kept diminishing very quickly, by 2.9 – 5°C for the beech wood, by 2.4 – 6.8°C for autoclaved aerated concrete, by 2.9 – 10.2°C for brick, depending on the water amount contained in the specimens. Also, the contact temperature kept diminishing by 0.6°C for expanded polystyrene and by 0.7°C for extruded polystyrene. During the minutes that followed, the temperature increased slightly and settled around a value that remained constant for 3 – 4 minutes, even for 7 minutes with the dry specimens. Finally, the contact temperature diminished slowly over time. One can also see that the contact temperature settled quicker and stayed constant for a longer time in the dry materials by comparison with the moist ones (Figures 3, 4 and 5).

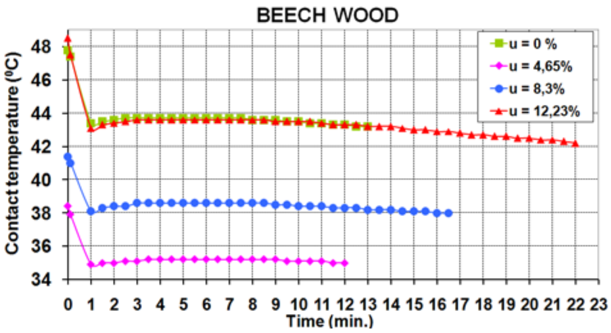

Fig. 3. Time - dependent evolution of contact temperature in the beech wood specimen

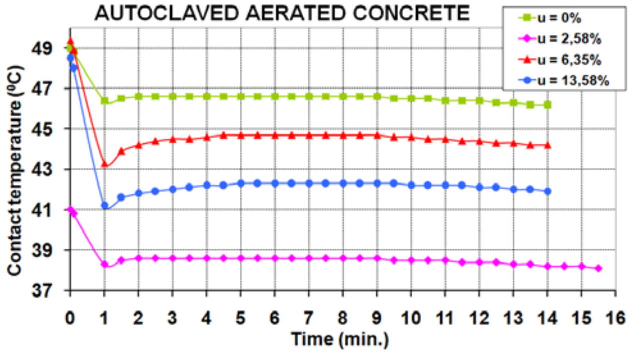

Fig. 4. Time - dependent evolution of contact temperature in the autoclaved aerated concrete specimen

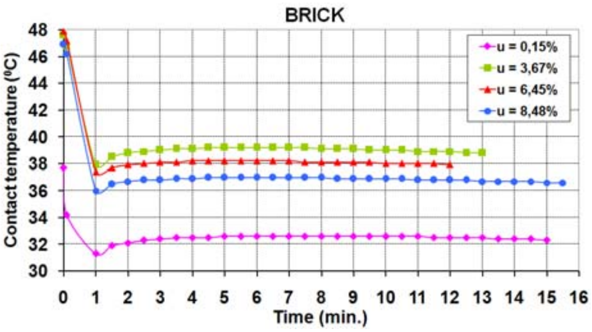

Fig. 5. Time - dependent evolution of contact temperature in the brick specimen

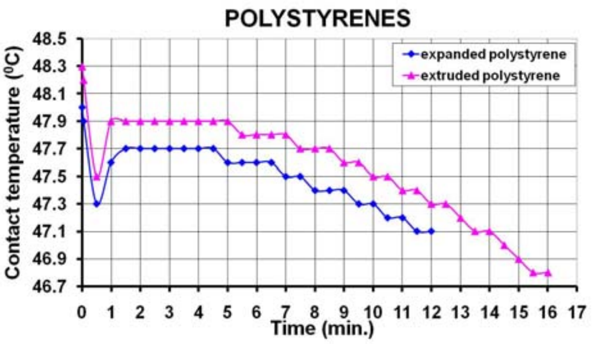

Fig. 6. Time - dependent evolution of contact temperature in the expanded and extruded polystyrene specimens

Table 1: Experimental results

Material	u (%)	c (J.kg^{-1}.K^{-1})	ρ (kg.m^{-3})	λ (W.m^{-1}.K^{-1})
Beech wood	0	2508	613.5	0.127
	4.65	2587	643.4	0.143
	8.30	2646	669.0	0.149
	12.23	2713	699.0	0.177
Autoclaved aerated concrete	0	836	589.5	0.135
	2.58	924	605.1	0.285
	6.35	1049	629.4	0.363
	13.58	1292	682.1	0.883
Brick	0	882	1576.0	0.630
	3.67	999	1636.0	0.723
	6.45	1091	1684.8	1.036
	8.48	1158	1722.0	1.286
Expanded polystyrene	0	1505	13.4	0.043
Extruded polystyrene	0	1505	33.6	0.032

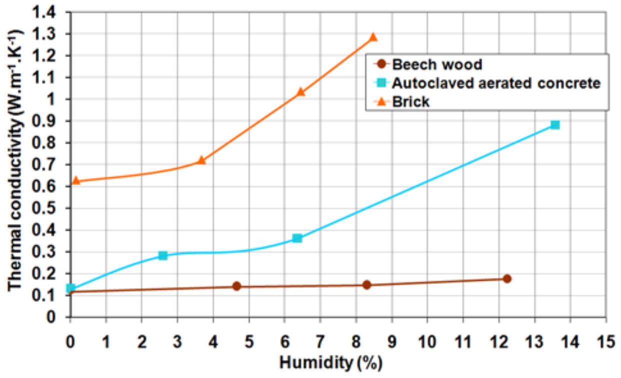

Fig. 7. Variation of thermal conductivity function of relative humidity in the investigated specimens

The results obtained in the experimental tests are synthesized in Table 1, while Figure 7 shows the evolution of thermal conductivity as a function of the relative humidity of materials, expressed in water amount percentages against total weight of moist specimen.

In all the investigated cases, the results have shown an increase in thermal conductivity when the water amount in the material increased (Figure 7 and Table 1). In the beech wood specimen one can see a more significant increase of conductivity at moisture values under 5% and higher than 9%, for the autoclaved aerated concrete – under 3% and higher than 7%, while for the brick specimen-higher than 4%.

The experimental results obtained in this research are in good agreement with those cited by the literature. Thus, investigations carried out by Laurent and Guerre – Chaley on autoclaved aerated concrete [8], by Pratt on wood [18] and by Suleiman on brick [14], show a general trend of thermal conductivity increase in materials containing either small or significant amounts of water. Their values are generally higher than ours (Tables 2, 3 and 4), the differences being due to using different density specimens and using a method in an unsteady state condition which differs from ours: the line source method in the Laurent's case, the flat source in the Pratt's case and the hot disk technique in the Suleiman's case. The measurements have highlighted the fact that this increase may be explained by the heat transfer due to water vapour diffusion, which overlaps other transfer ways.

Table 2: Autoclaved aerated concrete specimens

Humidity u (%)	Density in dry state ρ_o (kg.m^{-3})		Thermal conductivity λ (W.m^{-1}.K^{-1})	
	present work	Laurent J.P.	present work	Laurent J.P.
0	589.5	630	0.135	0.178
saturated	-	-	0.883	0.985

Table 3: Beech wood specimens tested normally on the fibres

Humidity u (%)	Density in dry state ρ_o (kg.m^{-3})		Thermal conductivity λ (W.m^{-1}.K^{-1})	
	present work	Pratt A.W.	present work	Pratt A.W.
0	613.5	640	0.127	0.137
4.65	-	-	0.143	0.148
8.3	-	-	0.149	0.158
12.23	-	-	0.177	0.167

Table 4: Brick specimens

Humidity u (%)	Density in dry state ρ_o (kg.m^{-3})		Thermal conductivity λ (W.m^{-1}.K^{-1})	
	present work	Suleiman B.M.	present work	Suleiman B.M.
0	1576	1444	0.630	0.751
saturated	-	-	1.286	1.239

4 Numerical modeling

The numerical modeling of the heat transfer between these two solid mediums was achieved by means of the computational program, based on the finite element method (FEM), in view of obtaining the time evolution of temperature at the contact between the bodies. The modeling was done bidimensionally under transient state conditions, for different sizes of the five materials (beech wood, autoclaved aerated concrete, brick, expanded and extruded polystyrene) in dry state. The computational domain was discretised into a structured, non uniform mesh with smaller cells near the contact surface and larger ones in the rest. The mesh size of the marble cube was 21 × 21 cells and for the tested materials is given in tables from 5 to 9.

Table 5: Beech wood specimen

Case	Length L (cm)	Thickness δ (cm)	Number of cells
1-1	24.3	3.95	43 × 11
1-2	10.37	3.95	21 × 11
1-3	35	3.95	63 × 11
1-4	24.3	10	43 × 21
1-5	24.3	20	43 × 44

Table 6: Autoclaved aerated concrete specimen

Case	Length L (cm)	Thickness δ (cm)	Number of cells
2-1	25	5.03	43 × 11
2-2	10.37	5.03	21 × 11
2-3	35	5.03	63 × 11
2-4	25	10	43 × 21
2-5	25	20	43 × 44

Table 7: Brick specimen

Case	Length L (cm)	Thickness δ (cm)	Number of cells
3-1	25.2	3.26	43 × 11
3-2	10.37	3.26	21 × 11
3-3	35	3.26	63 × 11
3-4	25.2	10	43 × 21
3-5	25.2	20	43 × 44

Table 8: Expanded polystyrene specimen

Case	Length L (cm)	Thickness δ (cm)	Number of cells
4-1	24.6	9.71	43 × 11
4-2	10.37	9.71	21 × 11
4-3	35	9.71	63 × 11
4-4	24.6	15	43 × 21
4-5	24.6	20	43 × 44

Table 9: Extruded polystyrene specimen

Case	Length L (cm)	Thickness δ (cm)	Number of cells
5-1	24.55	1.94	43 × 11
5-2	10.37	1.94	21 × 11
5-3	38.73	1.94	63 × 11
5-4	24.55	5	43 × 21
5-5	24.55	10	43 × 44

The sizes of the five tested materials were kept identical as for the experimental tests (basic cases 1-1, 2-1, 3-1, 4-1 and 5-1), and afterwards their length and thickness were varied (tables from 5 to 9). In all the cases under test, the marble cube sizes were kept the same as in the experimental stages.

The initial conditions imposed are similar to those resulting from the experimental tests (table 10), and for the limit ones the following were considered:

- the marble cube is insulated at the top and on its four lateral sides so as to avoid the heat transfer towards the environment;

- the five different specimens are insulated at the bottom by being placed on insulating material, while between the other sides and air there occurs a heat transfer by convection, where the convective transfer coefficient is h = 10 W.m^{-2}.K^{-1}.

Table 10: Initial conditions

Material	Temperature T_{ts} (°C)	Marble cube temperature T_{ss} (°C)	Air temperature T_a (°C)
Beech wood	18.5	47.8	19.9
Autoclaved aerated concrete	21.3	49	22.5
Brick	17.8	37.7	18.8
Expanded polystyrene	20.1	48	21
Extruded polystyrene	20.7	48.3	22.1

The results obtained from the numerical simulations have been compared to the experimental ones and plotted in figures 8, 10, 12, 14 and 16. It may be seen that the contact temperature obtained experimentally has decreased suddenly to 43.4°C for the beech wood (figure 8), 46.4°C for the autoclaved aerated concrete (figure 10), 31.3°C for the brick (figure 12), 47.3°C for the expanded polystyrene (figure 14) and 47.5°C for the extruded polystyrene (figure 16). This contact temperature drop may be explained by the removal of the marble cube from the oven and its transport up to its superposing on the investigated material. This phenomenon was left aside in the numerical cases, and consequently, the contact temperature decrease during the first minute is not as significant as in the experiments.

After the first minute, the contact temperature increased slightly in the experimental case and after that remained constant for 3 – 7 minutes (enough to enable its measuring) in all the cases. After this time interval the contact temperature decreased slowly in the numerical cases and quicker in the experimental one. The explanation may be that in the numerical case a constant value of h = 10 W.m^{-2}.K^{-1} for a certain air temperature was assumed, while, actually, all along the experimental testings there may occur variations of the environmental temperature and there may be air currents which might lead to a time variation of h.

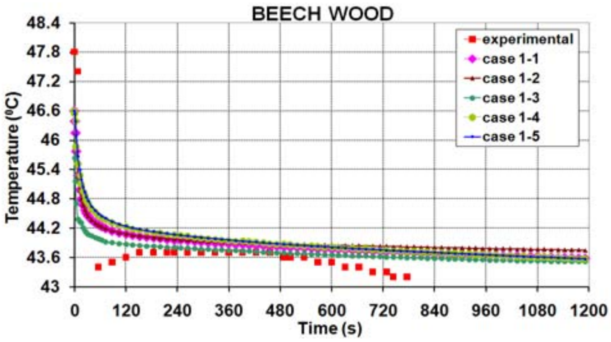

Fig. 8. Time-dependent evolution of contact temperature in the beech wood specimen

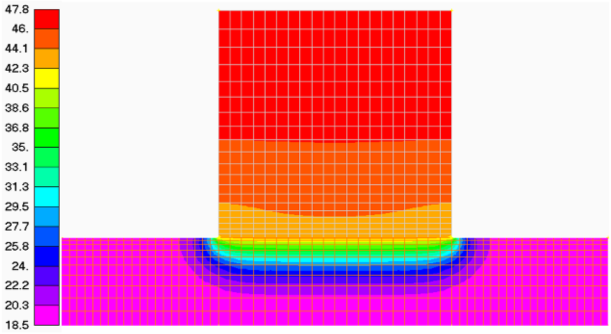

Fig. 9. Isotherms plot at t = 20’ after the contact between the marble cube and the beech wood specimen in the case 1-1

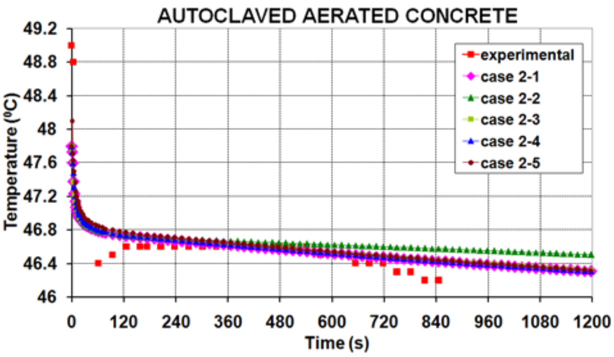

Fig. 10. Time-dependent evolution of contact temperature in the autoclaved aerated concrete specimen

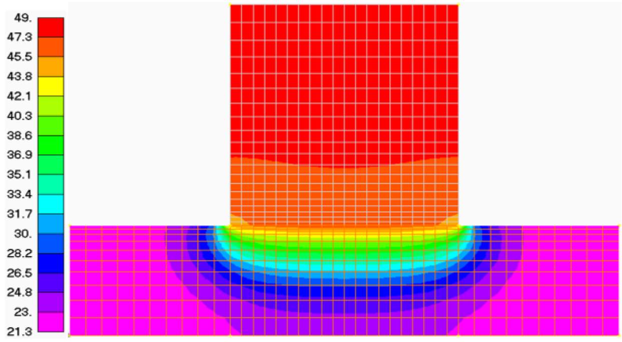

Fig. 11. Isotherms plot at t = 20’ after the contact between the marble cube and the autoclaved aerated concrete specimen in the case 2-1

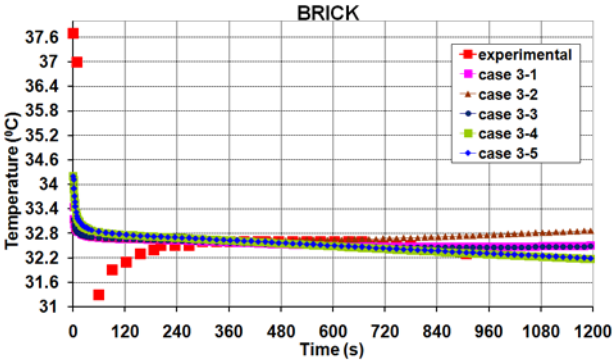

Fig. 12. Time-dependent evolution of contact temperature in the brick specimen

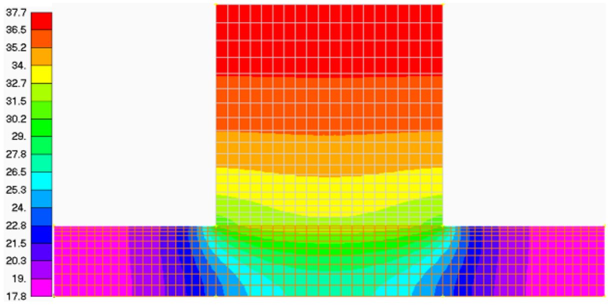

Fig. 13. Isotherms plot at t = 20’ after the contact between the marble cube and the brick specimen in the case 3-1

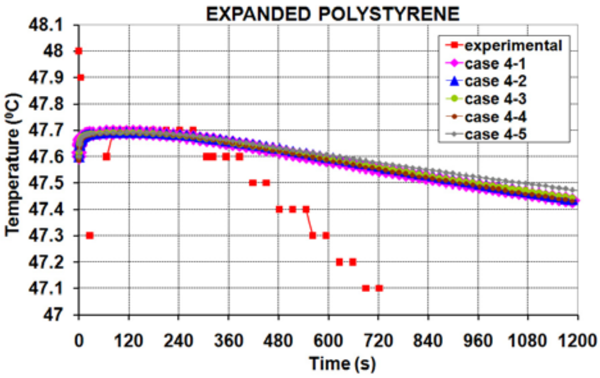

Fig. 14. Time-dependent evolution of contact temperature in the expanded polystyrene specimen

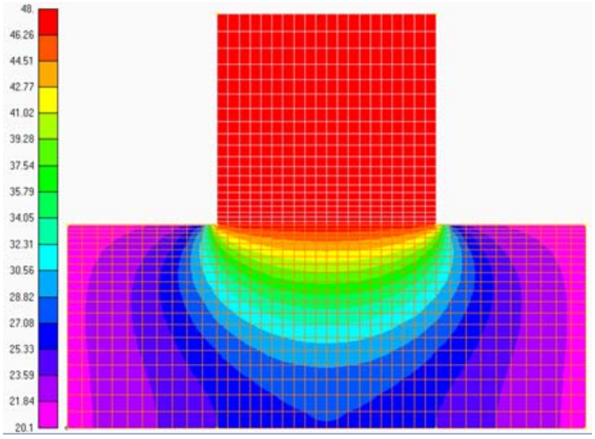

Fig. 15. Isotherms plot at t = 20' after the contact between the marble cube and the expanded polystyrene specimen in the case 4-1

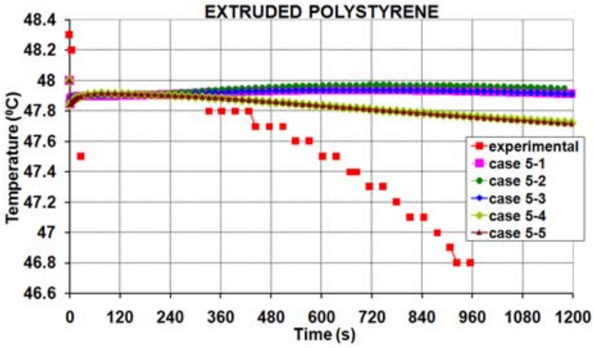

Fig. 16. Time-dependent evolution of contact temperature in the extruded polystyrene specimen

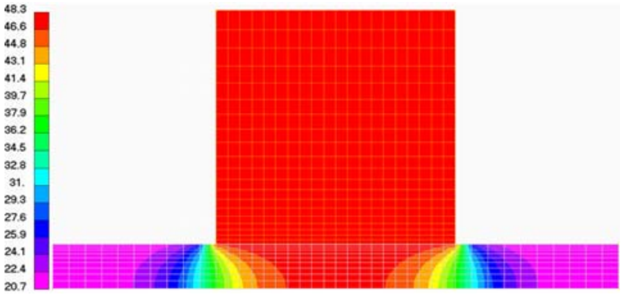

Fig. 17. Isotherms plot at t = 20' after the contact between the marble cube and the extruded polystyrene specimen in the case 5-1

In figures 9, 11, 13, 15 and 17 one may see the evolution of the temperatures field after 20 minutes from the contact of the marble cube with the five materials, for the basic cases 1-1, 2-1, 3-1, 4-1 and 5-1.

A good agreement between the experimental data and the numerical ones can be seen in the region where the contact temperature remains steady in time, in all the investigated cases.

The small differences between the contact temperatures obtained numerically over the 20 minutes simulation time indicate that the modification of the specimen size does not influence significantly the time-dependent variation of contact temperature.

The differences between the experimental and numerical results have been recorded, generally, during the first minutes from achieving the contact and after the contact temperature starts diminishing over time. But these differences are less relevant, as in calculating the materials thermal conductivity it is necessary to get the value of the temperature which settles over time. Furthermore, the differences that may occur stay under 1% for expanded polystyrene (Fig. 18), under 2.5% for extruded polystyrene (Fig. 19), under 3% for autoclaved aerated concrete (Fig. 20), under 4.5% for beech wood (Fig. 21) and under 9.5 % for brick (Fig. 22).

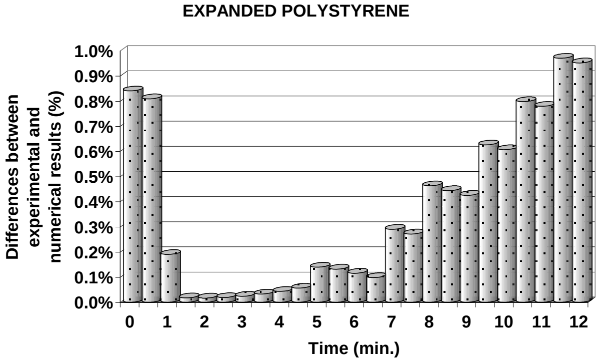

Fig. 18. Differences between experimental and numerical results for the expanded polystyrene specimen

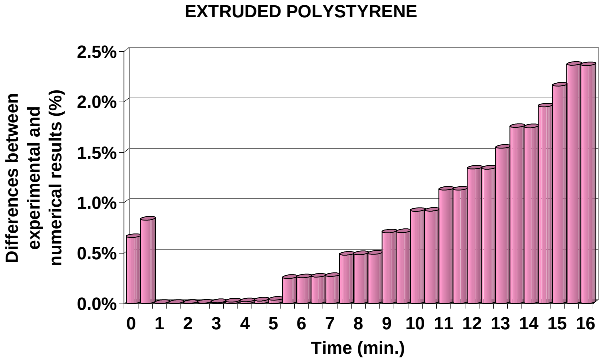

Fig. 19. Differences between experimental and numerical results for the extruded polystyrene specimen

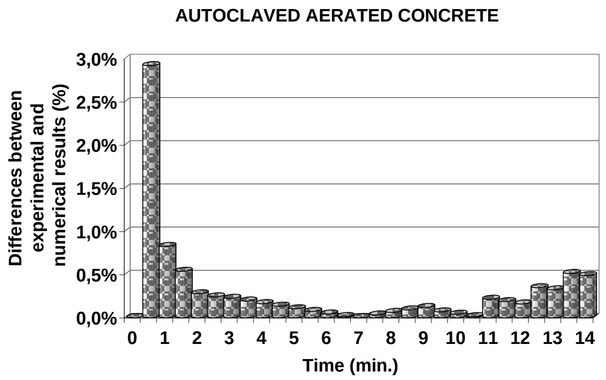

Fig. 20. Differences between experimental and numerical results for the autoclaved aerated concrete specimen

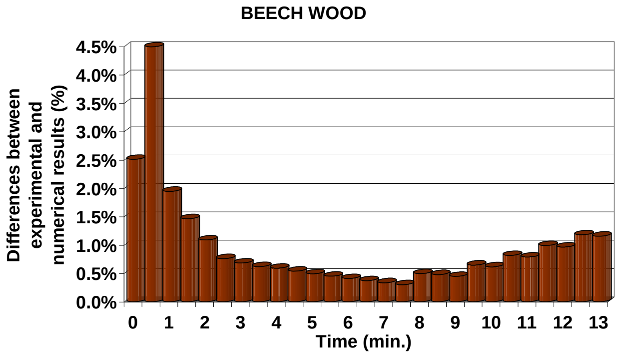

Fig. 21. Differences between experimental and numerical results for the beech wood specimen

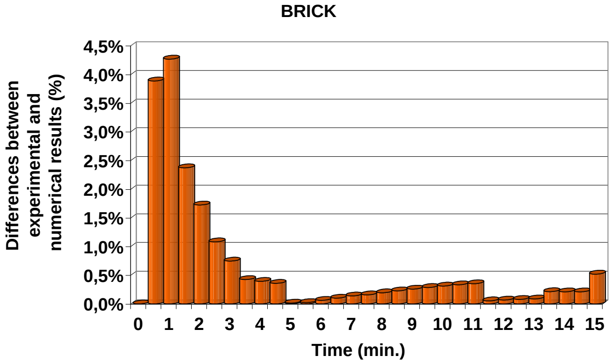

Fig. 22. Differences between experimental and numerical results for the brick specimen

5 Conclusion

During the last two decades, many advances have been made in thermal insulation technology, both in measurement techniques and in improved understanding of the principles of heat flow through insulating materials.

Using the contact temperatures method in determining the thermal conductivity of building materials in dry or moisture state, offers important advantages as compared to the procedures used so far, and these are: simplicity and quickness of measurement, small scale equipment, the small enough increase of temperature in the specimens, the short time for the test preparation and running, possibility of studying the thermal conductivity at different temperatures and humidity values.

Being an almost instantaneous method, this one can also be used in determining the thermal conductivity of moist materials because water has no time to migrate to the structure of the tested materials, thus eliminating the risk of disturbing the moisture field [19].

Consequently, the proposed procedure will eliminate to a great extent the factors that produce incongruities between the results obtained by using stationary or non-stationary determining methods and it may be used in measuring the dry and moist materials thermal conductivity and also in investigating them before using.

The method can be used for further investigations concerning the influence of humidity and moisture content on the overall thermal performance of others materials, especially soils, whose thermal proprieties are required in many areas of engineering, agronomy, and soil science.

6 Nomenclature

a - thermal diffusivity ($m^2.s^{-1}$)
c - specific heat ($J.kg^{-1}.K^{-1}$)
h - convection heat transfer coefficient ($W.m^{-2}.K^{-1}$)
L - length (m)
t - time (s)
T - temperature (^oC)
u - humidity (%)

Greek symbols
δ - thickness (m)
λ - thermal conductivity ($W.m^{-1}.K^{-1}$)
ρ - density ($kg.m^{-3}$)

Subscripts
a - air
o - dry material
c - contact
ss - standard specimen
ts - tested specimen
w - water

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