MODEL FOR THE ANALYSIS OF THERMAL CONDUCTIVITY OF COMPOSITE MATERIAL OF NATURAL ORIGIN

by

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Original scientific paper
https://doi.org/10.2298/TSCI181215267M

Thermal properties of the wall structure elements made from gel and straw ("Ethno-eco-passive houses") have been investigated. The gel was made from a mixture of clay, lime, and water. A 1-D mathematical model based on the continuum mechanics, for predicting the thermal conductivity, is proposed. The results obtained by applying the proposed mathematical model were compared with the measurement data of experimental tests, using the Isomet 2114 instrument. The program envisages the measurement of thermal conductivity of three specimens, 5-year-old, comprising three series within 365 days. In the theoretical analysis, the same parameters of thermal stability were treated as in the experiment. The average value of the material thermal conductivity is 0.0990 W/mK, so it can be concluded that, the composite material intended for the envelope of the proposed constructive system "Ethno-eco-passive house" is verified as thermally suitable.

Key words: *thermal analysis, thermal conductivity, composite plate*

Introductory remarks

In order to use the new material for building *Ethno-eco-passive houses* [1], it is necessary to check thermal properties. The reason for this is that the thermal stability of the basic and complementary elements of constructive systems is an important parameter in determining the category of energy efficiency of the structure [2-5]. In thermal analysis for determining the thermal conductivity of materials, depending on whether the temperature distribution within the specimen is time-dependent or not, two groups of methods are used: static and dynamic.

Static methods, *i. e.* methods of stable thermal conductivity conditions are obtained by using the Fourier's law for conducting heat by measuring the temperature gradient, *gradT*, and the heat flux, *q*.

In the case of a cylindrical form of a sample the dominant passage of thermal energy is in the axial direction with isothermal plane that are perpendicular to the axis of the cylinder. So, this is the basis of the physical model of linear heat energy implementation. On the other hand, due to the losses of heat caused by passing through the material it cannot be considered that the temperature gradient is always directed perpendicular to the isothermal plane. It is then necessary to pay a particular attention to the measurement of the temperature gradient value.

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Dynamic methods, *i. e.* the methods of unstable states treat the distribution of the specimen temperature as a variable size in time, whereby the application of the differential 3-D equation of heat propagation is necessary. If the test time is short, then the heat loss has less influence on the measurement results. Dynamic methods can be divided into two categories: transient – if the amount of heat is transferred to a sample with one function treated as a constant source, or periodic – with modulation of a certain period. Consequently, the temperature changes in the treated material specimen will be either transient or periodic. When the thermal conductivity of building materials of weak thermal insulation properties is tested, the application of stable state methods requires more time to achieve the thermal equilibrium. Therefore, the dynamic method of measurement is faster and more convenient. The most commonly used is the so–called thermal conductivity probe with linear heat source [6]. The treated mathematical 3-D model is based on the theoretical foundations of the Continuum Mechanics, for predicting the thermal conductivity, similar to [7-16].

In this paper, the thermal theoretical experimental analysis was carried out on the basis of which a model for estimating the thermal conductivity was formulated. In order to verify the accuracy of the model, an experimental analysis was performed on specimens collected from gel and straw. Gel is a mixture of clay, lime and water. The research was motivated by the need for examining the material for the construction of the building *Ethno-eco-passive house*, proposed by [1]. In the experiment realization, a non-standard method for testing the thermal conductivity was used. The results of the experiment confirmed the applicability of the tested building materials and were the basis for the validation of the proposed mathematical model for the prediction of thermal properties.

Material and methods of experimental research

Material for sample testing – composites

The new construction material in this study was put on site, dried at daily temperature and assembled as a mixture of minced straw and gel. The panel obtained by the method of incorporating a composite in wooden moulds 60×120×10 cm, fig. 1(c), was realized in two independent phases.

The first phase is the preparation of the gel, fig. 1(b), made up of a mixture of water, clay and slag lime prepared by mixing. The second phase is completely independent and represents the grinding of *dry* straw on a sieve with openings of 5.0 mm in diameter. Thus, fibrous

(a) (b) (c)

Figure 1. Preparation and installation of composite materials in wooden moulds

(needle) granulation is obtained as the dominant component of the composite material of natural origin, fig. 1(a).

Therefore, prepared straw fibres have, with volume ratio, the largest share in the new composite thermo insulating material. The next stage of the composite material preparation is mixing based on gel volume constraints (one mix design specified by the project) and the fibre of the ground straw to achieve the density of the material of about ρ = 600 kg/m^3. Thus, one feature is defined in the project *Ethno-eco-passive houses*, with a limit value for the density of the composite material.

Generally, this boundary classifies material with good thermal insulating properties, provide receiving and transmitting external impacts. Among other activities, the drying regime was another activity during the preparation and realization of the composite material. In fig. 2, a diagram of the registered air temperature for 28 days is shown in the area in which the prefabricated panels are made of the composite material.

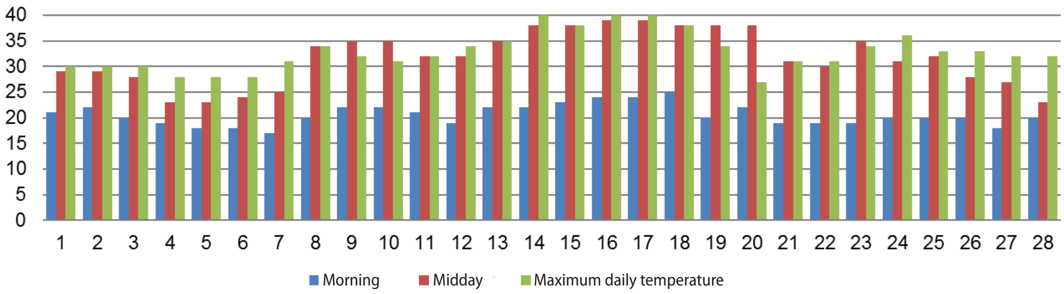

Figure 2. Temperature of air in Pelagicevo – Republic of Srpska (09.08. – 05.09.2012)

Based on the consistently presented, a composite material of natural origin should provide high thermal stability, *i. e.* good thermal properties for the future building envelope. Elements for mounting of the constructive system *Ethno-eco-passive houses* are coupled T-crossing cross-sections *wood-composite plate-wood* with steel screws as a means of clamping.

Since the thermal analysis of the composite slab was the subject of the study, it was realized by taking three samples of a prismatic form with a controlled geometry and by measuring the mass of the specimens during the course of the experiment, fig. 4.

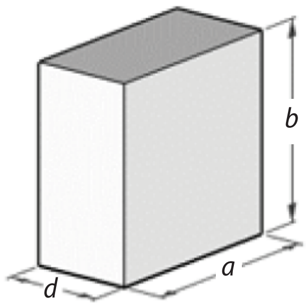

Figure 4. Geometry of the specimen of the prism tested

Measuring system for experimental testing

For the thermal analysis of specimens of the new composite material, the measuring system *Isomet 2114* [6] was used, a portable hand-held measuring instrument for direct measurement of heat transfer properties.

This system, fig. 3, uses a dynamic metering method to test composite specimens, and is equipped with two types of measuring probes: needle probe (for non-consolidated and composite materials) – applied in this study, and surface probe (for consolidated-solid and composite materials). On the basis of the above presented, non-standard procedures for testing specimens of composite materials in construction design from the point of view of determining the thermal conductivity under real environmental conditions were carried out.

Figure 3. The Isomet 2114 instrument for thermal conductivity measurements

The program envisages measuring of thermal conductivity in three series with three specimens, 5 years old, within 365 days. In the theoretical analysis, the same parameters of thermal stability as in the experiment were treated.

Geometry of specimens

Experimental test specimens were subjected to the geometry control and volume calculation. The data are shown in tab. 1.

Table 1. Geometric data of the specimens

Specimen	I				II				III			
a [mm]	195	195	198	198	192	191	190	190	189	190	191	191
a_{av} [mm]	196.5				190.75				190.25			
b [mm]	210	203	208	211	205	204	204	205	203	205	204	206
b_{av} [mm]	208				204.5				204.5			
d [mm]	87	80	80	85	89	84	79	84	88	80	83	80
d_{av} [mm]	83				84				82.8			
P_{av} [mm^2]	40872				39008.38				38906.13			
V_{av} [mm^3]	3392376				3276704				3219482			

Test results of composite specimens

The first specimen of the material *ILIJA1* was tested in the period from 11:18 to 12:49, with the measuring instrument Isomet 2114. In fig. 5, the display shows the results of measuring of the thermal parameters of the first specimen from the first series. Individually important results for all three specimens in all three series of tests are shown in tab. 2.

Table 2. The experimental results for all three specimens in all three series of testing

Specimen	I			II			III		
Series of test	1	2	3	1	2	3	1	2	3
Mass [g]	1760.2	1695.8	1692.4	1741.6	1678.2	1674.4	1757.0	1697.2	1692.8
ρ [kgm^{-3}]	518.87	517.53	525.67	513.39	512.16	520.08	517.93	517.96	525.80
λ [Wm^{-1}K^{-1}]	0.0989	0.1003	0.0976	0.0990	0.1004	0.0967	0.0982	0.1005	0.0993

Finally, the thermal conductivity of the composite material is found as the average value of the thermal conductivity of all three specimens from the three series of measurements:

$$\lambda = \frac{1}{3}\left(0.0987 + 0.1004 + 0.0979\right) = 0.0990$$

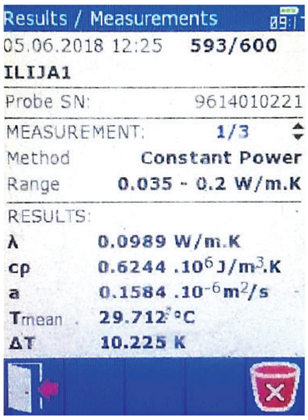

Figure 5. Display results of Isomet 2114

Theoretical analysis and mathematical modelling

The mathematical model of 3-D extending heat through a homogeneous mechanical body is based on the physical law on the maintenance of energy [7, 8]. Solving the problem of heat spreading is based on the determination of:

– the scalar temperature field – $T(x, y, z, t)$,
– vector field of intensity of heat flux (flow) – $\vec{q}(x, y, z, t)$.

The final solution is obtained when a connection between these two values is established. The law on energy maintenance must be satisfied at every material point of the mechanical body, so that the equation of the energy thermal equilibrium of the unit volume, dV, can be written in the form:

$$\mathrm{div}\,\vec{q} - \frac{\partial (T\rho c_p)}{\partial t} + f = 0 \tag{1}$$

where the operator of the divergence of the vector field of the heat flux is:

$$\mathrm{div}\,\vec{q} = \nabla \vec{q} = \frac{\partial q_1}{\partial x} + \frac{\partial q_2}{\partial y} + \frac{\partial q_3}{\partial z}$$

Provided that the temperature describes the field of the potential of heat energy, then Fourier's law is a constitutive relation, *i. e.* the connection between the heat flux vector, $\vec{q}$, per unit area in the chosen direction and the gradient temperature, grad T, for that direction. For the area or domain of the observed body, Ω, that is:

$$\vec{q} = -\lambda\,\mathrm{grad}\,T \tag{2}$$

that is, in the tensor form it is:

$$\begin{Bmatrix} q_x \\ q_y \\ q_z \end{Bmatrix} = -\begin{bmatrix} \lambda_{xx} & \lambda_{xy} & \lambda_{xz} \\ \lambda_{xy} & \lambda_{yy} & \lambda_{yz} \\ \lambda_{xz} & \lambda_{yz} & \lambda_{zz} \end{bmatrix} \begin{Bmatrix} \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \\ \dfrac{\partial T}{\partial z} \end{Bmatrix}$$

where the negative sign for Λ is introduced due to the convention for the direction of the heat flux, from a lower to a higher temperature level.

By connecting eqs. (1) and (2) it follows that:

$$\mathrm{div}\,(-\lambda \mathrm{grad} T) = \frac{\partial (T\rho c_p)}{\partial t} - f \tag{3}$$

that is, the strict form of the differential equation of the law on the maintenance of energy, suitable for solving the problem of spreading heat is:

$$\mathrm{div}\,\vec{\mathrm{q}} + f = \rho c_p \frac{\partial(T)}{\partial t} \tag{4}$$

where in eqs. (4) and (2) λ is the symmetric second-order tensor-the thermal conductivity coefficient which, in the case of a homogeneous body, is scalar, according to [7], f – the heat energy produced in unit volume material, ρ – the density of material, c_p – the specific heat of the material at constant pressure, and t – the time.

Therefore, the parameters (f, ρ, c_p, λ) in the eqs. (1)-(4) are in general the case of functions and positions and temperatures. However, the temperature, T, is the fundamental variable (primary size), while the heat flux, q, is dual size. This is especially important when choosing a disk space of discrete functions in the application of numerical methods, *e. g.* in physical discretization with finite elements, *i. e.* their networks [8].

The boundary conditions for the complete solution of the 3-D heat spread problem are defined for:

– temperature, T, by the body border element, $\partial\Omega_T$,
– the heat flux, q, along the elements of the body boundary ($\partial\Omega_q$), ($\partial\Omega_c$), and $\partial\Omega_r$, in the form:

$$T = T \quad \text{on the } (\partial\Omega T), \tag{5}$$

$$qn = q_h = h \quad \text{on the } (\partial\Omega q), \tag{6}$$

$$qn = q_c = h_c(T - T_a) \quad \text{on the } (\partial\Omega c), \tag{7}$$

$$qn = q_r = h_r \sigma A(T^4 - T_a^4) \quad \text{on the } (\partial\Omega r), \tag{8}$$

By the eq. (5) the boundary conditions are defined at the material points of the boundary of the body due to the known (set) temperature. Other boundary conditions are given by the eqs. (6)-(8) for the heat flux along the elements of the body's surface area, if it is: known or assigned, due to heat transfer by convection, and due to heat transfer by radiation; where n is the unit normal of body surface treated, h_c – the coefficient of convection, h_r – the coefficient of radiation, $\sigma = 5.67 \cdot 10^{-8}$ W/m^{2}K^4 – the Stefan-Boltzmann constant, T – the unknown body temperature on the observed surface, and T_a – the ambient temperature of the environment of the observed surface element.

If the observed body consists of several different homogeneous isotropic materials, which is not the case of the material considered in this paper, the second-order tensor, Λ, is reduced to a scalar, λ, according to [7], which will be different for each material in the structure. Therefore, the system of eqs. (1)-(8) represents a closed system of equations of the problem of the 3-D spread of heat in a material continuous medium. If the coefficients λ, ρ, c_p, are independent of the temperature, this is because they are poorly changed at the observed temperature interval. It is pointed out that this is characteristic for construction structures under normal service/operational conditions (not at high temperatures such as fire or explosions).

On the other hand, starting from a differential equation that describes the Newton's law of conducting heat (cooling), the change in the specimen temperature is proportional to the difference in specimen temperature and the environment. We consider the proportionality in this paper as a constant, k, and it is called the thermal conductivity, which is known to be different for all treated specimens of the material, so it can be written:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = k(T_l - T_d) \tag{9}$$

The expression (9) treats the temperature difference as an unknown function of time, t, represents a 1-D model for verification of measurement the thermal conductivity and with the method of separating variables according to (10):

$$\frac{\mathrm{d}T}{T_l - T_d} = k\mathrm{d}t$$
$$\int \frac{\mathrm{d}T}{T_l - T_d} = k\int \mathrm{d}t \tag{10}$$
$$-\ln\left|T_l - T_d\right| = kt + C$$

it follows that:

$$T_l - T_d = C\mathrm{e}^{-kt} \tag{11}$$

that is, we have the following cases:
– heating $T_l < T_d$ solution $T(t) = T_l + C\mathrm{e}^{-kt}$
– cooling $T_l > T_d$ solution $T(t) = T_l - C\mathrm{e}^{-kt}$.

Theoretical experimental comparative thermal analysis

In this theoretical thermal analysis, by the mathematical 1-D model of heat conduction (9) it is simpler to verify certain parameters obtained by measuring, with the measuring system *Isomet 2114*. The determined size is the thermal conductivity expressed on the basis of the heat capacity. Due to the fact that the parameters of the 3-D model of thermal conductivity of materials have become scalar quantities, we can separately verify those mathematically using measurement data. The treated parameters are those that indicate the rate of heating-cooling, or the ability to accumulate heat in a homogeneous material. The initial parameters of heat stability for heat accumulation are:
– volumetric heat (thermal) capacity, $c_\rho = \rho c$
– thermal diffusivity, $a = k/c_\rho = k/\rho c$
– coefficient of heat absorption, $b = (\lambda\rho c)^{1/2}$

Based on the registered values of the thermal capacity of the first specimen for all three measurements and density of the specimen material, tab. 2, there is a specific heat capacity in the form:

$$c = \frac{c_\rho}{\rho}$$

with which the thermal diffusivity, a, is verified in tab. 3.

Numerical analysis

Based on the solution (11) of the 1-D model for the case ($T_l < T_d$ and $T_l > T_d$) and the data presented in tab. 3, the numerical comparative thermal analysis of the first specimen was conducted for all three series of measurements of the thermal conductivity of the material. In the cross-section of two curves (heating and cooling) there is a point which gives the time, t, of the experimental registration of the thermal conductivity of the material and the mean value of the temperature, T_{mean}, in conducting the test. To confirm this hypothesis, it is accessed by computer simulations in the case of the first specimen with a test time of t = 1.5 hours. The

Table 3. Theoretical experimental results of the first specimen (Isomet 2114)

The first series	The second series	The third series
(08.09.2017.)	(12.03.2018.)	(20.06.2018.)
$c_\rho = 0.6244 \cdot 10^6$ J/m³K $\lambda = 0.0989$ W/mK $\rho = 518.87$ kg/m³	$c_\rho = 0.6224 \cdot 10^6$ J/m³K $\lambda = 0.0990$ W/mK $\rho = 513.39$ kg/m³	$c_\rho = 0.6198 \cdot 10^6$ J/m³K $\lambda = 0.0982$ W/mK $\rho = 517.93$ kg/m³
Specific heat capacity		
$c = 1.203 \cdot 10^3$ m²/Ks²	$c = 1.212 \cdot 10^3$ m²/Ks²	$c = 1.197 \cdot 10^3$ m²/Ks²
Thermal diffusivity		
$a = 1.584 \cdot 10^{-7}$ m²/s	$a = 1.591 \cdot 10^{-7}$ m²/s	$a = 1.584 \cdot 10^{-7}$ m²/s
Coefficient of heat absorption		
$b = 248.502$ kg/Ks$^{2.5}$	$b = 248.229$ kg/Ks$^{2.5}$	$b = 246.707$ kg/Ks$^{2.5}$

verification of the measurement results with the proposed 1-D model has extended the numerical analysis of the first specimen to all three series of the experiment carried out, showing the functions of the temperature distribution in time for:
- heating – $T1z(t)$, $T2z(t)$, and $T3z(t)$, that is
- cooling – $T1h(t)$, $T2h(t)$, and $T3h(t)$.

Let us look at three cross section points of the temperature distribution functions $T1z(t)$ and $T1h(t)$, $T2z(t)$, and $T2h(t)$ and $T3z(t)$, and $T3h(t)$, according to the solution (11), figs. 6-8. Since the test time of the first specimen in all three series is the same, then the ordinate for $t = 1.5$ goes through all three points of the intersection of the solution (11) and thus verifies three experimental data, $T_{mean} = 29.712$ °C, 29.654 °C, and 29.619 °C.

Accordingly, the solution (11) of the proposed 1-D model (9) based on the simulations for $t = 1.5$ hours successfully validates the experimentally registered quantities for the first specimen in all three batches during testing of $t = 1.5$ hours. On the other hand, by the proposed 1-D model, for the known experimentally registered thermal conductivity of materials, it is possible to predict the same registered size for all three specimens in three series, at different experiment time t =1, 1.5, 2, and 12 hours. Thus, based on the computer simulations performed, figs. 9 and 10, the mathematical 1-D model verifies the experimentally registered data for the mean temperature value: $T_{mean} = 29.712$ °C, the first series, $T_{mean} = 29.654$ °C, the second series, and $T_{mean} = 29.617$ °C, the third series.

Specimen 1 – first series

Experimental data: $\lambda = 0.0989$ W/mK

$t = 1.5$ hours

Numerical data according to (11):

$k = \lambda = 0.0989$ W/mK

$10.225 = Ce^{-0.0989 \cdot 1.5}$

$C = 11.86$

$T1z(t) = 39.937 - 11.86e^{-0.0989 \cdot t}$

$T1h(t) = 19.487 + 11.86e^{-0.0989 \cdot t}$

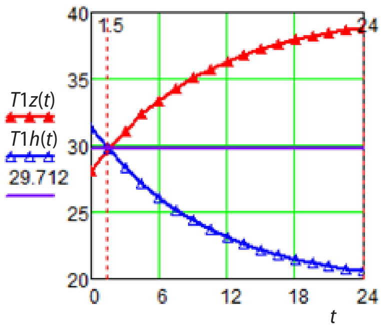

Figure 6. Distribution of the temperature of the first series

Specimen 1 – second series

Experimental data: $\lambda = 0.0990$ W/mK

$t = 1.5$ hours

Numerical data according to (11):

$k = \lambda = 0.0990$ W/mK

$9.9910 = C\mathrm{e}^{-0.0990 \cdot 1.5}$

$C = 11.59$

$T2z(t) = 39.645 - 11.59\mathrm{e}^{-0.0990 \cdot t}$

$T2h(t) = 19.663 + 11.59\mathrm{e}^{-0.0990 \cdot t}$

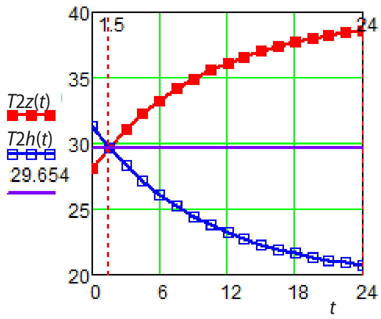

Figure 7. Distribution of the temperature of the second series

Specimen 1 – third series

Experimental data: $\lambda = 0.0982$ W/mK

$t = 1.5$ hours

Numerical data according to (11):

$k = \lambda = 0.0982$ W/mK

$10.057 = C\mathrm{e}^{-0.0982 \cdot 1.5}$

$C = 11.65$

$T3z(t) = 39.674 - 11.65\mathrm{e}^{-0.0982 \cdot t}$

$T3h(t) = 19.560 + 11.65\mathrm{e}^{-0.0982 \cdot t}$

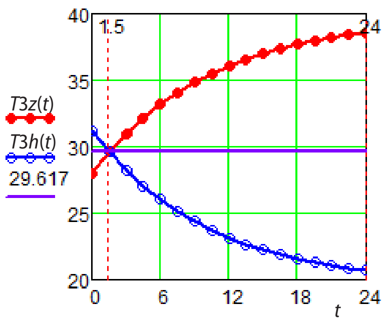

Figure 8. Distribution of the temperature of the third series

Finally, the results of all computer simulations for the assumed experiment time are separated for transparency, for $t = 1$ and $t = 1.5$ hours, on fig. 9, that is, for $t = 2$ and $t = 12$ hours, on fig. 10, for all three specimens materials and all three series of tests.

The presented solutions of the numerical analysis given in figs. 9 and 10 in the graphic form are:

– T$ijz(t)$ – the distribution function of the heating temperature,

– T$ijh(t)$ – cooling distribution function (Newton's law of conducting heat)

where i – the specimen number, j – the serial number of the test series, z – the fault of heating, and h – curve cooling.

Therefore, no matter how long time the measuring system needs when registering thermal parameters for one specimen of the material, it is possible to register one mean temperature, T_{mean}, and one thermal conductivity, fig. 5.

The results of numerical analyses with the proposed 1-D mathematical model for specimen 2 and 3 in all three series are not presented here due to their extensiveness.

Final remarks and conclusions

In this paper, the proposed 1-D mathematical model verified the results of the experimental analysis of thermal conductivity. For real environmental conditions, three series of

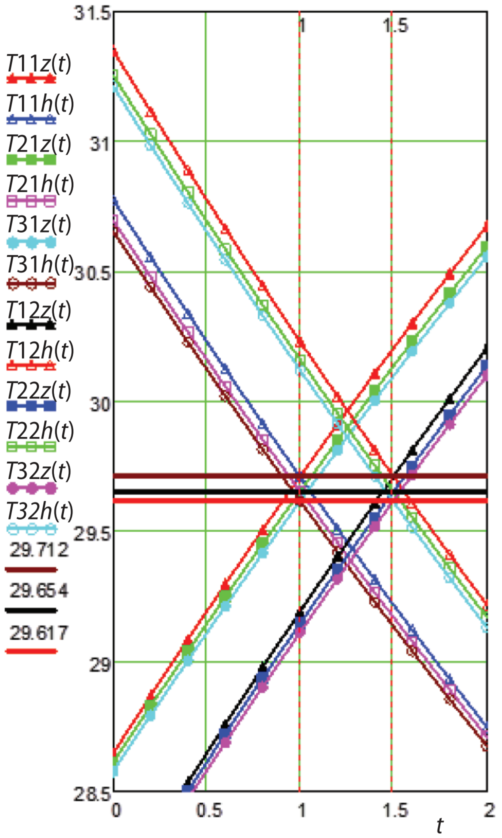

Figure 9. Enlarged part of the simulation results for t = 1 and 1.5 hours

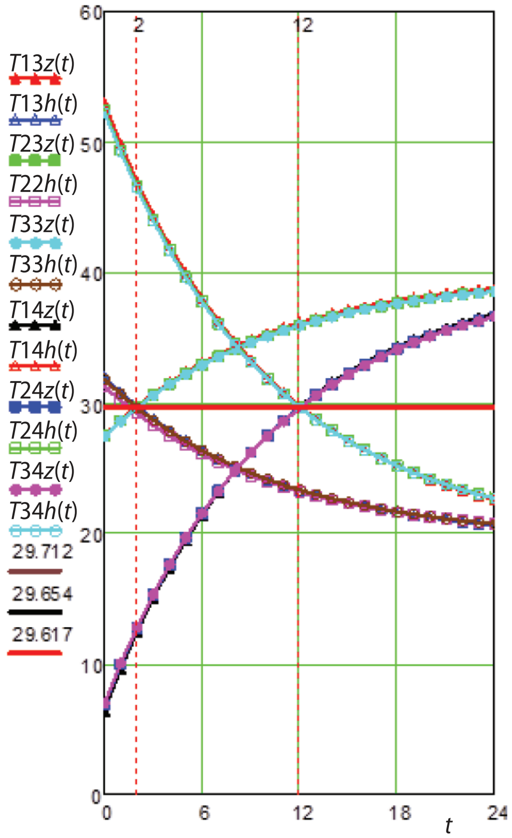

Figure 10. Simulation results for t = 2 and 12 hours

testing within 365 days, and age of specimen of 5 years, the obtained thermal conductivity of the tested material was 0.0990 W/mK.

Higher heat capacity of the material means that it can accumulate a higher amount of heat. Based on the numerical analysis carried out with the proposed 1-D mathematical model (9), it has been shown that higher density materials have a higher thermal capacity. This indicates the need for an adequate selection of the recipes, *i. e.* the share of individual components in the preparation of materials for building Ethno-eco-passive houses.

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Paper submitted: December 15, 2018
Paper revised: May 2, 2019
Paper accepted: May 20, 2019