

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

*Ilija M. MILIČIĆ^{*1}, Radomir FOLIĆ², Aleksandar PROKIĆ³, Arpad ČEH⁴*

^{1,3,4}University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, Serbia

²University of Novi Sad, Faculty of Technical Sciences, Dr Sime Miloševića 12, Novi Sad, Serbia

*Corresponding author; E-mail: milicic@gf.uns.ac.rs

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 one dimensional (1D) 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.*

1. 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] [3] [4] and [10]. 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.

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 3D 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 [18]. The treated mathematical 3D model is based on the theoretical foundations of the Continuum Mechanics, for predicting the thermal conductivity, similar to [5–9] and [11–15].

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 I. M. Miličić, 2010 [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.

2. Material and methods of experimental research

2.1. 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 60x120x10cm (Fig. 1c) was realized in two independent phases.

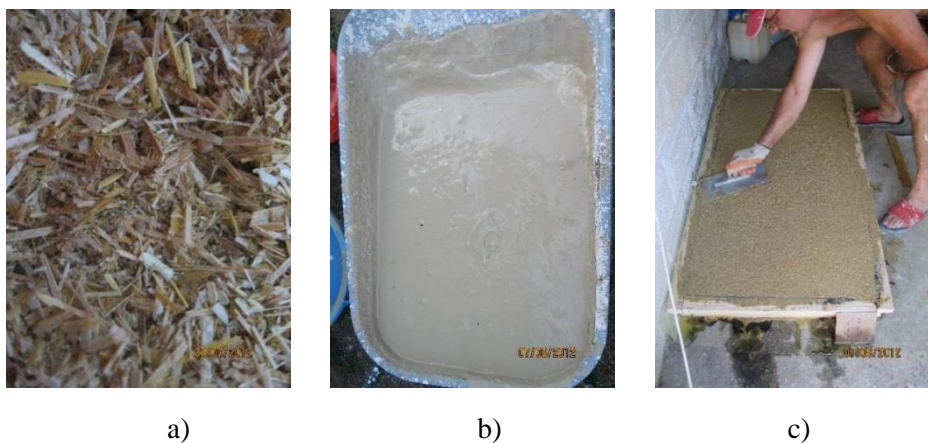


Figure 1 – Preparation and installation of composite materials in wooden moulds

The first phase is the preparation of the gel (Fig. 1b) 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 (needle) granulation is obtained as the dominant component of the composite material of natural origin (Fig. 1a).

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 $\rho = 600 \text{ kg/m}^3$. 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.

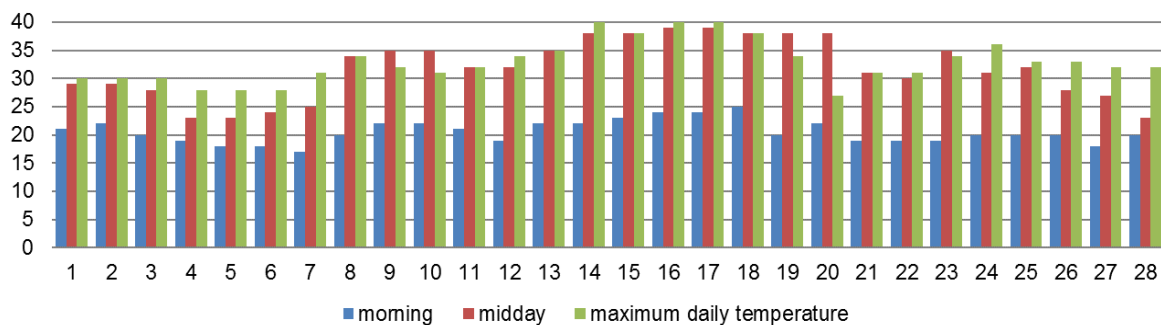


Figure 2 – Temperature of air in Pelagićevo – Republic of Srpska (09.08. – 05.09.2012)

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. 3).

2.2. Measuring system for experimental testing

For the thermal analysis of specimens of the new composite material, the measuring system "Isomet 2114" [19] was used, a portable hand-held measuring instrument for direct measurement of heat transfer properties.

This system (Fig. 4) 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.

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.



Figure 4 – The Isomet 2114 instrument for thermal conductivity measurements

2.3. Geometry of specimens

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

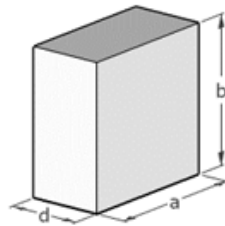


Figure 3 – Geometry of the specimen of the prism tested

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			

2.4. Test results of composite specimens

The first specimen of the material "ILJIA1" 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 Tables 4.

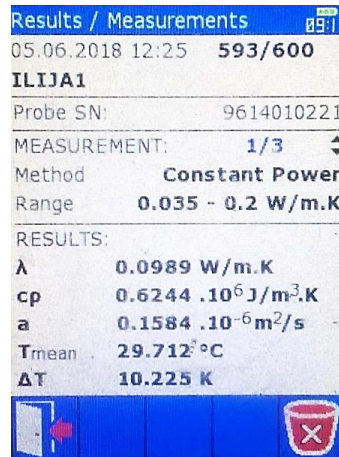


Figure 5 – Display results of Isomet 2114

Table 4 – The experimental results for all three specimens in all three series of testing

Specimen	I			II			III		
	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 (kg/m ³)	518.87	517.53	525.67	513.39	512.16	520.08	517.93	517.96	525.80
λ (W/mK)	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.

$$\lambda = \frac{1}{3}(0.0987 + 0.1004 + 0.0979) = 0.0990 \text{ (W/mK)}$$

3. Theoretical analysis and mathematical modelling

The mathematical model of 3D extending heat through a homogeneous mechanical body is based on the physical law on the maintenance of energy [5] and [6]. 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) – $q(x, y, z, t)$.

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,

$$\text{div } q - \frac{\partial(T \rho c_p)}{\partial t} + f = 0 \quad (1)$$

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

$$\text{div } q = \nabla \cdot q = \frac{\partial q_1}{\partial x} + \frac{\partial q_2}{\partial y} + \frac{\partial q_3}{\partial z}$$

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 (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:

$$q = -\lambda grad T \quad (2)$$

that is, in the tensor form it is,

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

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 equations (1) and (2) it follows that,

$$div(-\lambda \cdot grad T) = \frac{\partial(T \rho c_p)}{\partial t} - f \quad (3)$$

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:

$$div q + f = \rho \cdot c_p \cdot \frac{\partial(T)}{\partial t} \quad (4)$$

In the equations (4) and (2) are:

- λ – symmetric second-order tensor – the thermal conductivity coefficient which, in the case of a homogeneous body, is scalar, according to [5].
- f – heat energy produced in unit volume material,
- ρ – density of material,
- c_p – specific heat of the material at constant pressure,
- t – time.

Therefore, the parameters (f, ρ, c_p, λ) in the equations (1) (2) (3) and (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 [6].

The boundary conditions for the complete solution of the 3D 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:

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

$$q \cdot n = q_h = h \text{ on the } (\partial\Omega_q), \quad (6)$$

$$q \cdot n = q_c = h_c (T - T_a) \text{ on the } (\partial\Omega_c), \quad (7)$$

$$q \cdot n = q_r = h_r \cdot \sigma \cdot A \cdot (T^4 - T_a^4) \text{ on the } (\partial\Omega_r), \quad (8)$$

By the equation (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 equations (6), (7) and (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 – unit normal of body surface treated,
- h_c – coefficient of convection,
- h_r – coefficient of radiation,
- $\sigma = 5.67 \times 10^{-8}$ [W/(m²K⁴)] – Stefan–Boltzmann constant,
- T – unknown body temperature on the observed surface,
- T_a – 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 [5], which will be different for each material in the structure. Therefore, the system of equations (1–8) represents a closed system of equations of the problem of the three–dimensional (3D) 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:

$$\frac{dT}{dt} = k \cdot (T_l - T_d) \quad (9)$$

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

$$\begin{aligned} \frac{dT}{T_l - T_d} &= k \cdot dt \\ \int \frac{dT}{T_l - T_d} &= k \cdot \int dt \\ -\ln|T_l - T_d| &= k \cdot t + C \end{aligned} \quad (10)$$

it follows that,

$$T_l - T_d = C \cdot e^{-k \cdot t} \quad (11)$$

that is, we have the following cases:

- heating $T_l < T_d$ solution $T(t) = T_l + C \cdot e^{-k \cdot t}$
- cooling $T_l > T_d$ solution $T(t) = T_l - C \cdot e^{-k \cdot t}$.

4. Theoretical experimental comparative thermal analysis

In this theoretical thermal analysis, by the mathematical 1D 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 3D 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, $c\rho = \rho \cdot c$
- thermal diffusivity, $a = k/c\rho = k/\rho \cdot c$
- coefficient of heat absorption, $b = \sqrt{\lambda \cdot \rho \cdot c}$

Based on the registered values of the thermal capacity of the first specimen for all three measurements and density of the specimen material (Table 4), there is a specific heat capacity in the form,

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

with which the thermal diffusivity (a) is verified in Table 5.

Table 5 – 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.)
$c\rho = 0.6244 \cdot 10^6 (J/m^3 K)$	$c\rho = 0.6224 \cdot 10^6 (J/m^3 K)$	$c\rho = 0.6198 \cdot 10^6 (J/m^3 K)$
$\lambda = 0.0989 (W/mK)$	$\lambda = 0.0990 (W/mK)$	$\lambda = 0.0982 (W/mK)$
$\rho = 518.87 (kg/m^3)$	$\rho = 513.39 (kg/m^3)$	$\rho = 517.93 (kg/m^3)$
Specific heat capacity		
$c = 1.203 \cdot 10^3 (m^2/K s^2)$	$c = 1.212 \cdot 10^3 (m^2/K s^2)$	$c = 1.197 \cdot 10^3 (m^2/K s^2)$
Thermal diffusivity		
$a = 1.584 \cdot 10^{-7} (m^2/s)$	$a = 1.591 \cdot 10^{-7} (m^2/s)$	$a = 1.584 \cdot 10^{-7} (m^2/s)$
Coefficient of heat absorption		
$b = 248.502 (kg/K s^{2.5})$	$b = 248.229 (kg/K s^{2.5})$	$b = 246.707 (kg/K s^{2.5})$

4.1. Numerical analysis

Based on the solution (11) of the 1D model for the case ($T_l < T_d$ and $T_l > T_d$) and the data presented in Table 11, 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 verification of the measurement results with the proposed 1D 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) (Fig. 6, 7 and 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, $T_{mean} = 29.712^\circ\text{C}$, 29.654°C , and 29.619°C .

Specimen 1 – first series

Experimental data: $\lambda = 0.0989(\text{W/mK})$

$t = 1.5$ hours

Numerical data according to (11):

$$k = \lambda = 0.0989(\text{W/mK})$$

$$10.225 = C \cdot e^{-0.0989 \cdot 1.5}$$

$$C = 11.86$$

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

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

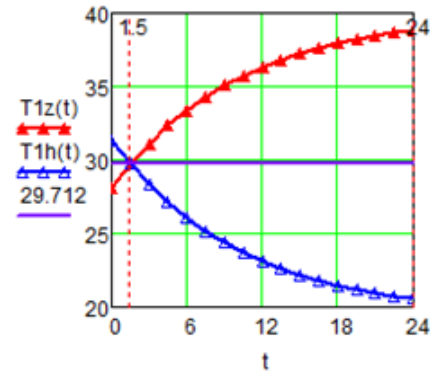


Figure 6 – Distribution of the temperature of the first series

Specimen 1 – second series

Experimental data: $\lambda = 0.0990(\text{W/mK})$

$t = 1.5$ hours

Numerical data according to (11):

$$k = \lambda = 0.0990(\text{W/mK})$$

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

$$C = 11.59$$

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

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

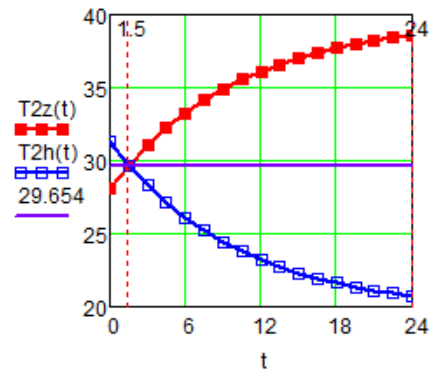


Figure 7 – Distribution of the temperature of the second series

Specimen 1 – third series

Experimental data: $\lambda = 0.0982(\text{W/mK})$

$t = 1.5$ hours

Numerical data according to (11):

$$k = \lambda = 0.0982(\text{W/mK})$$

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

$$C = 11.65$$

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

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

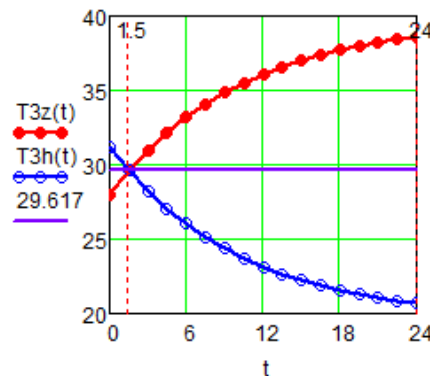


Figure 8 – Distribution of the temperature of the third series

Accordingly, the solution (11) of the proposed 1D 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 1D 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 (Fig. 9 and 10), the mathematical 1D model verifies the experimentally registered data for the mean temperature value: $T_{\text{mean}} = 29.712$ °C, the first series, $T_{\text{mean}} = 29.654$ °C, the second series, and $T_{\text{mean}} = 29.617$ °C, 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.

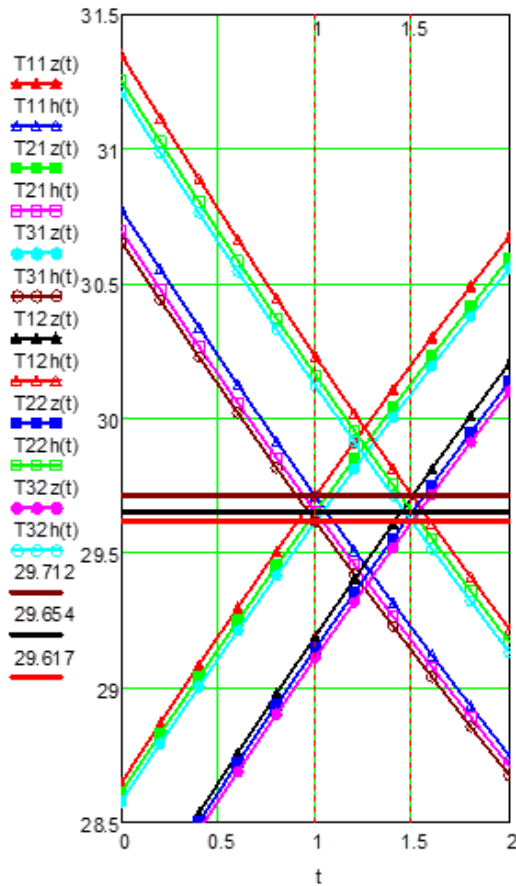


Figure 9 – Enlarged part of the simulation results for $t = 1$ and 1.5 hours

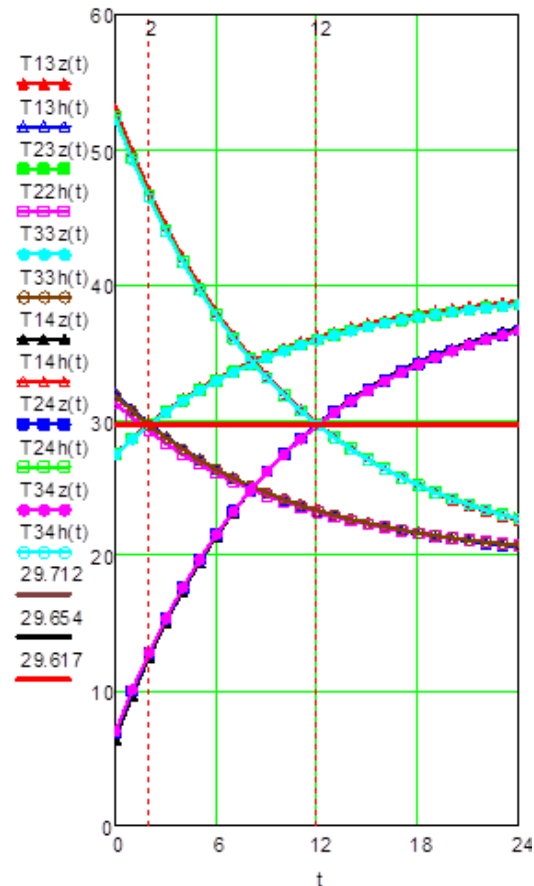


Figure 10 – Simulation results for $t = 2$ and 12 hours

The presented solutions of the numerical analysis given in (Fig. 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 1D mathematical model for specimen 2 and 3 in all three series are not presented here due to their extensiveness.

5. Final remarks and conclusions

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

References

- [1] Miličić, I.M.: Conceptual design “Ethno–eko–passive house” with plate elements made from composite natural material, Faculty of Civil Engineering, Subotica, Serbia, 2010
- [2] Milanović, R.A, Folić–Kurtović, N., Folić, R.: Earth–Sheltered House: A Case Study of Dobraca Village House near Kragujevac, Serbia, *Sustainability* 2018, 10, 3629; doi:10.3390/su10103629
- [3] Ferreira, M.G.P.R.: Experimental study of the Thermal Behavior on Green Façades, Extended Abstract, Instituto Superior Técnico, Lisboa, 2015
- [4] Ilinčić, N., Miličić, I.: Primena savremenih tehnologija građenja u Subotici i uzroci neuspeha, *Proceedings, Tehnologija građenja –građevinski menadžment '97*, Subotica, 1997, pp. 19–28 (in Serbian)
- [5] Jarić, J.: Mehanika kontinuuma, Građevinska knjiga, Beograd, 1988 (in Serbian)
- [6] Lienhard, IV H.J., Lienhard, V H.J.: A Heat Transfer Textbook. Phlogiston Press Cambridge, Massachusetts, 2003
- [7] Bowles, D.E., Tompkins, S.S.: Prediction of Coefficients of Thermal Expansion for Unidirectional Composites, *Journal of Composite Materials, Vol 23* (1998), Issue 4, pp. 370–388, <https://doi.org/10.1177/002199838902300405>
- [8] Bažant, Z. P., Kaplan, M. F.: Concrete at High Temperatures: Material Properties and Mathematical Models, Concrete design and construction series. Longman Group Limited, Harlow, 1996, pp. 412
- [9] Beneš, M., Štefan, R., Zeman, J.: Analysis of coupled transport phenomena in concrete at elevated temperatures. *In Applied Mathematics and Computation*, 219(2013), 13, pp. 7262–7274
- [10] Oka, S.N.: National energy efficiency program: Foundation, strategy, priorities formulation, and implementation activities. *Termotehnika*, 28 (2002), 1–4, str. 13–23
- [11] Balocco, C.: A simple model to study a ventilated facade energy performance, *Energy and Buildings*, 34 (2002), pp. 469–475

- [12] Blomberg, T.: Computer programs for transient and steady-state heat conduction in three dimensions HEAT3. Sweden: Department of building physics, Lund University, <http://www.buildingphysics.com/heat3.htm>
- [13] Pietrak, K., Wisniewak, T.S.: A review of models for effective thermal conductivity of composite materials, *Journal of Power Technologies*, 95(2015), 1, pp. 14–24
- [14] Mityushev, V.V., Pesetskaya, E., Rogosin, S. V.: Analytical Methods for Heat Conduction in Composites and Porous Media, Cellular and Porous Materials: Thermal Properties Simulation and Prediction. Edited by Andreas Ochsner, Graeme E. Murch, and Marcelo, J.S. de Lemos, Copyright WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim, 2008
- [15] Ran, Z., Yan, Y., Li, J., Qi, Z., Yang, L.: Determination of thermal expansion coefficients for unidirectional fiber-reinforced composites, *Chinese Journal of Aeronautics*, Vol.27 (2014), Issue 5, pp 1180-1187, <http://dx.doi.org/10.1016/j.cja.2014.03.010>
- [16] Tang, K.T.: Mathematical Methods for Engineers and Scientists 3, Springer Berlin Heidelberg New York, 2007
- [17] CEN European Committee for Standardization (1996) Building components and building elements–thermal resistance and thermal transmittance: Calculation method. Brussels, Ref. br. EN ISO 6946:1996
- [18] PTC, MathCAD 14.0, User’s Guide, February 2007.
- [19] Isomet 2114, Portable system for measurement of heat transfer properties of materials, Applied Precision Ltd. Staviteľska 1, 83104 Bratislava, Slovakia, www.appliedp.com (2015, September)

Submitted: 15.12.2018.

Revised: 2.05.2019.

Accepted: 20.05.2019.