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THERMAL INSULATING PROPERTIES OF STRAW-FILLED ENVIRONMENTALLY FRIENDLY BUILDING MATERIALS

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Abstract

The paper presents results of a research for determination of a few general thermal-physical properties of environmentally friendly building materials made by clay, sand and straw. The aim of this study is to establish their heat insulating and energy-efficient capacity. All specific measurements were carried out by using the newest generation thermal conductivity analyser Mathis TCi.
The results showed that the studied composite materials are good thermal insulators with thermal conductivity less than 0.5 W/m.K, which depends on the straw amount. Even less than 0.5 wt.% straw reflects on the insulating properties by decreasing the thermal conductivity coefficient with nearly 50 %.

Keywords:

Thermal conductivity;
Thermal effusivity;
Specific heat capacity;
Straw;
Modified transient plane source technique.

1. Introduction

The construction industry is one of the largest consumers of natural resources. In the production of building materials and in the construction process large amounts of energy are consumed and harmful substances that pollute the environment are emitted.

Eco-friendly materials are mainly based on natural raw materials that are renewable and recyclable. They should have a good set of mechanical properties such as strength, hardness and deformability to satisfy the requirements for building material. As well, thermo-physical properties such as thermal conductivity and reaction to fire are the main focus in their development. Last, but not least, it is necessary to be cheaper than concrete, plasterboard, mortar and other classic materials used in construction [1, 2, 3, 4]. The construction of eco-houses is not wide. There are several houses built entirely from natural materials in Bulgaria. There are such constructions elsewhere in the world - Finland, England, Germany, India, Australia and the United States [5].

One of the natural materials which are applied in new construction is straw [6 - 10]. It is possible to build unique houses with bales of straw or materials containing straw, even on few floors. It also provides good thermal insulation, reliability, and the construction is cheap and completely ecological.

There are various methods for determining the thermo-physical properties of materials, in particular - of building materials [11 - 13]. With the development of technologies new methods of thermo-physical measurements based on the principles of thermal engineering are worked out. The latest generation of such apparatus use non-destructive testing of materials and work on the principle of transient plane source [14 - 19]. The results of this method have very good correlation with the results obtained by well-known classical methods [20, 21, 22].

The purpose of this research is to measure a set of thermo-physical properties of samples of environmentally friendly building material made on the basis of clay, sand and straw in order to evaluate its thermal-technical characteristics. Measurements are performed with an analyser for non-destructive testing - TCi Mathis Thermal Conductivity Analyser, which uses a modified method of transient planar heat source.

2. Materials and Methods

Formulated purpose is achieved by determination of the coefficient of thermal conductivity, coefficient of thermal effusivity and specific heat capacity of samples of environmentally friendly material of clay, sand and straw. These three characteristics give the most accurate evaluation of the thermal parameters of the studied material and in particular of its heat-insulating properties.

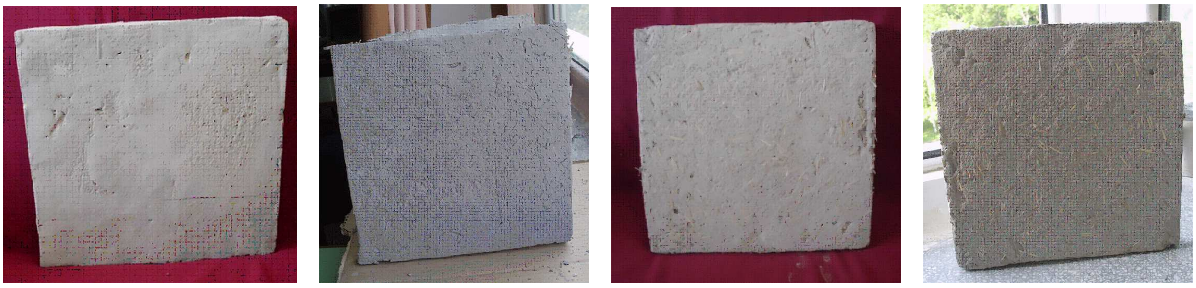
2.1. Experimental materials

For the purposes of the research four type samples in the form of plates with square section and a side length of 0.24 m and thickness of 0.02 m were made (Fig. 1).

The composition is clay (grey marl), sand and straw in proportions as follows:

- **type 1** – clay (grey marl) and sand (1:2);
- **type 2** – clay (grey marl) and sand (1:2) + 0.3 wt.% straw;
- **type 3** – clay (grey marl) and sand (1:2) + 0.4 wt.% straw;
- **type 4** – clay (grey marl) and sand (1:2) + 0.5 wt.% straw.

Water-clay ratio for all types is 0.2.



a b c d

Fig. 1: General view of tested samples: a) without addition of straw; b) with 0.3 wt.% straw; c) with 0.4 wt.% straw; d) with 0.5 wt.% straw.

The composition was mixed to a relatively homogeneity. The plates were dried in ventilated area at ambient temperature for 48 hours without sintering. The final surfaces roughness was obtained after treatment with sandpaper to have very good smoothing of any irregularities and to carry out more precisely subsequent measurements as a result.

In order to determine precisely the density ρ of the tested composite structures and after that to calculate accurately thermo-physical characteristics – especially specific heat capacity, the thickness δ of the plates was measured with a dial indicator. The data are shown in Table 1.

Table 1: Physical data for test samples.

Type	δ [m]	m [kg]	ρ [kg/m^3]
1	0.0240	2.765	2000
2	0.0241	2.606	1877
3	0.0245	2.451	1737
4	0.0247	2.394	1683

2.2. Experimental test method

TCi Mathis Thermal Conductivity Analyser for non-destructive measurement of thermal-physical characteristics was used for the research purposes.

In the scientific literature, there is no information for conduction of thermal measurements of clay-straw materials by modified transient plane source (MTPS) technique. TPS method was proposed by Gustafsson to measure thermal conductivity of bulk specimens, thin slab and film specimens [16]. In 2008, this method was standardized as ISO 22007-2 for determining thermal conductivity and thermal diffusivity of plastics [23].

A third generation C-Therm TCi analyser (Fig. 2a), based on TPS platform technology developed by Mathis Instruments Ltd. in 2004/2005 [24], was used for experiments. TCi analyser has a wide range for measurement of thermal conductivity coefficient (k = 0 - 220 W/(m.K)) in the temperature range from -50 °C to 200 °C [25]. The accuracy of measurements is ± 1 %. The time for performing a test is less than 1 minute. Calibrating elements were used to determine the accuracy.

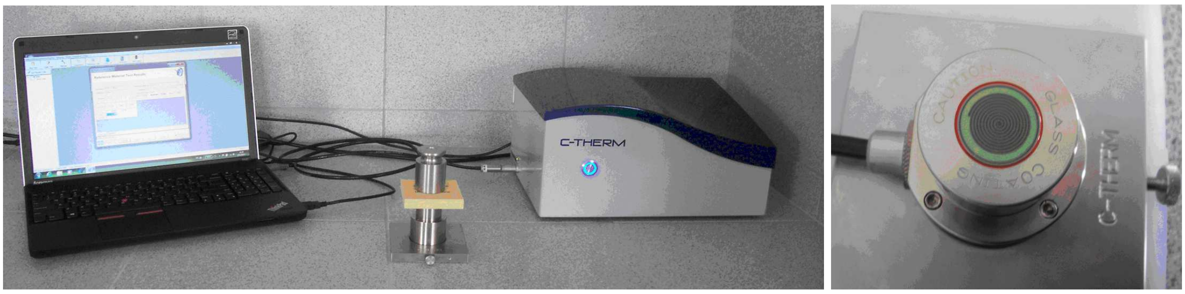


Fig. 2: TCi analyser (a) and C-Therm TCi Sensor (b).

The TCi sensor construction is shown on Fig. 2b. Housing is made of stainless steel. Chip surface is made of alumina (96 % aluminum oxide) with a thin sealing glass layer (DuPont P/N 5415A, screen printable, laser trimmable, air fired G1 glass encapsulant) [25].

The C-Therm sensor works by rapidly determining the rate of heat flow from one material to another. It supplies the heat source and detects the heat flow [14]. The voltage drop on the spiral heater is measured before and during the transient. The rate of increase of the sensors voltage is used to determine the material's thermal properties. The voltage data are used to measure the effusivity value of the tested material. Thermal conductivity is calculated from the voltage data by C-Therm's patented iterative method. The results of measurements are processed with specialized TCi-software (Fig. 2) [25].

Thermal effusuvity *e* and thermal conductivity k were measured directly by the TCi-analyser. The specific heat capacity was calculated by the formula:

$$c_p = \frac{e^2}{\rho.k}, \left[{}^{J}\!\big/_{kg.K} \right], [25] \tag{1}$$

The composite materials, object of this research, have an inhomogeneous structure and this is challenge to determine their thermal conductivity by this local in place of measurement method. Other studies [20, 21] indicate very good correlation between results obtained by MTPS method and those obtained by "hot-cold plate" method.

3. Results and Discussion

To achieve the objective and to obtain precise results four types of experiments were conducted.

A prior measurement of thermal conductivity of the material with known thermal characteristics was conducted in order to verify the accuracy of TCi-analyser. A specimen of potassium float glass in the form of a square plate with a side length of 0.24 m and a thickness of 0.015 m was tested. The coefficient of thermal conductivity of the glass is k_{glass} = 1.15 W/(m.K) [26].

The measurement with TCi-analyser was made in accordance with the methodology of C-Therm at ambient temperature T = 23 ^{o}C. According to ISO 22007-2:2008, the measurements at 3 points on the specimen surface were conducted. After processing of the obtained results, the value of the thermal effusivity of glass is e_{glass} = 1.556 W.s$^{1/2}$/(m^{2}K (RSD = 0.5 *%)* and the coefficient of thermal conductivity – k_{glass} = 1.18 W/(m.K) (RSD = 0.5 *%)*. Experimentally determined value of thermal conductivity coefficient is in good correlation with the tabular one (the difference is 2.6 %). Therefore, the results obtained by the analyser are reliable and tests of the composite materials can be performed.

Experiment №1 was performed with type 1 samples, **experiment №2** using type 2 samples, **experiment №3** with type 3 samples, and **experiment №4** with type 4 samples. Five measurements at 20 points on each sample were carried out due to the inhomogeneous structure of studied material. The processed results are presented in Table 2.

Table 2: Experimental results for thermo-physical characteristics of the tested composite materials.

Experiment №	Sample	e	Δe	c_p	Δc_p	k	Δk
		W.s$^{1/2}$/(m^{2}K)	%	J/(kg.K)	%	W/(m.K)	%
1	0 % straw	648.72 (RSD=0.7%)	-	456.78	-	0.498	-
2	0.3 % straw	629.9 (RSD=0.6%)	-2.9	721.45	57.9	0.379	-23.9
3	0.4 % straw	616.3 (RSD=0.8%)	-4.9	907.21	98.6	0.241	-51.6
4	0.5 % straw	591.42 (RSD=0.7%)	-8.8	968.83	112.1	0.219	-56.0

e – thermal effusivity, W.s$^{1/2}$/(m^{2}K);

Δe – relative change of the thermal effusivity toward to a sample without straw, %;

c_p – specific heat capacity, J/(kg.K) ;

Δc_p – relative change of the specific heat capacity toward to a sample without straw, %;

k – thermal conductivity, W/(m.K);

Δk – relative change of thermal conductivity compared to a sample without straw, %.

The results of the carried out experiments (Table 2) show that the addition of straw in a clay-sand mixture leads to:

- a reduction of the thermal effusivity e with 2.9 % for mixture with 0.3 wt.% straw up to 8.8 % for mixture with 0.5 wt. % straw;
- a significant increase in specific heat capacity c_p with more than 50 % for all types of samples;
- an appreciable reduction of the thermal conductivity k up to more than 50 % for type 3 samples and type 4 samples.

This could be explained by the addition of component with specific structure and properties – straw is a set of dry hollow tubes with closed-in calm air with very low thermal conductivity – k = 0.048 W/m.K [27].

The increasing of c_p values shows that the studied composites improved their capability to accumulate heat. The decreasing of k values is an indicator for improving thermal insulation capacity of the material. The achieved values of specific heat capacity and thermal conductivity coefficient are far from those of the best insulating materials, but could be compared to the thermal characteristics of ceramic bricks (k = 0.72W/m.K, c_p = 837 J/kg.K) and an autoclaved lightweight concrete (k = 0.130-0.384 W/m.K, c_p = 837 J/kg.K) [28].

Therefore, building materials based on clay-sand mixture with the addition of straw could contribute the achievement of thermal comfort and energy efficiency. The established thermal characteristics indicate that the studied environmentally friendly material could be used effectively in the implementation of passive techniques of building.

4. Conclusions

As a result of the carried out study, obtained data for thermal-physical characteristics and the analysis the following conclusions could be made:

1. The modified method of transient plane source could be used to reliably determination of the thermal characteristics of building materials with inhomogeneous structure.
2. Even small quantities of straw (less than 0.5 wt.%) result in significant change of the thermal behaviour of the composite material and contribute to a significant increase in specific heat capacity (more than 50 %) and appreciable decrease of the thermal conductivity (up to 56 %).
3. The addition of straw (even less than 0.5 wt.%) has as result improving the heat accumulative and thermal insulating properties of the environmentally friendly composite material, which makes it suitable material for energy efficient and even passive building.

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