Thermal properties of new ceramic biomaterial for building façades

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Abstract. The selection of materials for a building facade is based on the dimensions of sustainability: environmental, economic and social dimensions, which form the basis of design and construction in terms of environmental conservation and energy efficiency. Furthermore, this implies the formula for maintaining balance: comfort in the indoor environment, care for nature, minimal economic expenses. This paper focuses on the investigation of a new material composed of bio and recyclable materials: clay, sawdust, and slag, i.e. materials found in abundance in nature as well as materials left out of use. The selected materials offer significant potential for use in construction industry, for building façades. Laboratory testing of the thermal properties of the new material, particularly of the thermal conductivity λ (W/m·K) that is crucial for thermal comfort in buildings to promote energy efficiency, has been performed. Three sets of samples (9 samples in total) with different proportions of the constitutive materials were tested using the Heat Flow Meter (HFM) instrument. Based on the results obtained, several conclusions have been drawn to demonstrate the potential for interaction among used materials, offering advancements in terms of thermal properties. Namely, thermal conductivity of the tested samples varies between 0.14 W/m·K and 0.18 W/m·K, depending on the density of the samples. This value is 7-9 times lower than the thermal conductivity value of traditional clay full bricks without voids and cavities and indicates new possibilities for energy efficient facades, promising environmental preservation, harmonization with nature, offering the solution with the slag and sawdust deposition.

1 Introduction

The selection of materials for the construction of the building envelope is based on the dimensions of sustainability of the building: the social, ecological, and economic dimensions. They form the basis of design and construction under conditions of environmental preservation and energy efficiency. This implies the formula for maintaining balance: comfort in the indoor environment, care for nature, and minimal economic expenses.

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The constituent materials selected for research are clay, sawdust, and slag. These materials are obtained under various conditions from nature, such as clay being sourced from natural deposits in the earth, sawdust being derived from wood processing waste, and slag from metal processing residues. These three materials are combined in specific proportions in the field workshop, subjected to air flow processes in the external environment, they are pre-dried under the influence of external environmental conditions to lose the moisture gained during moulding, and then dried and baked at a temperature of 850°C in a kiln especially designed for baking clay products.

To ascertain whether this product, composed of these materials, offers possibilities for use in building enclosures, it must undergo testing and analysis.

1.1 Thermal comfort

Thermal comfort is characterized as a psychological state of subjective assessment by individuals expressing satisfaction with the environment, influenced by both personal and environmental factors [1]. Factors that affect thermal comfort should be mentioned: air temperature, average radiation temperature, air speed, relative humidity, metabolic rate and clothing [2]. Based on the premise that even individuals from similar cultures, when situated in the same space, may perceive comfort differently for that space, it follows that there is no absolute standard that can define thermal comfort [3]. Regarding the thermal comfort, the phenomenon of "sick building syndrome" is also addressed. Sick building syndrome is known as the process where residents experience adverse health effects while staying in the building, without any identifiable cause [4].

1.1.1 Thermal characteristics of buildings

To ensure optimal functionality within their interiors, buildings of various characters must meet specific thermal conditions:

- Building facade
- Climatic zone of the country
- The position of the building
- Heating, ventilation, and lighting
- Microclimate

Amongst these dimensions, the first dimension notably intersects with our research output, which subsequently necessitates integration with the other dimensions in a seamless continuum. The enumerated dimensions serve as pivotal points during the design phase of a building within the parameters of energy efficiency.

1.1.2 Thermal conductivity

When it comes to the insulation of the building facade, with the aim of ensuring thermal comfort within interior spaces while simultaneously impacting the structural stability of the building, consideration must be given to these dimensions in the design and construction process:

a) The thermal performance of the structural components of the building
b) Accumulation of heat
c) Thermal bridges
d) Quantitative ratio of the surface and volume of the object
e) Insolation

The first three dimensions in design, construction, and implementation can be considered in terms of efficiency, which are interconnected with the thermal transmittance coefficient. Achieving good thermal performance, meaning low thermal transmittance, is related to the thermal insulating ability of the materials used on the façade of the building. Within the framework of the thermal insulating ability of a material in thermal calculation practice, we distinguish these measurement units: the thermal conductivity λ (W/m·K), the thermal transmittance U (W/m^{2}K), the thermal resistance R (m^{2}K/W), R=1/U.

1.2 Standard thermal directives

Strict legislations exist in Europe, in order to effectively manage energy performance legislations, aimed at achieving efficiency standards in construction. These laws have the overarching objective of decarbonizing buildings by 2050, fostering the development of zero-emission buildings, and establishing a sustainable environment with specific targets for energy and climate. The legislative frameworks addressing building energy are referred to as EU/2010/31 Directive for energy performance of buildings and EU/2023/1791 Directive for energy efficiency [5]. According to the EPBD (Energy Performance of Building Directive) , 85% of the buildings within the European Union were constructed prior to the year 2000, with 75% of them exhibiting poor energy performance. Given this existing scenario, it enables the governments of European states to determine renovation measures that are tailored to their national context.

Table 1. Key facts on energy and EU buildings. Source [5]

42%	over 1/3	+/- 80%
of energy consumed in the EU in 2021 was used in buildings	of the EU's energy-related GHG emissions come from buildings	of the energy used in EU households is for heating, cooling and hot water

In addition to the thermal transmission "U" (W/m^{2}K) for specific elements of the building envelope, it is initially necessary to determine the thermal conductivity λ (W/m·K) for the basic construction materials. Through these, other calculations and comparisons are derived to ascertain the thermal behavior of a multi-layered material. Regarding thermal conductivity "λ", in most cases for certain products, it is provided by the construction industry, resulting from market competition for products with better performance in construction. It can be determined with laboratory testing only.

2 Materials and methods

Initiating from the premise that the research product aims at its utilization as a material for building facades and being aware of its thermal properties, it was imperative to conduct experiments to assess its thermal performance.

The research product, as outlined at the outset of this paper comprises clay, sawdust, and slag. The clay originates from the region of Kosovo (Location: Kosovo Plain-Mazgit, Fig.1), the sawdust likewise hails from the Kosovo Plain, sourced from beechwood, while the slag is procured from the Ferronickel Factory - Mitrovica (waste residues of iron and nickel, Fig. 2). The combination of these materials has been achieved in varying proportions, with clay material predominating in all such mixtures. Concerning the thermal conductivity λ

(W/m·K), these materials, in practical construction terms, exhibit the following values when used as sole materials: clay λ = 1 W/m·K [6], saw dust λ=0.1 W/m·K [7], slag λ=2.4 W/m·K [8]. Among these materials, sawdust material exhibits the lowest thermal conductivity (in the history of construction and thermal materials, wood materials are recognized as excellent temperature insulators), while metals in general are known for their high thermal conductivity.

Fig. 1. The location where the clay was taken, It is also a factory for baking bricks -Mazgit, Kosovo, photos taken from different angles

2.1 Preparation

The blending of these three materials Fig.2. was conducted under outdoor weather conditions at a temperature of 21-22°C and air humidity of 75%. Moulds were prepared from wooden material with dimensions of 30x30x2cm Fig.3. The moulds were prepared in these dimensions because the internal space of the instrument for measuring the thermal coefficient possesses such dimensions. The blending of these materials was done manually, but also with the assistance of conveying elements as shown in Fig.4, Fig.5.

During the mixing of these materials, an average of 17% water is required to achieve the desired plasticity of the mass. Afterwards, pouring into the moulds was carried out manually, and during pouring, the material was manually pressed into the moulds to eliminate air spaces / air bubbles in order to achieve a compact mass of samples.

After blending and placing in the moulds, the obtained samples were left in an open environmental setting for drying under the influence of air circulation due to their high plasticity Fig.6 and Fig.7. During this exposure period, they were protected from rain as they were covered at the top. After 14 days, they were sent to a factory (Mazgit, Kosovo) for 24-hour drying and 24-hour baking at 850°C in a kiln.

Fig. 2. Saw dust, Clay, Slag

The percentage of clay material mixtures, sawdust, and slag is given in Table 2. This table also presents specifications for the mass, volume, and density of the samples. Mass as a measure of the amount of material was determined by weighing after samples were taken from the baking kiln, then volume was obtained from the measured dimensions of the final samples also taken from the baking kiln. It can be noted here that the high plasticity of the samples at the beginning of their preparation, the specifications of the clay material, and the mixing with other materials such as sawdust and slag, in varying proportions, have influenced the dimensions of the bricks during drying and baking in the kiln. These dimensions have reduced on all three sides, meaning the dimensions of the samples shrink by 1.5cm to 2cm. This is a result of the high plasticity property of the clay during the initial preparation of the samples. Additionally, external weather conditions to which the samples were exposed during drying have also influenced the material shrinkage, such as exposure to sunlight angles in different samples, different air flow conditions in different samples, and water percentage.

Fig. 3. Wooden mold

Fig. 4. The equipment used for mixing the samples

Fig. 5. Mixing the ingredients

Fig. 6. Samples of bricks after pulling from the moulds

Fig. 7. Sample after 2 weeks, subjected to air flow in outdoor environmental conditions, specimens were protected from rain as they were covered at the top.

Table. 2. Specifications of samples with mixed materials

	Sample mark	Clay %	Wood saw dust (sawdust) %	Slag %	Mass [gr]	Volume [cm^3]	Density [kg/m^3]
1	19-1	78	12	10	3941	297.7	1.323
2	19-2	78	12	10	3910	297.7	1.313
3	19-3	78	12	10	4092	305.0	1.341
4	22-1	73	12	15	4425	307.0	1.441
5	22-2	73	12	15	4455	307.0	1.451
6	22-3	73	12	15	4442	307.0	1.446
7	25-1	68	12	20	4427	307.0	1.442
8	25-2	68	12	20	4726	307.0	1.539
9	25-3	68	12	20	4452	297.7	1.495

3 Laboratory research

After being extracted from the factory, the samples are sent to the laboratory of the Faculty of Civil Engineering in Skopje for testing of the thermal conductivity, Fig.8. The samples sent for testing consist of three sets in total, each set containing three samples for testing, making a total of 9 samples. These samples are designated as "19", "22", and "25". These designations stem from the number of samples worked and tested in the workshop until a compact, solid mass of the product is achieved, without cracks or other issues in their external physical structure. One of the reasons for choosing these combinations for thermal testing is because these samples have shown average results in freezing/thawing and water absorption tests compared to other samples tested in the mentioned characteristics.

After being sent to the laboratory of the Faculty of Civil Engineering in Skopje, the bricks underwent thermal testing Fig.9. The apparatus utilized for the thermal experiment is known as the Heat Flow Meter HFM 436 [9] , which generates data in accordance with the standards set forth by ASTM C518 [10], ISO 8301 [11], and DIN EN 12667 [12].

Fig. 8. Samples in the laboratory, waiting for testing

The materials that can be tested on this apparatus can vary, ranging from materials such as vacuum, insulation panels, polystyrene, fibreboards, oils, fibre insulation, wood, polymers and other thermal insulation materials with thermal conductivity not greater than 0.5 W/m·K.

Fig. 9. Heat flow meter HFM 436

Instrument "Heat Flow Meter HFM 436" operates within the following work system: a sample measuring 30x30x2cm is placed within the internal space of the instrument. Following closure through software commands and digital instructions, the heat flux begins to pass from the upper plate through the sample to the lower plate, which is connected to the cooling system Fig.10. After a specific time interval, typically ranging from one and a half to three hours, depending on the stabilization of the λ value (W/m·K), these conductivity values are recorded in the Q-Lab program.

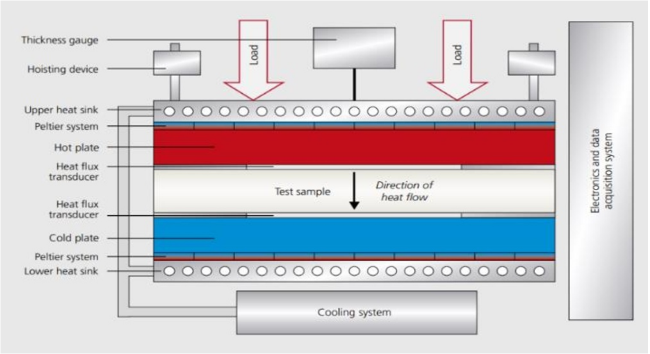


Fig. 10. Schematic design of the HFM 436/3/1 Lambda. Source [9]

The three sets of samples subjected to thermal testing in Laboratory labelled "19", "22" and "25", exhibit specific proportions of admixtures comprising clay, sawdust, and slag.

The thermal conductivity λ (W/m·K) varies from λ = 0.14 (W/m·K) to λ = 0.18 (W/m·K). These acquired values were generated over a time interval ranging from one and a half hours to three hours. From the results obtained, it is observed that the generation time of thermal conductivity varies in this affects the density of the material, the percentage of mixed materials in it as well as equipment as how it manages to generate and consume the temperature from other supplying equipment. The following data are presented in the table 3:

Table. 3. The data generated by the flow meter HFM 436

	Sample mark	Density [kg/m^3]	Thermal conductivity (W/m·K)	Time for testing
1	19-1	1.323	0.1592	02:08
2	19-2	1.313	0.1446	01:09
3	19-3	1.341	0.1400	01:34
4	22-1	1.441	0.1581	02:51
5	22-2	1.451	0.1543	02:56
6	22-3	1.446	0.1421	02:43
7	25-1	1.442	0.1468	01:46
8	25-2	1.539	0.1816	02:34
9	25-3	1.495	0.1674	02:34

The generated data directly from the software for Sample "19" is presented in Figures 11,12,13, and the same technique has been applied to the other tested.

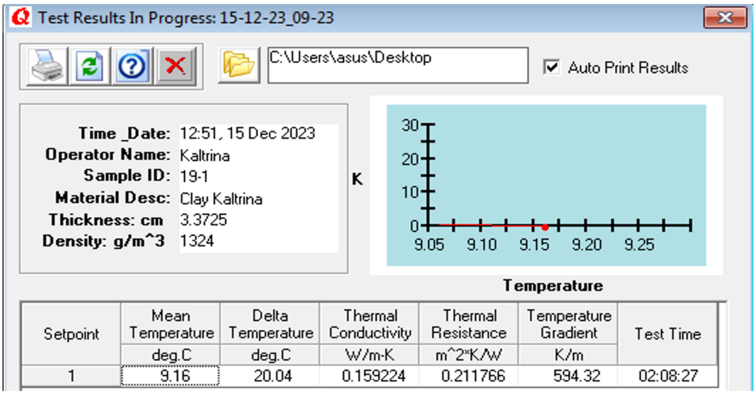


Fig. 11. Output results generated with the software

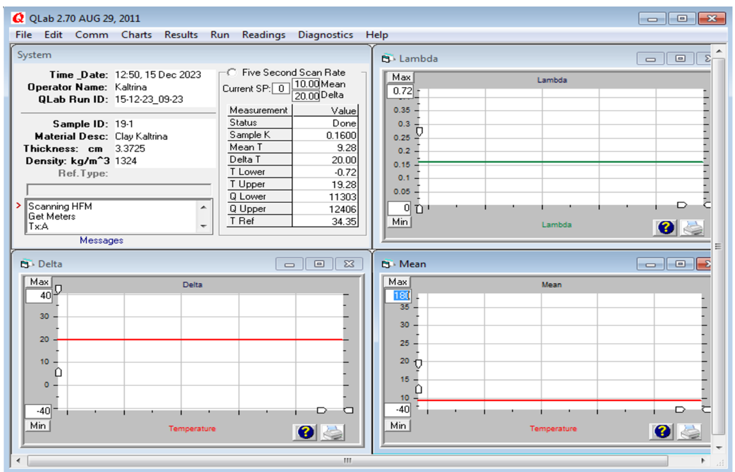
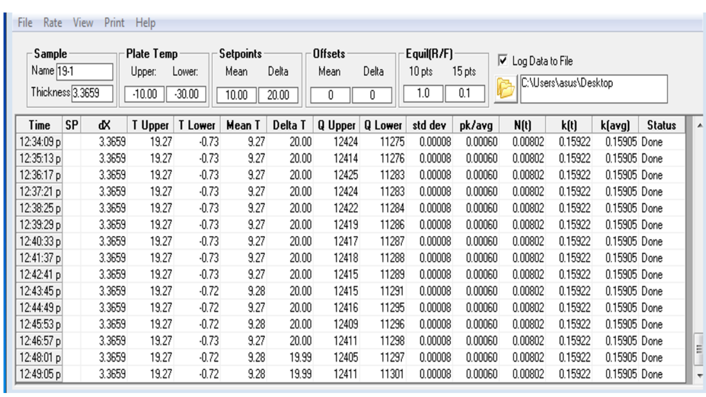


Fig.12. Values generated with the software



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Sample: Name 19-1; Thickness 3.3659 — Plate Temp: Upper -10.00, Lower -30.00 — Setpoints: Mean 10.00, Delta 20.00 — Offsets: Mean 0, Delta 0 — Equil(R/F): 10 pts 1.0, 15 pts 0.1 — Log Data to File: C:\Users\asus\Desktop

Time	SP	dX	T Upper	T Lower	Mean T	Delta T	Q Upper	Q Lower	std dev	pk/avg	N(t)	k(t)	k(avg)	Status
12:34:09 p		3.3659	19.27	-0.73	9.27	20.00	12424	11275	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:35:13 p		3.3659	19.27	-0.73	9.27	20.00	12414	11276	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:36:17 p		3.3659	19.27	-0.73	9.27	20.00	12425	11283	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:37:21 p		3.3659	19.27	-0.73	9.27	20.00	12424	11283	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:38:25 p		3.3659	19.27	-0.73	9.27	20.00	12422	11284	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:39:29 p		3.3659	19.27	-0.73	9.27	20.00	12419	11286	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:40:33 p		3.3659	19.27	-0.73	9.27	20.00	12417	11287	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:41:37 p		3.3659	19.27	-0.73	9.27	20.00	12418	11288	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:42:41 p		3.3659	19.27	-0.73	9.27	20.00	12415	11289	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:43:45 p		3.3659	19.27	-0.72	9.28	20.00	12415	11291	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:44:49 p		3.3659	19.27	-0.72	9.27	20.00	12416	11295	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:45:53 p		3.3659	19.27	-0.72	9.28	20.00	12409	11296	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:46:57 p		3.3659	19.27	-0.73	9.27	20.00	12411	11298	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:48:01 p		3.3659	19.27	-0.72	9.28	19.99	12405	11297	0.00008	0.00060	0.00802	0.15922	0.15905	Done
12:49:05 p		3.3659	19.27	-0.72	9.28	19.99	12411	11301	0.00008	0.00060	0.00802	0.15922	0.15905	Done

Fig.13. Values generated with the software

4 Analysis of the results

The results of the testing of three different clay mixtures, with the slag varying between 10%, 15% and 20%, regarding the thermal conductivity λ (W/m·K), are shown in the figures 14, 15 and 16. Figure 14 presents the results for the recipe “19” with slag of 10%, Figure 15 shows the thermal conductivity values for the three sampes of the recipe “22” with 15% slag. The thermal conductivity for the mixture “25” with 20% slag is presented in Figure 16.

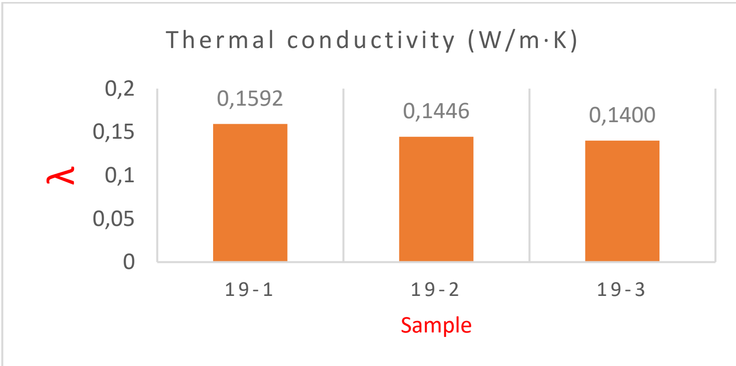

Fig.14. Thermal conductivity for clay samples of group “19”

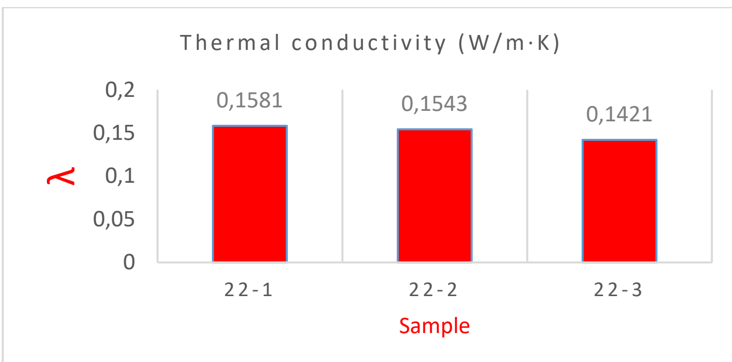

Fig.15. Thermal conductivity for clay samples of group “22”

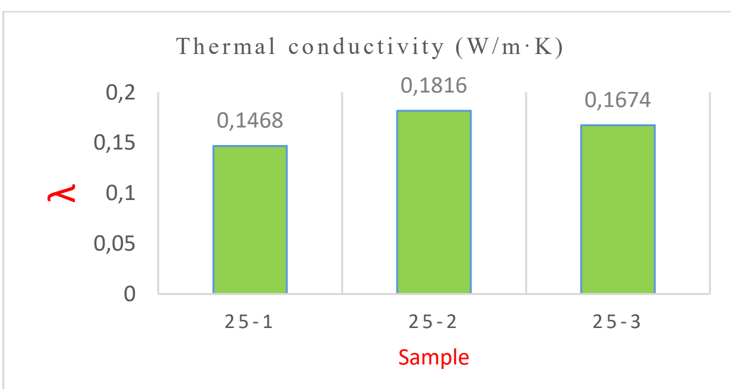

Fig.16. Thermal conductivity for clay samples of group “25”

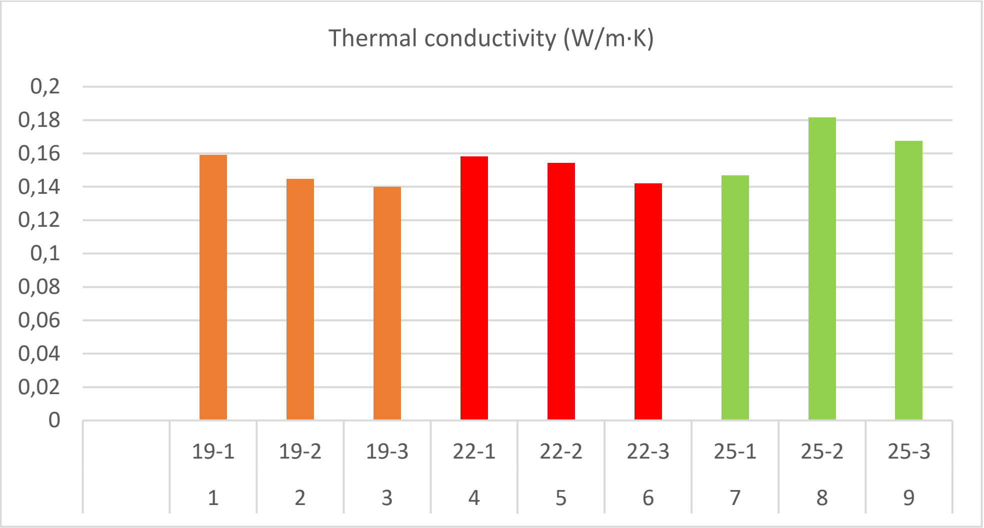

Fig.17. Comparison of the thermal conductivity for clay samples of groups “19”, “22”, “25”

The comparison of these thermal conductivity results for the samples is shown in Fig. 17. Based on these results, it can be stated that the average value of the thermal conductivity λ (W/m·K) of sample "19" is the best thermal value compared to the values of other samples; this value is λ=0.1515 W/m·K.

The average value of the coefficient of sample "19" compared to the thermal coefficient of ordinary clay, which is 0.82 W/m·K [13], shows a significant difference. The Figure 18 presents the nine samples with their thermal conductivity λ in relation to the density. The samples with lower average density exibit lower thermal conductivity.

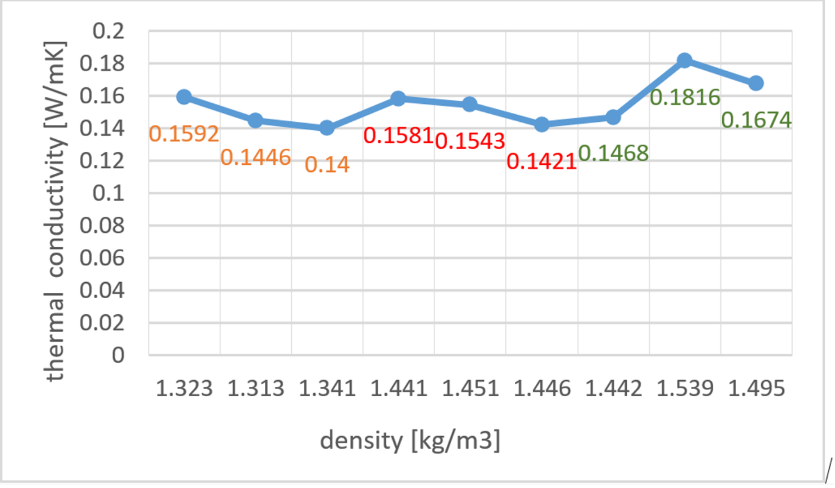

Fig.18. Relation between thermal conductivity and density for 9 samples.

5 Conclusion

The thermal conductivity of three different ceramic mixtures was tested, varying the mixture of the clay, slag and sawdust in the laboratory of the Faculty of Civil Engineering in Skopje. A total of 9 samples of 3 different clay mixtures were examined.

The results presented in this study reveal that for recipe "19", which contains the lowest amount of slag, only 10%, the average thermal conductivity is λ = 0.148 W/m·K. This value is lower compared to other two recipes, such as "22" with 15% of slag and λ = 0.1515 W/m·K and recipe "25" with 20% of slag and λ = 0.1653 W/m·K. However, all the three mixtures of the proposed new clay material shows a significant difference thermal conductivity in comparison to the ordinary clay bricks found in the market (λ = 0.84 W/m·K).

These results may signify progress in advancing existing materials commonly used in contemporary building insulation, as well as in other structural positions within the construction. On the other hand, waste slag from the metal industry and the sawdust from the wood industry obtain a new opportunity for reuse, instead of filling landfills with waste.

Simultaneously, a composite product incorporating bio-based and recyclable materials promises a brighter future in building insulation, contributing to sustainable architecture, indoor comfort, and harmonization with nature. Such materials with these mixtures, during this research period, has also undergone measurements and other specifications regarding stability and strength resistance, which are part of other studies for this product. These results have shown promising values for use in the building facades.

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