THERMAL PROPERTIES OF SUSTAINABLE CEMENT COMPOSITES WITH STRAW

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Energy efficiency, energy saving, recycling and reuse of materials and reducing the harmful impact of buildings on the environment, influence the idea of implementing composites that include ecological matrixes in daily construction operations, using natural or recycled materials. Straw is a widely available by-product of agricultural activity. By recognizing the properties of the straw, as well as other agro-waste materials, a new dimension is given to the thermal insulation of buildings. Furthermore, the building becomes highly efficient, sustainable and with lower costs.

Standardized samples of cement composites were tested and analysed, with partial replacement of the first fraction of the aggregate with straw in the range of 5%, 10%, 20% and 50%, with emphasis on the thermal properties. Thermal conductivity decreases with an increase in the percentage of straw in the cement composite. The average value for thermal conductivity for all samples is 0.310 W/m·K. The recipe with a share of 20% straw as a substitute for the smallest aggregate, proved to be the most suitable recipe, which also showed good mechanical properties. Its thermal conductivity is λ = 0.223 W/m·K, that is about 10 times lower than the thermal conductivity of ordinary concrete. However, with an increase in the percentage of straw, the compressive strength decreases. Therefore, the application of this type of material is limited to non-bearing structural elements.

Keywords: thermal conductivity, agro concrete, straw, sustainability

1. INTRODUCTION

The research activity nowadays is significantly directed towards the study of lightweight composites using plant materials instead of cement or aggregate. In this way, building materials and construction products are obtained that are characterized by lower density and lower thermal conductivity. Natural organic products have great potential to mitigate the carbon footprint left by conventional materials such as concrete, steel, polymers and ceramics during their production and processing, recognizing straw as one of the most significant substitutes, due to its wide availability as a by-product of the large agricultural activity at the local and global level. It has been proven in many studies that thermal insulation materials based on natural fibres have competitive thermal properties, such as heat capacity or thermal conductivity, compared to traditional thermal insulation materials.

One of the characteristics of sustainable and green buildings is the application of strategies based on technologies that favour the conservation of water, energy, and materials. These strategies include the use of energy-efficient equipment, alternative energy sources and low-energy materials. The second approach refers to the development of building materials from agro-waste. Using agro-waste to develop building materials reduces the pollution generated in the construction industry and helps to deal with waste disposal, which burdens the agricultural industry.

The aggregate is about 60-80% of the volume of the concrete; therefore, such enormous requirements attract attention and preservation of the natural aggregates, which are subject of serious concern. Straw, sugarcane bagasse ash, rice husk, cane, sawdust, peanut shell, oyster shell, tobacco waste, palm oil ash, coconut shell, etc. are part of the agricultural waste (or bio-waste in general) that can be used as a partial or full replacement of the aggregate in the concrete mix, and has been processed in many scientific studies. Studies by Chennakesava Rao & Prabath [1], Rahim et al. [2], Petkova-Slipets et al. [3], Shea et al. [4] are some of them.

2. MATERIALS AND METHODS

1.1 SUSTAINABLE STRAW

Straw is one of the oldest and most used materials for construction, the application of which remains current even today. This is a result of its wide availability, cost-effectiveness, sustainability and low carbon footprint. Straw is a material with low density and low thermal conductivity, thanks to its porous internal structure.

Usually, natural materials, classified as agro-waste, have a lower value of the thermal conductivity λ, unlike traditional materials.

The direction of stretching of the straw fibers in relation to the heat flow, in certain construction applications, such as straw bales, also has a great influence on the value of the thermal conductivity. The German national organization for building with straw bales FASBA [5], based on a series of researches, presents a value of λ = 0.080 W/m·K when the fibres are placed parallel to the heat flow and λ = 0.043 W/m·K when the fibres are placed perpendicularly, Fig. 1. When the fibres are placed normally, the heat flow trajectory increases, i.e. the thermal conductivity decreases.

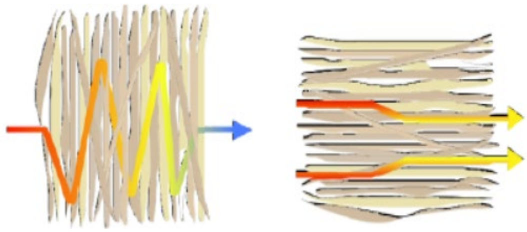

Figure 1. Heat flow in relation to the straw fibres orientation: a) perpendicular, b) parallel (FASBA [5])

1.2 SAMPLE PREPARATION

Testing the thermal properties of the cement composite with straw admixture implied preparation of 3 samples for each of the formulations, in which volume replacement was performed at 5%, 10%, 20% and 50% respectively of the volume of the aggregate (fraction 0-4 mm) with straw. Thermal properties were investigated on samples with dimensions at its base of 300 mm x 300 mm. They were kept in the laboratory for 28 days under standard conditions, until the composite hardens completely [6]. The main goal is to investigate the influence of the different percentage of straw on the thermal properties of this type of composite.

All materials used in the experimental research are in accordance with the current standard for concrete production and definition of concrete as a construction product MKS EN 206. Cement type CEM I 52.5 R was used as a binder. It is pure Portland cement with a small addition of gypsum to regulate setting time and up to 5% other mineral additives. It is characterized by high strength characteristics (in the early and late stages), but also by a relatively high heat of hydration. The aggregate used is with a maximum grain diameter of 16 mm obtained in the production facility, Govrlevo limestone mine.

Natural rice straw is taken as waste from a processing plant. It was cut into small pieces of no specific length, stored in a dry state and in a room with low humidity, Fig. 2. In general, straw as a material contains large amounts of cellulose, hemicellulose and lignin. This research was conducted with chemically untreated straw, even though many researchers recommend treating the straw with chemical solutions, in order to reduce the problems connected to hydration and hardening of the cement. The amount of water was defined during the mixing itself in order to obtain a homogeneous mixture.

Figure 2. Straw and preparation of samples

Figure 3. Fresh concrete samples for testing thermal conductivity

1.3 MEASUREMENT OF THERMAL CONDUCTIVITY

Testing of the thermal properties of the cement composites was performed in the Laboratory of the Faculty of Civil Engineering in Skopje. The Heat flow meter (HFM) instrument, Fig. 4, was used to measure the thermal conductivity λ of the samples that are subject of this research. Its temperature range ranges from -20 °C to +100 °C, and 0.5 W/m·K is the maximum thermal conductivity it can measure.

The heat flow measurement method is a standardized test technique. The following standards were used: MKS ISO 8301:2016 [7], MKS EN 12667:2009 [8] and MKS EN 12939:2009 [9].

Actually, the sample is placed between a hot and cold plate, then a temperature gradient is applied and the heat flow through the sample is measured, [10]. Already calibrated heat flux sensors measure the heat flux (q) of the test sample. Since the two plates of the instrument are set at different temperatures, the test ends after thermal equilibrium has been established in the sample, i.e., after heat transfer has ended.

Figure 4. Instrument HFM

The heat flux q (W/m^2) is the rate of heat transfer in the x direction per unit area and is proportional to the temperature gradient ($\Delta T/\Delta x$) in this direction. The proportionality constant is the heat transfer property of the material, known as thermal conductivity.

$$q = -\lambda \frac{\Delta T}{\Delta x} \tag{1}$$

3. RESULTS

The samples with 5% straw are with different densities of 1989, 1905 and 1950 kg/m^3, respectively, as shown in Table 1. To determine the thermal conductivity, two of these samples were examined, however, the examination did not converge to a constant value for both. Actually, they showed a thermal conductivity greater than 0.5 W/m·K, which is the upper limit of the measurement equipment.

Three samples were also made from the second mixture, for which volume replacement was performed from the first fraction of the aggregate (0-4 mm) with 10% straw. The measured thickness of the samples is 6.5 cm for the first sample and 5.5 cm for the other two. The density differs for all three samples: 1758 kg/m^3, 1583 kg/m^3 and 1758 kg/m^3, respectively. Figure 5 shows the comparison of the obtained results for the thermal conductivity (λ) for all three samples with a percentage of straw of 10% and their mean value was calculated.

The obtained value of the thermal conductivity does not have a large variation among the three samples with 10 % straw. The calculated mean value for $\lambda_{10\%}$ is 0.441 W/m·K.

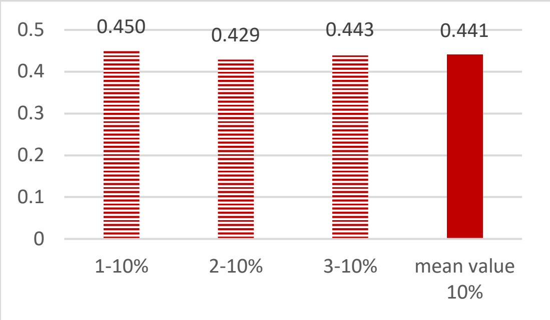

Figure 5. λ for samples with 10% straw

The measured densities for the series of examined samples with 20% of straw are 1288 kg/m^3, 1322 kg/m^3 and 1419 kg/m^3, respectively. The thicknesses of the samples are 5.2 cm, 5.4 cm and 4.5 cm. Figure 6 shows the results obtained for the samples where the aggregate was replaced with 20% straw.

The calculated mean value for the thermal conductivity is $\lambda_{20\%}$ = 0.223 W/m·K. The average temperature during examination of the samples is 20.53 °C, and the average value of the temperature difference between the two plates of the instrument is 19.56 °C. The average value for the thermal resistance *R* for the three samples is 0.2407 m^2/W·K.

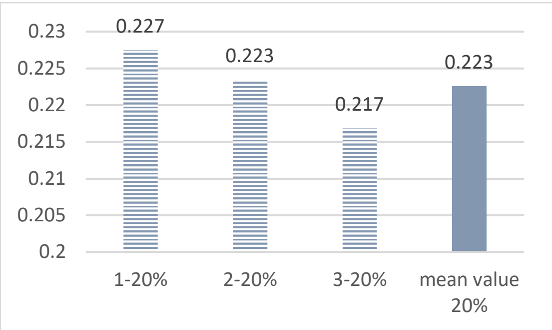

Figure 6. λ for samples with 20% straw

For testing the thermal characteristics in which straw replaces half of the aggregate volume or 50%, three samples were also prepared, but two of them experienced failure due to their own weight as a result of the inhomogeneity of the prepared mixture. The thermal conductivity, however, was investigated on the remained one sample (Figure 7), in order to make a comparison with the other samples in terms of how the percentage of straw affects the cement composites. The thickness of this sample is 6 cm, and the calculated density compared to other samples is the smallest: 1142 kg/m^3.

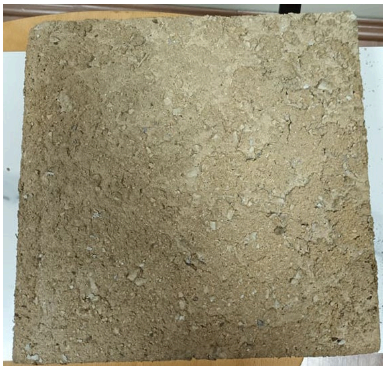

Figure 7. Sample with 50% straw

The test results are shown in Figure 8. The obtained thermal conductivity is λ = 0.1833 W/m·K, while the thermal resistance *R* is 0.567 m^{2}K/W.

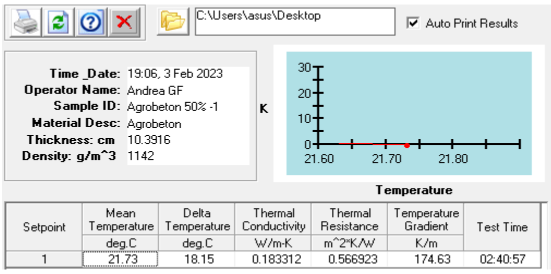

Figure 8. Results for the sample with 50% straw

4. ANALYSIS OF THE RESULTS

The obtained results for the thermal conductivity for all tested samples are shown in summary in Table 1 and in Figure 9.

Table 1. Density and thermal conductivity for all samples

sample	participation of straw [%]	density [kg/m^3]	thermal conductivity [W/m·K]
5% - 1	5%	1989	> 0.5
5% - 2	5%	1905	> 0.5
5% - 3	5%	1950	> 0.5
10% - 1	10%	1602	0.450085
10% - 2	10%	1583	0.429384
10% - 3	10%	1758	0.442659
20% - 1	20%	1288	0.227459
20% - 2	20%	1322	0.223422
20% - 3	20%	1419	0.216817
50% - 1	50%	1142	0.183314

In the research carried out and the results shown, the different percentage participation of straw in the creation of the cement composite affects the value of its thermal conductivity. The obtained results show that the lowest value of λ occurs in the tested sample with 50% straw, and the highest value occurs in sample 1 in which replacement is made with 10% straw. Increasing the percentage of straw decreases the thermal conductivity. Namely, the calculated mean value for λ for the samples with a share of only 10% straw as a substitute for the smallest aggregate is 0.441 W/m·K. The calculated mean value for the thermal conductivity for the samples with 20% straw, on the other hand, is λ = 0.223 W/m·K. The double share of straw gives almost twice lower thermal conductivity for the cement composite. This is due to the excellent thermal characteristics of straw.

The participation of 50% straw as a substitute for aggregate in the first fraction led to a decrease in the thermal conductivity to a value of 0.183 W/m·K. However, from the point of view of load-bearing capacity and durability, the sample with 50% straw does not show any strength characteristics, so its further application should be limited or subjected to further tests.

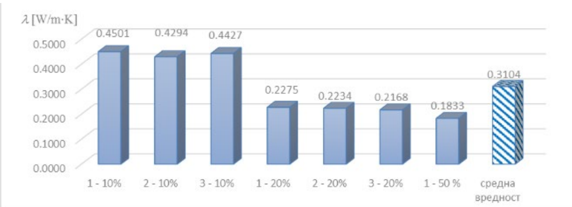

Figure 9. Thermal conductivity for all tested samples

Figure 9 also shows that for the samples in which the same percentage replacement of straw is carried out, the thermal conductivity values do not have a large variation. The mean value obtained from all seven samples is $\lambda = 0.310$ W/m·K.

The density of the material is one of the main factors affecting thermal conductivity. Increasing the percentage of straw decreases the density of the samples. The sample with 50% straw has the lowest measured density of 1142 kg/m^3. This is expected, knowing the porous structure of straw.

In this study, no directly proportional dependence between the thermal conductivity and density was established. Although it can be concluded that it is a very small difference in the densities, unlike the percentage of straw, it has no practical effect on the thermal conductivity, which may be due to the inhomogeneity of the material. However, Fig. 10 shows that the increase in density gives a general trend of increasing the thermal conductivity.

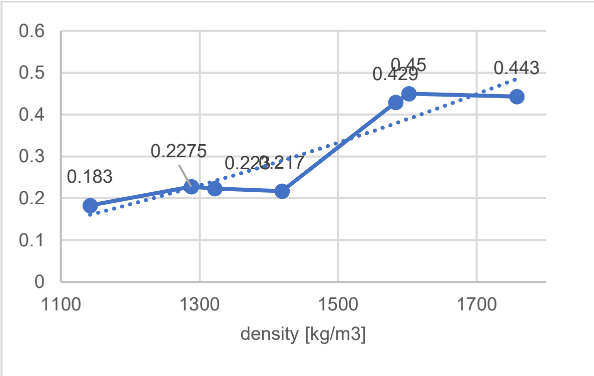

Figure 10. Thermal conductivity [W/mK] versus density

Finally, the cement composite that is subject of this research shows much lower thermal conductivity compared to traditional building materials. For comparison, concrete has a thermal conductivity of 2.0 – 2.5 W/m·K, and for reinforced concrete the value reaches up to 3.2 W/m·K. According to some research, increasing the percentage of reinforcement affects its value, because steel is characterized as a material with high thermal conductivity.

5. CONCLUSIONS

In this paper, the thermal properties of sustainable agro-concrete with the participation of straw, the most widely available agricultural by-product in our area, have been elaborated. Different mixtures of cement composite were tested in which the volume of the first fraction of the aggregate was partially replaced with 5%, 10%, 20% and 50% straw. The experimental test was performed according to a standardized procedure, with the instrument Heat Flow Meter.

From the obtained results, it can be concluded that the thermal properties of this composite are much better than traditional construction concrete. The thermal conductivity decreases with an increase in the percentage of straw in the cement composite. The average value for the thermal conductivity for all samples is 0.310 W/m·K. As the most appropriate recipe, which showed good mechanical properties also, the recipe with a participation of 20% straw as a substitute for the smallest aggregate is chosen. Its average thermal conductivity is λ = 0.223 W/m·K. The favourable heat-insulating characteristics are mostly due to the porous structure of the straw.

On the other hand, as the percentage of straw increases, the strength decreases. Therefore, the recommendation is that this type of material should be limited to non-bearing structural elements. The application of this composite would be most acceptable in infill blocks in partition and facade walls, in order to make the most of its potential for good thermal insulation.

The general conclusion that can be drawn from the presented paper is that the cement composite with a percentage of straw shows excellent thermal properties and justifies the use of straw in buildings construction. This type of cement composite has competence and potential for application in everyday construction practice, and considering that straw is a widely available by-product at a low price, it can show high competitiveness in the market of insulation materials. At the same time, cement composites that incorporate renewable resources such as straw into their matrix will generate a positive footprint on the environment and help eradicate the negative impact that the construction industry has had so far.

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