Thermal conductivity of geopolymer concrete with different types of aggregate

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Abstract. In this article the influence of aggregate of geopolymer concrete used in concrete printing of buildings and structures, architectural elements on its thermal conductivity is studied. All tests were conducted on device for measuring thermal conductivity called PIT-2 designed to measure the thermal conductivity of building and heat-insulating materials under stationary thermal conditions in accordance with ISO 7345:1987* and ISO 9251:1987. As the fine aggregate most commonly used river sand, quartz sand, ceramic foam, as well as one new coniferous shavings were taken. The results of 4 tests to determine the thermal conductivity of geopolymer concrete with various aggregates are listed in the summary table in the study. According to the test results, the lowest coefficient of thermal conductivity has geopolymer concrete on ceramic foam. In this study geopolymer concrete is considered as the main material for concrete printing of the houses and architectural forms. This material reduces CO2 emissions in the atmosphere.

1. Introduction
The necessity of reliable building materials is greatly increasing nowadays. Currently, one of the durable and most widely used material is Portland cement concrete (PCC). Its manufacturing technology was invented in 19 century and PCC is applied in construction for decades. However, there are sharp debates about the influence of PCC production on the environment [1]. The total energy consumption is critically increasing all over the world. It is highly connected with building energy consumption and, evidently, significant part of this energy is used for heating and cooling purposes [2]. A great number of recent research studies are dedicated to reduction of energy consumption, pollution in all industrial enterprises, in global manufacturing processes and to application of alternative cementitious eco-friendly materials with less energy consumption [3]. Manufacture of PCC has a disastrous effect on the environment. Production of Portland cement lead to the CO2 emission, which contributes to about 5–8% of the total CO2 emissions, and is the third man-made CO2 source after transport and energy generation [4]. Obviously, PCC has beneficial properties, such as low thermal conductivity, high specific heat capacity, high density, and high mechanical strength. Nevertheless, PCC exhibits a negative effect on the environment due to the emission of carbon dioxide (CO2) and a great amount of energy consumption during the production of cement, that is why it is vital to think about innovative and environmentally friendly material [5-13]. Geopolymer concrete (GPC) is an innovative building material that is applied in construction and 3D printing. The
composition of GPC includes components based on natural raw materials, for instance, kaolinite and clay, as well as substances based on recyclable materials that are considered to be industrial waste. Geopolymer is synthesized by alkali activation of materials rich in silica and alumina (from industrial waste materials such as fly ash, coal ash, rice-husk ash, red, mud and ground granulated blast furnace slag [14-24]. Geopolymer can be used as an alternative binder for concrete to decrease carbon dioxide emissions. Moreover, high pressures or temperatures are not required for production of GPC during which there are no dust wastes, while there are dust wastes during manufacturing of PCC from raw material factories, kilns, clinker refrigerators, cement mills. GPC has a great number of advantages over PCC such as high initial strength, small drying shrinkage, high fire resistance, superior acid resistance, shorter setting time, better thermal performances. Therefore, phase change materials can be integrated in GPC to reduce indoor temperature fluctuations, maintain thermal comfort, and minimize the peak of the cooling and heating loads [5-9,18-24].

Low thermal conductivity means good thermal insulation, and, hence, energy efficiency in operation. The thermal conductivity of concrete largely depends on the type of aggregate that is used. Apparently, lightweight concrete has less thermal conductivity by reason of density reduction and porosity increase, pores are filled with air that is considered to be a good heat insulator, that’s why lightweight concrete is suitable for construction of exterior walls. Thus, lightweight concrete blocks have been widely used around the world due to its low unit weight, high thermal insulation, and good freeze/thaw stability [24-27]. River sand, quartz sand, ceramic foam, coniferous shavings were chosen as aggregates due to their diverse weight, density and different coefficient of thermal conductivity. This study is focused on the lab scale experiment by mixing geopolymer cement, geosilicate with different fine aggregates. In this research the thermal conductivity of 3 GPC specimens were determined and compared.

The purpose of this study is to compare the thermal conductivity of geopolymer concrete with commonly used aggregates (river sand, quartz sand, ceramic foam) and new one (coniferous shavings) and define suitable aggregates for geopolymer matrix.

To achieve this goal it is necessary to solve the following tasks:
1. Prepare samples of geopolymer concrete with various aggregates;
2. To test samples on the installation of PIT-2.1;
3. Compare the values of the thermal conductivity of the samples.

2. Methods

2.1. Materials
To conduct the experiment with GPC 4 samples were prepared. The dimension of each concrete sample was 30x250x250mm. Mix proportions for GPC are shown in the table 1.

| Component          | Sample 1      | Sample 2    | Sample 3      | Sample 4      |
|--------------------|---------------|-------------|---------------|---------------|
| Fine aggregate,    | Quartz sand,  | Ker-wood    | Quartz sand,  | Coniferous    |
| kg                 | 2.871         | 0.375       | 1.435         | shavings,     |
|                    |               | Cera-mic    | River sand,   | 0.700         |
|                    |               | foam,       | 1.435         |               |
|                    |               | 0.375       |               |               |
| Geosilicate, kg    | 0.754         | 0.700       | 0.754         | 0.700         |
| Geopolymer cement, | 2.175         | 1.100       | 2.175         | 1.000         |
| kg                 |               |             |               |               |
| Density, kg/m³     | 1981          | 952         | 1900          | 1180          |
After mixing 4 samples of GPC, they were filled in the molds designed for samples with dimension 30x250x250 mm. 3 hours later samples were extracted from the molds and put into the drying chamber. After full drying specimens were ready for experiments on PIT-2.1 – thermal conductivity meter.

2.2. Principle of operation of the measuring device

PIT consists of two refrigerators (upper and lower), lower heater (cold plate), protective heater, protective ring, measuring heater, heat insulator (fig. 1).

Refrigerators are designed to provide PIT operation at average sample temperatures below ambient temperature. In the device refrigerators are made on thermoelectric elements Peltier with the possibility of additional cooling due to the flow of liquid. The safety heater and the safety ring are designed to eliminate losses from the measuring device.

The temperature of the security heater and the security ring is maintained at the same temperature measuring heater. The measuring heater is designed to determine the power P required to maintain set temperature difference ∆T between the measuring and lower heaters.

The essence of the method is to create a stationary heat flow passing through a flat sample of a certain thickness and directed perpendicular to the face (largest) faces of the sample, measuring the power required to create this heat flow, the temperature of the opposite face faces and the thickness of the sample. The coefficient of thermal conductivity is determined by the formula (1), where S is the area of the measuring heater and h is the height of the sample.

\[ \lambda = \frac{P \cdot h}{S \cdot \Delta T} \]  

(1)

2.3. Experiment conduction

Before experiment specimens were measured with calipers in four corners at a distance of (50.0 ± 5.0) mm from the top of the corner and in the middle of each side.

PIT-2.1 is designed for one sample. Firstly, specimen was installed in PIT-2.1 between top and bottom plates, after that the meter was turned on. The device display shows: the current thermal conductivity of the sample (in digital and graphical forms), the power P "allocated in the measuring heater, the temperature difference "ΔT" between the measuring and lower heaters, the average temperature of the sample "t" and the thickness of the sample «h». It was necessary also to specify average temperature and thickness of each sample in the meter. The discreteness of changes in the average sample temperature is 0.1 °C, and the sample thickness is 0.1 mm. The discreteness of changes in the average sample temperature is 0.1 °C, and the sample thickness is 0.1 mm.
Experiment lasts 2.5-3 hours for each sample. The device signals the output to stationary mode by changing the sign "≠" to the sign "=" before the number of measured thermal conductivity. For accurate determination of the device's output to the stationary mode a graph of the current thermal conductivity of the sample is displayed on the PIT display.

3. Results and Discussion
Environmentally-friendly geopolymer concrete specimens with same dimensions (30x250x250 mm) and different proportions of geopolymer cement and geosilicate were achieved. Moreover, diverse fine aggregates were used for manufacturing of samples. The humidity of sample has an important impact on the measured thermal conductivity. Thus, all samples were cured at 80 °C in the drying chamber for one month. Experiments were conducted on 4 specimens with various weight and density. The results of the experiments are shown in the table 2. Evidently, coefficient of thermal conductivity directly depends on the type of fine aggregate. Thus, the heavier were the aggregate, the higher thermal conductivity were achieved. The lowest coefficient of thermal conductivity had specimens number 2 and number 4 ($\lambda_2 =0.233; \lambda_4 =0.243$), in which ceramic foam and coniferous shavings respectively were used as a fine aggregate. Such geopolymer concrete are very light and cannot be used as a load-bearing structure without reinforcing. Specimens number 1 and number 3, in which quartz sand and river sand were used, had higher coefficient of thermal conductivity ($\lambda_1 =0.777; \lambda_3 =0.823$). Samples 1 and 3 were heavier and had higher density. Geopolymer concrete with such fine aggregates is suitable for 3D printing and can be applied in construction. Portland cement concrete has coefficient of thermal conductivity within the limits of 0.2 to 1.0 W/m*K (and higher), reinforced concrete has even more coefficient value, results are shown in Table 2.
Figure 3. Achieved samples.

Table 2. The results of the experiments.

|                  | Sample1 | Sample2 | Sample3 | Sample4 |
|------------------|---------|---------|---------|---------|
| Density, kg/m³   | 1981    | 952     | 1900    | 1180    |
| Weight, kg       | 3.714   | 1.784   | 3.860   | 2.212   |
| Coefficient of thermal conductivity, W/m*K | 0.777   | 0.233   | 0.823   | 0.243   |

Thermal conductivity coefficient of porous GPC, which was prepared using fly-ash, water glass and additive amount of sodium water glass and H₂O₂, is 0.0744 W/m*K, its density is 240-335 kg/m³. [5] Comparing such GPC with sample 2 and 4, which are the most porous in current study, it has a lower coefficient of thermal conductivity, however, it has a very low density and compressive strength, which is 0.82MPa [6], and can be applied only as insulation material. The near dried geopolymer foam concrete thermal conductivity coefficients are in range of 0.15 to 0.48 W/m*K and their densities change from 720 to 1600 kg/m³ [6]. Such GPC is similar to sample 2, determined parameters of which (density, thermal conductivity coefficient) are within specified limits. The thermal conductivity coefficient of oil palm shell foamed geopolymer concrete, where low-calcium fly ash and palm oil fuel ash as cementitious materials, and oil palm shell as lightweight coarse aggregate were used, is 0.47 W/m*K, which is lower than coefficients of samples 1 and 3 due to lower density, that was in range of 1300-1700 kg/m³ and higher porosity, that was varied between 25 and 40% [7]. Lightweight geopolymer concrete based on recycled expanded polystyrene as aggregate has coefficient of thermal conductivity in range of 0.121 to 0.207 W/m*K and density in range from 500 to 800 kg/m³ [8], which is lower than prepared specimens. Thermal conductivity coefficients of the materials for the multi-layer walls were determined in [10]. These coefficients are higher than the obtained values. Thus, thermal conductivity coefficient of GPC, which density was 2199 kg/m³, was 1.35 W/m*K. Thermal conductivity coefficient of GPC with microencapsulated phase change materials, which density was 1875 kg/m³, was 0.74 W/m*K. Thermal conductivity coefficient of GPC with pure phase change materials, which density was 825 kg/m³, was 0.2 W/m*K.
4. Conclusion

An experimental investigation on the thermal conductivity of GPC with various types of fine aggregate was presented in this study. From the experimental results, the following conclusions can be drawn:

Conducted experiments have shown that thermal insulation properties of GPC are greatly connected with the type of fine aggregate. Thus, GPC with kerwood, ceramic foam and with coniferous shavings has low coefficients of thermal conductivity 0.233 W/m*K and 0.243 W/m*K relatively, whereas GPC with quartz sand and river sand has higher coefficient value 0.777 W/m*K and 0.823 W/m*K respectively.

The density of prepared samples varied from 952 to 1981 kg/m$^3$ and the low the density is the higher the porosity of the specimen is, the low its compressive strength is. As a result, samples with high density have higher coefficient of thermal conductivity.

Thermal conductivity of GPC meets the building requirements and, apparently, can be improved, that is why the replacement of PCC by GPC in terms of thermal insulation properties is feasible. Eventually, it is clear that there is a necessity to focus on further research using mixtures characterized by different geopolymer cement and geosilicate ratio; by diverse fine aggregates and their proportions in composition and, then, apply achieved and analyzed results in calculation software complexes.

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