Determination of thermal conductivity of backfill

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Abstract. Shallow foundations with thermal insulation can be used in the construction of low-rise buildings. Thermal insulation prevents freezing of soils under the foundation. The article presents the results of determining the thermal conductivity of sand with the addition of crushed brick and concrete rubble. The research was carried out in a specially designed unit, which consists of two climatic chambers connected to each other. The soil sample is maintained into the special cell. Heat flow and temperature sensors are placed in the soil sample. Before soil testing a numerical simulation of laboratory test was implemented in GeoStudio. Due to numerical modelling optimal dimensions of testing cell was defined. Results of laboratory testing of sand with a known thermal conductivity with using designed parameters of cell has a good agreement with calculated value. The test procedure was extended to soils with construction waste. The addition of 20% crushed brick to the sand reduces its thermal conductivity coefficient by 20.6% in the frozen state and by 10.1% in the thawed state. At the same time sand with concrete rubble showed a decrease in the thermal conductivity coefficient in the frozen state by 6.4% and an increase by 13.4% in thaw. The effect is occurred because of the addition of particles of different mineralogical composition with different thermal conductivity. The results of testing can be used in making forecast of the thermal regime of soil stratum when designing shallow foundations.

1. Introduction

Now shallow foundations are spreading in low-rise building. As a rule the foot of shallow foundations is placed below frost front but in some cases when non frost-susceptible soils are bedded under foundations or special conditions are provided to prevent soil freezing below foundations. Special conditions include thermal insulation that keeps the soil temperature above 0 C throughout the year and heating the soil stratum under the foundation. Foundations with thermal insulation made from expanded polystyrene are widely used around the world as a simple and cost-effective solution [1]. Shallow foundations are designed by numerical modeling. Thermal characteristics of insulation and base soils are input as initial data [2].

Backfill soils may include brick and concrete rubble, which can affect the thermal characteristics of the soils [3]. The heat capacity of materials can be determined by calculation when the composition and volume of the brick and concrete rubble are known. Heat transfer in dispersed multicomponent materials is a more difficult process. The purpose of research was the experimental determination of the thermal conductivity coefficient of sand and its mixtures with construction waste.
2. Materials and methods

The thermal conductivity coefficient was determined for the following soils: sand, a mixture of sand with 20% broken ceramic bricks and sand with 20% crushed concrete. The water content of samples was on average 15%, the dry density of soil was 1.68–1.70 g/cm³, the size of the inclusions was no more than 10 mm.

The steady-state method was chosen to determine the thermal conductivity coefficient, which provides for the measurement of the heat flux through the sample and the determination of the temperature difference between the two planes [4]. Traditional devices are designed for soil samples in the form of a disk with a diameter of 120 to 250 mm and a height of 30 mm [5] or in the form of a parallelepiped, the dimensions of which are taken based on the size of inclusions in the soil [6], [7]. It should be noted that the heat flux sensors are placed in these devices at the ends of the samples. The authors offer to place the sensors inside the sample (figure 1a). To check the impact of the sensors on the heat flow and to define the dimensions cell for soil testing numerical simulation was carried out in the GeoStudio software.

The laboratory unit consists of two climatic chambers connected to each other. The soil sample is maintained into the special cell. Heat flux (HFP01) and temperature sensor are placed into the sample (figure 1b). The data from sensors are transmitted in the datalogger. Soil sample is placed between two climatic chambers. Each of the two the ends of the soil sample goes into one of the climatic chambers, in which the set the temperature in chambers is maintained with an accuracy of 0.1..0.3 K. The temperature gradient was 15..20 K/m.

![Figure 1. a – scheme of cell (dimensions in millimeters); b – testing equipment.](image)

The TEMP / W module of the GeoStudio 2012 program was used to simulate the processes of heat transfer and freezing by solving the steady-state heat problem.

The simulated cell has dimensions of 250 × 250 mm and is made of expanded polystyrene with a cylindrical soil sample inside. The diameter and height of the sample were selected to minimize the effect of the heat flow sensor and to get the smallest sample volume. Boundary conditions are applied to the ends of the cell. The heat flux sensor HFP01 has a diameter of 80 mm and a thickness of 5 mm and is placed in equal distance from both ends [7]. The heat flux follow the Fourier law in the software package [9]. Thermal properties of soil and materials are given in Table 1.
Table 1. Thermal properties of sand and materials.

| Parameter | Units | Sand | Insulation (expanded polystyrene) | Sensor (heat flux plate) |
|-----------|-------|------|-----------------------------------|--------------------------|
| Material model | Full Thermal | Simplified Thermal | Simplified Thermal |
| Thermal conductivity of material in: | KJ/m×K×day | (W/m×K) | 207.4 (2.40) | 2.6 (0.03) | 69.1 (0.80) |
| frozen state, $\lambda_f$ | | | 172.8 (2.00) | 2.6 (0.03) | 69.1 (0.80) |
| thawing state, $\lambda_{th}$ | | | | | |
| Volumetric heat capability of material in: | KJ/K×m$^3$ | | 1864 | 48 | 1500 |
| frozen state, $c_{vf}$ | | | 2400 | 48 | 1500 |
| thawing state, $c_{vth}$ | | | | | |
| Volumetric water content, $\theta$ | m$^3$/m$^3$ | | 0.25 | 0 | 0 |

3. Results

The numerical model of the cell and the steady-state heat flux through the sample are presented in Figure 2. The results of modeling the cell with sand showed that the optimal diameter and height of the sample are 150 mm (Figure 3). The impact of the sensor on the results is minimal at designed dimensions. Numerical modeling of laboratory test has significantly reduced the duration of laboratory testing.

Figure 2. a – model of cell; b – heat flow.
The cell for determining the coefficient of thermal conductivity was assembled considering the results of the numerical simulation. A quartz sand sample with a water content of 15% and a dry density of 1.68 g/cm$^3$ was tested to evaluate the laboratory results. The initial temperature of the sample was +20 °C. Then the sample was cooled to temperatures of +1 and +5 °C at the ends. Next the sample was frozen to -3 and -10 °C. The sample was kept at positive and negative temperatures for at least 5 hours after the heat flow had steady state. Heat flux and temperature in the sample at two points were measured every ten minutes during the experiment. The distance between the temperature sensors is 110 mm (Figure 4, the plots show measurements every hour).

The thermal conductivity coefficient was calculated as the ratio of the heat flux to the temperature gradient. The results were evaluated by comparing the test data with the calculated values obtained by various methods. Table 2 shows the test results in comparison with the values obtained by calculation methods. The experimental data are in the ranges of the calculated values.
Table 2. Thermal conductivity of quartz sand.

| Method              | Thermal conductivity, KJ/m×K×day (W/m×K) |
|---------------------|-------------------------------------------|
|                     | frozen sand, $\lambda_f$                  | thawing sand, $\lambda_{th}$ |
| Laboratory test     | 259.0 (3.00)                              | 171.7 (1.99)                  |
| M.Kersten [9]       | 222.5 (2.57)                              | 168.5 (1.95)                  |
| O.Johansen [11]     | 273.4 (3.16)                              | 215.8 (2.50)                  |
| Russian Code [12]   | 203.9 (2.36)                              | 171.4 (1.98)                  |

The thermal conductivity coefficients for samples of different compositions were measured in a similar way. The impact of the cell design on the experimental data was clarified by implementing backward analysis in the GeoStudio program. The thermal conductivity coefficient of the simulated soil was acquired so that the ratio of the heat flux passing through the soil sample with the sensor to the temperature gradient corresponded to the thermal conductivity coefficient determined in laboratory conditions. It was necessary to increase the coefficients by 0.9% for thawed soil and by 1.6% for frozen soil average. The results of laboratory and numerical experiments are presented in Table 3.

Table 3. Thermal conductivity of composite soils according to the results of experiments.

| Parameter | Units | Sand | 80% sand + 20% ceramic brick | 80% sand + 20% concrete |
|-----------|-------|------|-----------------------------|-------------------------|
| Laboratory test: |       |      |                             |                         |
| frozen material, $\lambda_f$ | KJ/m×K×day (W/m×K) | 259.0 (3.00) | 206.7 (2.39) | 243.2 (2.81) |
| thawing material, $\lambda_{th}$ | | 171.7 (1.99) | 154.8 (1.79) | 194.7 (2.25) |
| Improvement by numerical modelling: | | | | |
| frozen material, $\lambda_f$ | | 263.8 (3.05) | 209.3 (2.42) | 246.8 (2.86) |
| thawing material, $\lambda_{th}$ | | 173.4 (2.01) | 155.8 (1.80) | 196.6 (2.28) |

The results of research showed that the presence of construction waste in the sand affects its thermal conductivity. The addition of 20% crushed brick to the sand reduces its thermal conductivity coefficient by 20.6% in the frozen state and by 10.1% in the thawed state. At the same time sand with concrete rubble showed a decrease in the thermal conductivity coefficient in the frozen state by 6.4% and an increase by 13.4% in thaw. The effect is occurred because of particles of different mineralogical composition with different thermal conductivity.

4. Summary

Numerical simulation made it possible to design a cell for a laboratory apparatus. Results of numerical models have a good agreement with laboratory results and empirical expressions. Numerical modeling of laboratory test devices has significantly reduced the duration of laboratory testing.

The research has confirmed that the presence of foreign inclusions in the sand affects its thermal conductivity. The addition of 20% crushed brick to the sand reduces its thermal conductivity coefficient by 20.6% in the frozen state and by 10.1% in the thawed state. At the same time, sand with the addition of concrete rubble showed a decrease in the thermal conductivity coefficient in the frozen state by 6.4% and an increase by 13.4% in thaw. The effect is occurred because of particles of different mineralogical composition with different thermal conductivity.
The results of the research can be used in the design of shallow foundations, in calculating the depth of soil freezing near the foundations and underground utilities, which are backfilled with soil mixed with construction waste.

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