Research Article

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Compressive strength and thermal properties of sand–bentonite mixture

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Abstract: Sand–bentonite mixtures are used in road embankments as a protective material for protecting underground high-voltage cables and utility pipelines supplying water and gas etc. The sand–bentonite mixtures provide benefits while laying high-voltage cables. The purpose of this study is to determine the proportions as well as mechanical and thermal properties of a dry-mixed sand–bentonite mixture and to investigate the suitability of such mixtures for installation around high-voltage underground power lines in road embankments. When selecting a sand–bentonite mixture, the following requirements must be ensured: the compressive strength must be greater than 0.5 MPa after 24 h; the thermal resistivity must be greater than 1.2 K m/W (thermal conductivity 0,833 W/(K m)); and the moisture content of the sand–bentonite mixture must be less than 13%. The following materials were used when selecting the bentonite mixture: bentonite, 0–4.0 mm fraction sand, cement (CEM I 42.5R), and water. In this study, six groups of samples were formed, in which the parts of concrete, sand, cement, and water were added in different proportions. The strength and thermal conductivity of the samples were analyzed. Studies about the use of bentonite around high-voltage cables have revealed the need for wet mixing of bentonite suspensions. The required thermal conductivity properties of the soil were not achieved by dry mixing. This method of mixing can be useful only in cases when the thermal conductivity of the mixed soil is not relevant, because the work can be continued after a day.

Keywords: sand–bentonite mixture, compressive strength, thermal properties, uniaxial compression, thermal conductivity, bentonite, thermal resistivity

1 Introduction

Usually, road embankments are equipped for the possible laying of underground electricity cable lines, water, gas, or other supply pipelines [1,2]. The installation of underground cable lines under the road embankment is a rational use of space [3]. To protect underground cable lines from road loads, reinforced concrete U profiles can be installed or cables can be laid by enclosing them with a special layer of liquid soil, which is called controlled low-strength material (CLSM) [4]. Liquid soil is the result of the application of an innovative process, which is characterized by the fact that the on-site excavated soil with natural additives is temporarily made flowable in a mixing plant and returned to the excavation pit. The liquid soil can be processed quickly and easily. It encloses pipes and lines without cavities and does not need to be compacted. However, the protective liquid soil layer (flowability >200 mm spread), which later hardens within 28 days, acquires the necessary properties: mechanical strength (sufficient strength ≥0.5 MPa according to ref. [5]) and thermal conductivity (less than or equal to 1.2 K m/W according to ref. [6]). Mechanical strength and thermal conductivity parameters are relevant to ensure the successful maintenance of the underground cable line in the road embankment [7]. Also, the dry protective soil layer can be applied, in which case the mixture must acquire the required mechanical properties within a day. Dry-mixed mixture means that the water content is intended for binder activation and the prepared mixture is nonplastic without any flowability (Figure 2). The main difference is that such a mixture needs to be compacted [8], and there

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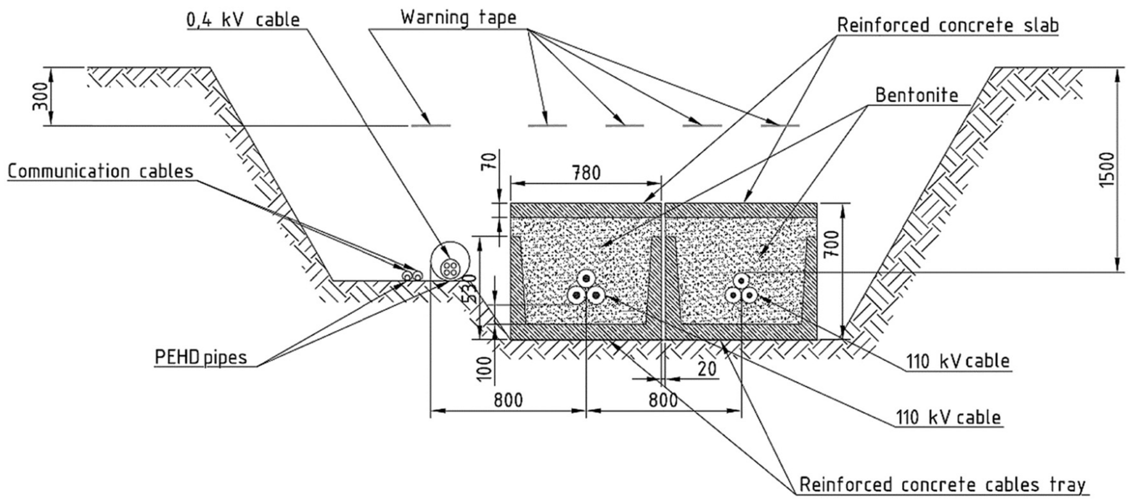

Figure 1: Cross-section of underground power line cable installation.

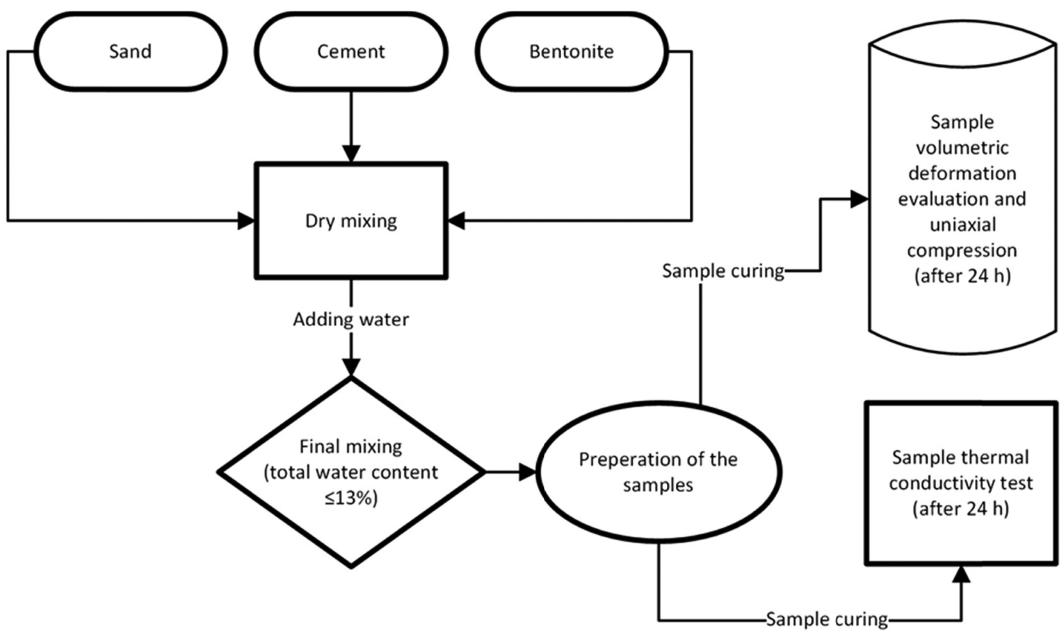

Figure 2: Flowchart of research program.

is no necessity to use flexible combination shaft system as in the CLSM method. Also, as per the CLSM method, during the installation of cable lines and/or water, gas, or other supply lines, temporary position fixing elements must be used to avoid the floating of pipes and lines. For dry-mixed mixtures the following materials are most commonly used: sand, water, clay, bentonite, and cement [9–12]. Sand–bentonite mixtures are used in road embankments as a protective material to protect underground utility cables and pipelines. This is beneficial while laying high-voltage cables [7]. Due to the abovementioned properties of bentonite mixtures, i.e., low thermal resistance, these mixtures have good thermal interaction with cables and provide a stable basis for underground cable installations [13]. The strength of the top layer is enough to protect underground cable lines from external forces and it is easy to accomplish re-excavation as in the case of the CLSM method. The sand–bentonite mixture is fine and therefore does not cause mechanical damage to the cables. These mixtures are resistant to freeze–thaw cycles and have low water permeability [14–16]. The most popular use of bentonite is for creating an artificial water barrier [17–19]. Also, bentonite is widely used in landfills to isolate waste [20,21] from groundwater [22]. The following ratio is usually used for bentonite mixtures [23,24]: 100 parts of 10:1 bentonite/water mix with 20 parts of sand and 8 parts of cement. This mixture must be pumped into the duct to totally eliminate air. When the duct is filled, it must be sealed to prevent any escape of bentonite mixture [8].

It has been observed that in sand-bentonite mixtures, bentonite is evenly distributed and fills the voids around sand particles [25]. An essential property that results in water impermeability is that bentonite mixed with water can expand up to ten times [26]. Upon desiccating, the products of bentonite mixtures crack [27]. The higher the bentonite content and the lower the water content, the more cracks appear on the surface [28]. However, cracks close up moistened with water due to the swelling process [29]. Bentonite does not have good strength properties, but compressibility tests have shown that the strength of a sand–bentonite mixture can be substantially increased by adding cement [14,30,31]. By replacing part of the cement with bentonite, the compressive strength of the replaced sample becomes similar to that of the original sample [31]. The amount of bentonite and water has a significant influence on compaction and its quality [17]. Another property characteristic of mixtures containing bentonite is its low thermal resistivity [14]. The thermal resistivity of the soil depends on the type of soil and moisture and can range from 0.80 to 3.00 K m/W [32].

Bentonite or sand–bentonite mixtures have been investigated as a water leakage inhibitor [33] and different mixtures have been formulated, namely the Kunigel-V1 bentonite [34], the MX80 bentonite [35,36], the Calcigel bentonite [37], and others [11]. Sand–bentonite mixtures can be very diverse [31] – different types of bentonite (sodium bentonite, calcium bentonite, magnesium bentonite), the content of which varies from 3 to 80%. Different kinds of sands are supplemented with binders (Portland cement) and water [38]. Different quantities of bentonite and water affect the rate of stabilization, and it highlights different properties [20].

The purpose of this study is to determine the proportions as well as mechanical and thermal properties of a dry-mixed sand–bentonite mixture and to investigate the suitability of such mixtures for installation around high-voltage underground cable lines in road embankments. When selecting a sand–bentonite mixture, the following requirements of this research must be ensured: the compressive strength must be greater than 0.5 MPa after 24 h; the thermal resistivity must be less than 1.2 K m/W; and the moisture content of the sand–bentonite mixture must be less than 13%. If compressive strength is less than 0.5 MPa, it can be used with reinforced concrete tray and a reinforced concrete slab on top of it.

2 Source information

This research is related to one of the Lithuanian projects – the Vilnius Combined Heat and Power (CHP) plant. Waste incineration is beneficial in reducing the amount of waste accumulated in the Vilnius regional landfill. At the CHP plant, there are 110 kV underground power lines which cross the road embankment. Here, due to limited space, underground power line cables cannot be at the same level, and there is a certain distance between them [39]. So the cables must be installed in triangular shape (Figure 1), where three single cables are laid in a single reinforced concrete tray.

Underground power line cables are installed with a reinforced concrete base, and have at least a 20 cm layer of bentonite mixture around them. In this case, the bentonite layer must ensure thermal soil properties. Also, one of the requirements of the bentonite mixture is to use not more than 13% of water content and after 24 h the cables must be installed on bentonite mixture. After cable laying the next layer of bentonite mixture is installed, and on top of it a reinforced concrete slab is placed. Work on the road embankment starts only after all this is done.

3 Experimental set-up

The following materials were used for the sand-bentonite mixture: bentonite, 0–4.0 mm fraction sand, cement (CEM I 42.5 R), and water. The investigated main component of bentonite is montmorillonite $My^{+}nH_2O(Al_{2y}(Fe,Mg)_y)Si_4O_{10}(OH)_2$, where M stands for Na/Ca minimum exchangeable cations 75%, and maximum carbonate content is 1.5%. In addition, bentonite contains accompanying minerals (impurities), such as smectites, calcite, dolomite, feldspar, kaolinite, and quartz in various percentages, which is related to the variability of the deposit. Bentonite swelling index is up to 8.0 cm^3/2 g, bulk density – 0.8–1.0 g/cm^3, pH value varies from 7 to 9, and grain size ≤0.056 mm. The used sand was even graded, and the mineral composition was with dominating quartz [40]. Only dry materials were mixed initially, later a small amount of water was added. The proportions of the substances are given in Table 1. The dry materials were mixed for 1–2 min, then water was added in and mixed for 1–2 min (Figure 2). After adding the water (small amount of water activates the cement), the mixing is still dry, because all the mixed mass does not reach plastic or even liquid limit.

The tests were performed at a constant temperature of 20°C. All the samples were prepared using template

Table 1: Investigated bentonite mixture proportions (%)

Sample group no.	Bentonite	Cement	Water	Sand
1	100	—	10	—
2	78	6	10	16
3	36	9	10	55
4	55	9	10	36
5	45	9	20	45
6	9	9	10	82

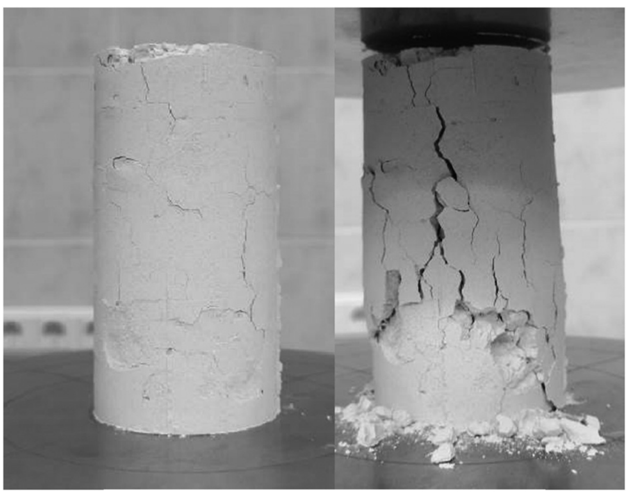

Figure 3: Signs of cracks in the samples after 24 h: on the left – before the compressive test, on the right – after the compressive test.

form of 50 mm diameter and 100 mm height. After the preparation of the samples, none of them showed any visible signs of cracks. All the defects occurred within 24 h after the sample preparation (Figure 3).

Before the compressive and thermal conductivity tests, the natural moisture content of the bentonite in the package and bentonite samples was determined. The test procedure of oven dry method was applied by these steps: the natural specimen was weighed and placed in a hot air oven with a temperature of 110 ± 5°C, and dried for 4 h. The weight of the dried soil sample was measured at 20°C. The natural moisture content of the bentonite in the package was determined to be 3.00% (with oven dry method). After 24 h, none of the prepared mixtures had a moisture content higher than 13.00%. The dimensions of the samples were measured immediately after preparation and after 24 h. In this way, the volumetric deformation (expansion) of the samples due to the interaction of water and bentonite, i.e., swelling of the bentonite mixture due to moisture appearing in the bentonite, was evaluated.

The compressive strength of the samples was determined with Walter + Bai AG 100 kN electromechanical universal testing machine. The samples were loaded with the sanded surfaces contacting the testing machine plates. The top loading plate has a spherical hinge. Uniaxial compression ramp 2 mm/min was applied.

The thermal conductivity coefficient is usually determined experimentally. There are several methods to determine it, which are based on comparatively simple principles. First, all methods are divided into steady and transient (unsteady) [41]. The tests to determine bentonite thermal conductivity were conducted using the steady method.

For testing the thermal properties, two samples were prepared (see positions 2 and 4 in Table 1) with a width and length of 300 mm and a height of 40 mm. The thermal conductivity tests were performed on the thermal conductivity test bench IZOL-01P (Figure 3).

In Figure 4, a schematic of the thermal conductivity test bench with the main elements is presented. This test bench consists of the ALMEMO 5690 multichannel data logger from Ahlborn (see No. 1 in Figure 4). A heat flow measuring board (3) "FQA018C" with a length and width of 120 mm, a measuring range from –40 to +80°C and an accuracy of 5% at +23°C is connected to this data logger. Temperature sensors are also connected to this data logger; they record the surface temperatures of the heated (5) and cooled plates (4) and are adjacent to the sample. The temperature of these surfaces is recorded by NiCr-Ni T 190-0 thermocouples, measuring range from –25 to +400°C, and they are assigned to accuracy class 2. To measure the thickness of the sample, a position sensor "FWA050T" (6) is connected to the data logger. The maximum length of the position sensor measurement is 50 mm and its resolution is 0.01 mm. The surface temperature of the heating plate (5) is

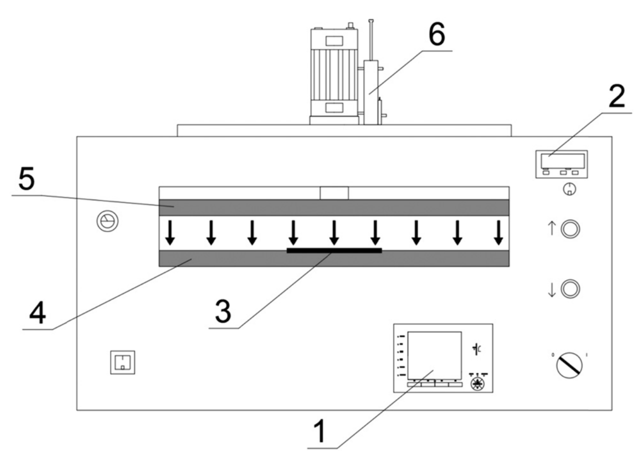

Figure 4: Thermal conductivity measuring test bench IZOL-01P.

regulated by a temperature controller (2), which turns on or off the relay that supplies electricity to the electric heater on the plate. The cooled surface (3) is cooled with water.

A digital photograph showing how the sample is placed into the test bench is provided in Figure 5. In this photograph, it can be seen that the sample is prepared in a special form (dashed rectangular) so that it does not collapse during the test when a hot plate is pressed against it. A layer of sand 40 mm thick is supported by four thinner supporting forms.

The next principle followed in determining the thermal conductivity of a given material by steady method is the following: a heat source with an evenly distributed heat flow is placed near one side of the sample and a cooler near the other side. At steady state (the temperature at individual points does not change over time), the same heat flows near the hot and cold sides of the sample.

Knowing its value and the surface temperatures of the sample, according to Fourier law, the numerical value of the thermal conductivity coefficient can be found by evaluating the form of the sample. In direct mode, a steady heat flow passing through the test plate:

$$Q = \frac{\lambda}{d}(t_1 - t_2), \tag{1}$$

where λ is the thermal conductivity coefficient (W/(m K)); d is the tested plate thickness (m); t_1 is the temperature of heated side of the plate (°C); t_2 is the temperature of cooled side of the plate (°C); and Q is the heat flow (W/m^2).

Using the following equation thermal conductivity is determined:

$$\lambda = \frac{d \cdot Q}{t_1 - t_2}. \tag{2}$$

Thermal resistance of material is calculated according to the following equation:

$$R = \frac{d}{\lambda}, \tag{3}$$

where λ is the thermal conductivity coefficient (W/(m K)); R is the thermal resistance ((m^2 K)/W); and d is the material thickness (m).

The results of the test are discussed below.

4 Obtained results

The proportions of tested bentonite mixtures and their strengths after 24 h are given in Table 2. According to the determined compressive strengths, only sample No. 6 had strength greater than 0.5 MPa [5]. The bentonite mixture can be installed in a reinforced concrete tray with reinforced concrete slab on top, thus lower strength values can be accepted. All samples were prepared with a moisture content of 13% (estimating the natural moisture content of bentonite equal to 3%). After a setting time of 24 h, the maximum moisture was found in a mixture of 100% bentonite and 10% water, which was 9.38%. It was

Figure 5: Sample A is placed into the thermal conductivity measuring test bench.

Table 2: Properties of bentonite mixtures

Bentonite (%)	Cement (%)	Water (%)	Sand (%)	Sample group no.	Diameter (mm)	Height (mm)	Density (cm^3/g)	Water content after 24 h (%)	Failure load (kPa)
100	—	10	—	1.1	50.0	100.0	1.17	9.38	3.31
				1.2	50.0	100.5	1.19		2.50
				1.3	50.0	100.9	1.19		8.56
				Average	50.0	100.5	1.18		4.79
78	6	10	16	2.1	50.0	102.3	1.28	8.33	10.34
				2.2	50.0	102.0	1.31		25.73
				2.3	50.0	102.0	1.32		23.24
				Average	50.0	102.1	1.30		19.77
36	9	10	55	3.1	50.0	101.7	1.65	4.59	93.64
				3.2	50.1	101.8	1.63		117.14
				3.3	50.1	101.9	1.63		109.27
				Average	50.1	101.8	1.64		106.68
55	9	10	36	4.1	50.9	102.0	1.49	6.15	33.65
				4.2	51.1	102.2	1.48		53.92
				4.3	51.0	102.3	1.46		49.12
				Average	51.0	102.2	1.48		45.56
45	9	20	45	5.1	50.0	102.2	1.73	6.85	494.43
				5.2	50.5	101.9	1.70		347.00
				5.3	50.3	101.7	1.69		324.85
				Average	50.3	101.9	1.71		389.03
9	9	10	82	6.1	51.0	101.8	1.95	4.13	475.61
				6.2	51.2	102.0	1.94		564.59
				6.3	50.9	102.1	1.92		555.32
				Average	51.1	102.0	1.94		531.84

Table 3: Changes of samples' volume

Sample group	Volume after sample preparation (cm^3)	Volume after 24 h of sample preparation (cm^3)	Volume change (%)
1	196.25	197.23	0.50
2	196.25	200.37	2.06
3	196.25	200.48	2.11
4	196.25	208.67	5.95
5	196.25	202.39	3.03
6	196.25	209.08	6.14

observed that by increasing the ratio of the sand fraction in the mixture, the samples desiccated faster, i.e., the sample evaporated the free water faster. Also, the volumetric deformations of the samples were observed, which occurred within 24 h (Table 3).

By analyzing the two criteria, i.e., the bentonite content of the bentonite–sand mixture is more than 50% [42] (including the volumetric deformations of the samples) and the bentonite mixture is enclosed in a reinforced concrete tray, it was decided to perform tests to determine the thermal resistivity for the second and fourth groups of samples (Table 1). The second group is indicated as sample A and the fourth group is indicated as sample B (Table 4). Sample A has a low compressive strength (Table 2), but cracks a little (Figure 6). Sample B has a high compressive strength (Table 2), but the signs of cracking are higher than in sample A (Figure 7).

The thermal conductivity is determined for samples A and B (Table 4). Sample A (composition corresponds to sample No. 2 in Table 1) has a thickness of about 45.1 mm and a measurement time of 20 h. The data are recorded and stored at 1 min intervals. Sample B (composition corresponds to sample No. 4 in Table 1) has a thickness of 46.5 mm and a measurement time of 21 h. About 1,200 measurements were collected for each sample.

Figure 8 shows the measurement results of sample A, i.e., the temperature of the heated (see black dotted line in Figure 8) and cooled (see black dashed line in Figure 8) surfaces and thermal conductivity (see black line in Figure 8) determined according to equation (2). In this figure, it can be seen that the temperature of the warm plate has stabilized within 40 min since the start of the test (see vertical black line with one arrow pointing to

Table 4: Selected samples for determination of thermal conductivity

Sample group	Sample group in Table 1	Bentonite (%)	Cement (%)	Sand (%)	Failure load (kN)
A	2	78	6	16	19.77
B	4	55	9	36	45.56

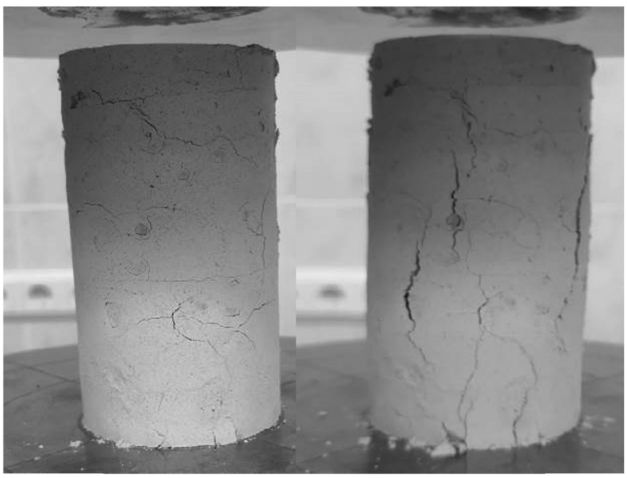

Figure 6: Signs of cracks in the second group of samples after 24 h: on the left – before the compressive test, on the right – after the compressive test.

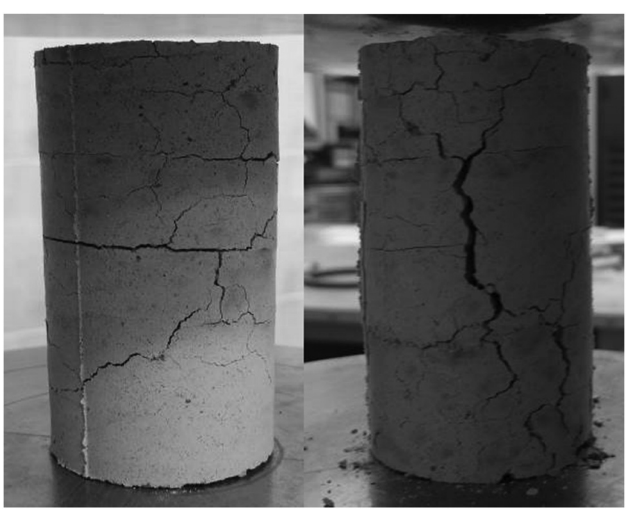

Figure 7: Signs of cracks in the fourth group of samples after 24 h: on the left – before the compressive test, on the right – after the compressive test.

the right), the temperature of the cooled surface (see vertical black line with three arrows pointing to the right) has stabilized after approximately 6 h, and the thermal conductivity (see vertical black line with two arrows pointing to the right in Figure 8) has stabilized after approximately 7 h. It can also be observed that as the thermal conductivity process stabilizes, it has gradually decreased over time. This decrease is possible because the sample was measured 1 day after it was manufactured, so it may not be completely desiccated and the moisture content in it decreased during the measurement. The thermal conductivity is estimated as the average value of the steady state, which is equal to 0.307 W/(m K).

The notations in Figure 9 are the same as in Figure 8. In Figure 9, it can be seen that the temperature of the warm plate has stabilized within 40 min. From the start of the test, the temperature of the cooled surface has stabilized after approximately 6 h, and the thermal conductivity (see Figure 9 vertical black line with the two arrows pointing to the right) has stabilized after approximately 7 h. It can also be observed that after the stabilization of the thermal conductivity process, it gradually decreased over time as in test A. The reasons for this decrease are the same as for sample A, i.e., variation in humidity in the sample over the period measured. The thermal conductivity is estimated as the average value of the settled period, which is equal to 0.385 W/(m K).

Figure 10 shows the values of thermal conductivity and thermal resistance during the analyzed period of both the samples. Here, the maximum coefficient of thermal conductivity is observed in sample B’s case. The values of the thermal conductivity coefficient stabilize after approximately 7 h of measurement (see Figure 8 vertical black line with the two arrows pointing to the right) and remain constant for most of the remaining period. A very small decrease in the coefficient of thermal conductivity can be observed, which can be related to the evaporation of moisture from the samples.

The thermal conductivity coefficient of sample A was found to be 0.307 W/(m K), and the transfer coefficient of the sample B was about 20% bigger than that of sample A, i.e., 0.385 W/(m K). Therefore, for laying high voltage electrical cables it is more appropriate to use the bentonite mixture of sample B.

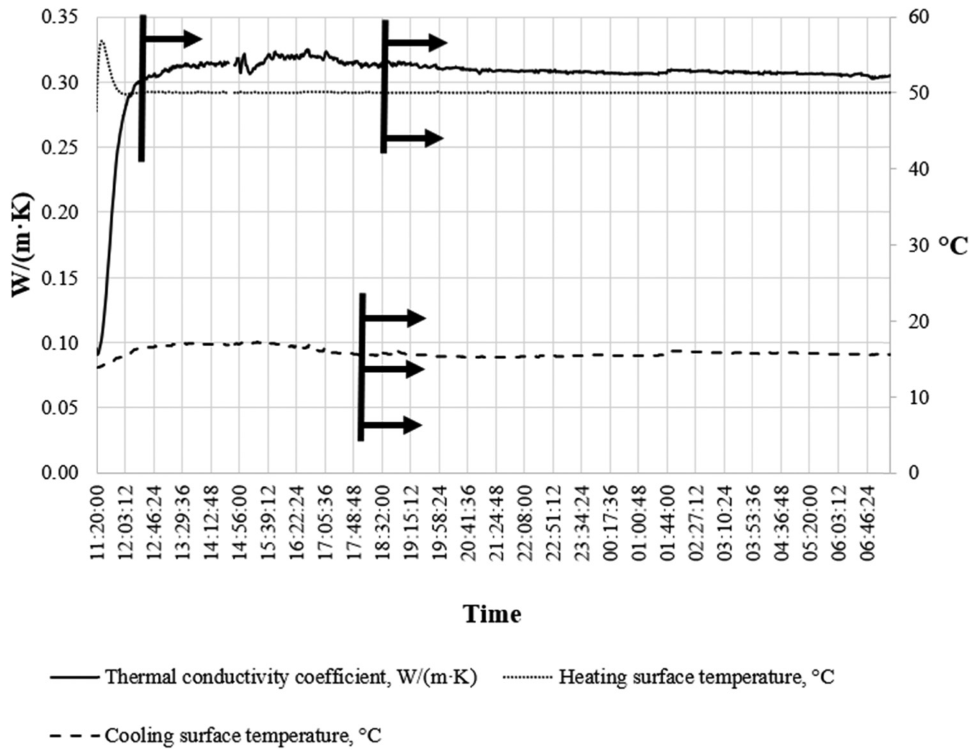

Figure 8: Sample A measurement data and conductivity coefficient values.

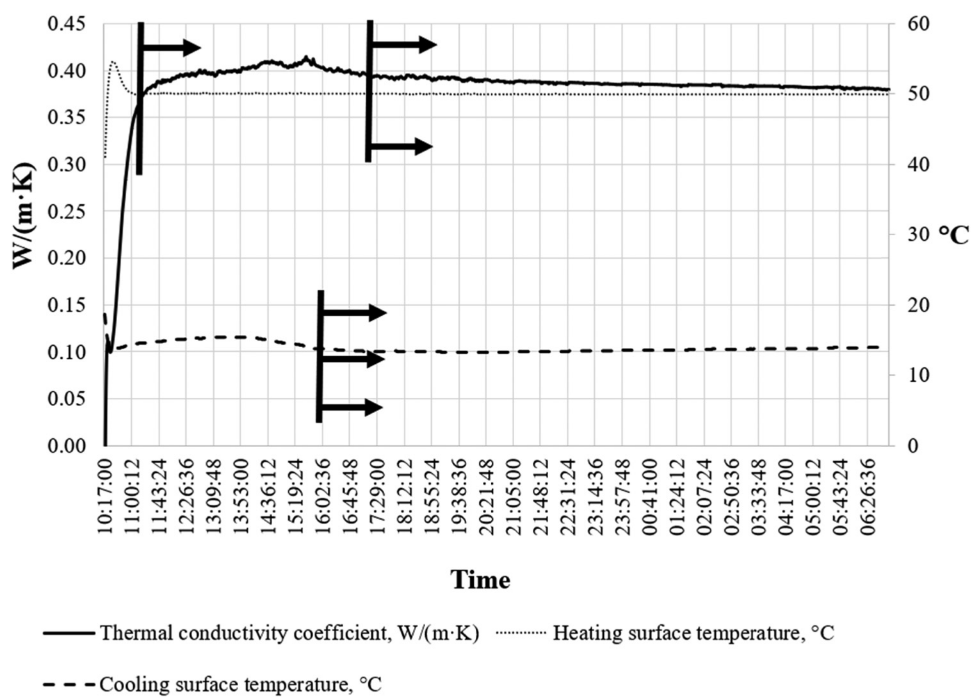

Figure 9: Sample B measurement data and conductivity coefficient values.

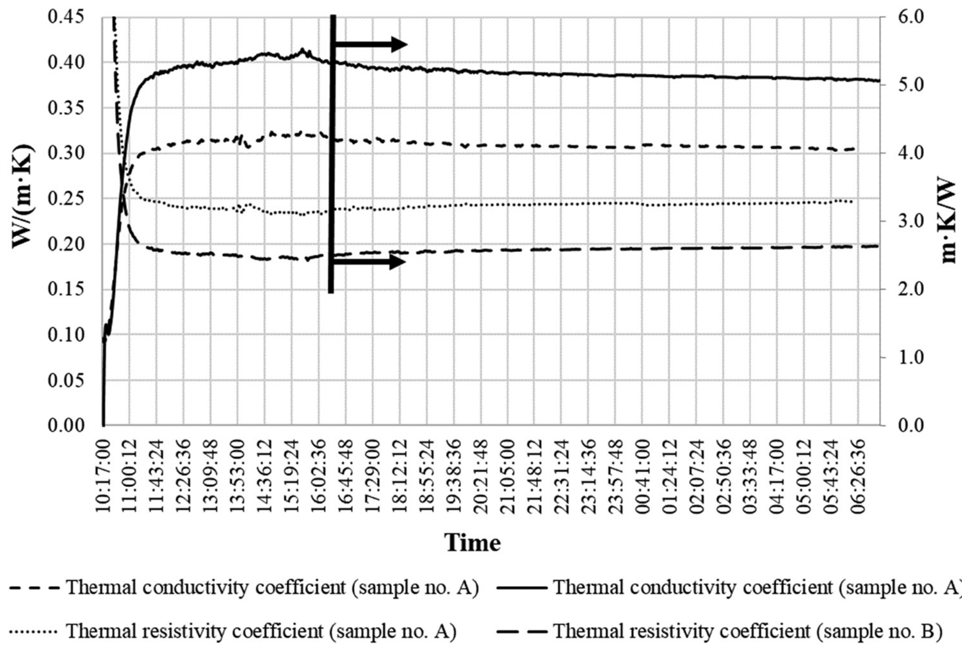

Figure 10: Thermal conductivity coefficient values for tested samples.

5 Conclusion

The analysis of the strength and thermal conductivity of bentonite, sand, cement, and water mixture of various compositions revealed:

- According to the determined compressive strengths, only sample No. 6 had strength greater than 0.5 MPa. The compressive strength of other samples ranged from 0.0025 up to 0.564 MPa. The obtained strength values allow to continue construction works in site after 1 day of mixture laying, as the bentonite mixture is applied in a reinforced concrete tray.
- The thermal conductivity coefficient of sample A was found to be 0.307 W/(m K) (thermal resistivity 3.25 m K/W), and the transfer coefficient of sample B was about 20% bigger than that of sample A, i.e., 0.385 W/(m K) (thermal resistivity 2.597 m K/W). Therefore, for laying high voltage electrical cables it is more appropriate to use the bentonite mixture of sample B.
- A very small decrease in the coefficient of thermal resistivity can be observed, which may be related to the evaporation of moisture from the samples.

The required thermal conductivity properties of the soil are not achieved by dry mixing. The disadvantage of dry mixing – sand mixed with bentonite and cement which has very low water content (<13%) forms a heat insulating layer. For those cases, when compression strength is less than 0.5 MPa, it is necessary to use reinforced concrete tray with reinforced concrete slab on top. This method of mixing can be useful only in cases in which the thermal conductivity of the mixed soil is not relevant, because the work can be continued after 1 day.

Author contributions: Š.S. conceived and planned the experiments. M.Z. and J.B carried out the experiments. M.Z. and J.B. contributed to sample preparation. Š.S. and G.Š. contributed to the interpretation of the results. Š.S. and G.Š. took the lead in writing the manuscript. All authors provided critical feedback and helped conduct the research and analysis, and to prepare the manuscript.

Conflict of interest: Authors state no conflict of interest.

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