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Analysis of Thermal Parameters Variability During Thawing of Cohesive and Non-cohesive Soils

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ABSTRACT

Storage of heat and cold in the rock mass creates a need to identify the long-term variability of soil behavior under freezing and thawing conditions. Phase change cycles during the system operation can lead to deterioration of the ground in the immediate vicinity of the heat exchanger and changes in its thermal properties. The article presents the influence of phase transformation on the change of thermal properties of soil (thermal conductivity, thermal resistivity, volumetric heat capacity, thermal diffusivity). Samples of cohesive and non-cohesive soils (medium sand, silt and clay) were analyzed. Samples prepared according to the previously developed methodology were frozen at temperature of about -20° C, then were subjected to thawing at defined temperature. The temperature change of the sample was monitored during the measurement of thermal parameters (transient line source method). At the same time the temperature change in the part of the sample not affected by the thermal needle heating phase were observed.

1. INTRODUCTION

Determination of rock and soil thermal properties has crucial importance for variety of purposes like direct utilization of geothermal heat e.g. geothermal power plants, geothermal heat exchangers, thermal storage systems combined with heat pumps, geothermal pile foundations, thermo-active energy tunnels (DiPippo, 2012; Ryżyński & Bogusz, 2016; Baralis et al. 2018). Permafrost geotechnics is another important field on which such knowledge can be useful (Andersland & Ladanyi, 2003). Awareness of soil thermal parameters variation in different conditions also has pivotal importance for agriculture, hydrogeology etc. (Gontaszewska 2010; Aguilar, 2018). The thermal conductivity (λ), volumetric heat capacity (Cp), thermal resistivity (Rλ) and thermal diffusivity (α) are often used as an input data for heat flow and soil water models (Łydżba et al., 2014).

The subject of the research of this publication was to identify differences in the properties of the above-mentioned parameters recorded for frozen and thawed soils. To achieve that, three representative soil samples (medium sand, silt and clay) were selected. Measurements were performed in a temperature range from -10 to +10° C with the use of thermal needle probe method. The choice of the subject of this publication was inspired by the need to expand data from measurements and empirical experiments.

2. METHODOLOGY

The thermal parameters were investigated by the thermal dual needle probe test with the use of KD2 Pro analyzer with SH-1 sensor. Thermal needle probe test, also called transient hot wire method, is one of the transient heat transfer methods of thermal conductivity measurement. During the test, a steel needle probe is embedded in a soil specimen and then heated for a designated time period (usually a half of total measurement time). Temperature changes, for heating and cooling phases, are recorded.

During the measurements samples were placed inside cooled incubator, due to fulfill assumptions of the experiment i.e. keeping the temperature of the sample stable while recording thermal parameters. At the same time, temperature stability of the sample was monitored by TK04 Thermal Conductivity Meter.

2.1 Samples Used in Testing Procedure

Two cohesive soil samples (silt and clay) and one non-cohesive soil (medium sand) were utilized for the purposes of this paper (Figure 1). Physical properties of the samples including particle size distribution are given in *Table 1*. Cohesive soil samples were examined undisturbed, which means they were collected in a way that allows preserving its natural structure as well as full range of the soil's physical and mechanical features - A. sampling category (Eurocode 7).

Table 1 Physical properties of tested soils

Sample no	Soil type	Particle size distribution [%]				Dry density [g/cm^3]	Water content [%]
		>2 mm	2-0,5 mm	0,05-0,002 mm	<0,002 mm		
PS-1	silt	0	16	76	8	2,67	24,7
PS-2	clay	0	11	56	33	2,72	24,9
PNS1	medium sand	2	3	94	1	2,65	-

2.2 Measuring Equipment

- KD2Pro Thermal Properties Analyzer with SH-1 sensor (dual needle 1.3 mm diameter x 30 mm long each), that measures thermal conductivity, thermal resistivity, diffusivity and volumetric heat capacity. The sensor is designed i.a. to perform measurements in frozen materials (KD2 Pro, 2016).

Measuring range:

- thermal conductivity: 0.02 to 2.00 W/(m·K), accuracy ± 10% from 0.2-2 W/(m·K), ±0.01W/(m·K) from 0.02 -0.2 W/(m·K);
- thermal resistivity: 50 to 5000 °C·cm/W;
- diffusivity: 0.1 to 1 mm^2/s, accuracy ±10% at conductivities above 0.1 W/(m·K);
- volumetric heat capacity: 0.5 to 4 $mJ/(m^3K)$, accuracy ±10% at conductivities above 0.1 W/(m·K).

- TK04 Thermal Conductivity Meter – temperature monitoring during measurements
  - Standard size needle probe for laboratory use (Standard VLQ). Temperature range from -25 to 125°C
  - TK04 Measuring unit (TeKa, 2016).

- NUVE ES110 cooled laboratory incubator (temperature control accuracy: heating: 0.5°C, cooling: ±1°C) was used to keep the set temperature stable during measurements.

Figure 1. Left: Analyzed samples after three cycles of freezing and thawing (medium sand, silt, clay), right: KD2Pro Thermal Properties Analyzer with SH-1 dual needle sensor.

2.3 Sample Preparation and Performing the Analysis

Before starting the analysis medium sand was fully saturated with water. In case of undisturbed cohesive soils, measurements were carried out without any additional preparation of the samples.

The KD2 Pro needle sensor was placed carefully in the center of the sample. About 2 cm of material were allowed parallel to the sensor in all directions. TK04 VLQ sensor was installed in part of the sample not affected by the thermal needle heating phase, in order to monitor temperature changes *Figure 2*).

Samples were frozen in the temperature about minus 20°C, then hermetically packed and placed inside laboratory incubator to thaw in defined temperature. Thawing temperature ranged from -10°C to +10°C with 2°C interval. To better recognize thermal properties of thawing soils, between -1,5°C and +1,5°C readings were taken with 0.5°C interval. After each temperature change a proper time period (length depending on the sample) was given to minimize temperature drift.

Each sample was exposed to freezing-thawing cycle three times.

Low power mode (0,73-0,78 W/m) was used to obtain KD2 Pro thermal properties measurements. In low power mode small current is applied to the needles resulting in less heating of the sensor. Decreased heat input in LPM is less likely to cause phase change (melting) of the frozen sample (KD2 Pro, 2016). One measuring cycle in defined temperature point comprised 3 measurements, 5 minutes each.

Figure 2 Left: measuring equipment: a. laboratory incubator, b. TK04 measuring unit, c. KD2 Pro Thermal Properties Analyzer, right: undisturbed cohesive soil sample during measurements.

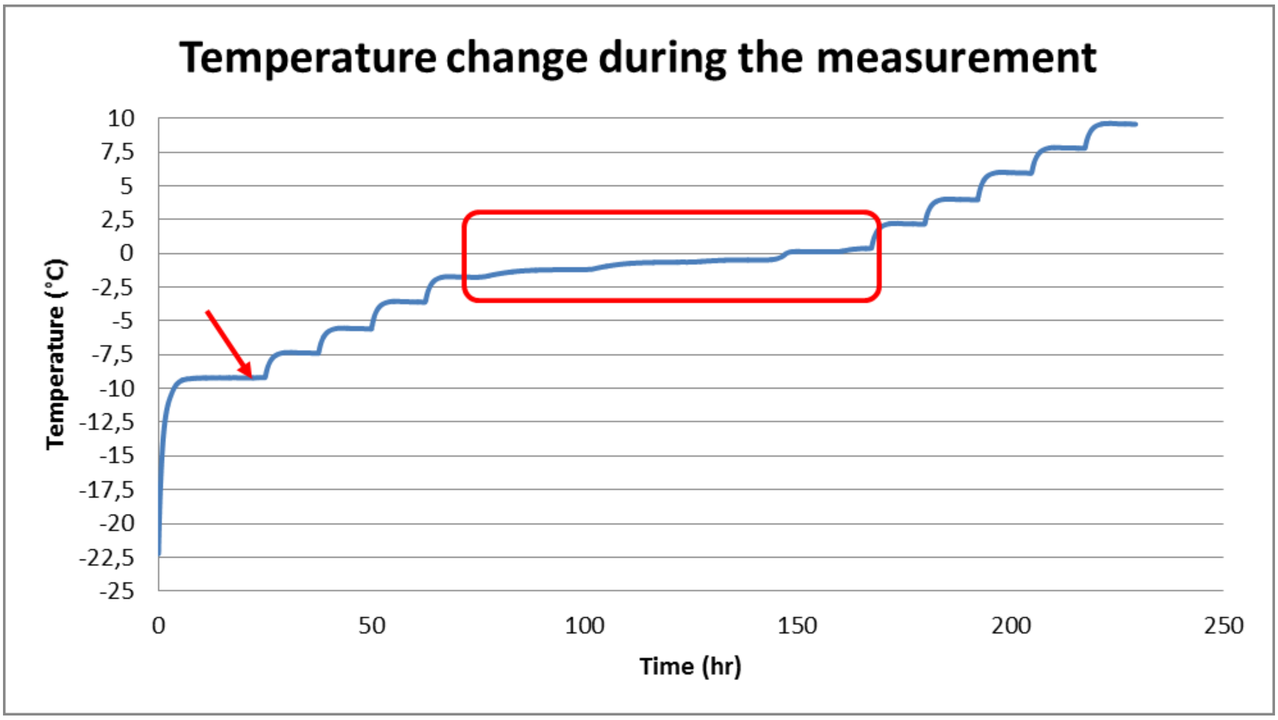

Figure 3 Temperature change recorded by TK04 VLQ standard probe during measurement cycle on silt sample.

The graph shows the change in silt sample temperature during one measurement cycle. The chart also indicates (red arrow) the moment of starting the test after the sample were stabilized at the required temperature (Figure 3). 24 hours have passed since the frozen sample was inserted into the incubator and the measurement process of thermal properties started. Then, after three measurements of thermal properties (duration about 55 minutes), the temperature was raised by about 2°C. The time taken to equalize the sample temperature with the ambient temperature was 12 hours.

When approaching 0°C (rounded rectangle) the test resolution, i.e. the frequency of measurements was increased. The assumption was that the test was to be carried out every 0.5°C, but the precision and ability of the incubator to maintain the set temperature in such a low resolution did not allow complete fulfillment of this assumption.

One measurement cycle for each soil sample from the beginning, i.e. placing chilled to about -22°C until the last measurement at a temperature close to 10°C, was in about 220-230 hours.

3. RESULTS

3.1 Analysis and Interpretation of Results

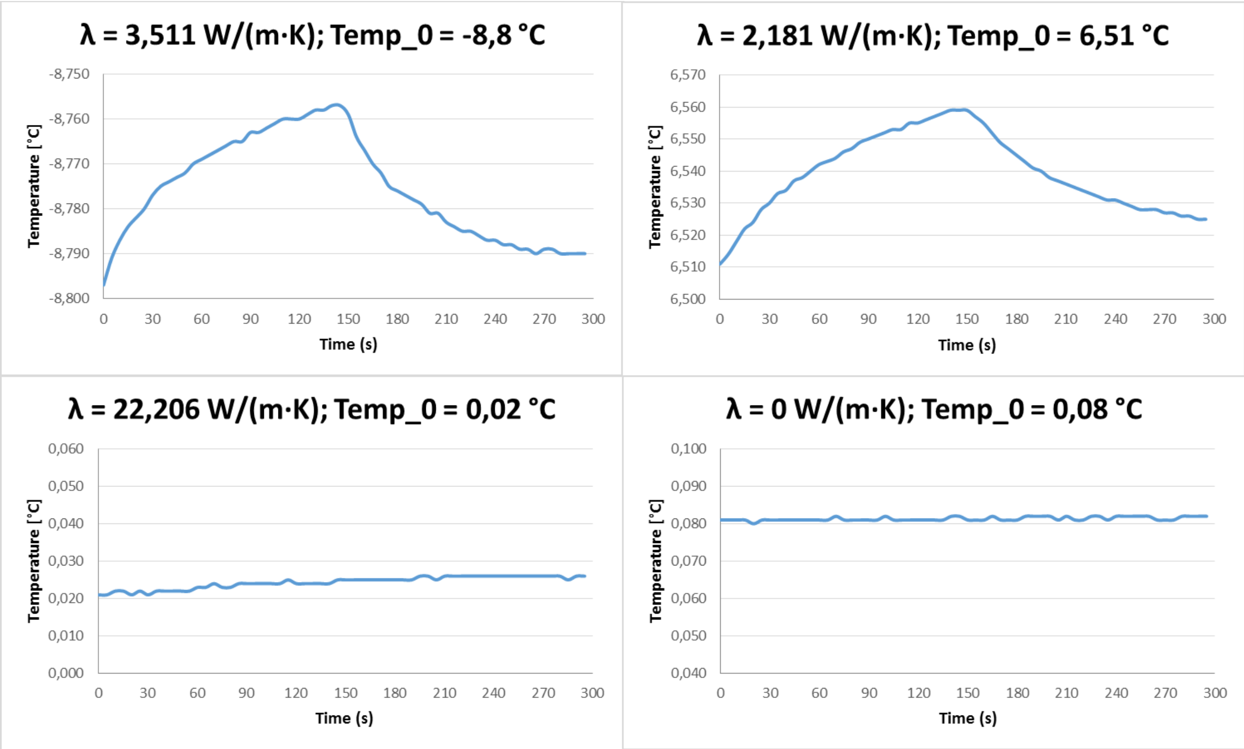

Figure 4 Temperature change during the measurement under given temperature conditions.

The graphs show the temperature change during the measurement under given temperature conditions. The shape of the top two curves shows the change in temperature on the basis of which the device correctly calculates the value of thermal conductivity and thermal resistivity. The bottom two temperature records prevent the calculation of the above mentioned parameters (Figure 4). Based on the shape of the curves, the reliability of the obtained results were assessed.

In both cases, the measurement was carried out in the same KD2Pro power mode (0.75-0.76 W/m). Device applied a relatively small current to sensor which result in less heating of probe. The authors perceive here the impact of the phase change taking place (water changing its phase from solid to liquid during thawing - ice melting process). The amount of energy absorbed during the phase transformation makes it impossible to increase the sample temperature by a value that will allow to calculate thermal conductivity and thermal resistivity of the tested soil correctly. Moreover authors also tried to use different power mode of measuring device (18.8-19.0 W/m) which resulted in melting of ice accumulated in porous space of sample in temperature around 0,40 - 0,45°C without significant influence on changing the incorrect shape of temperature record curves. Again values of thermal conductivity and thermal resistivity were faulty.

3.2 Obtained Results

Overall 146 measurements of thermal conductivity (λ), volumetric heat capacity (Cp), thermal resistivity (Rλ) and thermal diffusivity (α) for each of three soil samples were taken. All of the results were pictured in graphs below (Figures 5-7). Comparison of mean values of results obtained during research was given in Table 2.

All of the parameters show different values for frozen and thawed soils. For each investigated sample thermal conductivity (λ) and thermal diffusivity (α) values are higher in frozen soils than in thawed soils. Opposite relationship is observed in case of thermal resistivity (Rλ) – its values are significantly lower in frozen soil. Volumetric heat capacity (Cp) values in general trend to rise from subzero to 0°C in frozen soil. In case of thawed soil there volumetric heat capacity tend to stay at the similar level.

Substantial dispersion of the results can be noticed when specimen’s temperature reaches 0°C. While in frozen and thawed soil thermal properties values more often than not remain rather constant, they tend to fluctuate upwards (thermal conductivity, volumetric heat capacity) and downwards (thermal resistivity, thermal diffusivity) close to 0°C.

There are no prominent differences between thermal properties values obtained during first, second and third freezing-thawing cycle.

In case of all the samples obtained effective thermal conductivity coefficient (λ) values in frozen ground and during thawing are different. For each frozen soil specimen effective thermal conductivity coefficient λ is significantly higher than in thawed specimen. Since ice has times higher λ: 2.210 W/(m·K) in 0°C, than water: 0.591 W/(m·K) and air: 0,024 W/(m·K) (Powell et al., 1966), the relation depends on whether the space between soil grains is filled with ice, water and air (frozen ground) or water and air (thawed ground). Specimens investigated for the purpose of this paper have about 60% higher λ when frozen than thawed. The authors recognize this as moisture content influence. Similar relationship were found in case of thermal diffusivity. Thermal resistivity and heat capacity values are lower in frozen than in thawed soils.

Mineral composition also has significant effect on thermal conductivity (Čermák & Rybach, 1982). The highest values of thermal conductivity were noted considering medium sand sample. This is most probably related to a high content of quartz and the shape of the pores. The lowest λ and the highest Rλ were obtained in clay. This is due to the relatively low value of thermal conductivity of clay minerals (Robertson, 1988).

The slightest differences of the thermal parameters measurements results were noted in frozen vs. thawed clay sample. Non-typical values were recorded only during 8th measurement series. Clay minerals have ability to bound water molecules inside their chemical structures (Spostio et al., 1999). This fact can also explain different results observed in clay sample in comparison with silt and sand. Silt and sand sample thermal parameters tend to differ substantially between 8th and 10th measuring series (Table 2). Since soils containing silt and sand as main fraction most of the water remains unbounded in pores. Obtained results suggest that thermal properties of less cohesive soils are more susceptible to phase change.

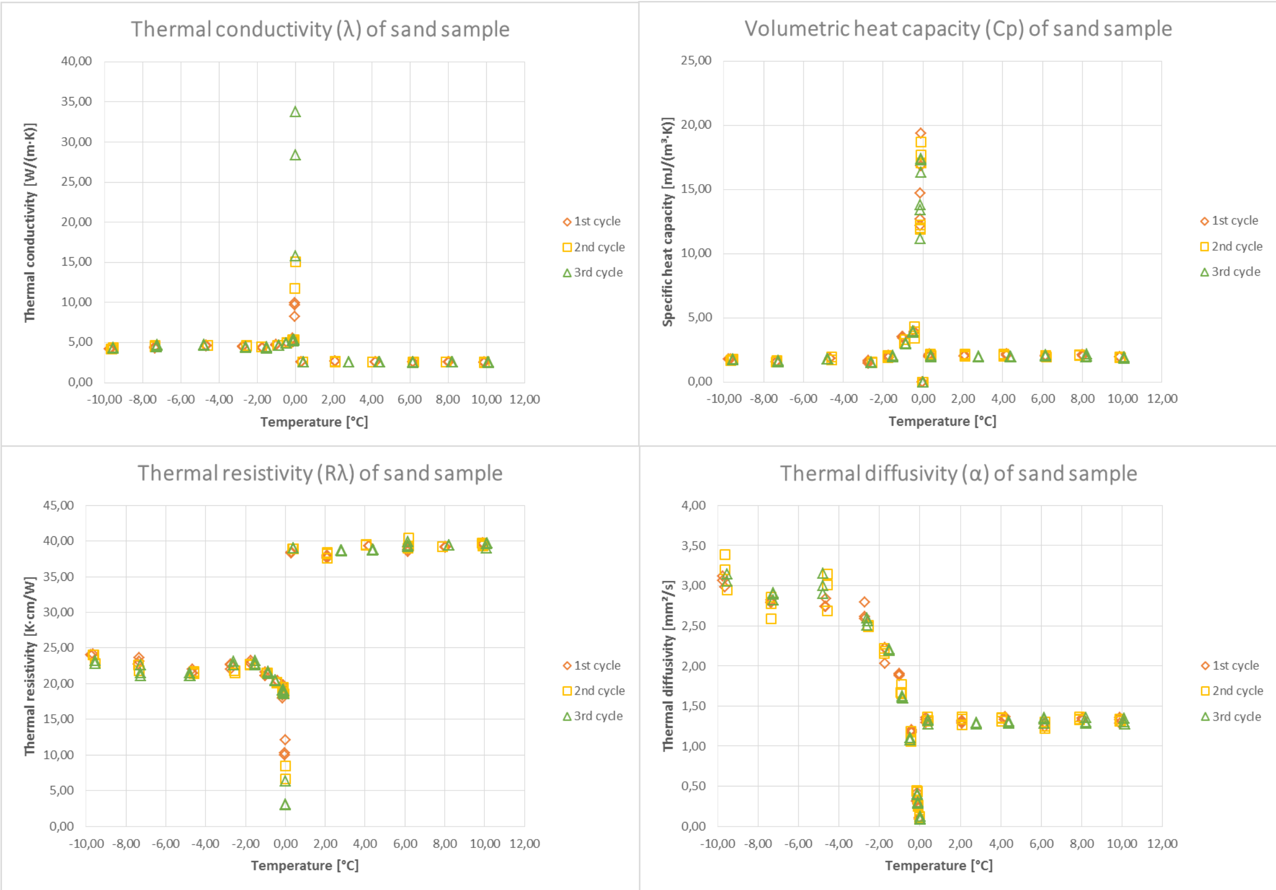

Figure 5 Relation between temperatures of medium sand specimen and its thermal properties.

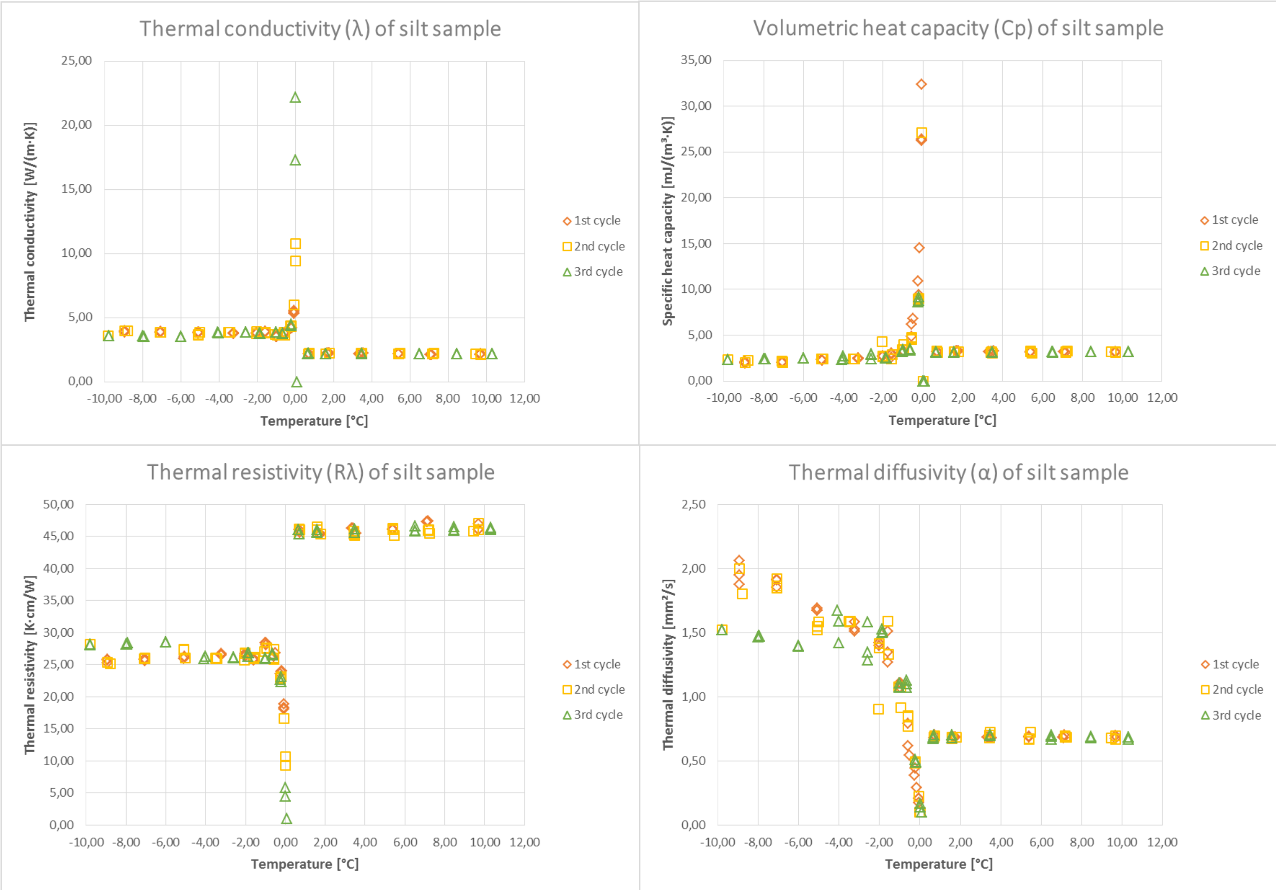

Figure 6 Relation between temperatures of silt specimen and its thermal properties.

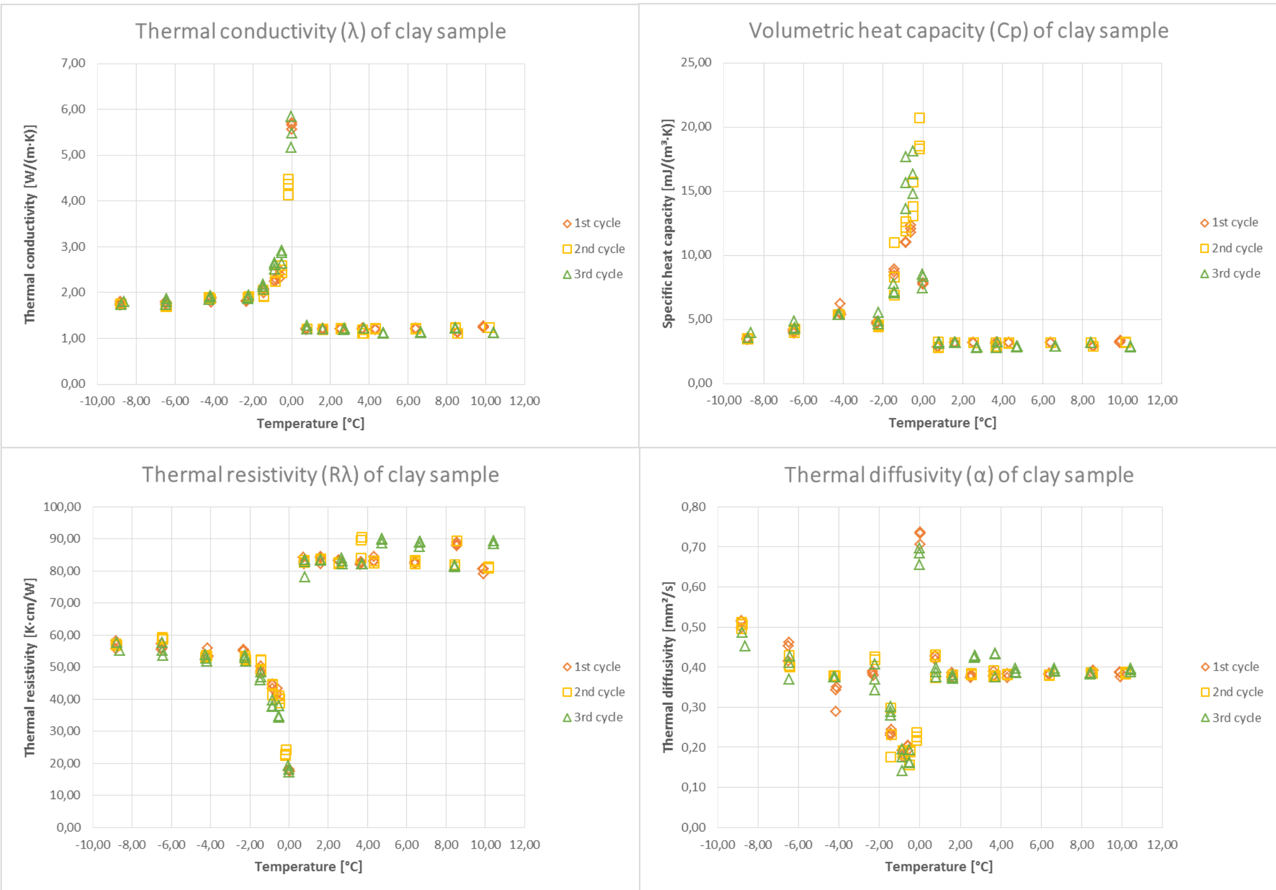

Figure 7 Relation between temperatures of clay specimen and its thermal properties.

Table 2 Mean values of thermal parameters of tested soils

		Sand					Silt					Clay				
Mesurement series	Mesurement cycle	Mean temperature [°C]	Mean λ [W/(m·K)]	Mean Rλ [K·cm/W]	Mean Cp [mJ/(m³·K)]	Mean α [mm²/s]	Mean temperature [°C]	Mean λ [W/(m·K)]	Mean Rλ [K·cm/W]	Mean Cp [mJ/(m³·K)]	Mean α [mm²/s]	Mean temperature [°C]	Mean λ [W/(m·K)]	Mean Rλ [K·cm/W]	Mean Cp [mJ/(m³·K)]	Mean α [mm²/s]
1	1	-9,74	4,16	24,03	1,72	3,09	-8,94	3,88	25,77	2,01	1,935	-8,83	1,76	56,73	3,46	0,51
	2	-9,64	4,16	24,03	1,70	3,19	-8,89	3,96	25,27	2,04	1,953	-8,82	1,74	57,50	3,47	0,50
	3	-9,54	4,37	22,93	1,75	3,05	-9,78	3,55	28,17	2,33	1,521	-8,73	1,77	56,57	3,68	0,48
2	1	-7,35	4,33	23,13	1,56	2,80	-7,06	3,88	25,77	2,05	1,892	-6,49	1,78	56,17	4,03	0,44
	2	-7,15	4,53	22,07	1,58	2,74	-7,07	3,86	25,93	2,09	1,878	-6,46	1,70	58,90	4,13	0,41
	3	-7,25	4,60	21,73	1,60	2,87	-7,95	3,54	28,27	2,41	1,469	-6,46	1,80	55,57	4,49	0,40
3	1	-4,66	4,62	21,63	1,83	2,77	-5,07	3,83	26,10	2,28	1,678	-4,14	1,85	54,07	5,70	0,33
	2	-4,59	4,63	21,57	1,80	2,95	-5,06	3,72	26,90	2,40	1,550	-4,22	1,88	53,33	5,37	0,38
	3	-4,79	4,71	21,23	1,76	3,02	-6,00	3,51	28,50	2,51	1,397	-4,22	1,89	52,83	5,35	0,38
4	1	-2,74	4,46	22,43	1,56	2,66	-3,23	3,76	26,57	2,45	1,539	-2,32	1,81	55,23	4,71	0,38
	2	-2,54	4,61	21,70	1,49	2,50	-3,47	3,85	25,93	2,43	1,585	-2,23	1,89	52,77	4,50	0,42
	3	-2,61	4,39	22,77	1,50	2,55	-4,04	3,82	26,17	2,47	1,559	-2,23	1,90	52,83	5,01	0,37
5	1	-1,72	4,37	22,93	1,93	2,16	-2,01	3,77	26,50	2,68	1,411	-1,43	2,04	49,07	8,67	0,24
	2	-1,75	4,42	22,67	1,96	2,19	-2,02	3,78	26,40	3,21	1,234	-1,44	1,97	50,97	8,73	0,23
	3	-1,51	4,38	22,87	2,00	2,20	-2,58	3,84	26,07	2,76	1,404	-1,45	2,12	47,13	7,33	0,29
6	1	-1,01	4,70	21,27	3,49	1,89	-1,57	3,88	25,77	2,84	1,374	-0,85	2,27	44,10	11,02	0,18
	2	-0,92	4,66	21,47	3,09	1,70	-1,57	3,84	26,00	2,58	1,501	-0,85	2,30	43,43	12,22	0,19
	3	-0,86	4,63	21,57	2,99	1,61	-1,86	3,76	26,63	2,49	1,510	-0,86	2,59	38,47	15,66	0,17
7	1	-0,41	4,90	20,37	3,90	1,18	-0,98	3,53	28,30	3,23	1,095	-0,60	2,41	41,60	12,07	0,20
	2	-0,44	4,97	20,17	3,86	1,11	-0,98	3,66	27,37	3,60	1,023	-0,49	2,50	39,97	14,18	0,18
	3	-0,49	4,88	20,47	3,90	1,09	-1,01	3,85	25,97	3,31	1,086	-0,50	2,82	35,60	16,44	0,17
8	1	-0,14	5,37	18,63	13,18	0,37	-0,55	3,78	26,47	5,94	0,650	0,01	5,64	17,73	7,77	0,73
	2	-0,14	5,25	19,03	12,06	0,44	-0,57	3,79	26,40	4,62	0,821	-0,17	4,33	23,13	19,20	0,23
	3	-0,13	5,20	19,13	12,78	0,40	-0,65	3,75	26,63	3,42	1,099	-0,01	5,51	18,20	8,11	0,68
9	1	-0,09	5,13	19,50	17,67	0,26	-0,21	4,20	23,83	11,61	0,373	0,76	1,20	83,07	2,83	0,42
	2	-0,09	5,24	19,07	17,81	0,26	-0,23	4,35	22,97	8,89	0,490	0,78	1,20	83,13	2,95	0,41
	3	-0,08	5,32	18,80	16,99	0,29	-0,22	4,41	22,70	8,86	0,498	0,80	1,23	81,53	3,17	0,39
10	1	-0,02	9,30	10,80	0,00	0,10	-0,05	5,44	18,37	28,35	0,193	1,60	1,20	83,57	3,16	0,38
	2	-0,01	12,84	7,87	0,00	0,11	-0,01	8,73	12,17	9,05	0,141	1,61	1,20	83,53	3,17	0,38
	3	0,01	25,96	4,13	0,00	0,10	0,04	19,76	5,15	0,00	0,134	1,62	1,20	83,37	3,19	0,38
11	1	0,31	2,61	38,37	2,06	1,33	0,72	2,18	45,83	3,16	0,690	2,53	1,20	83,27	3,18	0,38
	2	0,39	2,57	38,90	2,08	1,33	0,71	2,18	45,90	3,17	0,687	2,54	1,21	82,53	3,17	0,38
	3	0,41	2,57	39,00	2,01	1,31	0,66	2,18	45,87	3,18	0,687	2,71	1,20	83,07	2,82	0,43
12	1	2,10	2,65	37,80	2,04	1,30	1,72	2,20	45,40	3,24	0,681	3,66	1,21	82,40	3,18	0,38
	2	2,10	2,63	38,07	2,08	1,32	1,65	2,18	46,00	3,20	0,681	3,68	1,14	88,07	2,98	0,38
	3	2,81	2,59	38,67	1,95	1,29	1,58	2,18	45,77	3,16	0,692	3,73	1,22	82,23	2,95	0,41
13	1	4,20	2,55	39,30	2,12	1,35	3,43	2,17	46,03	3,19	0,681	4,32	1,20	83,43	3,16	0,38
	2	4,05	2,53	39,47	2,10	1,34	3,45	2,20	45,43	3,15	0,700	4,32	1,21	82,90	3,16	0,38
	3	4,40	2,58	38,77	1,97	1,29	3,49	2,18	45,80	3,13	0,699	4,73	1,12	89,60	2,86	0,39
14	1	6,17	2,58	38,80	2,03	1,27	5,40	2,17	46,13	3,15	0,687	6,41	1,21	82,50	3,17	0,38
	2	6,18	2,53	39,57	2,02	1,25	5,43	2,18	45,83	3,18	0,688	6,41	1,21	82,77	3,18	0,38
	3	6,16	2,53	39,50	2,06	1,32	6,51	2,17	46,10	3,17	0,685	6,66	1,13	88,60	2,88	0,39
15	1	8,03	2,56	39,13	2,06	1,34	7,12	2,11	47,33	3,17	0,687	8,56	1,13	88,37	2,91	0,39
	2	7,88	2,55	39,20	2,08	1,34	7,20	2,18	45,83	3,17	0,687	8,49	1,19	84,30	3,09	0,38
	3	8,21	2,54	39,40	2,02	1,31	8,45	2,17	46,17	3,17	0,684	8,44	1,23	81,60	3,18	0,39
16	1	9,90	2,52	39,63	1,94	1,32	9,69	2,16	46,40	3,15	0,686	9,90	1,25	80,17	3,25	0,38
	2	9,90	2,53	39,50	1,90	1,32	9,61	2,16	46,30	3,18	0,679	10,18	1,23	81,13	3,20	0,39
	3	10,11	2,54	39,43	1,88	1,31	10,32	2,16	46,23	3,19	0,679	10,43	1,13	88,80	2,87	0,39

4. CONCLUSIONS

The primary objective of this paper was to investigate the influence of phase transformation on the change of thermal properties (thermal conductivity, thermal resistivity, volumetric heat capacity, thermal diffusivity) of different kinds of soils. Three samples of cohesive and non-cohesive soils (medium sand, silt and clay) were analyzed.

Thermal parameters of soils were measured at frozen and thawed condition. Each sample was exposed to three freezing-thawing cycles.

Measurements were carried out in laboratory environment with the use of the cooled laboratory incubator, thermal needle method analyzer and sample temperature change monitoring system.

The following conclusions can be drawn from the laboratory investigations:

- Frozen soils present higher thermal conductivity values than thawed soils, opposite to the thermal resistivity.
- Volumetric heat capacity tends to increase from subzero temperatures to 0°C and presents nearly constant values above 0°C, whereas thermal diffusivity turns into reverse trend.
- Clay sample shows lesser variability of thermal parameters around 0°C (phase change temperature zone) which is probably caused by clay minerals' ability to bound water molecules inside their chemical structures.
- Applied method gives repetitive results in temperature range in which there is no solid to liquid phase transition.

Development of reliable laboratory test method for the soils exposed to freezing↔melting phase change will be the subject of further research.

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