

Improvement of Thermally Durable Soil Material with Perlite Additive

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Abstract

Thermal changes affect the engineering behavior of surrounding soils at energy geostructures. For that reason, there is a need for durable soils which are not affected from high temperatures or thermal cycles. Such kind of soil mixtures can be developed by adding temperature resistant materials such as perlite to the sand-bentonite mixtures. In this study, 10% and 20% perlite additives were added to 10% and 20% sand-bentonite mixtures, in order to develop the durable soil mixture under high temperatures. Direct shear and hydraulic conductivity tests were performed under room temperature and high temperature. The results of the experiments showed that the perlite additive reduced the unit weight of the sand-bentonite mixtures and had a positive effect on the shear strength of 20B-80S mixtures both under room and high temperature. The perlite addition increased the angle of internal friction of sand-bentonite mixtures under room and high temperature especially for 20B-80S mixtures. The hydraulic conductivity (k) values of both mixtures increased with increasing temperature. As a results of thermal cycles, it was seen that the samples cannot turn back to their initial k values.

Introduction

Temperature increase and thermal cycles occur in the surrounding soils at energy geostructures such as; gas pipelines, geothermal power plants, buried power cables, energy piles, solid waste and nuclear waste storage areas. Changes in the engineering properties of soils as a result of high temperatures may cause undesirable situations.

Previous studies have shown that engineering properties of soils change under high temperatures. Hydraulic conductivity and shear strength parameters are also subject to this change. Cekerevac and Laloui (2004) investigated the shear strength behavior of kaolin clay by increasing the temperature from 22°C to 90°C. In the opposite direction another finding reported that; the triaxial compression tests on the Pontida silty clay have shown that shear strength decreased when temperature increased from 18°C to 115°C (Hueckel and Baldi 1990). De Beruyn and Thimus (1996) conducted triaxial tests at 20, 50, 80 and 110°C temperatures. According to the unconsolidated-undrained (UU) and consolidated-undrained (CU) test results for Boom clay, a significant decrease in strength was determined when the temperature increased. Noble and Demirel (1969) reported that since the density and viscosity of the water affected by temperature, decrease in shear strength of clay and silt under 60°C was investigated. The soils have different phase structures; the intergranular space, a solid part and a liquid part. It was reported that when soil is heated, all components of soil expand. If this soil is a clay group, this expansion results change in the distance between the clay particles and a decrease in the strength of the adsorbed layers (Fleureau, 1979; Robinet et al. 1996). Similarly, it was determined that the elastic modulus increases and preconsolidation pressure decreases when soil is heated (Cekerevac and Laloui 2004).

The hydraulic conductivity tests at elevated temperature showed that hydraulic conductivity changes depending on soil temperature (Abuel-Naga et al. 2006; Ye et al. 2013). Increase in temperature changes the viscosity of the water, leading to increase in hydraulic conductivity (Cho et al. 1999). Mingarro et al.

(1989) observed that the hydraulic conductivity coefficients of the high-density mixtures of bentonite and granite increased to a degree of magnitude by increasing the temperature from 20°C to 100°C. This increase has been associated with increased porosity as a result of degeneration of water adsorbed in the clay pore wall (Pusch 1980).

It is known that in solid waste and nuclear waste storage areas, sand-bentonite mixtures, or only bentonite, are used to seal and perform a buffer function. Buffer function is to prevent leakage of radioactive wastes from bedrock to groundwater. It should be noted that the materials to be used as a buffer have to have low hydraulic conductivity and high swelling potential, that is, the capacity to adsorb liquid or water is high (Yong et al. 1986). For storage of high-level radioactive wastes (HLW) into bedrock, materials with compressed clay content are used as a buffer surrounding HLWs (SKBF/KBS 1983; Simmons and Baumgartner 1994). Bentonite has been preferred buffer material due to its low hydraulic conductivity, high absorption capacity, self-sealing properties and durability (Smith et al., 1980). Due to its sufficiently low hydraulic conductivity, compacted clay layers are used more as a buffer (Cho et al. 1999). High gas permeability and low hydraulic conductivity of sand-bentonite mixtures are among the reasons to be preferred as buffer material. In the literature, it is emphasized that the mechanical properties of sand-bentonite mixtures change depending on the density of the clay, and generally sand only acts as a filler (Graham et al. 1989; Dixon et al. 1993). The Swedish solid waste disposal practice, which began in the 1970s, was to bury high-level vitrified waste into containers surrounded by a buffer of 10% bentonite/90% sand at a depth of approximately 500 m in the bedrock. In Canada, sand-bentonite mixtures are widely used as a multi-component buffers (Lingnau et al. 1996).

In order to increase thermal durability of buffer materials (i.e. bentonite or sand-bentonite mixtures) some additives may be used. A one of candidate additive material is perlite. Perlite is used in many sectors such as construction, food, agriculture, medicine, chemistry and metallurgy. Expanded perlite is widely used in the construction industry as heat and sound insulation material. Expanded perlite is produced from raw perlite. Its structure is an amorphous aluminosilicate of volcanic origin. It has a highly porous structure, low density, low cost and good thermal reliability (Karaman et al. 2011). The chemical structure of perlite contains compounds such as SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , Na_2O , K_2O , MgO (Mekaddem et al. 2019). In expansion process, raw perlite powder consisting of large particles is heated to about 1150 K (876.9°C) and the material is softened. With this softening, the water in the structure of the perlite evaporates to form many pores. The pore diameters are generally from 10 μm to about 100 μm . The general porosity of the expanded perlite powder varies between 84% and 98% (Beikircher and Demharter 2013; Allameh-Haery et al. 2017). Due to its thermal insulation properties perlite can be used as an additive material in the buffer materials for energy geostructures.

In the present study, the hydraulic conductivity and shear strength behaviors of perlite-added sand-bentonite mixtures under high temperature (80°C) were investigated. The compaction, direct shear and hydraulic conductivity experiments were performed on the 10% and 20% sand-bentonite mixtures in the presence of 10% and 20% perlite. The direct shear and hydraulic conductivity experiments were carried out under both room and high temperature and the results were compared. In addition, thermal

conductivity values of the sand-bentonite mixtures were measured in the presence of 10% and 20% perlite.

Material And Methods

Material Characterization

Perlite sample was supplied from local supplier and Na-bentonite was used in the experiments. The X-Ray diffraction (XRD) analyses were performed in the focusing geometry from 0° to 89°, with a scanning speed at 0.1° 2θ/s and radiation at 60 kV, 5–60 mA on Thermo Scientific ARL X'TRA X-Ray diffraction equipment. The XRD analyses results of bentonite and perlite samples were given in Fig. 1. According to the results, the aluminum oxide, iron oxide, calcium magnesium aluminum oxide and silicon dioxide were observed in the perlite. The bentonite sample contains montmorillonite, quartz and illite minerals.

Sieve analysis of sand was performed according to ASTM D6913 (ASTM 2017) and 20.7% passed through No.200 sieve. The clay fraction of bentonite was 60%. Table 1 shows the physico-chemical properties of the materials used in the present study. In the tests, sand was sieved through No.6. Sand and bentonite samples were oven dried at 105°C for 24 hours before being used in the tests. Perlite was used without drying and percentage of natural water content was insignificant (~1–2%).

Table 1
The physico-chemical properties of the materials

Property	Sample		
	Bentonite	Sand	Perlite
Specific gravity	2.70	2.63	2.23
Liquid limit (%)	476.0	-	375.0
Plastic limit (%)	70.10	-	NP
pH	9.50	-	8.96

The scanning electron microscope (SEM) photos were taken with COXEM EM-30 Plus device. The samples were compacted under the same conditions of the tests then they were freeze-dried at least 24 hours in order to prevent shrinkage. The SEM photo of the perlite sample is shown in Fig. 2. The flake shaped particles of the perlite can be seen clearly from Fig. 2.

Methods

The samples were prepared by adding 10% and 20% perlite to 10% bentonite-90% sand (10B-90S) and 20% bentonite-80% sand (20B-80S) mixtures. The 10% and 20% of the total dry weight was weighted as perlite. The remaining weight was sand-bentonite mixture. The mixtures were abbreviated as; bentonite "B", sand "S", perlite "PE". For example, the mixture of 10PE-18B-72S contains 10% perlite, 18% bentonite,

72% sand. The samples were mixed in dry state homogenously and then water added by spraying. After preparing the samples, they were kept in a closed container for 24 hours. The Standard Proctor Test was performed according to the ASTM D698-12 (ASTM 2012).

Direct shear tests were carried out according to ASTM D3080 (ASTM 2011). The dry samples were mixed in a vessel until becomes homogeneous. The water content was adjusted as 2% wet side of the optimum water content ($w_{opt} + 2\%$) of each mixture. The samples were compacted in three layers at maximum dry unit weight in the 6x6 cm molds (Fig. 3). The samples were kept in submerged condition in water for 24 hours, in order to prevent swelling weight was placed on the samples. After 24 hours, the mold was placed in the shear box which was filled with tap water. Under three different normal stress values (49, 98 and 196 kPa) the samples consolidated. When change in deformation amounts became insignificant shearing part was started. The direct shear experiments were performed under room ($\sim 25^\circ\text{C}$) and high (80°C) temperatures. In order to maintain high temperature, 80°C , in the shear box specially designed heat rod was used (Fig. 3). The temperature of the water in the cell was kept constant at 80°C by using thermostat. Two separate K-type thermocouples and a digital thermometer measured and recorded the temperature of the water and soil sample (Fig. 3). At the end of the tests, the samples were placed in an oven at 105°C to determine the final water content.

Hydraulic conductivity tests were carried out according to ASTM D5084 (ASTM 2001) using flexible wall permeameters. Samples were placed in plastic bags in an airtight manner and kept for 24 hours. The samples were compacted at maximum dry unit weight and $w_{opt}+2\%$ water content then removed from the mold by using jack. It was known that preparing a sample on the wet side of the w_{opt} provides higher dry unit weight with less energy and consequently lower hydraulic conductivity. For that reason, all mixtures were prepared at their 2% wet side of the w_{opt} . Geotextiles with a diameter of 15 cm on the top and bottom of the sample placed in the permeameter, latex membrane around it and O-rings on the membrane were used (Fig. 4).

The hydraulic conductivity tests were carried out in two different temperature conditions; room temperature and 80°C . The water in the cell, hence the soil was heated by using specially designed heat rod (Fig. 4). The applied cell pressure was 50 kPa. Instead of plexiglass, aluminum material was preferred as a cell material in order to prevent negative temperature effects. In the upper part of the cell, there were three separate holes; one of them for heat rod, the others for thermostat and thermocouple. In case of leakage from the holes, their surroundings were covered with heat-resistant liquid gasket. A hole of approximately thermocouple diameter was opened on the geotextile and the thermocouple was reeved from this hole by passing through a valve of the permeameter. Thus, temperature measurement of the soil was also provided. The temperature of the water was measured by thermocouple by opening an inlet from the top of the cell. The two thermocouples were connected to digital thermometer and temperature values were recorded depending on time. The thermostat system was used to keep the water temperature inside the cell constant at 80°C . Hydraulic conductivity tests were expressed as the pore volume of flow. Inflow and outflow amounts were recorded during the tests and Q_{out}/Q_{in} values were between $0.75 \sim 1.25$.

The thermal conductivity values of the mixtures used in this study were measured with the Shotherm QTM instrument. Measurements were carried out at ambient temperature was between 20~22°C. The samples were compacted at the same void ratio ($e = 0.6$) and were kept closed for 24 hours for homogeneity. Before the tests, the samples were mixed again to ensure homogeneity and compacted in a mold with a volume of 12x12x4 cm³ with a total of 3 layers and 104 impacts. The number of impacts and the order of application to the sample were determined by trial tests. Samples were tried to compact under equal energy level. Measurements were taken from five different places of the sample in order to avoid inhomogeneity (Fig. 5). The thermal conductivity values were determined by averaging these five values.

Results

The thermal conductivity, compaction, direct shear and hydraulic conductivity experiments were performed on the 10B-90S and 20B-80S mixtures in the presence of 10% and 20% perlite additives. Direct shear and hydraulic conductivity tests were carried out both in room and 80°C temperatures.

The compaction parameters of the samples were determined by Standard Proctor tests (ASTM D-698, 2012). The test results of perlite-added sand-bentonite mixtures were given in Table 2. The maximum dry unit weight of the 10B-90S mixture was determined as 16.6 kN/m³ and w_{opt} as 13%. The dry unit weight of perlite was 2.9 kN/m³ and w_{opt} was determined as 240%. It should be noted that perlite have high water holding capacity and low dry density. Hence maximum dry unit weight of the mixture with 10% perlite decreased to 14.8 kN/m³ and w_{opt} increased to 20%. When the perlite percentage in the mixture was increased from 10–20%, the maximum dry unit weight decreased to 13.1 kN/m³ and the w_{opt} reached to 30%. The test results showed that the perlite additive decreased the dry unit weight of 10B-90S mixtures and increased the optimum water content.

Table 2
Compaction parameters of the mixtures

Mixtures	$\rho_{d,max}$ (kN/m ³)	w_{opt} (%)
10B-90S	16.6	13.0
9B-81S-10PE	14.8	20.0
8B-72S-20PE	13.1	30.0
20B-80S	15.6	17.5
18B-72S-10PE	11.1	25.0
16B-64S-20PE	8.8	50.0

Addition of perlite to 20B-80S mixtures showed same trend similar to 10B-90S mixtures. While the dry unit weight of the 20B-80S mixture was 15.6 kN/m^3 , this value decreased to 11.1 kN/m^3 and 8.8 kN/m^3 , respectively with addition of 10% perlite and 20% perlite. On the other hand, the w_{opt} values increased from 17.5–25% and 50%, with 10% and 20% perlite additives, respectively.

Shear Strength Behavior Under High Temperatures

The direct shear tests of sand-bentonite mixtures were performed in the presence of 10% and 20% perlite additives under room temperature and 80°C . It was observed that the shear strength decreased when the temperature of additive-free 10% bentonite-sand mixture was increased from room temperature to 80°C (Fig. 6). The angle of internal friction values did not change significantly, however the cohesion value decreased from 40.4 to 31.5 kPa. The perlite addition increased the angle of internal friction of sand-bentonite mixtures under room and high temperature for 20B-80S mixtures (Table 3). In addition, perlite addition to 10B-90S mixtures had a decreasing effect on the shear strength under both room and high temperature.

Table 3
Internal friction angle and cohesion values of 10% and 20% perlite added sand-bentonite mixtures

Mixtures	Room Temperature		80°C	
	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)
10B-90S	32.7	40.4	31.5	31.5
9B-81S-10PE	28.9	34.4	28.6	26.3
8B-72S-20PE	25.1	26.0	31.5	6.4
20B-80S	7.0	38.5	13.4	20.0
18B-72S-10PE	20.0	17.6	12.1	38.3
16B-64S-20PE	23.3	31.1	27.9	24.5

Figure 7 shows the shear stress-horizontal displacement curves of the 20B-80S and 16B-64S-20PE mixtures at 80°C . It was observed that compared to the additive free sand-bentonite, sand-bentonite mixture in the presence of 20% perlite achieved higher shear stress values at the same deformation value. For example, the shear stress value for 9.7% horizontal displacement under 200 kPa normal stress in the 20B-80S mixture was 58.8 kPa, while that of the 16B-64S-20PE mixture at the same deformation and normal stress was 112.9 kPa. This behavior was valid under three different normal stress values.

The effect of temperature on the mechanical properties of soil depends on its overconsolidation ratio, plasticity, expansibility and compaction water content (Baldi et al. 1988; Romero et al. 2001). Delage et al. (2000) studied the plastic contraction behavior of normally consolidated Boom clay at high temperatures.

According to this study, the water expulsion caused thermal contraction. In addition, the plastic volumetric strains caused by contraction had a hardening impact on the soil. De Bruyn and Thimus (1996) and Kuntiwattanakul et al. (1995) reported that the soil strength decreased under undrained condition immediately after heating, while Laguros (1969) observed that the shear strength increased with the temperature as a result of uniaxial compression tests. These opposite findings show that the mineralogy, overconsolidation ratio and water content are the most important factors affecting on the shear strength behavior. In the present study, the samples were compacted at their maximum dry unit weight. It was observed that during shear according to the vertical deformations samples contracted. The increase in temperature caused increase in shear strength especially for additive-free 20B-80S mixture. The reason of this behavior can be hardening behavior of sample as a result of plastic contraction. Another reason can be increase in temperature transforms the smectite mineral into more constant silicate phases (Wersin et al. 2006). As a result of this phenomenon, the water adsorption capacity of clay reduces so the strength of clayey soil increases. The results have shown that perlite has positive effects on the shear strength of sand-bentonite mixtures. There are two reasons of this increase; one of them chemical reaction and the other one is the material replacement. Perlite has silanol (Si-OH) groups at the surface and silanol group bounds hydroxyl groups at the edges of the clay platelets (Ogawa et al. 1998). For that reason, perlite is held by the clay surface. Eventually the shear strength of the sand-bentonite mixture increases. Another reason of the increase in shear strength is material replacement. Because when the perlite added to the sample both bentonite and sand content was decreased. The bentonite material was replaced with perlite mineral which has a very high thermal resistivity and very low thermal expansion. For that reason, the material replacement may be another reason of the increase in shear strength of sand-bentonite mixtures under high temperature.

Hydraulic Conductivity Behavior Under High Temperatures

In this study, flexible wall hydraulic conductivity (k) experiments were performed on the 9B-81S-10PE and 16B-64S-20PE mixtures at room temperature and high temperature. Initially, the hydraulic conductivity experiments were started at room temperature then the sample were subjected to temperature increase with the achievement of stable flow. The temperature was gradually increased from 25°C to 50°C and 80°C, respectively. At each temperature increment step, the tests were run until outflow to inflow ratio becomes within 0.75–1.25. As a result of this 25°C-50°C- 80°C temperature cycle was applied. There were two thermocouples in the cell, one of them for water temperature the other one for the soil temperature. According to the temperature measurements, it was observed that the soil in the cell reached a lower temperature than the water. Generally, the temperature difference between the water and soil was approximately 10–15°C. With the help of thermocouple placed in the soil, it was determined that the soil temperature was 20, 40, 60°C when the water temperature was 25, 60, and 80°C, respectively. The hydraulic conductivity experiments were conducted on the 10B-90S and 20B-80S mixtures at room temperature in order to compare the results under high temperature. While the k value for the 10B-90S mixture was 1.7×10^{-11} m/sec, it was determined as 1.4×10^{-11} m/sec for the 20B-80S. The k values of 9B-81S-10PE and 16B-64S-20PE mixtures were given in Figs. 8 and 9 under room temperature and high temperatures, respectively. The k values reached at 25°C-50°C- 80°C temperatures to 7.0×10^{-11} m/sec,

7.5×10^{-10} m/sec and 1.4×10^{-9} m/sec, respectively. The effect of temperature increase was clearly seen with the increase in hydraulic conductivity values. When the temperature cycle was applied to 9B-81S-10PE mixture, the hydraulic conductivity values decrease to 1.2×10^{-9} m/sec (from 80°C to 50°C) and 5.4×10^{-10} m/sec (from 50°C to 25°C). After that the hydraulic conductivity value increased to 6.6×10^{-10} m/sec when the temperature was increased from 25°C to 50°C. The results have shown that after temperature cycles the mixture could not reach its initial k value.

The k value of 16B-64S-20PE mixture under room temperature was determined as 4.5×10^{-10} m/sec. Then k value increased to 7.3×10^{-10} m/sec and 9.1×10^{-10} m/sec when the temperature was increased to 50°C and 80°C, respectively. The hydraulic conductivity of the 16B-64S-20PE mixture increased approximately two times when the room temperature was increased to 80°C.

The SEM photos of additive-free 20B-80S mixtures at room temperature and 80°C are given in Fig. 10. Decrease in pore structure and contraction of the sample by temperature increase was seen from these photos. The SEM photos of the expanded perlite sample at room temperature, 16B-64S-20PE mixture at room temperature and 80°C are given in Fig. 11. From Figs. 11b and c, it was seen that although the perlite ratio is 10% and 20% in the mixtures, it took up a large volume due to its light weight. In a previous study, it was reported that the flake-shaped perlite particles clogged the pores and may form impermeable filter cake layer (Bageri et al. 2020). However, according to results of this study that mentioned clogging effect was not seen. The perlite addition to the sand-bentonite mixtures increased the hydraulic conductivity values of the samples at room temperature and high temperatures. In terms of hydraulic conductivity, highly porous structure of expanded perlite allows water to drain.

The hydraulic conductivity value can be calculated by help of the empirical equations. For example, an equation showing the relationship between saturated hydraulic conductivity k_s and temperature T were used by Ye et al. (2013). The Eq. 1 gives the calculated hydraulic conductivity value, while Eq. 2 shows the temperature dependent viscosity change. In Eq. 3 k_m is the intrinsic permeability value obtained from the measured hydraulic conductivity values.

$$k_s = k_{in} \rho_w g / \eta(T) \quad (1) \quad (\text{Ye et al. 2013})$$

$$\eta(T) = 0.0002601 + 0.001517 \exp[-0.034688x(T - 273)] \quad (2) \quad (\text{Ye et al. 2013})$$

$$k_s = \frac{k_m \times \rho_w g}{0.0002601 + 0.001517 \exp[-0.034688x(T - 273)]} \quad (3) \quad (\text{Ye et al. 2013})$$

Where $\eta(T)$: is defined as the viscosity of water depending on temperature, k_{in} : intrinsic permeability, g: gravitational acceleration, T: absolute temperature in Kelvin and ρ_w : density of water.

The Table 4 shows the change in water density and viscosity at different temperatures.

Table 4. Temperature influence on some properties of water (Lide 1995)

Temperature (°C)	Water density (g/cm ³)	Water viscosity (10 ⁻⁶ Pa s)
10	0.9997	1307
20	0.99821	1002
30	0.99565	797.7
50	0.98803	547
80	0.97182	354.4

Equation 3 is defined as a relation that only takes into account the effect of temperature on water viscosity. The hydraulic conductivity values of 9B-81S-10PE and 16B-64S-20PE mixtures at 25°C, 50°C and 80°C were calculated by using Eq. 3. Figure 12 compares calculated and measured hydraulic conductivity values of 9B-81S-10PE and 16B-64S-20PE mixtures. It can be seen that the measured hydraulic conductivity values were lower than predicted values.

Similar differences between calculated and measured values were reported by Ye et al. (2013) and Rivas et al. (1991). It means that only change in water viscosity is not enough to fully explain the change in hydraulic conductivity values. The former studies have shown that, as temperature increases fabric structure changes in clays and larger gaps form in the soil (Pusch and Güven, 1990; ; Pons et al., 1994; Thomas et al., 1994; Romero et al. 2001). Figure 13 shows the change in hydraulic conductivity values of sand-bentonite mixtures in the presence of perlite additive. This graph does not include the temperature cycling part of the 9B-81S-10PE mixture. According to the Fig. 13, it can be concluded that the hydraulic conductivity values of both mixtures increased with increasing temperature. The hydraulic conductivity values of 9B-81S-10PE mixture increased more than 16B-64S-20PE mixture. One of the factor that cause to this result is the reduced permeability due to the increase in the percentage of bentonite in the mixture.

Figure 14 shows the heating-cooling cycle of the 9B-81S-10PE mixture. The results have shown that with increasing temperature hydraulic conductivity increases whereas it decreases with decrease in temperature. As a results of thermal cycles, it was seen that the samples could not turn back to their initial k values. It means that, temperature changes the pore structure of the samples. Similarly, Romero et al. (2001) reported that hydraulic conductivity affected not only by changes in viscosity, but also thermal changes have effects on soil-water interaction at the microstructural level. It has been reported that heating leads to weakening of microstructure, because larger voids are formed by heating (Chen et al.2017).

Thermal Conductivity Results

The thermal conductivity values of 10% and 20% sand-bentonite mixtures in the presence of perlite were measured. The results showed that the thermal conductivity values decreased as the perlite was added to the sand-bentonite mixtures (Table 5). As the perlite additive percent increases, the decrease in thermal conductivity will prevent the spread of heat formed around the energy structures and facilities by using

mixtures with perlite additives. As bentonite content increased in the sample thermal conductivity value increased. The main reason of this the higher water adsorption capacity of bentonite.

Table 5
The measured thermal conductivity values of mixtures

Mixture	Thermal Conductivity (λ , $W m^{-1}K^{-1}$)
10B-90S	1.153
9B-81S-10PE	0.868
8B-72S-20PE	0.299
20B-80S	1.971
18B-72S-10PE	0.992
16B-64S-20PE	0.715
100PE	0.477

Conclusion

In this study, the direct shear test and hydraulic conductivity tests were performed on the 10% and 20% perlite added sand-bentonite mixtures under room temperature and 80°C. The following conclusions can be drawn from the present study:

1. When perlite additive was added to the 10B-90S mixture under room temperature, the maximum shear stress value did not increase, its shear strength at both room and high temperatures decreased. In addition to these, perlite additives in both room and high temperatures in 20B-80S mixtures increased the shear stress values and had a positive effect on strength.
2. It has been observed from hydraulic conductivity tests, which were carried out at room temperature, and 80°C that perlite additive increased the hydraulic conductivity coefficient (k) with increasing temperature. During heating-cooling cycles, there is a direct relationship between the hydraulic conductivity and temperature. As temperature decreased the k values increased.
3. The hydraulic conductivity test results under high temperature showed that; the hydraulic conductivity was less than the expected due to viscosity decrease. According to the results perlite did not improve the hydraulic conductivity values under high temperature.
4. As the perlite ratio in the sand-bentonite mixtures increased, the thermal conductivity of the mixtures decreased. This decrease supports that it may be advantageous to use perlite with the buffer material where prevention of heat diffusion is preferred.

Declarations

Data Sharing and Data Accessibility statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest Statement

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Declaration of Competing Interest

The authors declare they have no financial interests.

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Figures

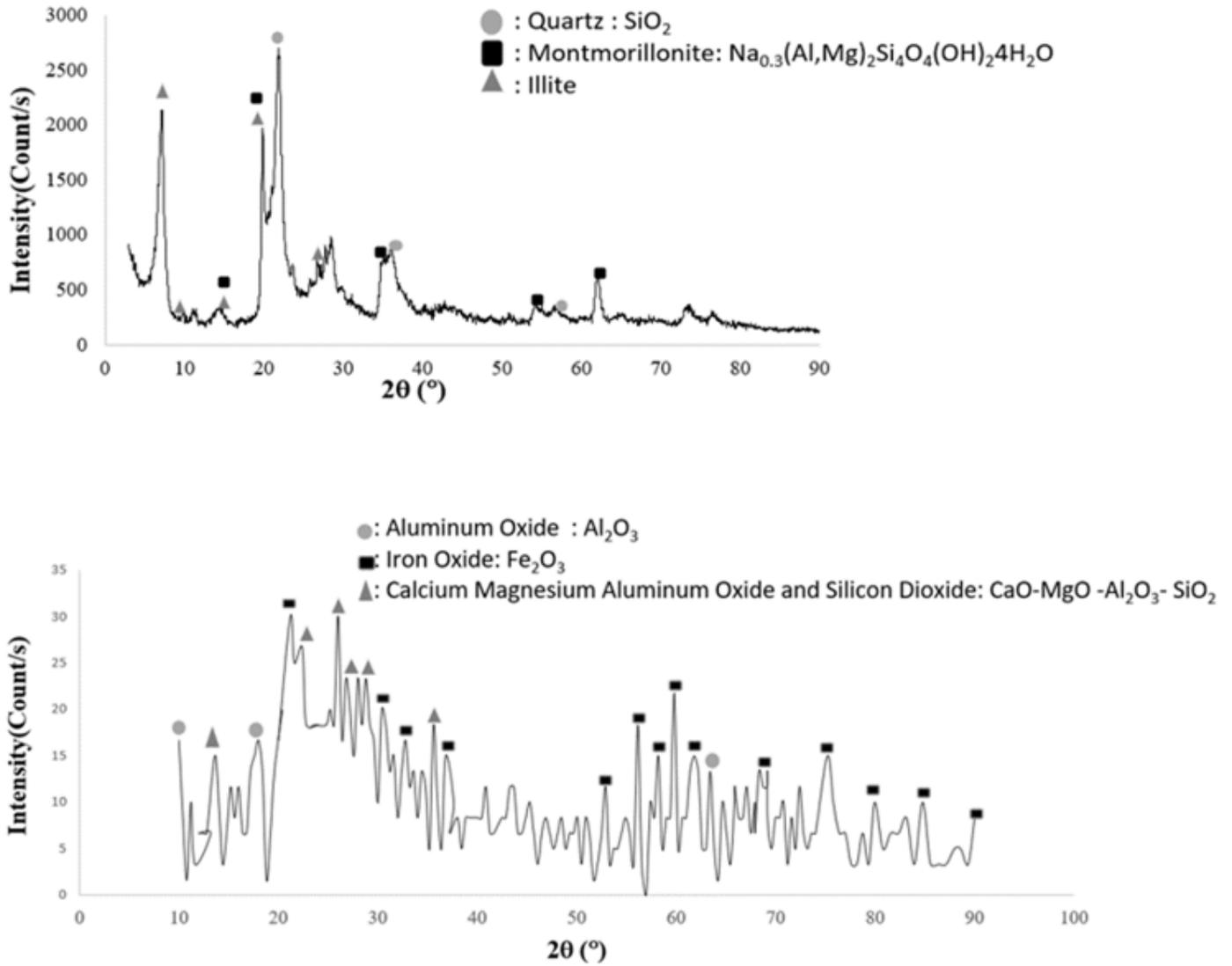


Figure 1

The X-Ray diffraction analysis (XRD) results of the samples a) bentonite, b) perlite

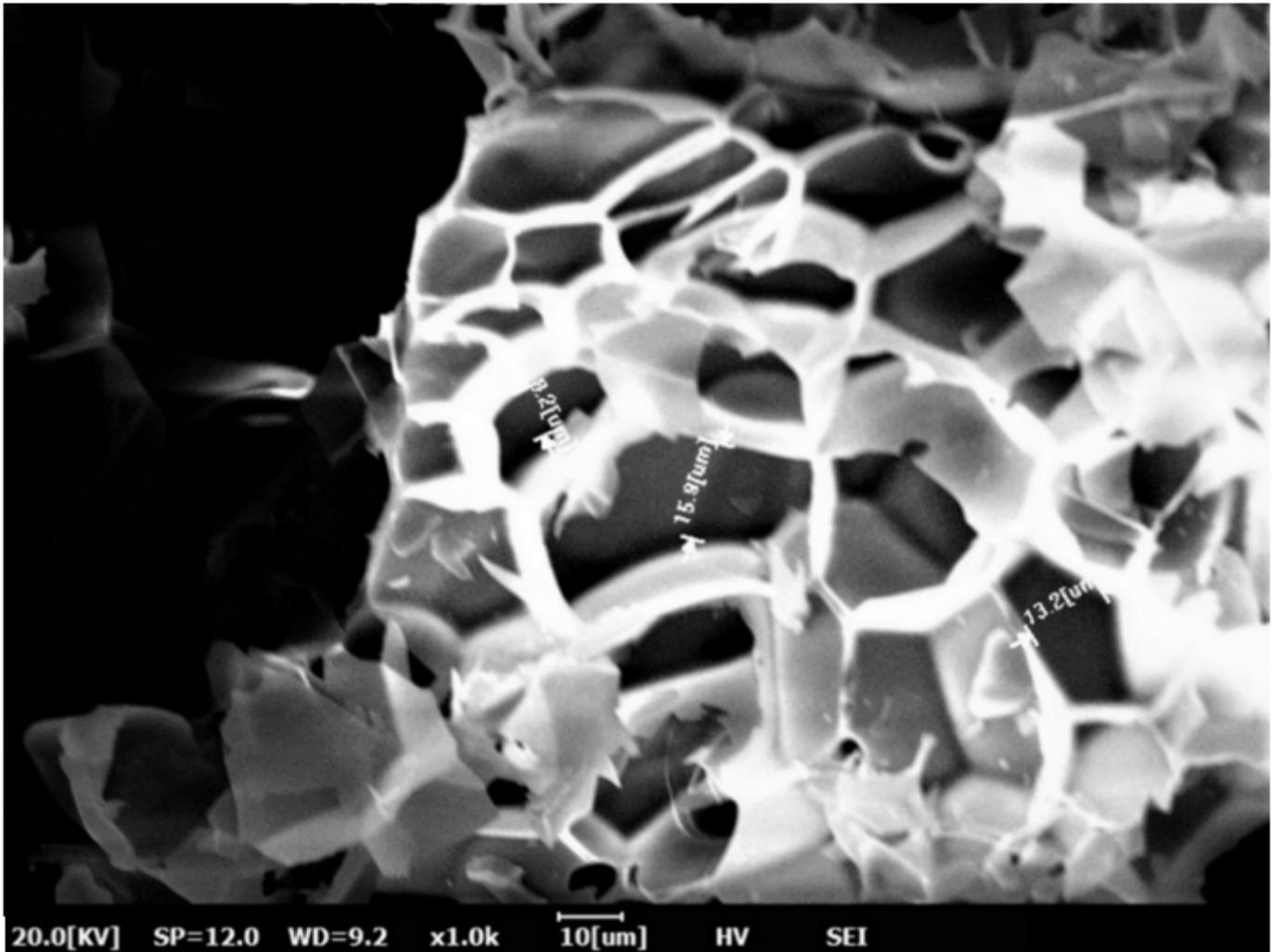


Figure 2

SEM photos of the expanded perlite samples at room temperature (x500)

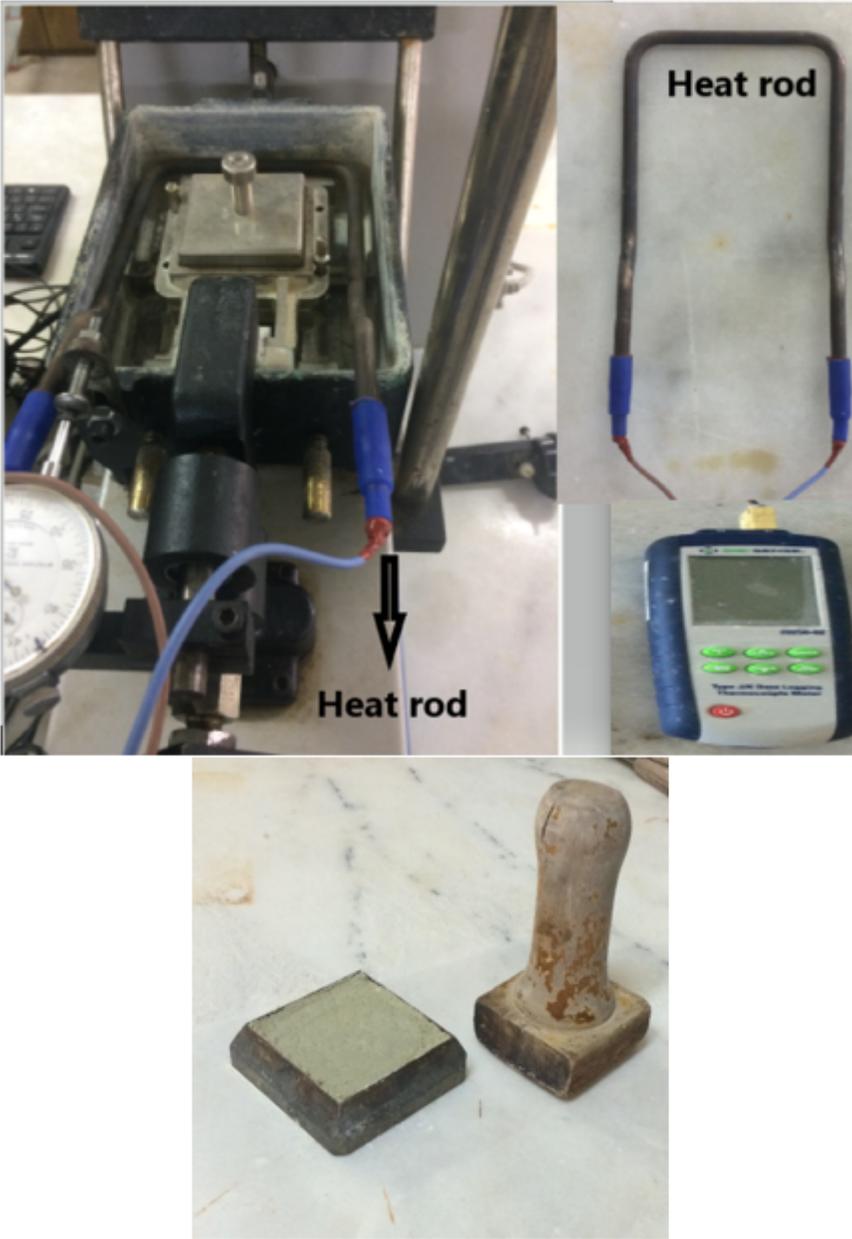


Figure 3

The equipment used in the direct shear tests

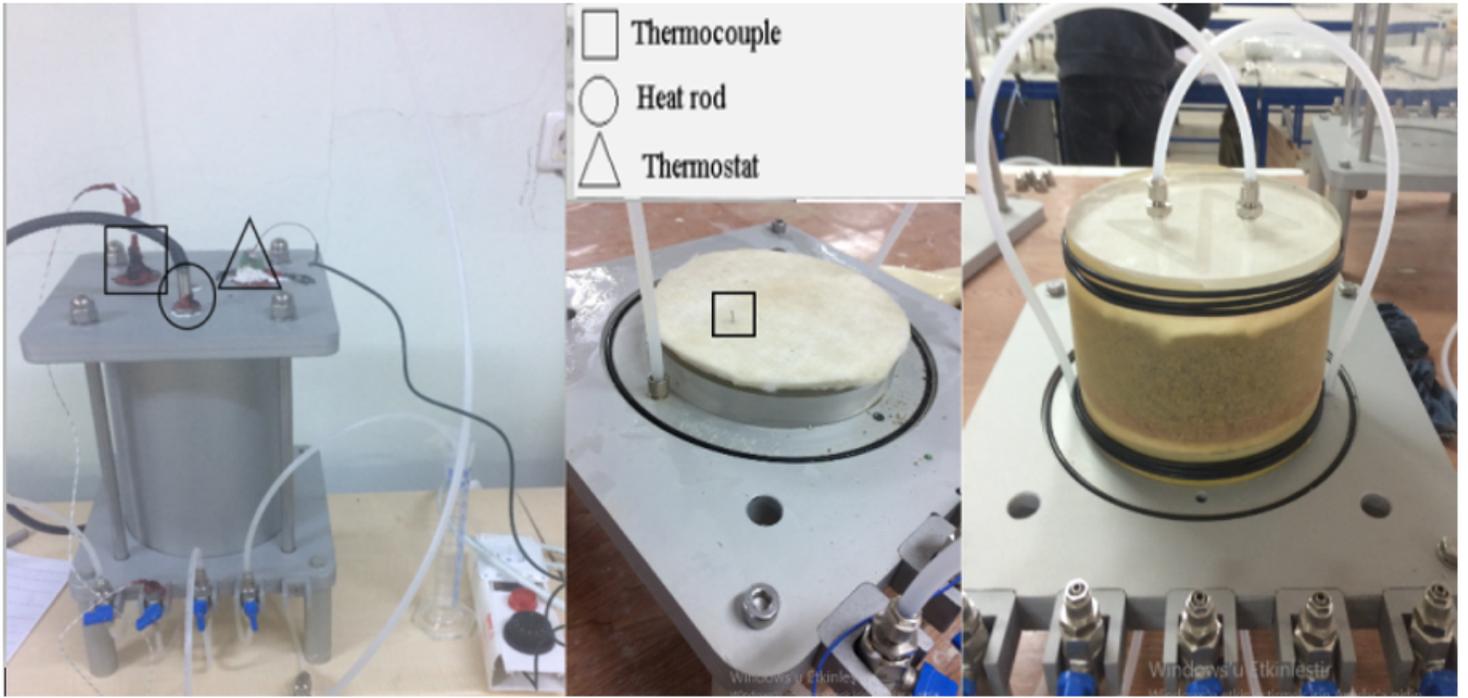


Figure 4

Demonstration of the equipment used in hydraulic conductivity tests

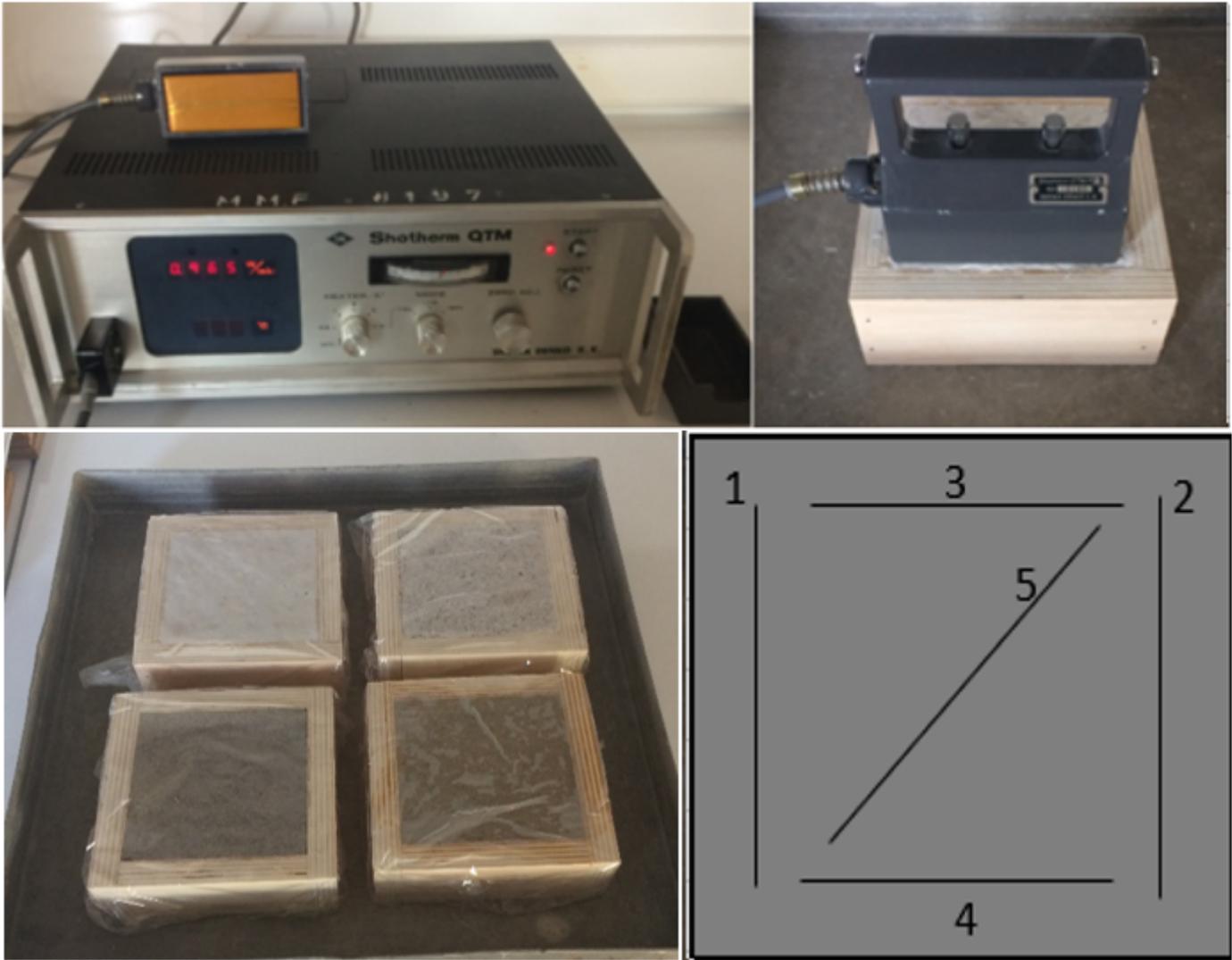


Figure 5

Thermal conductivity equipment and measurement directions

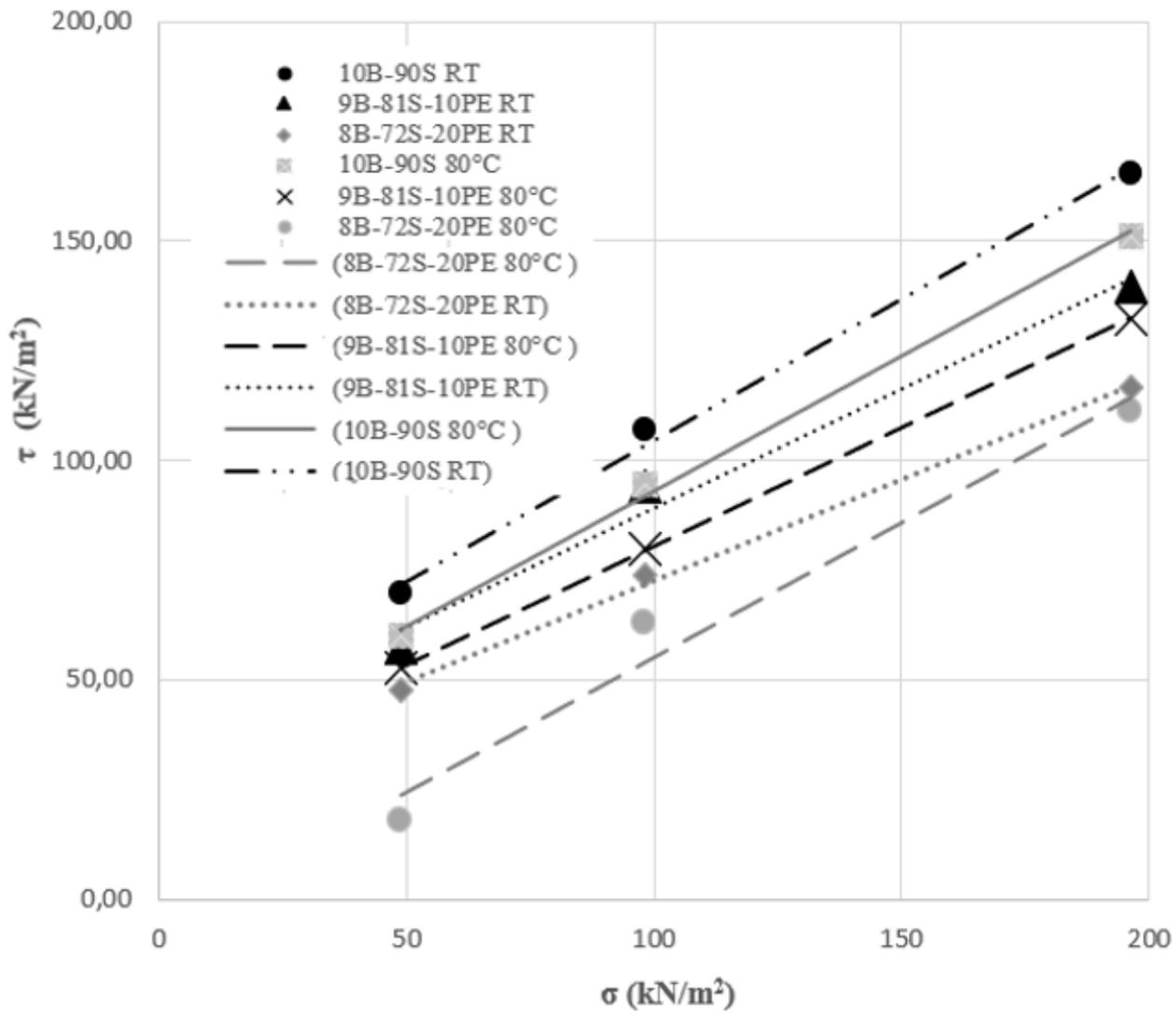


Figure 6

τ - σ graph of 10B-90S mixtures in the presence of 10% and 20% perlite additives under room temperature and high temperature

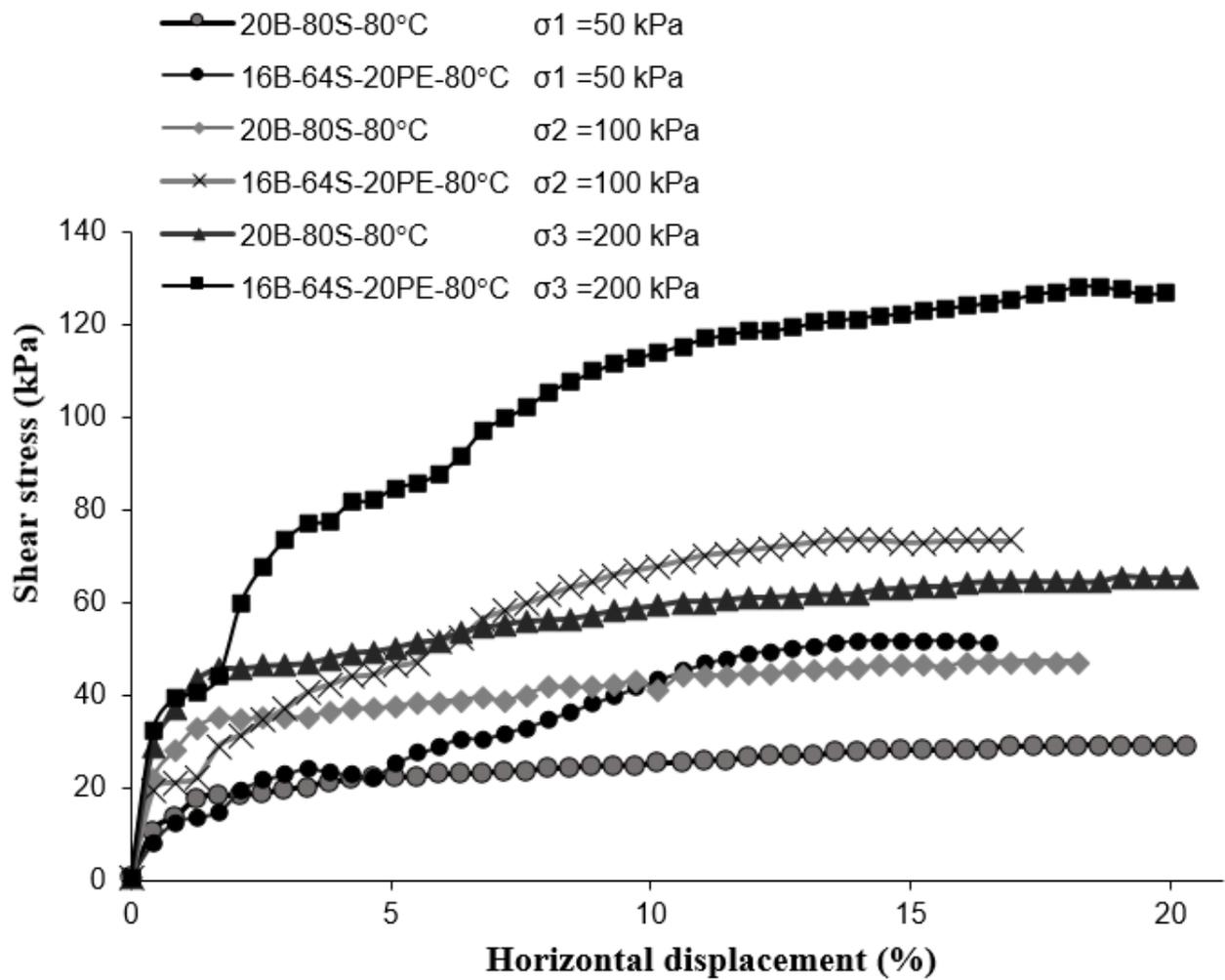


Figure 7

Shear stress- horizontal displacement of 20B-80S and 16B-64S-20PE mixtures at 80°C

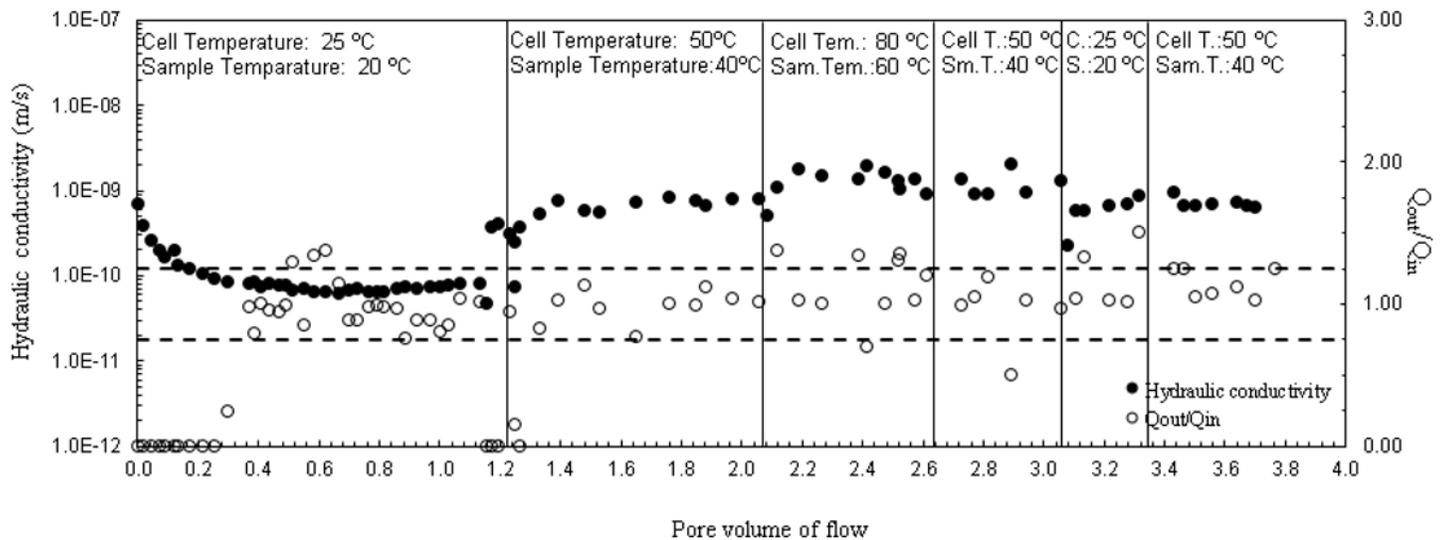


Figure 8

Hydraulic conductivity behavior of 10B-90S mixture with 10% perlite added at room temperature and high temperature

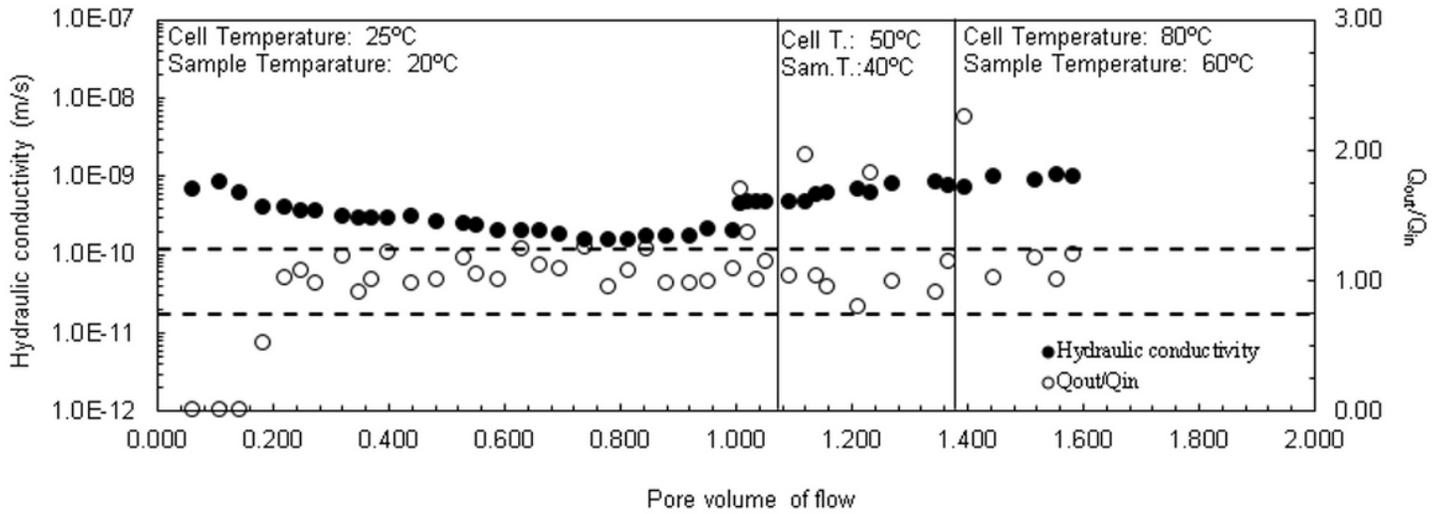


Figure 9

Hydraulic conductivity behavior of 20B-80S mixture with 20% perlite added at room temperature and high temperature

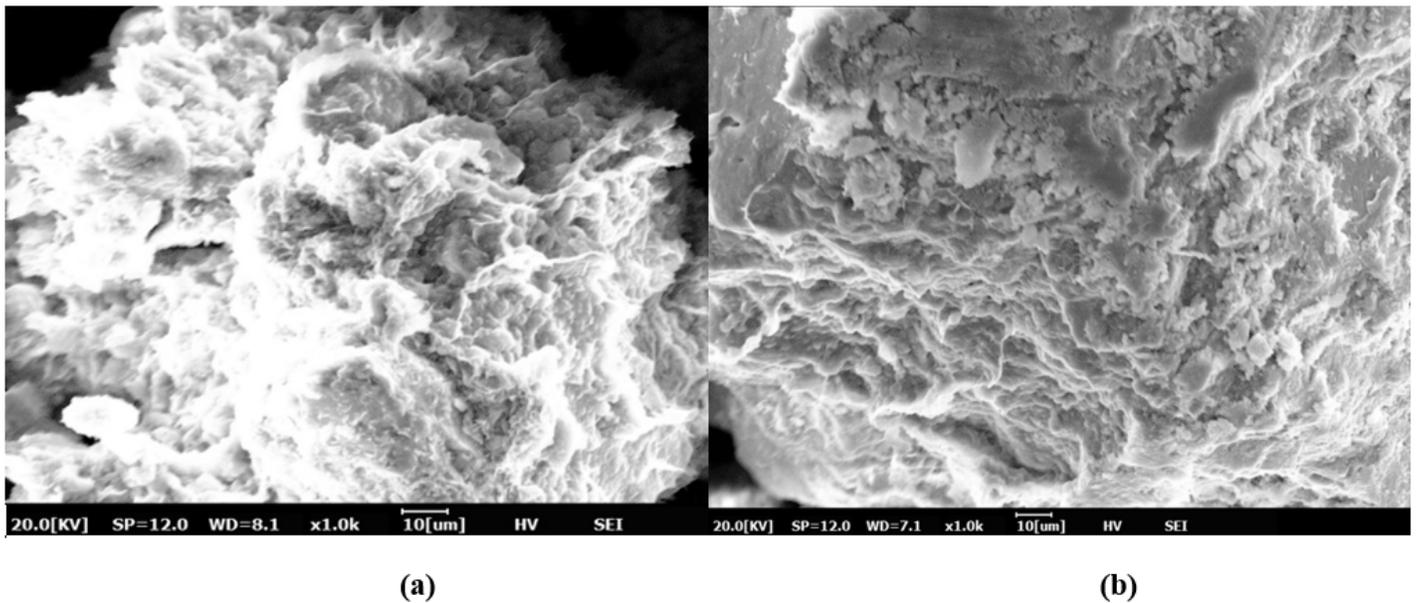
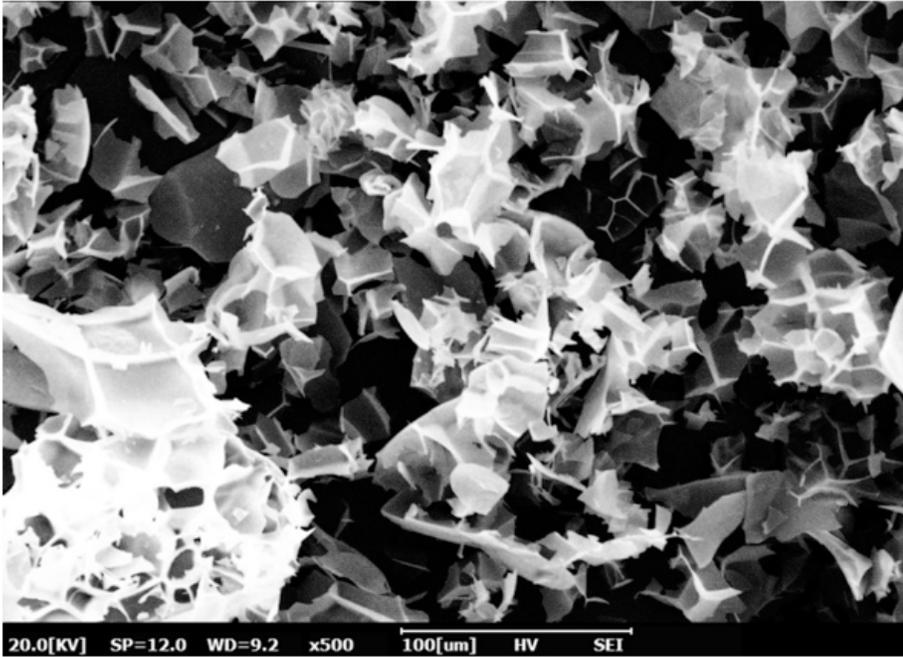
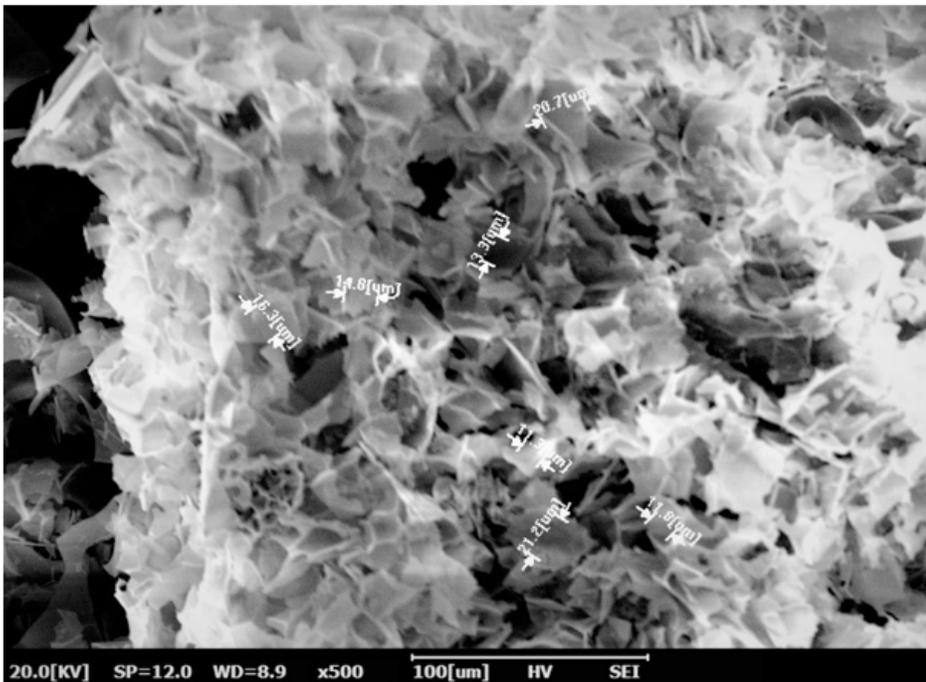


Figure 10

Scanning electron microscope photos of the samples (a) 20B-80S (x1000) at room temperature, (b) 20B-80S (x1000) at 80°



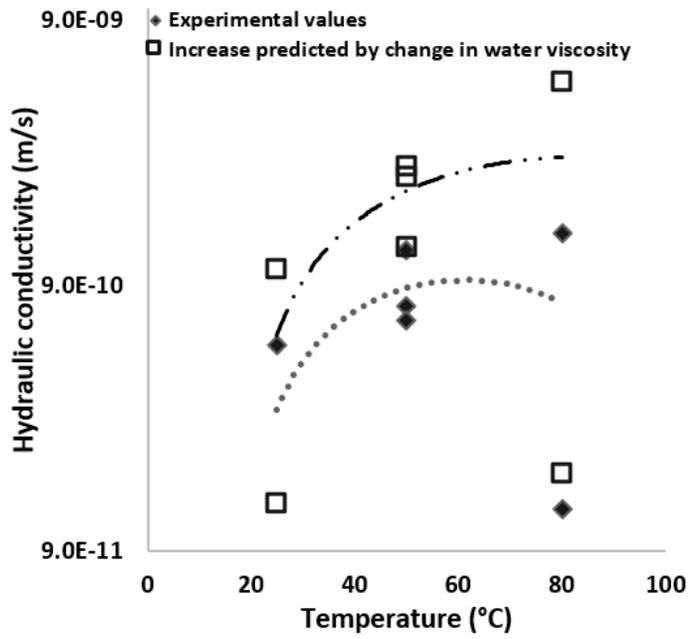
(a)



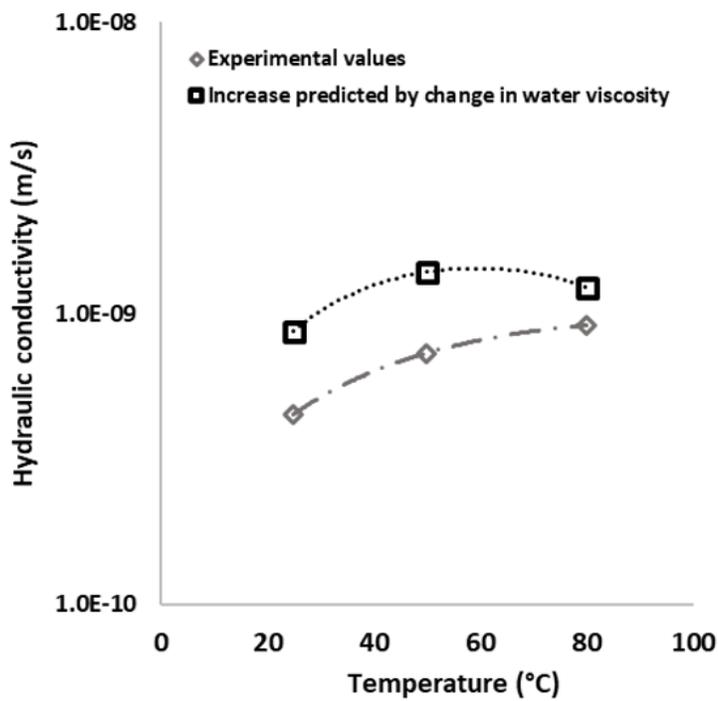
(b)

Figure 11

Scanning electron microscope photos of the samples (a) Expanded perlite samples at room temperature (x500), (b) SEM image of 16B-64S-20PE at RT (x500), (c) SEM image of 16B-64S-20PE at 80°C (x500)



(a)



(b)

Figure 12

Change of calculated and measured hydraulic conductivity values as a function of temperature 81S-10PE, b) 16B-64S-20PE

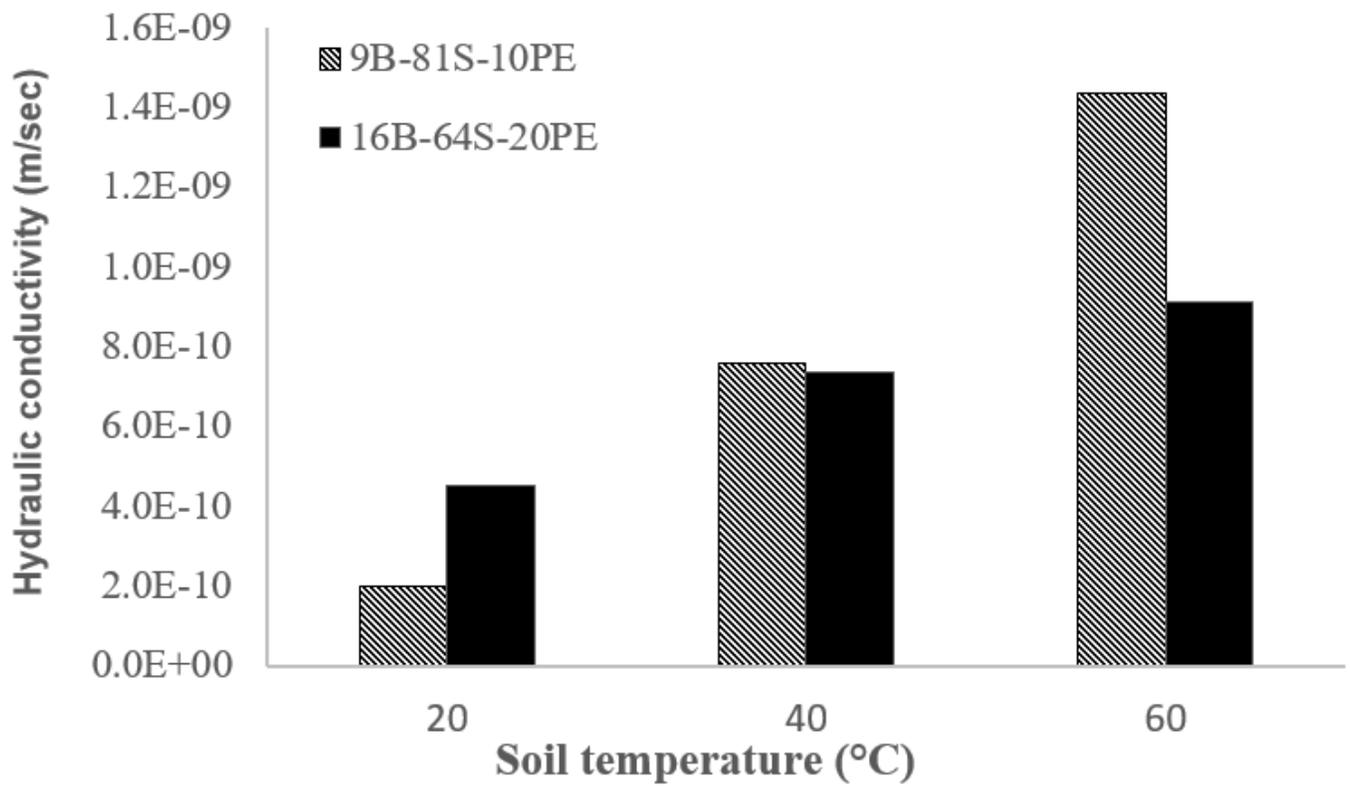


Figure 13

Hydraulic conductivity coefficients of perlite-added sand-bentonite mixtures

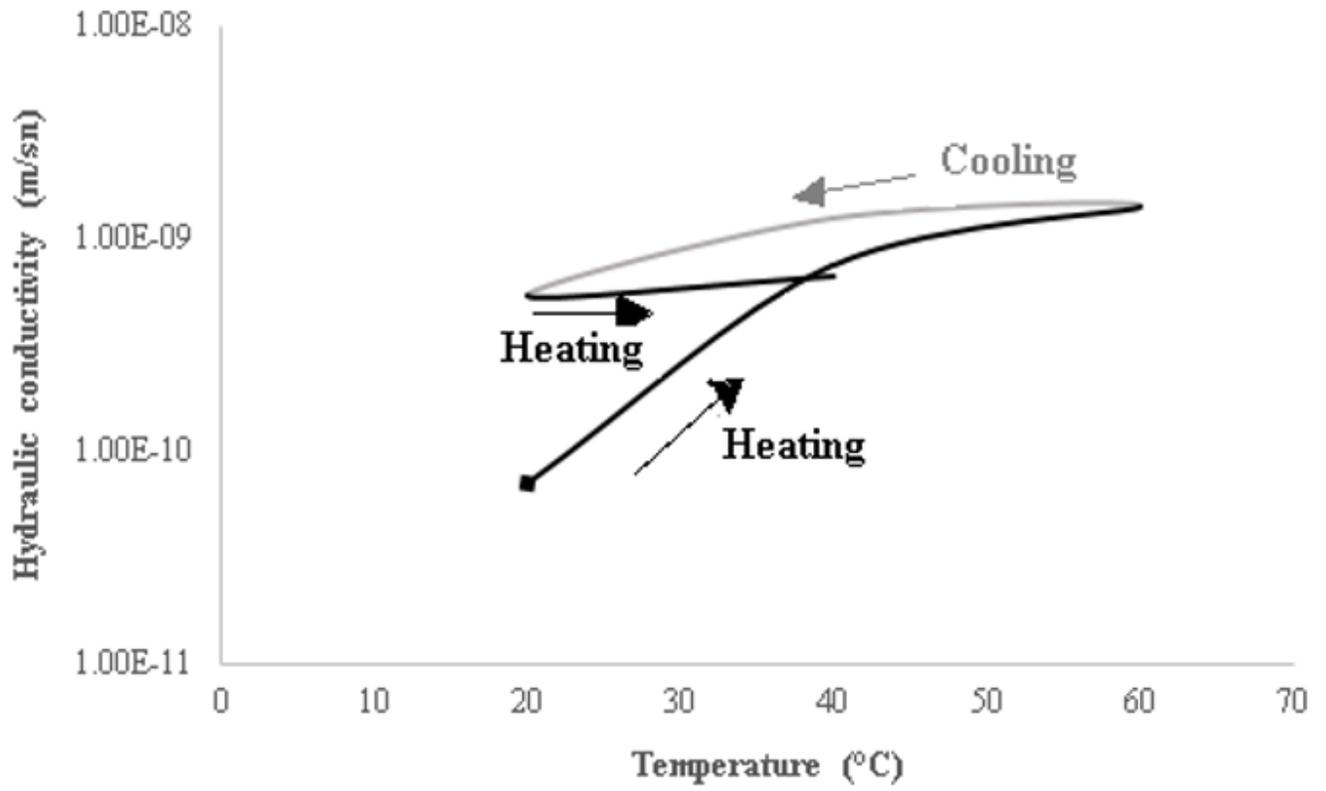


Figure 14

Variation of the hydraulic conductivity during heating-cooling cycles for 9B-81S-10PE mixture