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High Temperature Effect on the Engineering Performance of Pumice Added Sand-Bentonite Mixtures

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ABSTRACT

Soils surrounding energy geo-structures must perform for long periods of time under high temperatures and thermal cycles. Engineering properties of soils are affected by temperature. Pumice is a thermally durable material and it may be used to increase thermal durability of soils. For this reason, it was aimed to develop thermally durable soil material by adding pumice additive to sand-bentonite mixtures. 10% and 20% pumice were added to 10% and 20% sand-bentonite mixtures and compaction, consolidation, direct shear and hydraulic conductivity tests were performed. The direct shear and hydraulic conductivity tests were performed both at room temperature and 80 °C. The consolidation test results showed that as pumice content was increased the total vertical deformation decreased at room temperature. Pumice additive reduced the maximum shear stress values when temperature increased for 10B-90S mixtures. However, the pumice additive increased the internal friction angle of the mixtures at high temperature. It was observed that the hydraulic conductivity increased with increasing temperature. Thermal conductivity measurements showed that pumice additive reduced the thermal conductivity value of the mixtures.

Keywords: Consolidation, permeability, pumice, sand-bentonite, strength, high temperature.

1. INTRODUCTION

The thermal behavior of soils has gained importance because of increase in number and type of energy geo-structures such as energy piles, nuclear waste repositories, waste handling facilities, electricity transmission and gas pipelines. The buffer (bentonite, bentonite-sand) barrier, which is used as a sealing material at underground depot for high-level radioactive waste, is exposed to high temperatures. Hence, change in hydraulic and mechanical properties of buffer is a matter to be considered in the design of nuclear waste repositories.

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Moreover, the buffer material is needed which keeps its engineering parameters unchanged under different thermal conditions especially in nuclear waste repositories.

Previous studies have shown that engineering properties of clayey soils change under high temperatures [1]. High temperature alters soil physico-chemical properties; hydro-mechanical properties as well [2, 3]. Increase in temperature of saturated fine-grained soils to a level lower than the boiling point of water affects the permeability, compressibility and shear strength behavior [4]. Thermal effects on shear strength, stiffness and yielding behavior can be attributed to the volume change of soil [5]. The temperature increase in fine grained soils such as clay and unsaturated soils can cause permanent changes in volume [6, 7, 8, 9, 10]. The over-consolidated clays show the elastic expansion behavior, while the normally consolidated soil exhibits elasto-plastic thermal shrinkage (contraction) during heated consolidation [6, 7, 10, 11, 12, 13]. Also at same dry density, high temperature significantly reduces the swelling pressure of clayey soil, while diminishing swelling capacity vaguely [14].

The shear strength of the normally consolidated (NC) clay increases with increasing soil temperature [15]. For example, the axial stress in the peak deviatoric stress was lower than that of the specimen at elevated temperature for the sample that subjected to temperature history prior to shearing. However, the slope of the shear strength envelope is independent of temperature [15]. The heated normally consolidated clay showed contraction during the direct shear test. The reason for this behavior is thought to be the hardening of the clay during heating [16].

Previous studies have shown that hydraulic conductivity increased with increasing temperature [14, 17, 18]. The properties of pore water vary depending on temperature and viscosity of the liquids passing through the porous structure of soils [15]. In addition, the structural interaction of soil with water is also important.

In liner applications, due to the low hydraulic conductivity, bentonite is mixed with sand and used as a reinforced filling material with high thermal conductivity and stiffness [1]. Sand-bentonite mixture is more preferred as a filling material because of its low permeability and high swelling properties [19]. Pumice is an amorphous aluminum silicate formed as a result of volcanic activities. Chemical structure of pumice includes SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O. Aluminum oxide in the chemical structure of pumice is known to provide high heat resistance [20]. Due to its high heat resistance it can be used to improve engineering properties of soils under high temperatures. Pumice's spongy structure is formed by the outflow of gas from sudden cooling during pumice formation [21]. Since the gaps in the porous structure of the pumice are independent of each other, it is a material with low hydraulic conductivity [22]. The pumice does not undergo any volume changes below 760 °C and does not enter the chemical reaction with any acid other than hydrofluoric acid. Already the dissolution rate of pumice in an acid is maximum 2.9% [23, 24]. It was determined that the pumice samples had a glassy structure and when they were heated up to 850 °C, no thermal reactions occurred in their structure and the pumice did not undergo a structural deterioration [22].

Because of superior thermal features of pumice, the addition of pumice to sand-bentonite mixtures may improve the thermal durability of soils against high temperatures. The thermal durability defines the ability of soils to maintain their engineering properties unchanged under temperature cycles or high temperatures. It is known that many properties of soils change such as compressibility, shear strength, hydraulic conductivity under temperature cycles and high temperatures. This change depends on many parameters such as soil type, rate of temperature increase, exposure time to temperature. In the present study, it was aimed to improve engineering properties of sand-bentonite mixtures with pumice additive. To this end; compaction, consolidation, direct shear and hydraulic conductivity tests were performed on the pumice added sand-bentonite mixtures. The direct shear and hydraulic conductivity tests were carried out both under the room and high temperature (80 °C). The effect of pumice and high temperature were analyzed.

2. MATERIAL CHARACTERIZATION AND TEST METHODS

2.1. Material Characterization

In this study, sand-bentonite mixtures were prepared with pumice additive. Pumice was supplied from local supplier. The used bentonite sample was Na-bentonite. According to the results of sieve analysis 20.7% of the sand is fine material. The sand was sieved through No.6 sieve. Sand and bentonite samples were oven dried at 105 °C for 24 hours before being used in the experiments. Pumice was used as it is (without drying) in order to keep its natural state since the natural water content of the pumice was very low, it was not subjected to drying process, however at each experiment the initial water content of pumice (2-3%) was determined and this amount of water was taken into account. The mixtures were prepared by adding pumice to sand-bentonite mixtures in two different bentonite ratios of 10% and 20%. The pumice additive was determined by weight as 10% and 20% of the total dry weight. The mixtures without pumice additives are referred as 10B-90S and 20B-80S, respectively. The physico-chemical properties of the materials were given in Table 1. The bentonite sample passed through No.200 sieve. The grain size distributions of bentonite, pumice and sand are given in Figure 1.

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 analysis results of bentonite and pumice samples were given in Figure 2. According to the results, the calcium silicate, sodium calcium aluminum silicate was observed in the pumice sample. The bentonite sample contains montmorillonite, quartz and illite minerals.

Table 1 - The physico-chemical properties of the materials

Property	Material		
	Bentonite	Sand	Pumice
Specific gravity	2.70	2.63	2.50
Liquid limit (%)	476.0	-	37.0
Plastic limit (%)	70.0	-	Non-plastic
pH	9.50	-	8.86

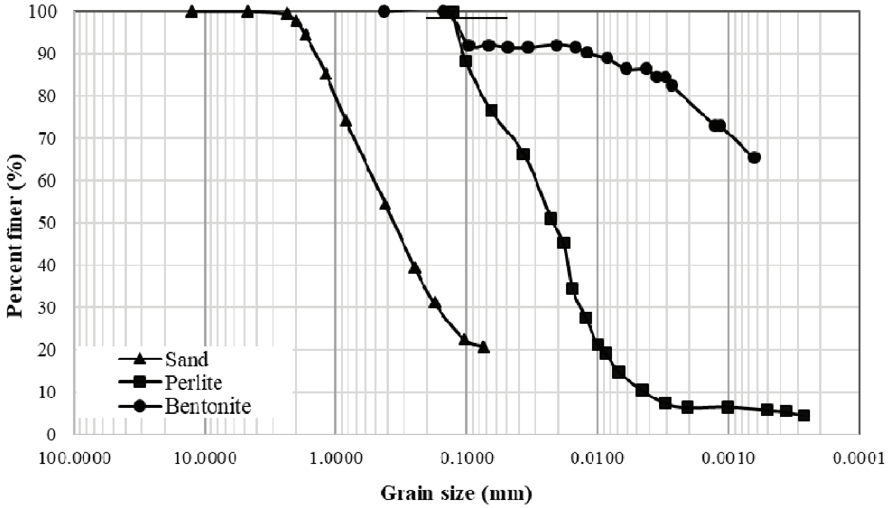

Figure 1 - Grain size distribution curves of bentonite, pumice and sand

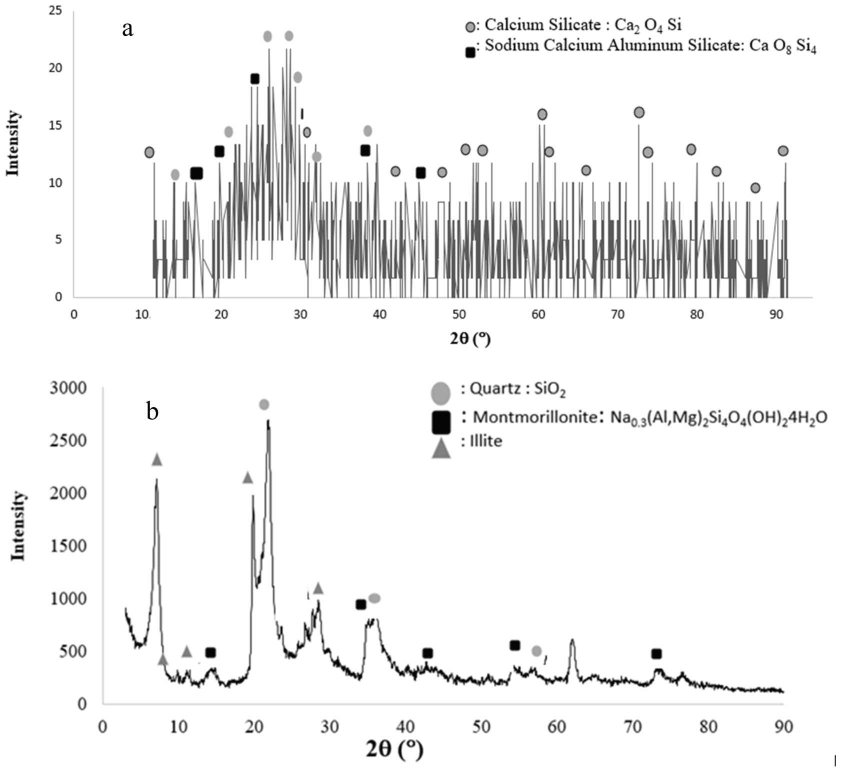

Figure 2 - The X-Ray diffraction analysis (XRD) results of the samples
a) pumice, b) bentonite

The scanning electron microscope (SEM) photos of the samples were taken with COXEM EM-30 Plus device. The samples were compacted at their dry unit weight and w_{opt}+2% water content then they were freeze-dried at least 24 hours in order to prevent shrinkage.

2.2. Test Methods

The samples were prepared by adding 10% and 20% pumice to 10B-90S and 20B-80S mixtures. The 10% and 20% of the total weight of the mixture was weighed as pumice, the remaining dry weight was sand-bentonite mixture. The water added and samples were mixed homogenously and they were kept in a closed container for 24 hours to ensure that the water was homogeneously dispersed in the mixture. For the compaction tests, samples were prepared in four different water contents and Standard Proctor Test was performed according to ASTM D698 [25].

The oedometer test samples were compacted at the 2% wet side of the optimum water content (w_{opt}) corresponding to the maximum dry unit weight (γ_{dmax}). The samples were kept under seating pressure (6.86 kPa) for 24 hours. The consolidation tests were performed to according to ASTM D2435 [26]. The load increment ratio (LIR) was 1.0 (24.5, 49, 98, 196, 392 and 784 kPa). After the completion of the loading stage, unloading stage was initiated. At the unloading stage the loads were decreased from 784 kPa to 196 kPa, then to 49 kPa.

Direct shear tests were performed according to ASTM D3080 [27]. The dry samples were mixed in a vessel until becomes homogeneous. Water was added to these mixtures so that the water content was at 2% wet side of the optimum water content. Each sample was compacted into three layers in the 6x6cm molds. The molds were kept submerged in a container for 24 hours. It should be noted that the water contents of the 10B-90S and 20B-80S samples were increased from 15% to 22.7% and 19.5% to 27.0%, respectively at the end of this process. The initial water contents of the samples increased and changed between 22.7-32.7% at the beginning of the tests. The initial water contents of the samples are given in Table 4. While the samples were kept in water, weight was placed on them to prevent swelling. After 24 hours, the mold was placed in the shear box and cell was filled with water. Three different normal stresses (49, 98, 196 kPa) were applied in the direct shear experiments and samples were consolidated and sheared under these stresses.

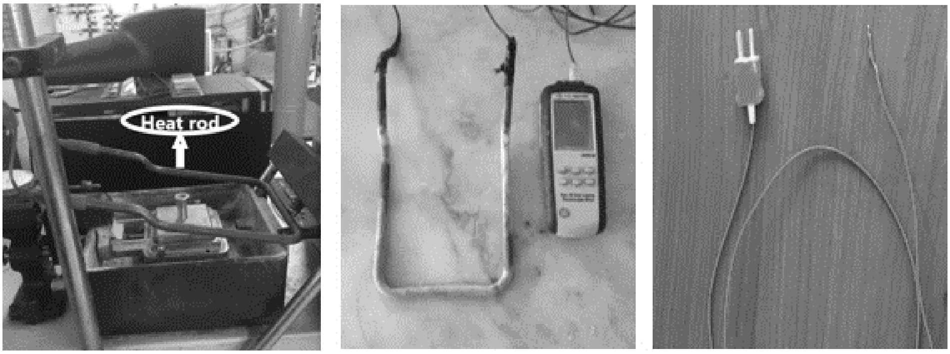

Figure 3 - Temperature controlled direct shear test equipment

The direct shear experiments were conducted under two different temperatures, at room temperature and 80 °C. The water in the shear box was heated with specially designed heat rod (Figure 3). The temperature of the water in the cell was kept constant at 80 °C by help of thermostat. Two K-type thermocouples and a digital thermometer measured and recorded the temperature of the water and soil sample (Figure 3). At the end of the experiments, the samples were placed in an oven at 105 °C to determine the water content.

Hydraulic conductivity tests were carried out according to ASTM D5084 [28] using flexible wall permeameters. The samples were kept in airtight plastic bags for 24 hrs. In order to compact samples with less energy, the samples were compacted at γ_{dmax} and w_{opt}+2% water content. The hydraulic conductivity tests were performed in two different temperatures: room temperature and 80 °C. During the tests, the temperature was provided using heat rod (Figure 4).

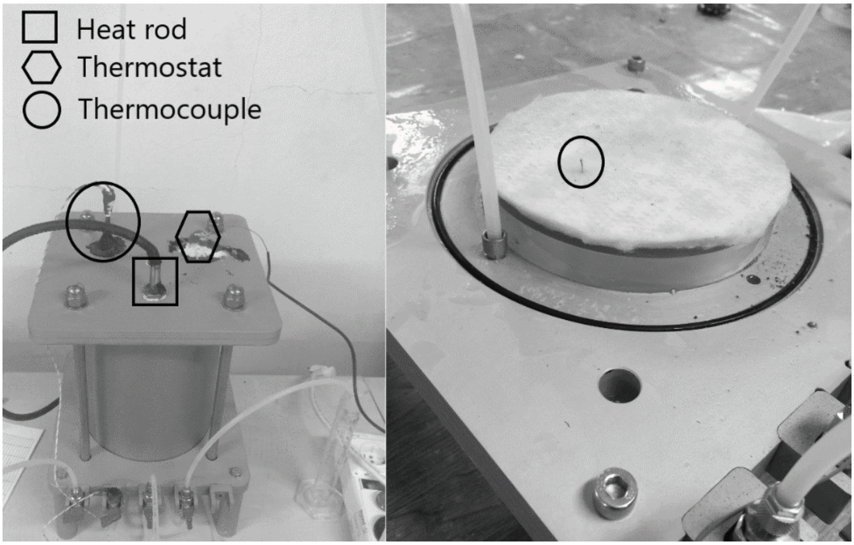

Figure 4 - Hydraulic conductivity test set-up

The soil was heated by heating the water in the cell. The deterioration in the structure of plexiglass cells, fragmentation or rupture may occur under high temperature. For that reason, the outer cell of flexible wall permeameters were made of aluminum in order to prevent temperature negative effects on the plexi-glass material. There were three separate holes at the top of the permeameter cell, for heat rod, thermostat and thermocouple. A hole was drilled in the bottom geotextile large enough for the thermocouple to pass through. With the use of geotextile in hydraulic conductivity tests, it was ensured that the soil sample was not dragged during the water flow. The water flow was distributed homogeneously on the sample by using geotextile. The thermocouple was inserted through a valve of the permeameter through this hole and soil temperature measurement was supplied. The temperature of the water was measured from the top of the permeameter cell with a thermocouple placed in the cell. Two thermocouples were connected to the digital thermometer and temperature values were recorded depending on time. With the help of a thermostat, the water temperature inside the cell was kept at 80 °C. The hydraulic conductivity values of the mixtures were expressed in terms of pore volume of the flow. Thermal cycling was applied on the 8B-72S-20PU sample. The test was initiated under room temperature, a cycle was carried out by gradually increasing the temperature (25-50-80 °C) and then gradually lowering (80-50-25 °C) it back to room temperature. At each temperature level, the test was continued until the flow became stable.

The thermal conductivity values of sand-bentonite mixtures in the presence of pumice were measured with Shotherm QTM device. The ambient temperature indicated by the device during the measurements was recorded between 20~22°C. The samples were prepared and compacted at the same saturation degree. The samples were grouped into two groups. According to the bentonite content the sample properties especially optimum water content values became different. One of them was 10B-90S mixture and 10%-20% additives and the other 20B-80S mixture and 10%-20% additives. The void ratio and saturation degree values of the mixtures were determined, and then the samples were prepared at that water content. According to each group the average saturation degree values were obtained and the samples were prepared at their group saturation degree value. The samples kept closed in a plastic bag for 24 hours in order to distribute the water homogeneously in the mixture. The amount of samples to be compacted into the molds was calculated and the number of impacts was determined by trial and error. The needed number of impact was determined for each layer. All samples were compacted in the same compaction scheme. Then samples were compacted in three layers and 104 drops in a 12x12x4 cm^3 mold. Measurements were made from five different regions of each sample (Figure 5). The thermal conductivity values were determined by taking the average of these values.

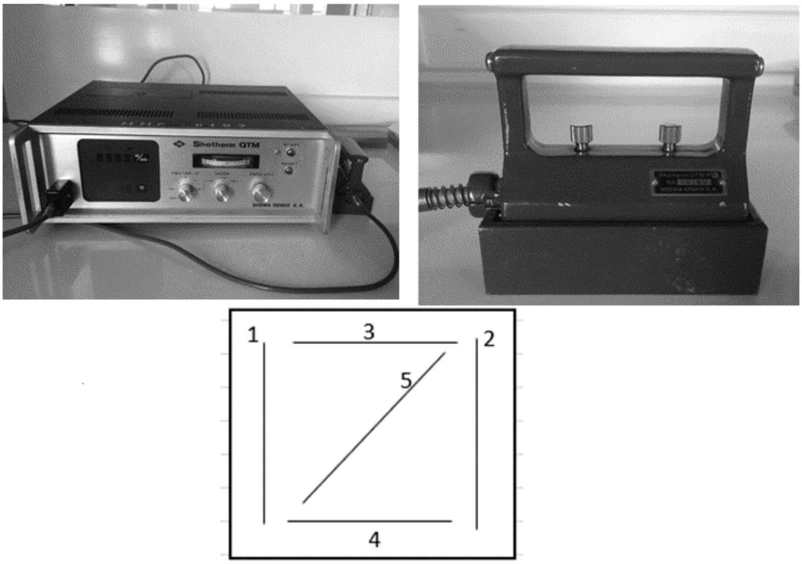

Figure 5 - Thermal conductivity equipment and measurement directions

3. RESULTS AND DISCUSSION

3.1. Compaction Test Results

The Standard Proctor tests were performed on the 10% and 20% bentonite-sand mixtures in the presence of 10% and 20% pumice additives. The compaction test results showed that the γ_{dmax} of 10% bentonite-sand mixture was 16.7 kN/m^3, then it decreased to 16.2 kN/m^3 and 15.6 kN/m^3 in the presence of 10% and 20% pumice, respectively (Table 2). It should be noted that, the γ_{dmax} of the pumice was determined to be 12.9 kN/m^3. The low dry unit weight value is a reason of decrease in dry unit weight values of bentonite-sand mixtures. On the other hand, pumice additive changes the w_{opt} values insignificantly. The maximum dry unit weight and optimum water content values were used in order to prepare compacted samples for oedometer and direct shear tests.

Table 2 - Compaction parameters of the 10% and 20% sand bentonite mixtures

Mixtures	Max. dry unit weight (kN/m^3)	Optimum water content (%)
100 PU	12.9	30.0
10B-90S	16.7	15.5
9B-81S-10PU	16.2	17.0
8B-72S-20PU	15.6	16.0
20B-80S	15.6	17.5
18B-72S-10PU	15.2	17.0
16B-64S-20PU	14.7	17.0

3.2. Volume Deformation of the Pumice Added Sand-Bentonite Mixtures Under Room Temperature

The oedometer tests were conducted and the volume deformation behavior of sand-bentonite mixtures in the presence of pumice were observed. The vertical strain (ε) versus logarithmic effective stress (σ') curves of the 10B-90S, 20B-80S mixtures and pumice were given in Figures 6 and 7. The total vertical deformation value of the 10B-90S mixture and 100% pumice were 4.6% and 4.0%, respectively. In the presence of 10% pumice additive of 10B-90S mixture, the vertical deformation value was determined as 3.7% and increased to 5.9% when the pumice content was increased to 20%. The vertical deformation value of 20B-80S mixture was found to be 10.1%. The vertical deformation values decreased to 17.1% and 16.7% with 10% and 20% pumice contents. According to the results, pumice additive increased the vertical deformation amount under room temperature.

The compression index (C_c) is an important parameter used to estimate the consolidation settlement. As can be seen in Table 3, as the pumice content was increased, the total deformation of the mixtures increased for 20B-80S mixtures.

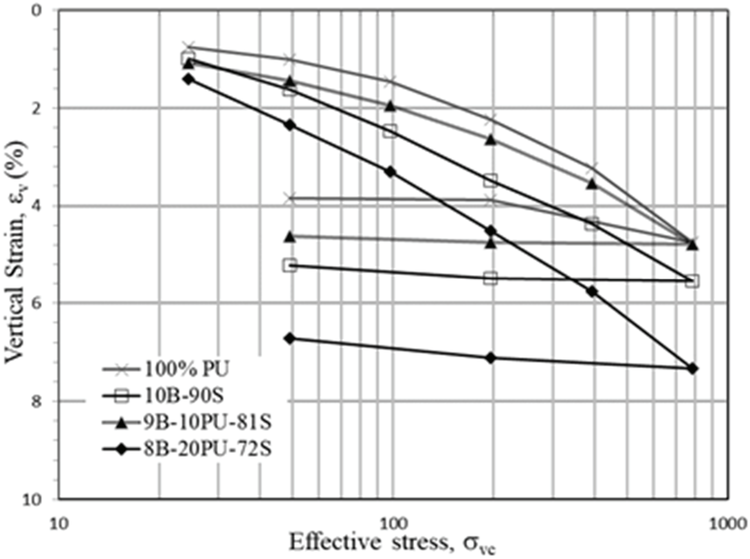

Figure 6 - ε-log σ' curves of 10B-90S mixtures with pumice additives under room temperature

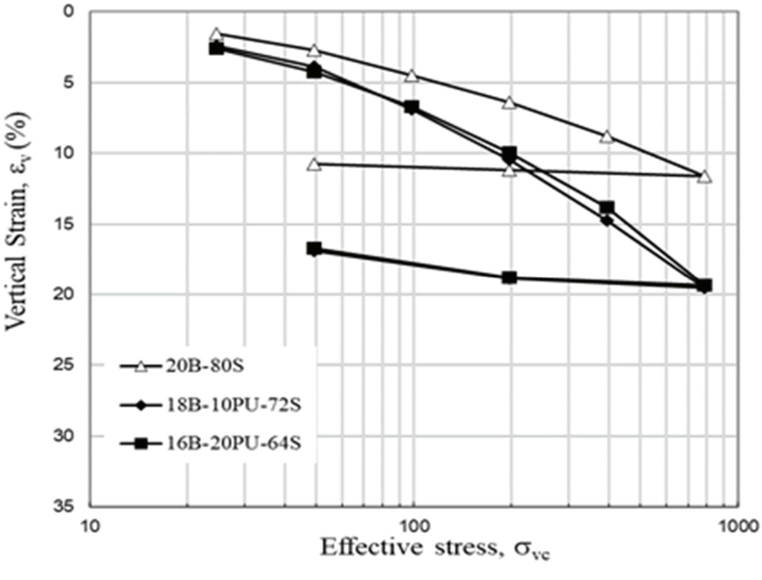

Figure 7 - ε-log σ' curves of 20B-80S mixtures with pumice additives under room temperature

Table 3 - C_c values of the 10% and 20% bentonite-sand mixtures with pumice additive

Sample	Compression index (C_c)
Pumice	0.083
10B-90S	0.056
9B-81S-10PU	0.056
8B-72S-20PU	0.079
20B-80S	0.153
18B-72S-10PU	0.265
16B-64S-20PU	0.259

3.3. Shear Strength Parameters of Sand-Bentonite Mixtures Under High Temperature

The 10% and 20% pumice were added to the 10B-90S and 20B-80S mixtures and direct shear tests were performed under room and high temperatures. It was observed that while the drained internal friction angle (ϕ') of the 10B-90S mixture at room temperature was 32.7°, it decreased to 31.5° under high temperature (80 °C). The ϕ' values did not change with 10% pumice but increased to 36.7° with 20% pumice content under room temperature. When 10% and 20% pumice were added to 10B-90S mixtures under high temperature, ϕ' values increased to 34.1° and 34.7°, respectively. It was observed that the ϕ' values increased as pumice was added for 10B-90S mixture under high temperature. The maximum shear stress value was 106.9 kPa of 10B-90S mixture at room temperature (Figure 8). Generally, the shear stress values of 10B-90S mixtures decreased slightly when temperature was increased from room temperature to 80 °C. In addition, maximum shear stress (τ_{max}) values of the 10B-90S mixture in the presence of 10% and 20% pumice additives increased by approximately 10 kPa under high temperature. Generally, increase in shear strength is reported as temperature increases. However, some studies reported decrease in shear strength depending on temperature increase. For example, as a result of unconsolidated-undrained (UU) and consolidated-undrained (CU) tests at 20, 50, 80 and 110 °C for a Boom clay, a significant decrease in strength was determined when the temperature increased [29]. Similarly, it was reported that temperature affects density and viscosity of water, a decrease in the strength of clayey soil sample and silt under 60 °C was determined [30]. Opposite to these findings, other studies have shown that the internal friction angle is not affected by temperature and the shear strength of soils reaches higher values when the specimens are heated [7]. According to the former studies, it is obvious that the changes on the shear strength depends on the soil mineralogy, stress and temperature levels, etc.

The internal friction angle of the 10B-90S mixture increased both at room and high temperatures in the presence of 20% pumice, while 10% pumice additive caused a slight increase only under high temperature (Figure 8). This effect also reflected on the shear strength and affected the maximum shear stress (10% pumice, 102.9 kPa and 20% pumice, 103.8 kPa) values to a negligible extent. Table 5.5 shows the internal friction angle and cohesion values of the 10B-90S and 20B-80S mixtures in the presence of 10% and 20% pumice additives.

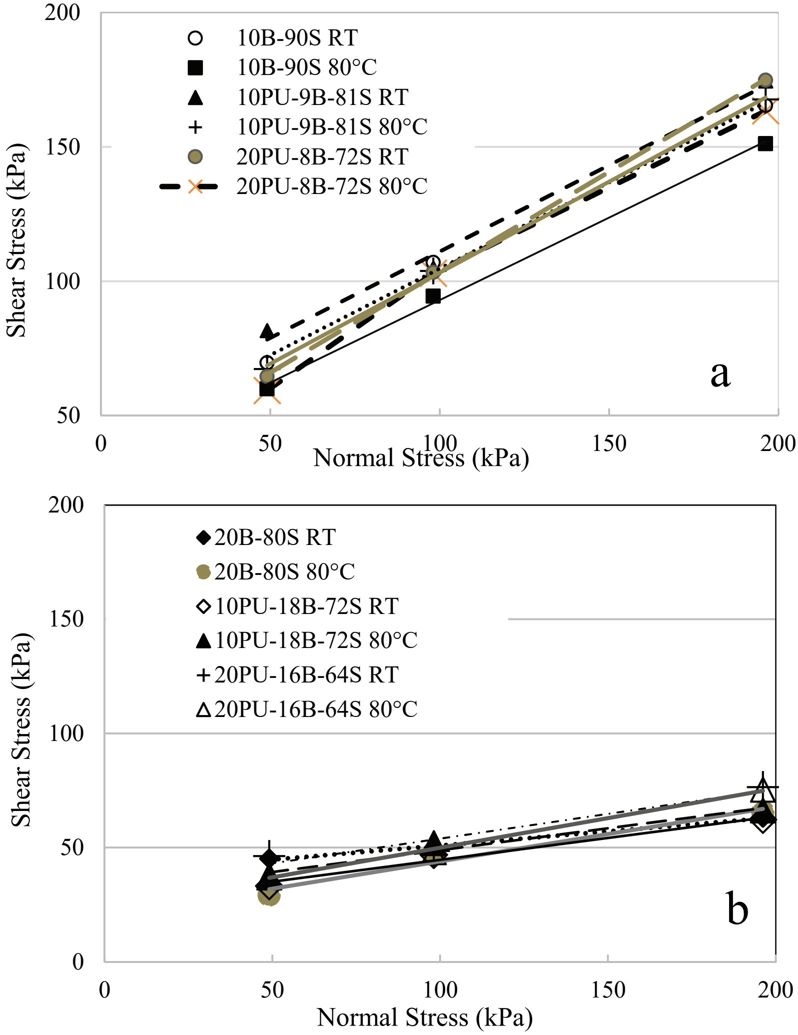

Figure 8 - Shear stress-normal stress relationship of sand-bentonite mixtures at room and high temperatures in the presence of 10% and 20% pumice additive a) 10B-90S, b) 20B-80S

Direct shear tests results of 20B-80S mixtures showed that pumice additive increased the internal friction angle values under room temperature. The ϕ' value of the 20B-80S mixture at room temperature was 7.0°, while this value increased to 11.1° and 12.2° with 10% and 20% pumice additives, respectively. The cohesion (c') value decreased with both 10% and 20% pumice addition to the 20B-80S mixtures under room temperature (Table 4). Under high temperature, the addition of 10% pumice reduced the internal friction angle from 13.6° to 11.6°. In contrast, the addition of 20% pumice increased the internal friction angle to 14.5°.

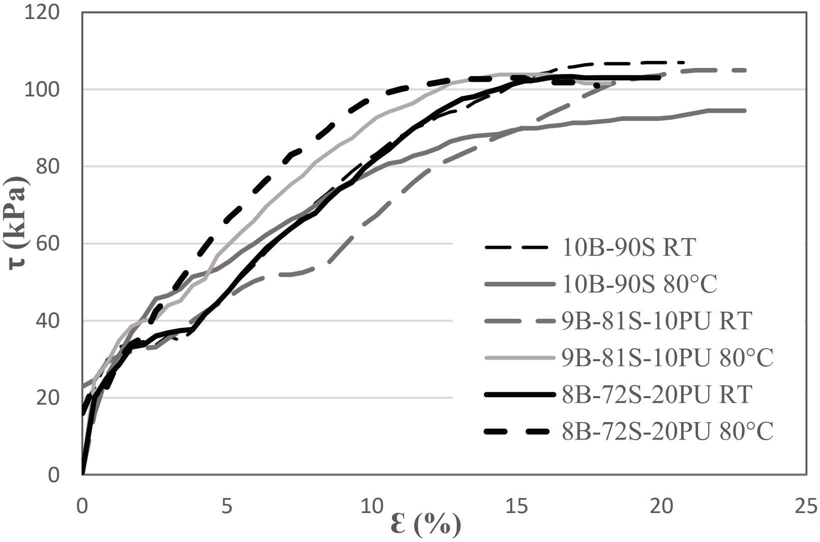

Figure 9 - τ- ε relationship of of 10B-90S mixtures under 98.1 kPa

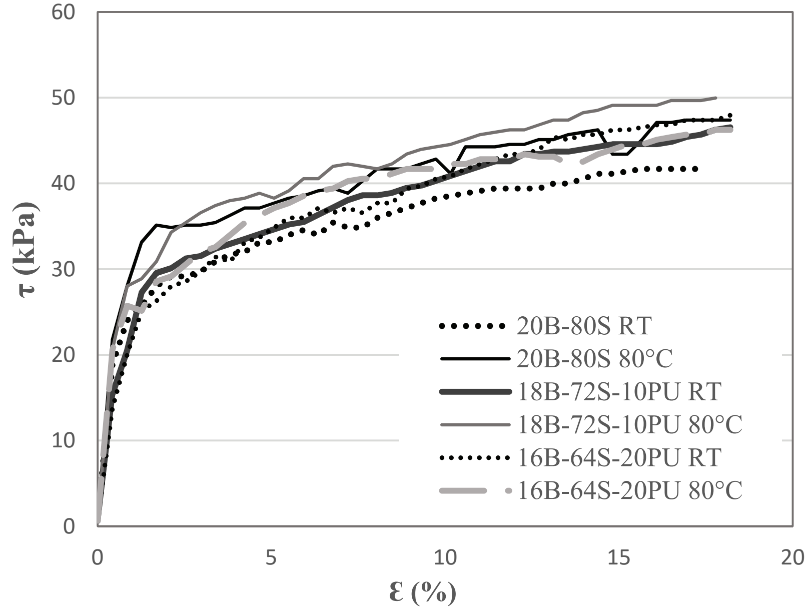

Figure 10 - τ- ε relationship of of 20B-80S mixtures under 98.1 kPa

The maximum shear stress values slightly increased for 20B-80S mixtures when temperature was increased from room temperature to 80 °C. However, it should be noted that the ϕ' values increased in the presence of 20% pumice additives under high temperature (Figure 9 and 10). The test results of the same mixtures are shown in Guneri and Yukselen Aksoy (2020) [31]. The tests on the same samples were repeated on the new device with new calibration. The angle of internal friction values did not change however cohesion values changed with compared to previous test results.

Table 4 - The shear strength parameters of the mixtures

	Initial water content	Room Temperature		80 °C	
Mixtures	*w* (%)	ϕ' (°)	c' (kPa)	ϕ' (°)	c' (kPa)
10B-90S	22.7	32.7	40.4	31.5	31.5
9B-81S-10PU	23.8	32.7	46.8	34.1	35.4
8B-72S-20PU	25.7	36.7	28.7	34.7	29.1
20B-80S	27.0	7.0	38.5	13.4	20.0
18B-72S-10PU	28.3	11.1	25.4	11.6	29.7
16B-64S-20PU	32.7	12.2	32.2	14.5	24.0

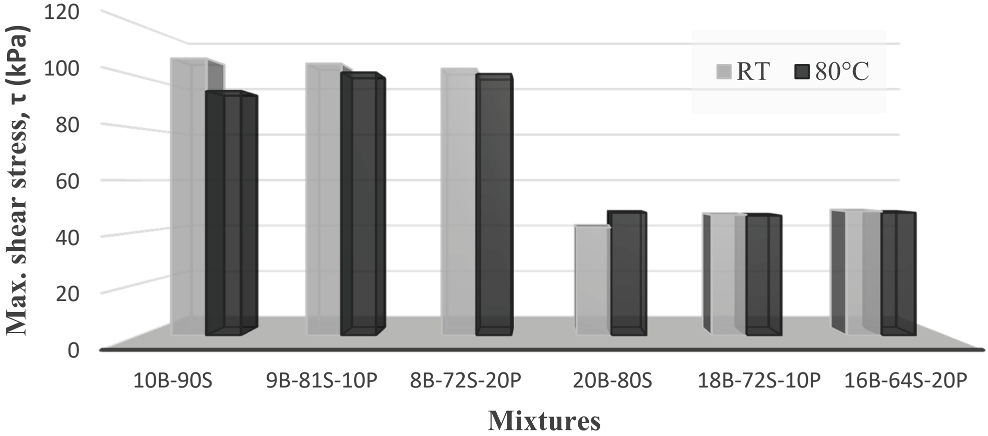

Figure 11 - Maximum τ_{max} values for all mixtures under room temperature and 80 °C (under 98.1 kPa)

The results have shown that pumice contributes to the shear strength of sand-bentonite mixtures under high temperature. Pumice has silanol (Si-OH) groups on its surface and this silanol group binds hydroxyl groups at the edges of the clay platelets [10]. As a result, the pumice is held by the clay surface and positive charge increase on the clay surface. Hence, shear strength of bentonite increases. Another reason is when pumice is added to the sample, both the bentonite and sand content of the mixture decrease. With the decrease in the amount of bentonite, the shear strength increases.

The maximum shear stress values under room and high temperature for all mixtures were given comparatively in Figure 11. For all 10B-90S mixtures, the maximum shear stress value decreased with increase in temperature; however, τ_{max} values of 20B-80S mixtures increased under high temperature. According to the results obtained, the maximum shear stress decreased as pumice additive was added to 10B-90S mixtures at room temperature, while the addition of pumice to 10B-90S mixtures increased the shear stress values under high temperature. In 20B-80S mixtures, while the maximum shear stress increased with 10%-20% pumice at room temperature, only the maximum shear stress of 10% pumice added mixture increased at high temperature.

3.4. Hydraulic Conductivity Tests under High Temperature

The hydraulic conductivity (k) tests on the 10B-90S mixture under room and high temperature in the presence of 10% and 20% pumice were conducted. The water temperature was gradually increased to 25, 50 and 80 °C. The measured soil temperatures corresponding to these water temperature values were determined as approximately 20, 40 and 60 °C, respectively. 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 and 1.25. The dashed lines show the 0.75 and 1.25 Q_{out}/Q_{in} values, respectively. Figures 12 and 13 show the hydraulic conductivity-pore volume of flow graphs of 10B-90S mixtures in terms of hydraulic conductivity-pore volume of flow in the presence of 10% and 20% pumice additive. Temperature versus k values of the 9B-81S-10PU mixture are given in Table 5. When the water temperature was increased from 25 to 50 °C, the k value increased 4.5fold and followed by when temperature was increased from 50 to 80 °C the k value increased 1.5fold. The results showed that the hydraulic conductivity of the mixture increased with increasing temperature. This is mainly due to the decrease in the viscosity of the water as the temperature increases. However, it was reported structural changes in the body of soil may cause change in hydraulic conductivity as well [13].

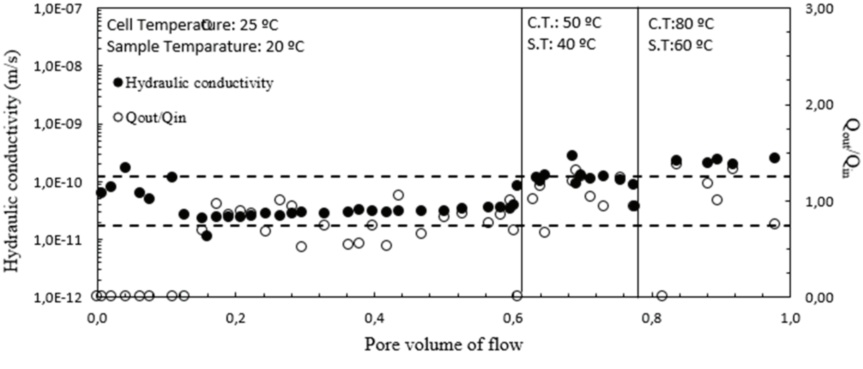

Figure 12 - Hydraulic conductivity graph in terms of pore volume of flow for 9B-81S-10PU mixture

Table 5 - The change of hydraulic conductivity values of the 9B-81S-10PU mixture with the temperature

Temperature (°C)	k (m/s)
25	3.1×10^{-11}
50	1.4×10^{-10}
80	2.1×10^{-10}

Table 6 shows the hydraulic conductivity values of the 8B-72S-20PU mixture under high temperature and temperature cycles. As mentioned above, the hydraulic conductivity increased with increase in temperature. Although the hydraulic conductivity values decreased when the sample was cooled (returned to room temperature), it could not return to the initial hydraulic conductivity value. This is explained not only by the change in water viscosity but also structural changes in bentonite [14, 17, 18].

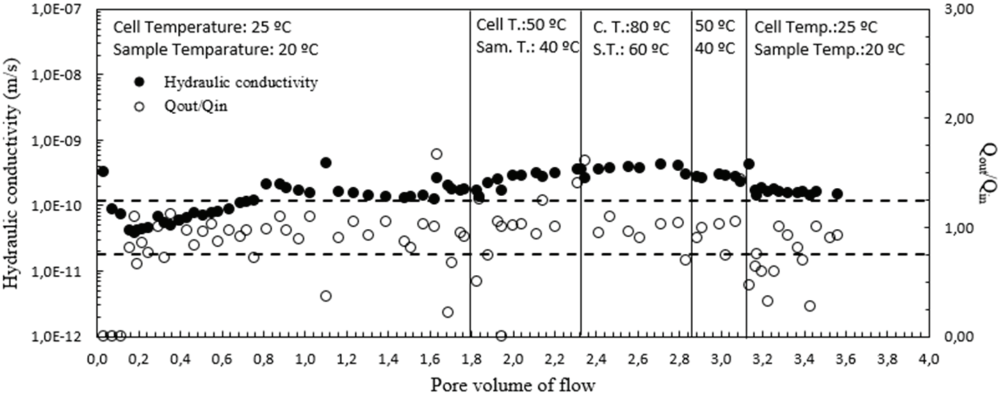

Figure 13 - Hydraulic conductivity graph in terms of pore volume of flow for 8B-72S-20PU mixture

Table 6 - The change of hydraulic conductivity values of the 8B-72S-20PU mixture with the temperature cycle

Temperature (°C)	k (m/s)
25	1.4×10^{-10}
50	2.0×10^{-10}
80	3.8×10^{-10}
50	2.9×10^{-10}
25	1.6×10^{-10}

3.5. Thermal Conductivity

The thermal conductivity values of 10B-90S mixtures and 20B-80S mixtures were measured in the presence of 10% and 20% pumice. The thermal conductivity value of 100% pumice was measured to be 0.878 W/mK. Thermal conductivity values of additive free (sand-bentonite) mixtures were higher than this value, and as the pumice added to the mixtures, the conductivity value of the mixtures decreased (Table 7). In the nuclear waste repositories double layer model was used by [32]. Near canister there is a thermally conductive barrier. However, in order to protect host rock there is a need for a thermally insulating layer.

Table 7 - The measured thermal conductivity values of the mixtures

Mixtures	Thermal Conductivity (λ, W/mK)
10B-90S	1.779
9B-81S-10PU	1.588
8B-72S-20PU	1.426
20B-80S	1.461
18B-72S-10PU	1.950
16B-64S-20PU	1.776
100PU	0.878

Previous studies show that sand can reduce the shrinkage of clay to a certain extent [33] and increase the thermal conductivity [1, 16]. In this case, it is expected that the thermal conductivity value of the 10B-90S mixture should be higher than the 20B-80S mixture. As the pumice additive was increased the thermal conductivity of the mixture decreased, indicating that pumice, which is already used in thermal insulation, can be used as a thermal insulating barrier.

Previous studies report that the thermal conductivity of the mixture increases as the percentage of sand increases. However, in one study it is shown that, depending on the sample's dry density and water content, the thermal conductivity may remain constant or even decrease with the increase of the sand content (at values above the limit value it will reach) [34]. In this case, the thermal conductivity value of the 10B-90S mixture is expected to be higher than the 20B-80S mixture. While measurement results based on the constant void ratio and saturation degree support this behavior.

3.6. Scanning Electron Microscope (SEM) Analyses

The SEM photos of the pumice samples which were prepared under room and 80 °C temperatures were taken. The flake shaped particles of the pumice can be seen clearly from the SEM photo in Figure 14. The gaps in the structure of pumice increase its water adsorption capacity [35]. But at the same time, its hollow structure reveals that any liquid that will pass through it can find a way in the mixture and provide a transition to the fluid and cannot have a reducing effect on hydraulic conductivity.

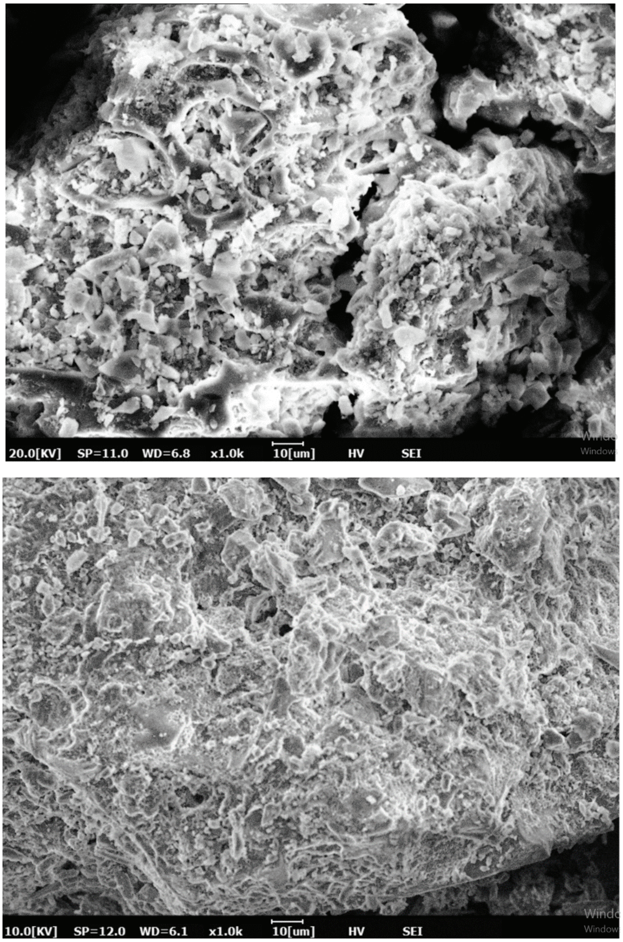

Figure 14 - Scanning electron microscope photos of the samples (x1000) (a) pumice sample at room temperature, (b) pumice sample at 80 °C

4. CONCLUSIONS

In the present study, compaction, consolidation, shear strength and hydraulic conductivity behaviors of pumice-added sand-bentonite mixtures were investigated. The shear strength and hydraulic conductivity behavior of the mixtures were also investigated under high temperature. The compaction test results showed that the addition of pumice reduced the maximum dry unit weight values of the 10B-90S and 20B-80S mixtures due to the very low dry unit weight of the pumice. The optimum water content values did not change significantly. The pumice addition to the 20B-80S mixtures decreased vertical deformation. However, this effect was not observed in 10B-90S mixtures. According to the direct shear test results, maximum shear stress values decreased when the temperature increased from room temperature to 80 °C for 10B-90S mixtures. On the other hand, the maximum shear stress of 20B-80S mixtures generally increased with the effect of high temperature. The angle of internal friction values of mixtures generally increased under high temperature in the presence of pumice. Hydraulic conductivity test results show that as temperature increased, the hydraulic conductivity increased. The test results of 8B-72S-20PU with thermal cycling showed that the hydraulic conductivity decreases with cooling and at the end of thermal cycling the sample hydraulic conductivity value did not return to its initial value. The thermal conductivity values of the mixtures were measured and it was determined that the pumice additive reduced the thermal conductivity value of the mixtures.

In line with all this data, it was observed that the hydraulic conductivity values of the 20B-80S mixture exceeds the barrier limit value (1×10^{-11} m/s) for nuclear waste repositories or municipal solid waste landfills. However, the bentonite amount can be increased in the mixture in order to maintain the hydraulic conductivity limits. Considering the thermal conductivity values, the pumice additive increases the insulating property. Besides the thermally insulative characteristic of the pumice, it has the positive contributions to the engineering properties of the sand-bentonite mixtures. For that reason, pumice and a material thermally conductive like graphite can be used together. Also, it can be used as a second layer (in double layer systems) in order to protect the host rock. The pumice additive has a positive effect on compression behavior of 20B-80S mixtures. In terms of shear strength pumice additive can be used for increasing shear strength of 20B-80S mixtures under high temperatures.

Symbols

C_c	is the compression index
ϕ	is the internal friction angle
c	is the cohesion
τ_{max}	is the maximum shear stress
σ'	is the effective stress
ε	is the strain
k	is the coefficient of permeability
λ	is the value of thermal conductivity
100PU	is the 100% pumice
10B-90S	is the 10% bentonite and 90% sand mixture
20B-80S	is the 20% bentonite and 80% sand mixture
9B-81S-10PU	is the 9% bentonite, 81% sand and 10% pumice mixture
8B-72S-20PU	is the 8% bentonite, 72% sand and 20% pumice mixture
18B-72S-10PU	is the 18% bentonite, 72% sand and 10% pumice mixture
16B-64S-20PU	is the 16% bentonite, 64% sand and 20% pumice mixture

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