Research Square

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Volume Deformation and Hydraulic Conductivity Behavior of Sand-Bentonite Mixtures with Fiberglass Additives Under High Temperatures

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Research Article

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Abstract

The performance of energy geo-structures is also dependent on the surrounding soil properties in the presence of high temperatures or thermal cycles. Change in temperature may affect many engineering parameters of soils. Sand-bentonite mixtures or bentonite which are used as a buffer should keep their performance at design level for a long time.

Purpose: In order to improve engineering behavior of soils under high temperatures thermally durable materials can be used. Volume deformation and hydraulic conductivity behavior of 30% bentonite-70% sand mixtures in the presence of fiberglass additives were investigated.

Methods: Consolidation tests were performed at both room and high temperatures (80 °C), hydraulic conductivity tests were started at room temperature and temperature cycle (25-50-80°C) was applied.

Results: Fiberglass increased the amount of compression insignificantly under room temperature, whereas the total compression amount increased remarkably under high temperature. On the other hand, the hydraulic conductivity increased under high temperature with fiberglass additive.

Conclusions: Fiberglass added sand-bentonite mixtures can be used around energy structures as an alternative buffer material with high temperature resistance.

1 Introduction

The engineering properties of soils such as compressibility, permeability and shear strength especially when considering temperature changes must be taken into account for performance of energy geo-structures. For that reason, the number of researches increase on the temperature effects on soil behavior in last decades.

Saturated clays made up of two phases and all components expand when heated. As a result of this expansion, there is a loss of strength in the parts where water is absorbed. The effect of repulsive and attractive forces also present here. As a result of phenomenon, contraction behavior occurs in normally-consolidated (NC) clays. Even if the soil cooled, the resulting deformation is largely irreversible [1, 2]. Delage et al. [3, 4], as a result of oedometer tests on OC Boom clay, observed that the change in c_v and m_v was negligible at temperatures exceeding 60 °C. Cekerevac and Laloui [5] reported that compression index (C_c) is almost the same and the compression index is independent of temperature, as a result of the tests at two different temperatures (22°C and 90°C). On the other hand, Marques et al. [6] emphasized that compression curves affected by temperature in the experiments completed at 10°C and 50°C, unlike the others. Shariatmadari and Saeidijam [7] revealed that the slopes of the consolidation curves of bentonite-sand mixtures at high temperature increase and it was related to the decrease in the void ratio at high temperature.

Studies have emphasized that many different factors affect the hydraulic conductivity of soils, such as viscosity of the fluid, properties of the solid matrix, physico-chemical interactions, and chemical content of the pore fluid [8, 9]. Because the viscosity of free pore water changes with temperature, the flow rate of the water changes and accordingly hydraulic conductivity changes [10]. Bouazza et al. [8] revealed that with the increase in temperature, there may be changes in the size of the voids in the clay structure and therefore the hydraulic conductivity may change. In addition, the redistribution of the pores also affects this behavior. It was reported that the porous structure and texture of the soils change with temperature and the permeability can change with the repositioning of the grains by changing their arrangement [11]. Ye et al. [12] observed that there is a linear relationship between hydraulic conductivity and temperature, and this is associated with a decrease in viscosity. In addition, Ye et al. [12] emphasized that the temperature affects the hydraulic conductivity, but its increase or decrease does not have a significant effect on the hydraulic conductivity.

Bentonite or sand-bentonite mixtures are preferred as a barrier material around energy structures. Bentonite is a material with a very low permeability, densely compacted with very low water content [13]. Considering that barriers should preserve their properties up to 10^6 years, bentonite is being a geological material that can preserve its structure for a long time. The sealing effect created by swelling pressure have highlighted its use as a buffer material [14]. In addition, properties such as the expansion of bentonite in contact with water and its large surface area support the use of bentonite as a buffer. In addition to these, there is a possibility that some of the bentonite, which can expand with high temperatures during the thermal period, will turn into non-expandable illite [15]. However, Wersin et al. [16] emphasized that although it was assumed that bentonite performance decreased above 120°C, leakage probably occurred above 150°C, but that bentonite still retains with its sealing ability. Sand-bentonite mixtures are also used as buffer material in order to prevent the possible negative effects of swelling behavior due to the high water absorption capacity of bentonite. The anti-shrinkage effect of sand contributes to the buffer material [14].

The performance of buffer materials around energy geo-structures may be improved by mixing of some additives. If thermally durable materials are added to the buffer materials the intact engineering properties may be preserved under high temperatures. In this study, the fiberglass material was choosen because of its superior properties under high temperatures. Fiberglasses are obtained by melting silica-based glass into thin strips. Commercial fiberglasses are made from pure silica rods and from silicate melts containing 50–70% SiO_2 and 10–25% Al_2O_3 [17]. Although there are many different glass classes such as A, E-CR, C, D, R, S-glass, the most widely used is E-glass. Pure silica requires very high temperatures to be converted into fiber glass. Fiberglass is used in many fields such as insulators, transportation, construction due to its anti-corrosion behavior, good mechanical properties, heat resistance [18]. The thermal stability of fiberglass is very high, hence it can remain intact and durable for years at temperatures lower than the softening temperature. Fiberglasses are composed of metal oxides or alkalis (Figure 1) dispersed in a silica system, which is an example of a three-dimensional system of oxygen tetrahedra [19].

It should be noted that Djeghader and Redjel [20] revealed that in contact of fiberglass with water, water can enter between the fiber and whatever other material forming the mixture, due to capillarity, and this may weaken the structure of the fiberglass and lead to crack formation [22-24]. It also causes an increase in weight, expansion of non-reinforced sections, and deterioration of the soil matrix [25].

In this study, consolidation and hydraulic conductivity tests of fiberglass added sand-bentonite mixtures were carried out under room temperature and high temperatures. The effect of fiberglass on the compressibility and hydraulic conductivity behavior of sand-bentonite mixtures were investigated under high temperatures and temperature cycles.

2 Material And Methods

2.1 Material Characterization

The fiberglass sample was obtained from local supplier. X-Ray diffraction (XRD) analyzes were performed with Thermo Scientific ARL X'TRA from 0° to 89° in focusing geometry with a scanning speed of 0.1° 2θ/s and radiation at 60 kV, 5-60 mA on the bentonite sample. Figure 2 shows the mineralogic content of bentonite, according to results it contains montmorillonite, quartz and illite minerals.

Sieve analyses were performed according to ASTM D6913 [26] standard. The bentonite and sand were used after sieving through No.200 and No.6 sieves, respectively (Figure 3). Sand and bentonite were dried in an oven at 105°C for 24 hours before being used in the experiments. Fiberglass was not subjected to any processing before being used in the tests. The specific gravity value of the fiber glass was obtained from the supplier. The clay content of bentonite was determined as 60% as a result of test according to the ASTM D422-63 [27]. Table 1 shows the physico-chemical properties of the materials used in this study.

Table 1. The physico-chemical properties of the materials

Property	Sample		
	Bentonite	Sand	Fiberglass
Specific gravity	2.70	2.63	2.60
Liquid limit (%)	476.0	-	-
Plastic limit (%)	70.10	-	-
Length (mm)/diameter (μ)	-	-	3/13

2.2 Methods

In this study, compressibility and hydraulic conductivity parameters of 0.5% and 1% fiberglass added sand-bentonite mixtures at room temperature and high temperature were investigated. In the samples, 0.5% and 1% of the total dry weight was fiberglass, 30% of the remaining part was bentonite and the

resting amount was composed of sand. The mixture expressed as 1GF-30B-70S symbolizes the mixture which contains 1% fiberglass and 30% bentonite-70% sand. The Standard Proctor tests were performed according to ASTM D698-12 [28]. Before the compaction test, the samples were kept closed for 24 hours in order to distribute the water content homogeneously.

The oedometer tests were performed according to ASTM D2435 [29]. The oedometer tests were carried out at under both room and 80°C temperatures. The test samples were prepared at maximum dry unit weight and w_{opt}+2% which were obtained from the Standard Proctor tests. In the tests, the temperature was provided with the help of the heat rod shown in Figure 4 and the thermostat was used to keep constant the temperature. In order to prevent evaporation, the top of the cell was covered with a black thick membrane. In addition, in order to keep water level constant, water was supplied from the water reservoir with the help of a pipe. The experiment was terminated when the deformations reached negligible amount. The loading was started from 24.5 kPa and the load increment ratio was 1.0. The unloading process was reduced to 784 kPa to 196 kPa and 49 kPa. The temperature was adjusted to be 80°C from the beginning to the end of the test.

Hydraulic conductivity tests were performed according to ASTM D5084 [30]. Test samples were prepared of 2% wet side of optimum water content. Before compaction, the samples were kept in an airtight bag for 24 hours. The aluminum permeameters were used instead of plexiglass because of high temperature effect on the cell material. In order to monitor the soil temperature, a thermocouple was used which was passed through the lower geotextile to the soil. In addition, a thermocouple was placed inside the hydraulic conductivity cell to measure the water temperature. The temperature was provided with the help of the heat rod (Figure 5) and it was kept under control with the help of the thermostat. The tests were started at room temperature and the temperature was gradually increased (25, 50, 80°C). It was noted that the measured soil temperature was lower than the water temperature (20, 40, 60°C). The temperature cycles were applied during the experiments, and when the flow became stable, the next step was started.

3 Results

In this study, compressibility and hydraulic conductivity behavior of the mixtures were obtained by adding 0.5% and 1% fiberglass to 30% bentonite-70% sand mixtures. The experiments were carried out both at room and at high temperature, and also temperature cycles were applied in the hydraulic conductivity tests. As a result of Standard Proctor tests the maximum dry unit weight of the 30B-70S mixture was determined as 14.6 kN/m^3 and the optimum water content was 22.5%. These values were used while preparing the test samples for fiberglass added mixtures, since the additive ratios were quite low, they did not change the w_{opt} and γ_{dmax} values of the mixtures, significantly.

3.1 Compressibility Behavior of the Mixtures Under Room and High Temperatures

The compressibility behavior of the mixtures was determined with oedometer tests under room and high temperatures. In Fig. 6, the compressibility curves of 0.5% and 1% fiberglass added sand-bentonite mixtures at room temperature and 80°C was given.

The compression and swelling deformation amount of the additive-free sand-bentonite mixture was 14.07% and 1.37% under room temperature, respectively. When 0.5% fiberglass additive was added to the 30B-70S mixture the compression deformation did not change and determined as 14.01%. However, when the fiberglass content was increased to 1%, the compression deformation amount increased to 15%. While the swelling deformation amount remained constant with 0.5% fiberglass, it increased to 1.79% with 1% fiberglass additive. According to the results, the 0.5% and 1.0% fiber glass additives, did not have a significant effect on compression deformations under room temperature. However, the swelling deformation increased in the presence of 1% fiber glass.

The results of the oedometer tests performed under high temperature (80°C) showed that the compressibility deformation amounts from 14.4% increased to 16.2% and 19.8%, with 0.5% and 1% with fiberglass additives, respectively. The deformation of the mixtures increased in the presence of high temperature when compared room temperature. The amount of swelling deformation amount was found to be 1.73% for the 30B-70S mixture without additives, while it was 1.49% with 0.5% and 1.0% fiber glass.

Shariatmadari and Saeidijam [7] examined the compressibility parameters of sand-bentonite mixtures under high temperature and reported an increase in the slope of the compressibility curves. The reason for this phenomenon is explained as the temperature increases, void ratio decreases and accordingly the amount of compression increases [10]. Delage et al. [4] observed contraction behavior in the normally consolidated clay soil as a result of their tests in the presence of high temperature. The plastic volumetric deformations occur in the soil after contraction [31]. In Fig. 7, the compression curves are shown under different temperatures. The change in slope of the compression curve clearly can be seen in Fig. 7 under high temperature for the 30B-70S mixture and 0.5% fiberglass added sand-bentonite mixture.

In contrary expansion behavior with high temperature was observed in OC clays. However, Towhata et al. [32] observed the expansion behavior up to 90°C in the test, which carried out by heating an OC sample in the study and revealed that after 90°C, the soil was contraction even though it was OC. Contraction is interpreted as the deterioration of the skeleton of the soil due to heating, while expansion is interpreted as the enlargement of the spaces in the soil skeleton due to temperature. Increase in the amount of compressibility deformation in the presence of fiberglass added sand-bentonite mixtures under high temperature was observed by increasing the void ratio with temperature.

3.2 Hydraulic Conductivity Behavior Under High Temperatures

In this study, falling head hydraulic conductivity tests of 30B-70S, 0.5GF-30B-70S and 1.0GF-30B-70S mixtures were carried out in flexible wall permeameters. The temperature of the tests was started from room temperature (~25°C) and increased to 50°C and 80°C, respectively. While the cell temperature was

25, 50, 80°C, the water temperature was measured as 20, 40, 60°C. The hydraulic conductivity coefficients (k) obtained under different temperatures are given in Table 2. The results have shown that the hydraulic conductivity values increased with increase in temperature. This increase is due to the decrease in the viscosity of water as the temperature increases, as emphasized in the previous studies. At the same time, the interaction of the soil with water also has an effect on this situation [11, 33–35]. On the other hand, it was observed that as the fiberglass additive content increased, the hydraulic conductivity of the mixtures increased and the fiber acted as a way to the flow of water. According to the results, it can be noted that the fiberglass does not contribute to the hydraulic conductivity, increased the hydraulic conductivity of the sand-bentonite mixture under high temperature. Djeghader and Redjel [20] revealed that in contact of fiberglass with water, water can enter between the fiber and whatever other material forming the mixture, due to capillarity, and this may weaken the structure of the fiberglass and lead to crack formation [22–24]. It also causes an increase in weight, expansion of non-reinforced sections, and deterioration of the soil matrix [25].

Table 2
Hydraulic conductivity values of the mixtures at different temperatures

Cell Temperature (°C)	30B-70S k (m/sec)	0.5GF-30B-70S k (m/sec)	1.0GF-30B-70S k (m/sec)
25	4.3E-11	2.5E-10	3.3E-10
50	3.2E-10	3.8E-10	4.1E-10
80	5.0E-10	5.4E-10	5.6E-10
50	-	3.2E-10	3.7E-10
25	-	3.1E-10	3.4E-10

Figure 8, 9 and 10 shows the hydraulic conductivity values of the additive free sand-bentonite mixture and the fiberglass additive mixtures in terms of pore volume of flow under different temperatures. It was observed that the hydraulic conductivity increased as the temperature increased due to the decrease in viscosity, as observed in former studies [9, 12]. According to this, the fluctuations in the hydraulic conductivity values depending on the temperature clearly can be seen from Figs. 8, 9, and 10.

The Fig. 11 shows the hydraulic conductivity for different temperatures when 0.5% and 1% fiberglass additives were added to the 30B-70S mixtures. It was observed that the hydraulic conductivity increased as the fiberglass content increased at all temperatures, but the most significant increase occurred under room temperature. As can be seen from Fig. 11, the increase in the ratio of fiberglass additive in the mixture caused the increase in hydraulic conductivity the most under room temperature. While each mixture experienced an increase in hydraulic conductivity with the increase in temperature, it was observed that the differences between different additive ratios for the same temperature were in small

amounts. It was determined that the role of the fiberglass additive in affecting the hydraulic conductivity is quite low as the amount of additive increases under high temperature.

4 Conclusions

In the present study, consolidation and hydraulic conductivity tests were conducted on the 0.5% and 1% fiberglass added sand-bentonite mixtures under room and high temperatures. The results of the consolidation tests carried out at room temperature revealed that fiberglass did not affect the compressibility of the mixtures, but increased it at high temperature, and this was due to the increase in the voids formed in the structure. It was determined that the hydraulic conductivity values increased as the temperature increased, depending on the decrease in viscosity. According to the test results showed that the performance of fiberglass under room temperature can be more pronounced compared to high temperature. The higher bentonite and fiberglass contents should be studied to meet the hydraulic conductivity criterion for buffer materials.

Declarations

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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

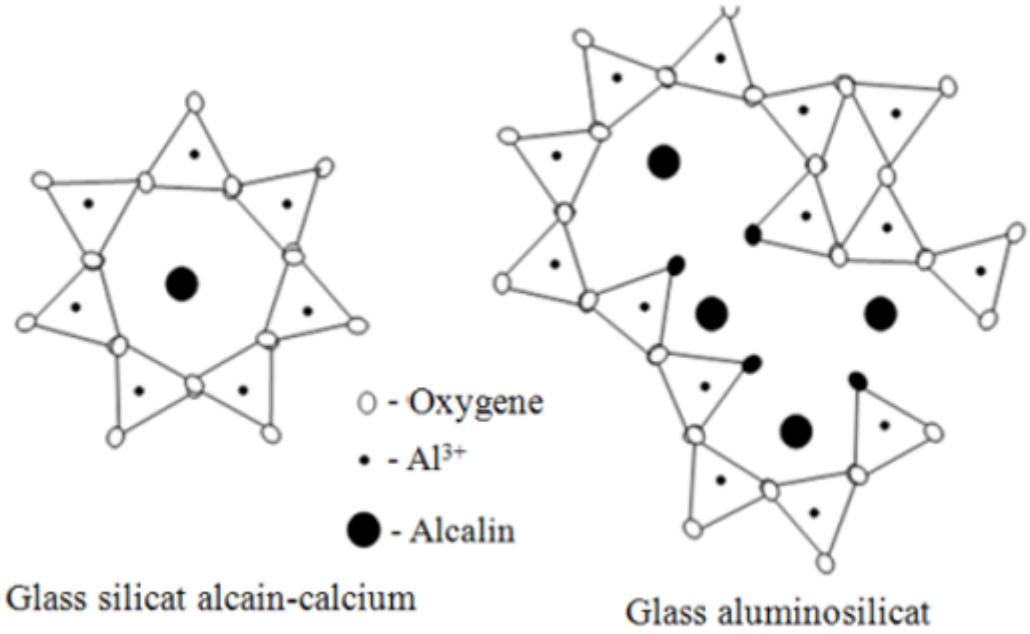


Figure 1

Structure of fiber glass [20, 21]

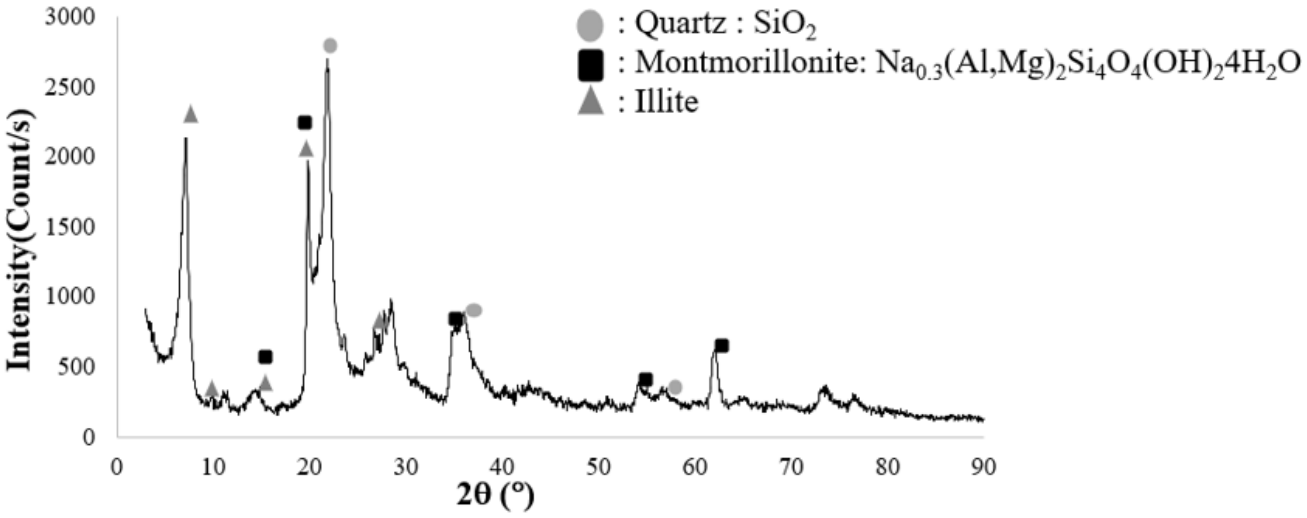


Figure 2

The X-Ray diffraction analysis (XRD) results of the bentonite

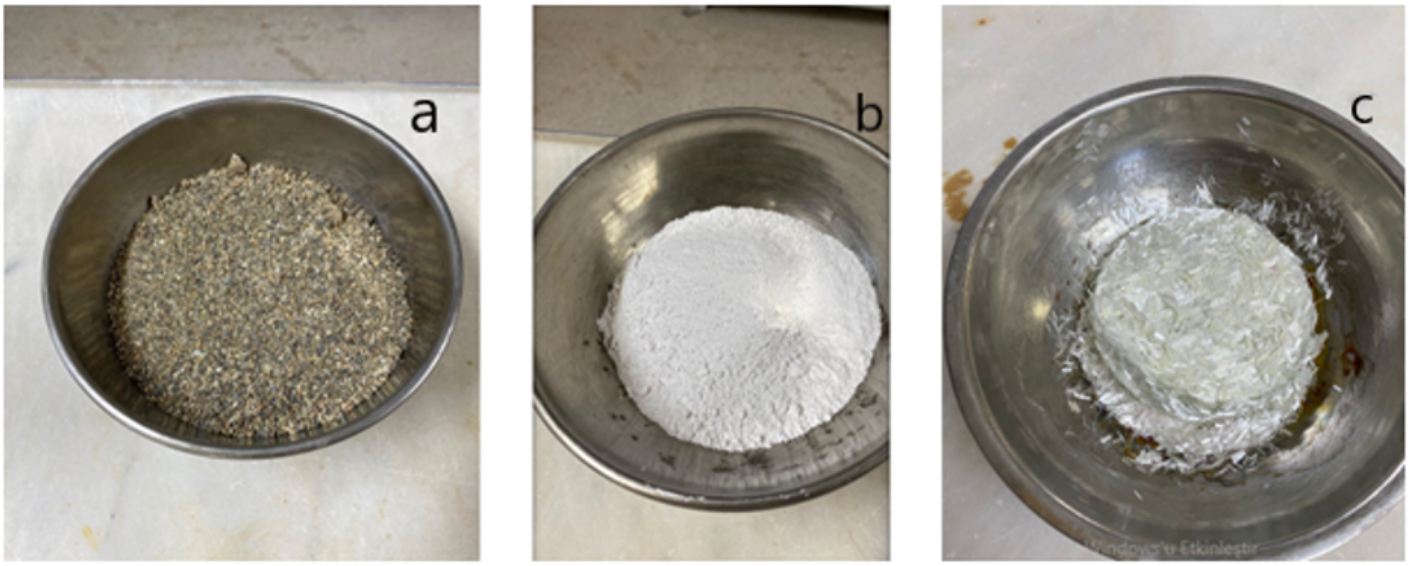


Figure 3

Materials used in the tests a) sand b) bentonite c) fiberglass

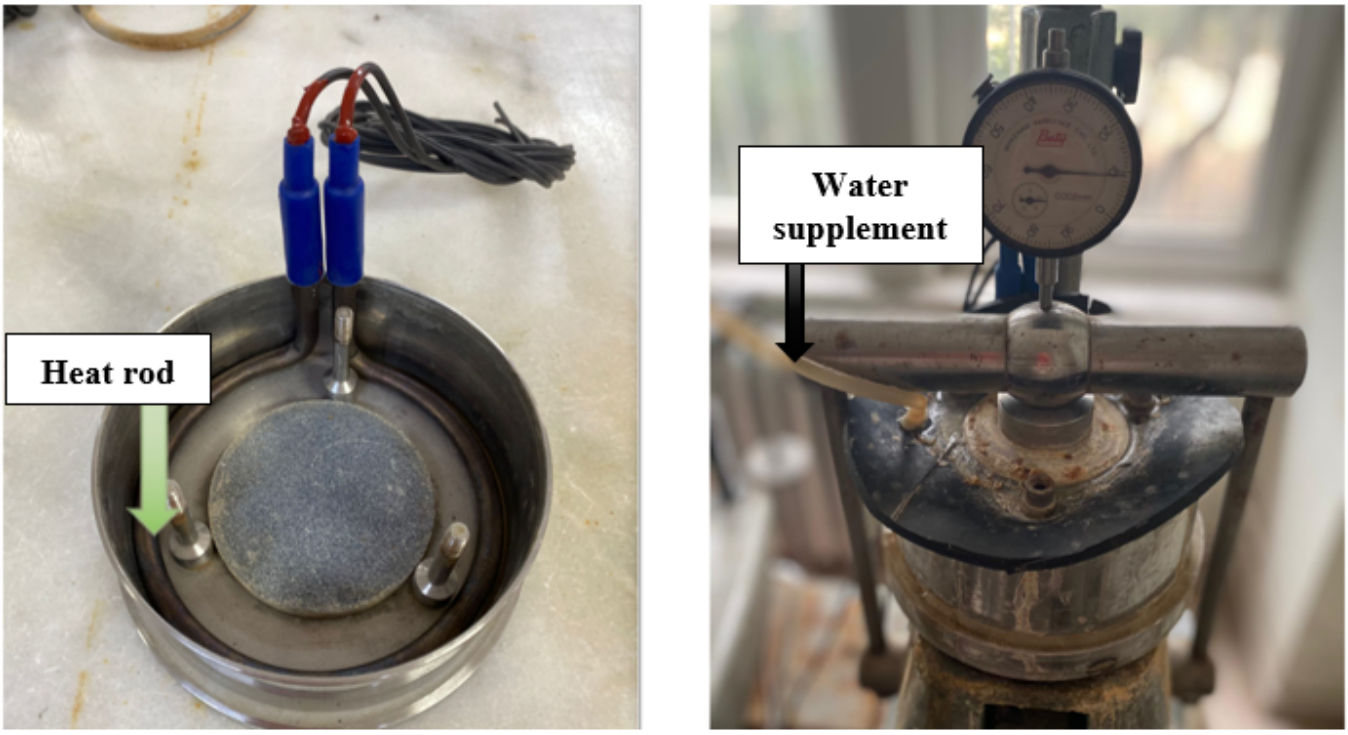


Figure 4

The equipment used in the consolidation tests under high temperature

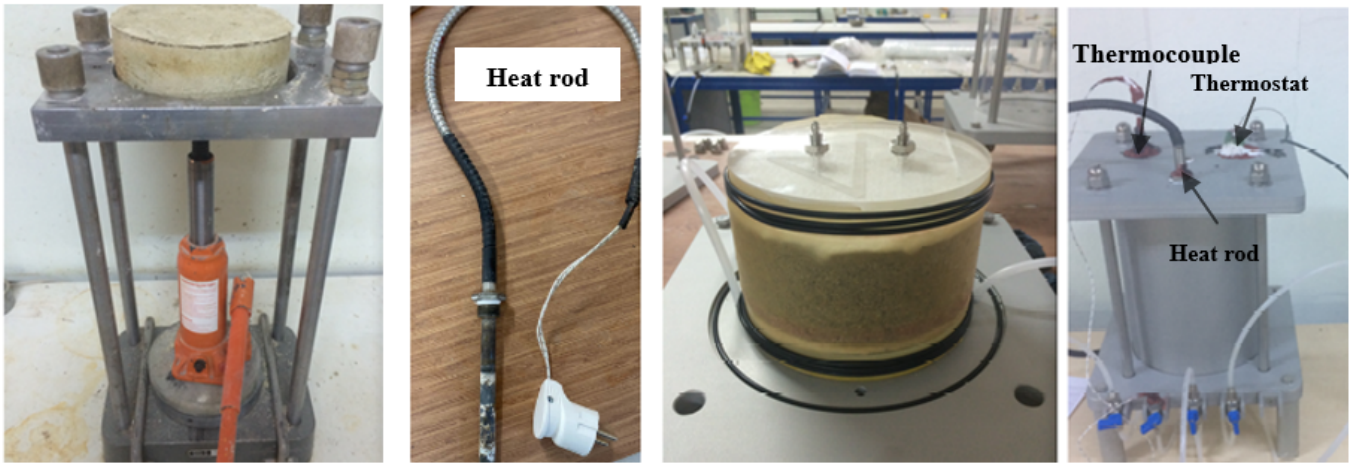


Figure 5

The equipment used in hydraulic conductivity tests

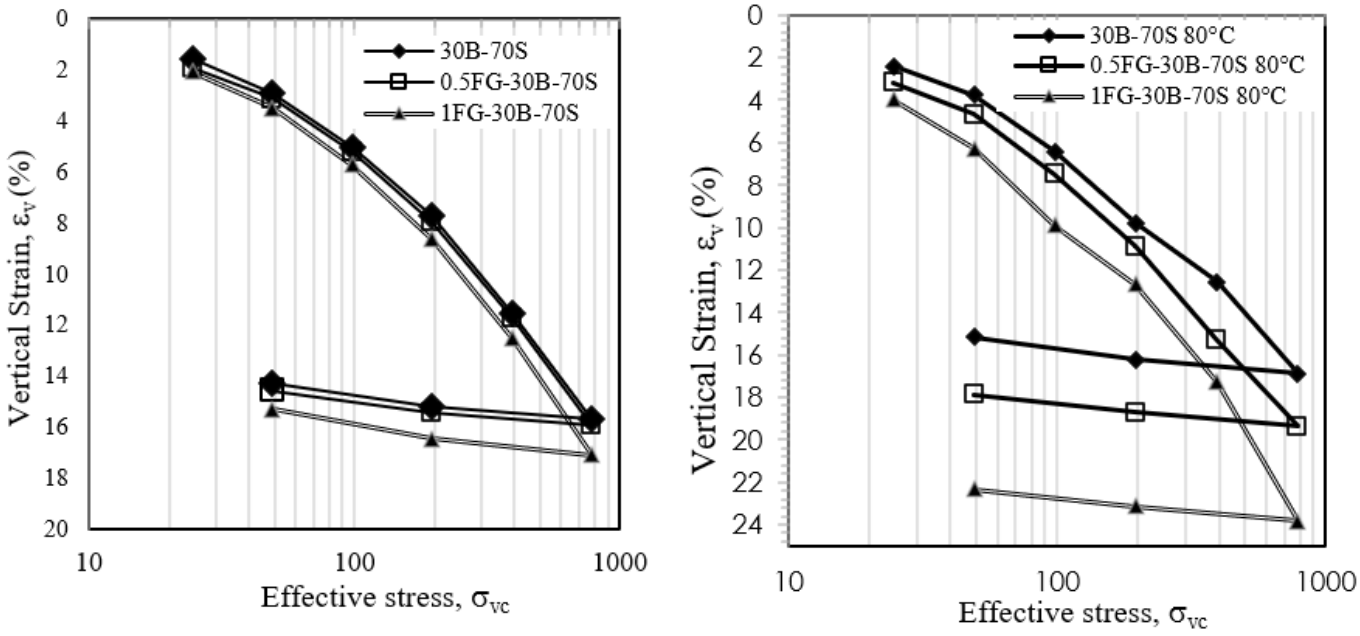


Figure 6

σ- graph of 30B-70S mixtures in the presence of 0.5% and 1% fiberglass additives under room and high temperatures

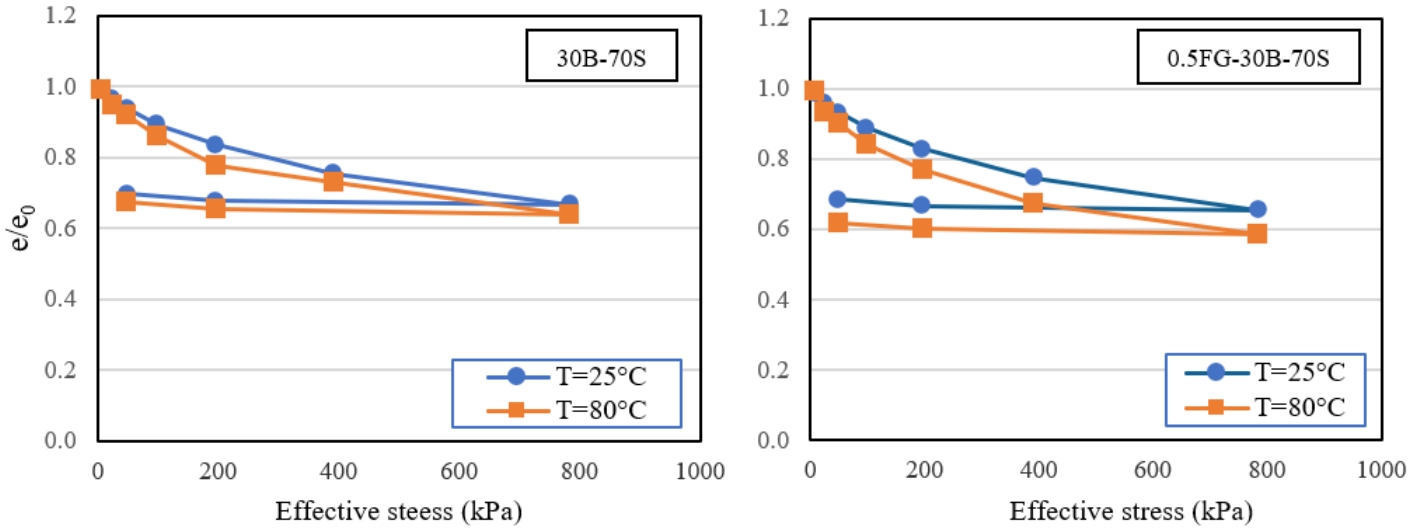


Figure 7

Effective stress graphs vs e/e0 for 30B-70S and 0.5% fiberglass added sand-bentonite mixtures at different temperatures

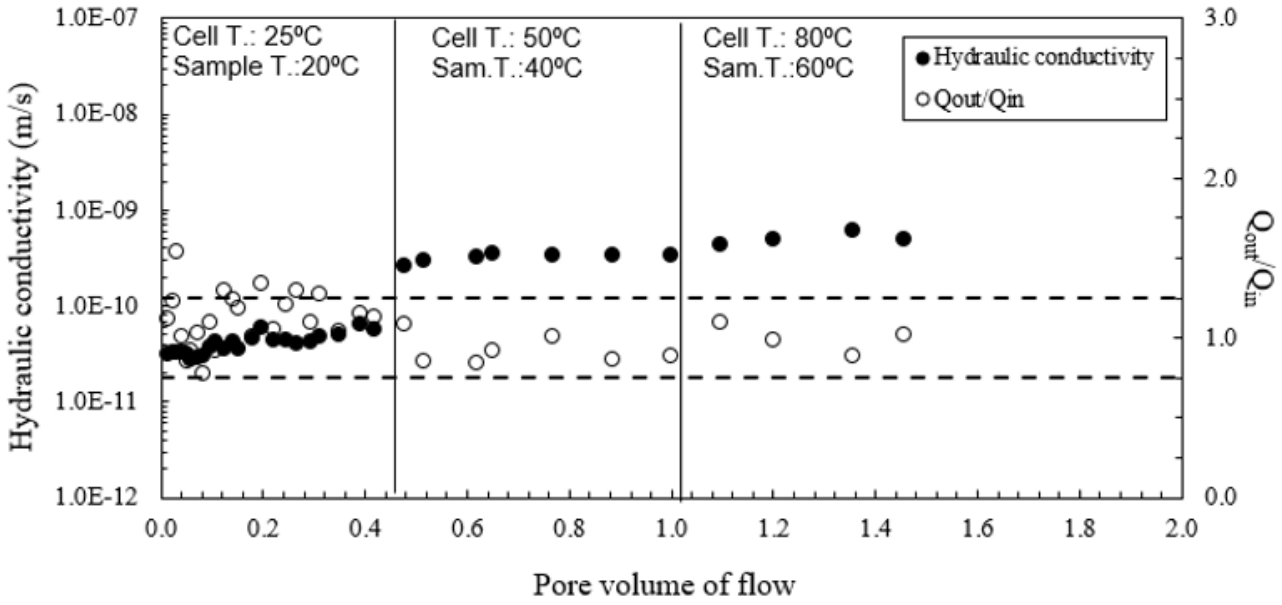


Figure 8

Hydraulic conductivity behavior of 30B-70S mixture at room temperature

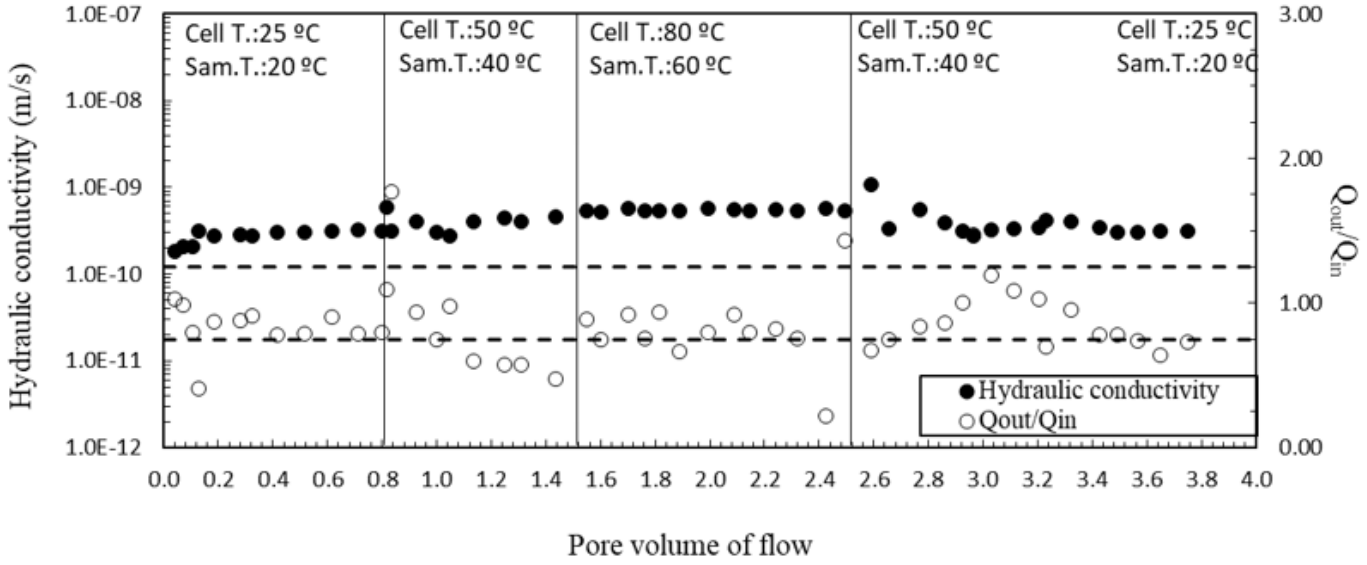


Figure 9

Hydraulic conductivity behavior of 30B-70S mixture with 0.5% fiberglass added at room and high temperatures

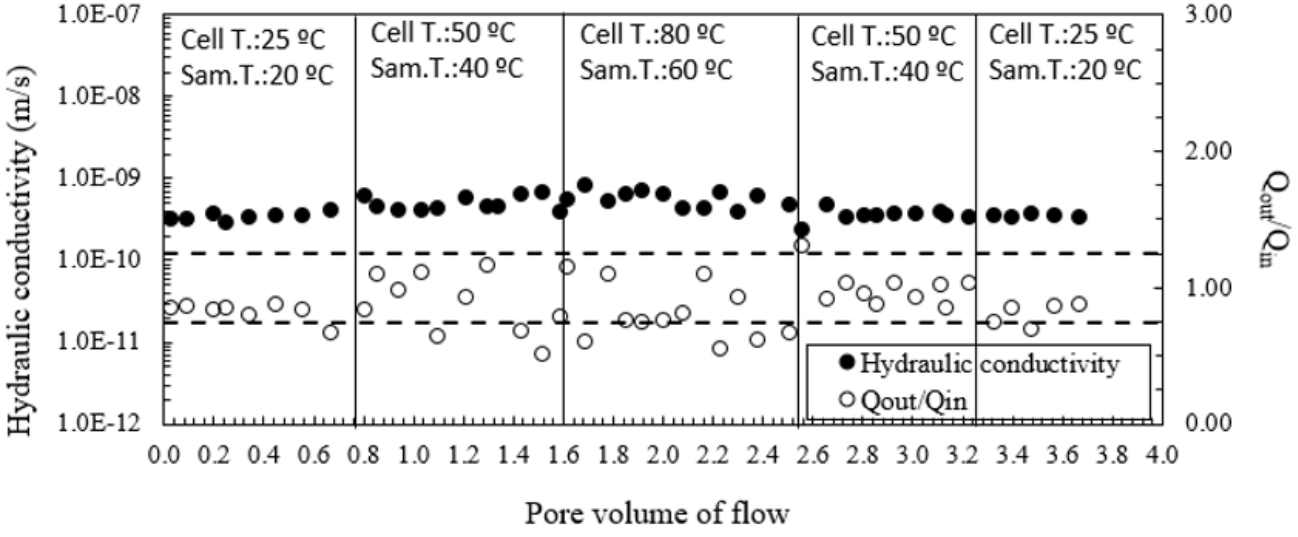


Figure 10

Hydraulic conductivity behavior of 30B-70S mixture with 1% fiberglass added at room and high temperatures

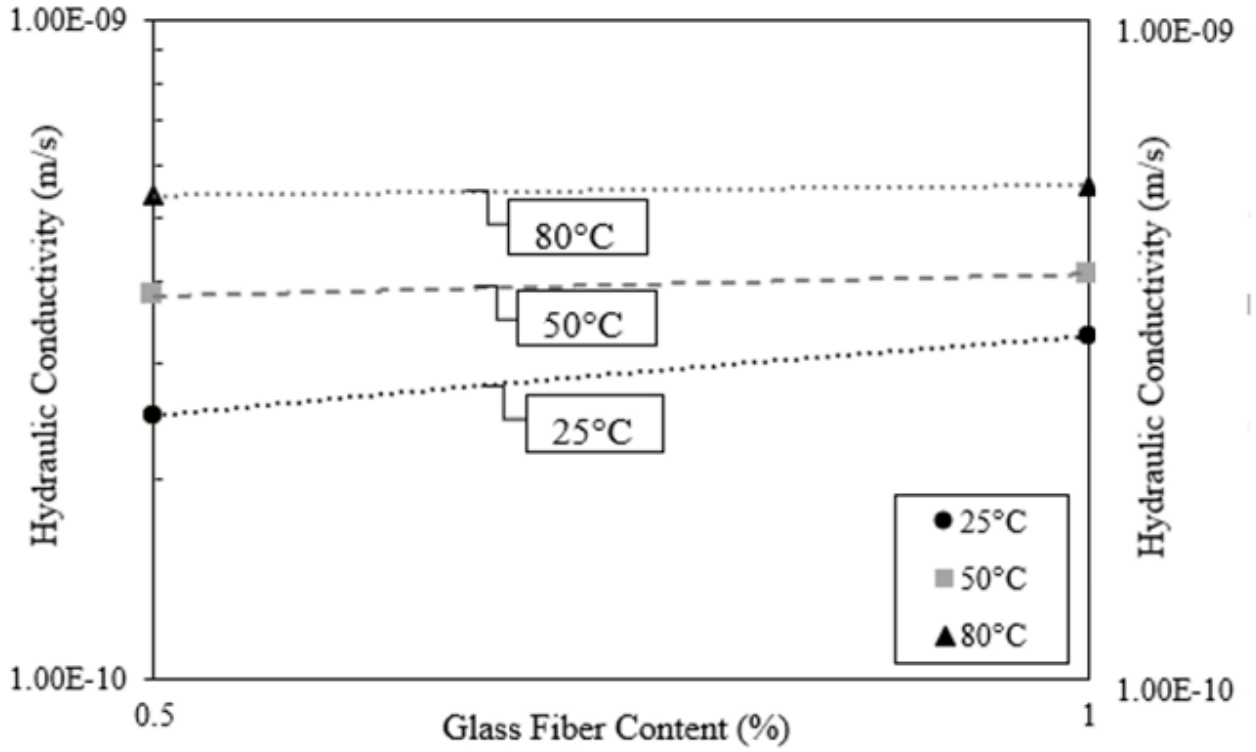


Figure 11

The graph of change in hydraulic conductivity depending on fiberglass content for different temperatures