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Suction Behavior of Sand-Bentonite Mixtures under High Temperatures with Carbon Fiber

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ABSTRACT

Soils that are not saturated with water have a greater tendency to absorb water, and the potential of soils to suction water varies depending on the different conditions. In addition, the suction behavior of soils is also affected by high temperatures. The soils around energy related underground structures are subjected to high temperatures. In order to determine the engineering behavior of these soils, the higher temperature effects should be investigated. In order to examine the impact of high temperature on the suction behavior of soils, this study aimed to determine the matric and total suction measurements of carbon fiber added sand-bentonite mixtures under high temperatures with the filter paper method. Equilibrium periods were 1 and 3 days for sand-bentonite mixtures. The same tests were performed under 55 °C temperature. Thermal conductivity measurements were also made for all samples. The test results show that carbon fiber increased the thermal conductivity values of sand-bentonite mixtures and as temperature increased, while the matric and osmotic suction values decreased.

Keywords: Bentonite, carbon fiber, sand, suction, thermal conductivity, temperature.

1. INTRODUCTION

The behavior of soils varies depending on many factors and it may not be possible to fully represent reality. In addition, environmental factors are also effective (1). One of the main reasons why soils are examined under a separate heading as "saturated" is due to the fact that the behavior of the soil's water content and moisture change cannot be fully revealed. However, the change in the water content of the soil will cause the volume of the soil to change; if it is fine-grained soil, it swells as the water content increases, and if the water is removed from its body, it dries out and forms cracks (2). As a result, loss of properties may

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be experienced. Conventionally, saturated soil mechanics, to a large degree formulated on the premise of Terzaghi's effective stress theory, fails to reflect the complex behavior of soils in states of partial saturation. Unsaturated soils, with air and water present in the pores, have their own unique characteristics, which call for special testing and analytical procedures. The consequences of neglecting unsaturated soil behavior can be dramatic, resulting in slope instability, foundation failure, and decreased performance of earthworks infrastructure.

The fact that soils have a multi-phase structure and the gas and liquid states of these phases change depending on factors such as temperature and pressure plays an important role in correctly evaluating soil behavior. The concept of "suction" is the difference in the water retention potential of the soils (2). The presence of air-water interfaces within unsaturated soils leads to matric suction (negative pore water pressure), which significantly contributes to the shear strength and stiffness of the soil (3). The adsorbed water layer thickness is one of the most fundamental factors in determining soil behavior (4). When the absorption mechanism was examined, researchers revealed that free water and soil water are different concepts and have different amounts of energy. Without this energy difference, flow would not occur (2). The mechanism of the suction is shown in Figure 1.

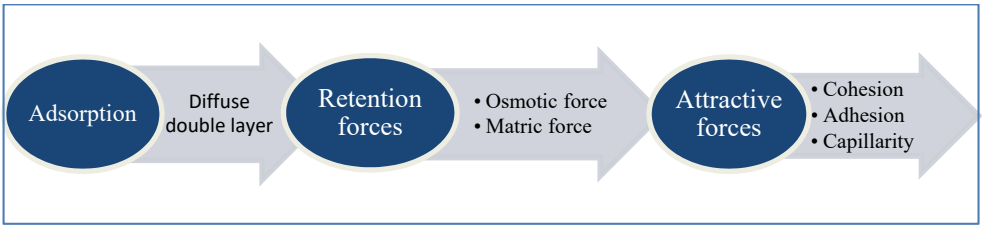


Fig. 1 - Forces in suction behavior (5-7)

Undoubtedly, determining suction makes it easier to predict many soil parameters. Factors such as fine or coarse-grained soils or cohesive and non-cohesive soils and their mineralogical structure require different solutions to problems. Selection of the appropriate buffer materials is crucial to the success of many engineering endeavors. The role of these materials is based on a list of characteristics like mineralogy, geochemistry, and more importantly, their physical form, i.e., their porosity. Porosity, as the ratio of void volume to total volume, is a characteristic property controlling fluid flow, chemical reactivity, and mechanics in a buffer material. Porosity must be maximized for the optimum functional characteristics and durability performance in applications under consideration. Transport in a fluid phase within a buffer material is controlled by pore structure, including pore size, shape, connectivity, and distribution. Hydraulic conductivity and diffusion coefficient are the most appropriate transport-related parameters, and both are controlled directly by porosity.

In the design of deep geological repositories for safely storing high-level radioactive waste, the engineering behavior of buffer is crucial. Compacted bentonite-sand mixtures are also favored as sealing materials due to their low permeability, ability to swell, and high retention qualities. Initially, compacted sand-bentonite buffers are in a dry state (8). However, groundwater penetration makes the buffer almost fully saturated (9). For that reason, compacted buffers are exposed to volume changes and swelling tendencies in the repository

environments (10). The buffer material is in contact with the canister; therefore, the buffer is exposed to high temperatures for over a hundred years. The buffer material becomes unsaturated during this stage. Therefore, the measurement of suction is crucial for investigating groundwater movement in unsaturated compacted sand-bentonite mixtures. The water level around energy piles may be lower than the pile cap. In this case, some part of the surrounding soil of the pile may be in the unsaturated state. For that reason, it is crucial to determine the suction behavior of buffer materials around energy-related underground structures.

Because of the growing need for energy-related geo-structures, such as underground heat pumps, nuclear waste repositories, and underground electric power cable tunnels, the determination of soil thermal conductivity has attracted considerable attention (11,12). Considering that the geothermal operation of energy piles leads to temperature change not only along the piles but also in the adjacent soil due to the phenomenon of heat exchange, investigation of thermal effects on the behavior of soils and soil-structure interfaces has become as important as the responses of energy piles (13). The heat from these structures should be rapidly removed for the safety and performance of energy-related underground structures. For that reason, researchers have been working on buffer materials with high thermal conductivity in recent years. Carbon fiber is used as a strengthening and improving additive in both concrete and soils. High strength, high carbon content and low specific gravity are reasons it is preferred (14). The raw materials of carbon fiber can be listed as polyacrylonitrile fiber, viscose fiber and asphalt fiber (15). Fiber has generally been used by many researchers since the friction at the interface with the soil is strong (16, 17). Carbon fibers can have thermal conductivity values in the range of 20 to 1000 W/m·K, depending on the grade. These high values are due to the graphitic structure aligned along the fiber axis, which allows for efficient heat transport. The sand-bentonite-carbon fiber mixtures may be a candidate buffer material with superior properties, like high thermal conductivity. Because of temperature increase and thermal cycles, the unsaturated case may occur. In terms of performance of energy pile, the behavior of soils should be investigated under unsaturated state. It is crucial to understand buffer materials reaction to the variations in water saturation and temperature fluctuations (11). The water retention characteristics of sand-bentonite mixtures are crucial for evaluating its performance as a barrier material, as these characteristics significantly impact its hydraulic and thermal conductivity, as well as effective stress.

Carbon materials, like carbon fibers, are often characterized by having a high surface energy. High surface energy is more conducive to adsorption as it allows for better interaction and adsorption of nearby medium molecules. However, since carbon fibers are often dense, porosity in the matrix material can be reduced. Reduction in porosity results in reduced additional channels for fluid entry and retention (18). Carbon fiber isn't "toxic" in the way that certain chemicals like heavy metals. If the fiber contains or is coated with resins, sizing agents, or epoxy, these could leach and potentially contaminate the soil. For that reason, because of environmental concerns, these types should not be used in soil improvement. Mechanical and chemical recycling methods exist, but they’re energy-intensive, costly, and not widely adopted. Most carbon fiber products end up incinerated or landfilled, both of which can have environmental drawbacks. End-of-life disposal of carbon fibres is potentially one of the most serious environmental problems. The dumping of CF waste in landfills may contribute to land degradation and depletion of resources, and the slow

degradation rate of carbon fibres ensures that they are stored in landfills for decades. Carbon fibre burning releases greenhouse gases, including carbon dioxide, and harmful by-products such as dioxins and furans (19).

The sand-bentonite mixtures are chosen as a buffer material in nuclear waste repositories and landfills. One of the main reasons for this preference is that bentonite has low hydraulic permeability if saturated (20). It was shown that when sand and bentonite are used together, their properties depend on their density in terms of clay, and sand is used for filling purposes (21, 22). At the same time, the swelling property of bentonite creates an advantage in situations where filling the voids is essential (23). An alternative buffer material to be used in the presence of high temperatures around energy structures (buried power cables, heat piles, solid waste and nuclear waste storage areas, etc.) is expected to maintain these properties for up to 10^6 years (23). Generally, 20-30% bentonite contents were used in the sand-bentonite mixtures for liner applications. The former studies reported that the limit hydraulic conductivity values (less than 10^{-8}-10^{-10} m/s) is met for compacted soil with a minimum bentonite content of 12% (24). Another study have shown that one bentonite type can be safely used as an alternative for clay starting from 10% bentonite content which achieves the minimum requirement for landfill liners however another type bentonite achieved that requirements content more than 14% (25).

The aim of the study is to examine the total and matric suction sucton values of sand-bentonite mixturesunder high temperatures in the presence of carbon fiber. In addition, the thermal conductivity values of the samples were determined at ambient temperature. All experiments that were carried out at ambient temperature, were repeated under 55° C and the effect of temperature on suction was also determined.

2. MATERIALS AND METHODS

2.1. Material Characterization

In this study, the suction and thermal conductivity determination tests were performed on the sand-bentonite mixtures. The bentonite sample was taken from local company and it is Ca-bentonite. Carbon fiber was supplied from local company and length of sample is 6 mm. According to the results of sieve analysis 20.7% of the sand is fine material and it was used as sieved through No. 6 sieve. The bentonite sample passed through the No. 200 sieve and the natural water content was determined to be approximately 7.5% (26). The physico-chemical properties of the materials are given in Table 1. In the Figure 2, images of carbon fiber and mixture of carbon fiber-sand-bentonite are given.

Table 1 - The physico-chemical properties of the materials

Property	**Sample**	
	Bentonite	**Sand**
Specific gravity	2.60	2.63
Liquid limit (%)	270	-
Plastic limit (%)	63	-



Fig. 2 - Carbon fiber and carbon fiber added sand-bentonite mixture

These XRD analyses were conducted on the Thermo Scientific ARL X'TRA X-ray diffraction equipment (Figure 3). The XRD analysis of Ca-bentonite indicated the presence of montmorillonite, quartz, calcite, and albite minerals.

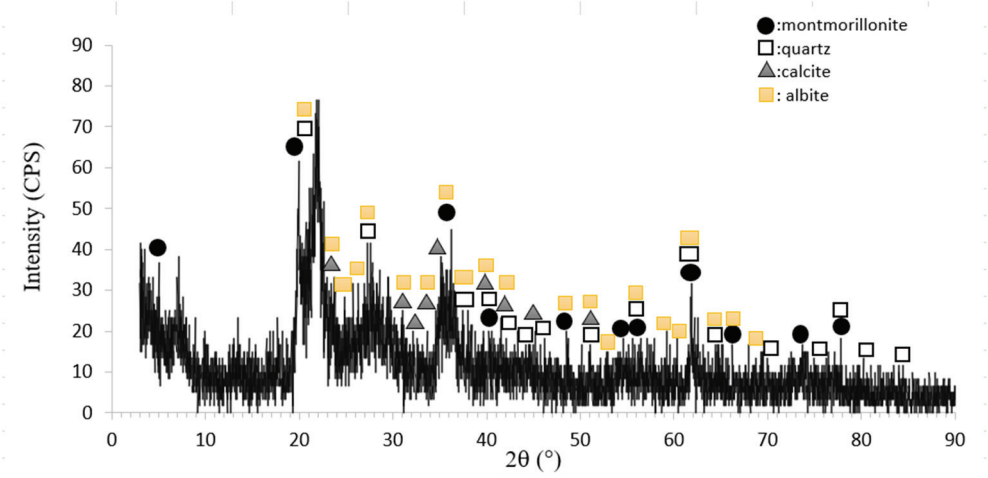


Fig. 3 - The XRD analysis of the Ca-bentonite

2.2. Methods

For the sand-bentonite mixture, 20% bentonite content was selected. The carbon fiber contents were 2% and 1% by dry weight. When naming the mixtures, sand is indicated with "S", bentonite with "B" and carbon fiber with "CF". The test samples were compacted in compaction molds (R=3.78 cm and V=84.8 cm^3) with the help of mini compaction apparatus at the determined maximum dry unit weight and optimum water content values from Standard Proctor compaction tests (Figure 4). The compaction apparatus used is similar to the apparatus in the study of Sridharan and Sivapullaiah (2005) (27). After the compaction, the samples were divided into two equal parts for a total height of 5 cm. The mixtures were left to dry for 1 and 3 days. Shrinkage values of the samples were determined using a caliper.



Fig. 4 - The equipment used for compression of the samples

Suction measurements due to drying were made using the filter paper method. Matric and osmotic suction values were determined. A total of three filter papers were placed between the samples divided into equal pieces in order to measure the matric suction (measurements were made with the filter paper in the middle of these filter papers). A lid was placed on the upper sample to measure and determine the osmotic suction, and filter paper was placed on the lid. Then, the samples were kept in a closed container, the filter papers were weighed at regular intervals, and the tests were terminated when the suction values reached equilibrium. (Figure 5).

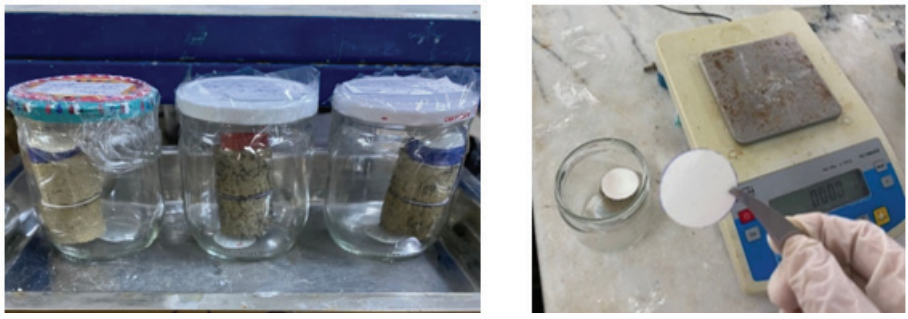


Fig. 5 - Measurements of samples under ambient temperature



Fig. 6 - Preparation of samples with high temperature suction values

After completing the tests at ambient temperature, tests were initiated under high temperature (55°C). The samples were prepared by compacting them at ambient temperature and dividing them into two equal parts. The prepared samples were placed in the oven by closing the jars and wrapping them with heat-resistant tape to prevent air intake (Figure 6).

The samples were kept in the oven at approximately 55°C for 1 and 3 days. At the end of these periods, measurements were taken from the samples and matric and osmotic suction values were determined. In addition, the thermal conductivity values of the samples were measured with Tempos Thermal Properties Analyzer. The samples were prepared at w_{opt} and $\gamma_{dry,max}$ values. Thermal conductivity values of the samples compacted in three layers were determined using the appropriate probe.

3. RESULTS AND DISCUSSIONS

In the present study, 1% and 2% contents of carbon fiber were added to the sand-bentonite mixtures and suction values were determined under ambient temperature (22~25 °C) and 55 °C. In addition, the thermal conductivity values of all the mixtures were determined under ambient temperature. The Standard Proctor test results showed that the max. dry unit weight of the sand-bentonite mixture was as 17.3 kN/m^3 and the optimum water content was 14.1%. Since the carbon fiber contents were very low, the compaction parameters of the carbon fiber added mixtures were kept the same.

The suction values were calculated accordingly using calibration suction-water content curves (Figure 7) (28). The Whatman No. 42 curve was used in two different formulations, taking into account the cases where the water content was less than and greater than 45.3% (28). The time-dependent water content graphs of the samples in the matric and osmotic states at ambient temperature (22~25 °C) and 55°C are given in Figure 8.

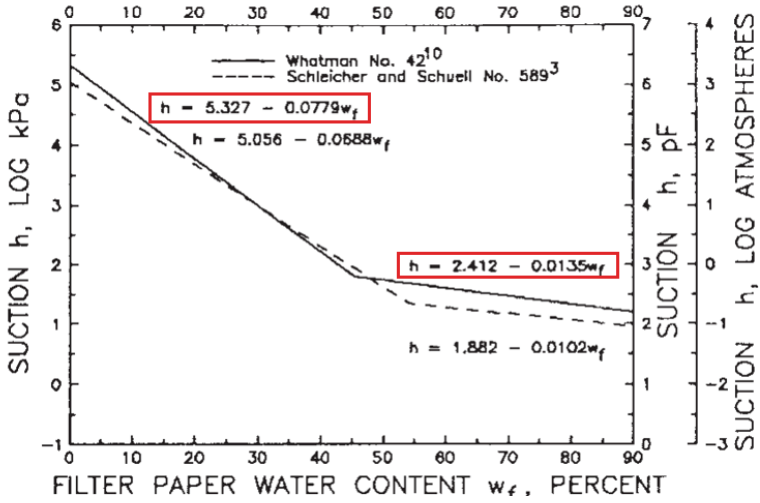


Fig. 7 - Calibration Suction-Water Content Curves for Wetting of Filter Paper (28)

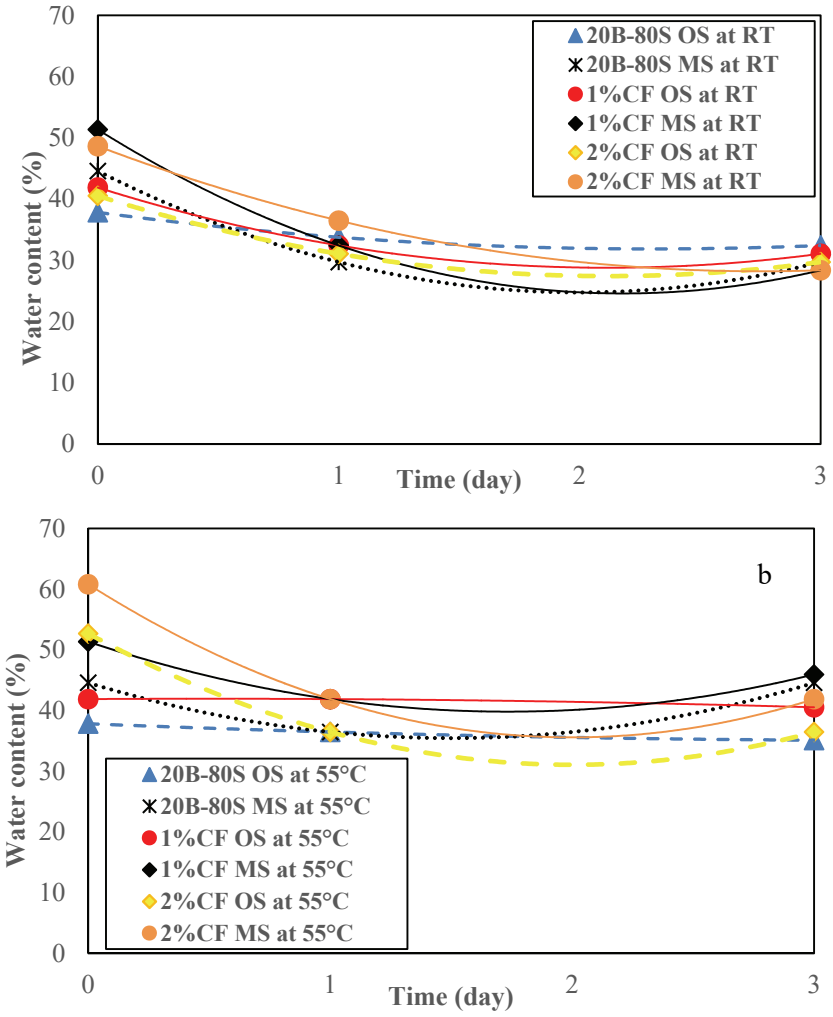


Fig. 8 - Change in water content content values of the mixtures depending on time a) osmotic (OS), b) matric suction (MS)

When the two different temperature conditions were examined, it was determined that the water contents of the samples were generally higher at 55°C. The initial water content value of the additive free sand-bentonite mixture was 44%. At the end of one day curing period, these values were determined as 29.7% for the sand-bentonite mixture, while fiber added mixtures decreased to 32.4% and 36.5% in the presence of 1% and 2% additives, respectively. The curing period was determined as a maximum of 3 days and at the end of this period, it was observed that the water content value of the mixture without additives did not change, but the water content value of the mixtures with fiber additives decreased by 4% to 6%. All these values calculated as a result of the tests were determined for the matric suction case.

When the water content of the filter papers was examined in the tests carried out under high temperature, it was seen that the change was at lower rates compared to ambient temperature. For instance, it was seen that the additive free mixture' water content value decreased to 36.5% for the 0. day (Figure 8). When all mixtures were examined, it was observed that the carbon fiber had an increasing effect on the water content of the sand-bentonite mixture under both temperature conditions. As a result of this effect, it was revealed that the suction values of the mixtures with carbon fiber was lower than the mixtures without additives.

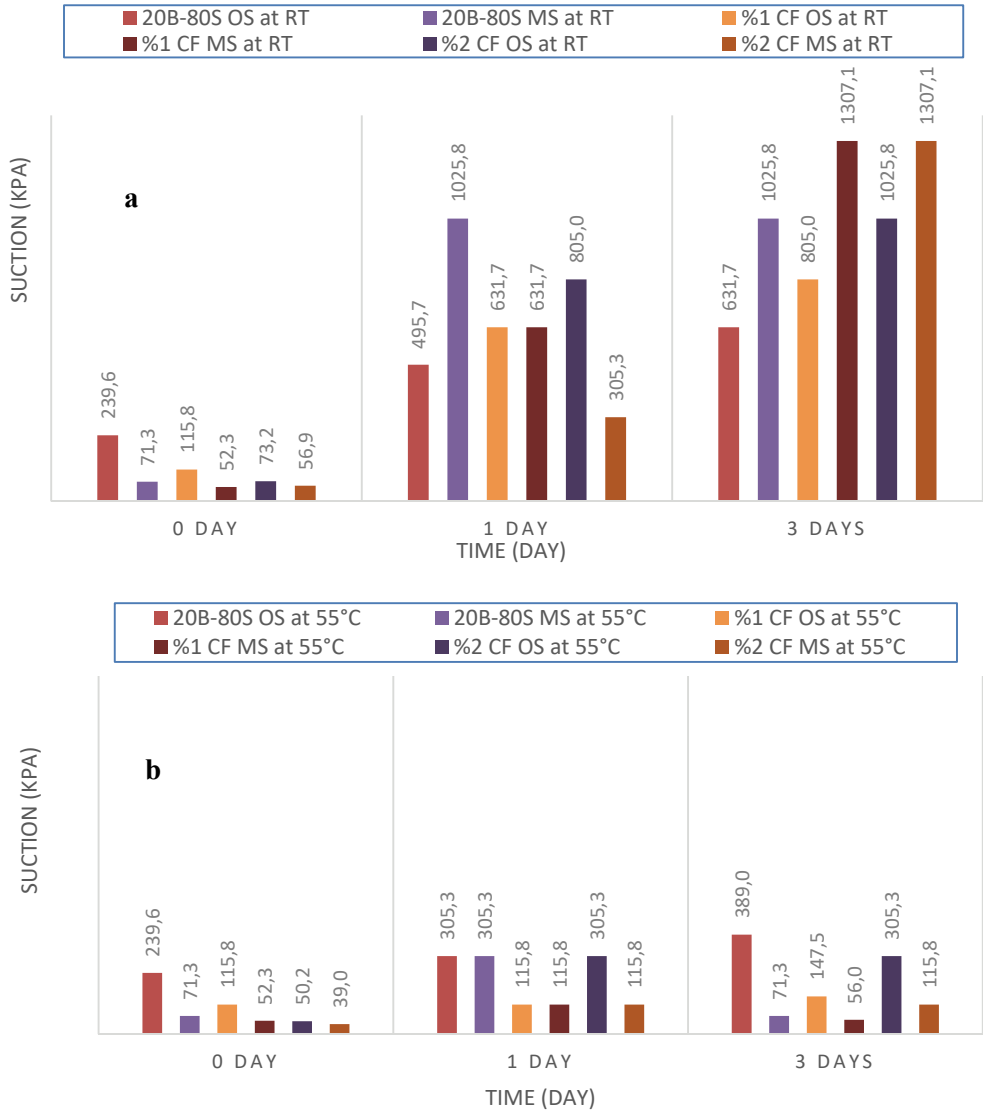


Fig. 9 - Matric suction (MS) and osmotic suction (OS) values of the mixtures a) at ambient temperature (RT) b) at high temperature (55°C)

The results showed that temperature had a significant effect on the suction results. As temperature increased, the matric and osmotic suction values decreased. The carbon fiber content generally decreased the suction values of the samples. This effect is valid for both ambient temperature and 55 °C. The effect of %2 CF is more significant than %1 CF content (Figure 9). The 2% carbon fiber kept the total suction value of the mixture unchanged when compared to 1% carbon fiber.

It was observed that the matric suction value for the 20B-80S mixture without additives at ambient temperature was greater than the osmotic suction value of approximately 530 kPa on the first day, and these values were equalized when the temperature was increased to high temperatures. In the mixtures with additives, it was determined that the numerical magnitude of the osmotic suction value at ambient temperature with 2% CF decreased below 55 °C compared to the matric suction. While it is observed that osmotic suction pressures at ambient temperature were generally lower than matric suction values, it revealed that osmotic suction pressures determined under high temperatures are generally higher than matric suction values (Figure 9).

Table 2 shows the total suction values of the mixtures at ambient and 55 °C. The carbon fiber lowers the suction pressure under both temperature conditions. However, when the high temperature, the existing suction pressures were further reduced due to the higher water content of the filter papers at high temperatures.

Table 2 - Total suction values of the mixture at ambient and high temperatures depending on the time

	Total Suction (kPa)					
	Ambient Temperature (°C)			**High Temperature (°C)**		
Mixtures	**Time (day)**			**Time (day)**		
	0	**1**	**3**	**0**	**1**	**3**
20B-80S	310.9	1521.5	1657.5	310.9	610.6	460.3
20B-80S-1CF	168.1	1263.4	2112.1	168.1	231.6	203.5
20B-80S-2CF	130.1	1110.3	2332.9	89.2	421.1	421.1

The suction tests showed that the matric and osmotic suction values generally decreased when the temperature was changed from ambient to high temperature. The suction pressure of the additive free sand-bentonite mixtures decreased with the carbon fiber in both temperature conditions (Figure 10). The former studies have shown that soil matric suction can vary depending on the soil's own texture, particle size distribution, density and organic matter content (29, 30). The carbon fiber used in this study is a material with low thermal expansion and widely used in many sectors (31, 32). A low coefficient of thermal expansion means that the material exhibits low levels of expansion when exposed to temperature changes, thus demonstrating stability in dimensional change. Since carbon fiber has low thermal expansion, grain sizes do not change much in the presence of heat and the amount of

water in it does not decrease. Accordingly, the suction pressure decreases. The distribution of the carbon fibers in the sample is shown in Figure 11.

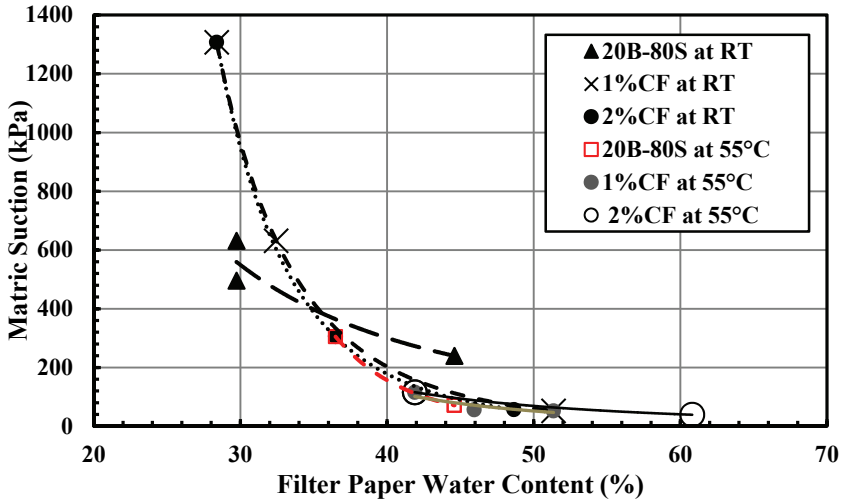


Fig. 10 - Effect of time (0, 1 and 3 days) on the matric suction of the mixtures



Fig. 11 - The distribution of the carbon fibers in the sample

The thermal conductivity values of the carbon fiber added sand-bentonite mixtures were determined. The obtained values are given in Table 3. The experimental results showed that the carbon fiber has an effect of increasing the thermal conductivity. While the thermal conductivity value of the 20B-80S mixture was 0.882 W/mK, this value increased by approximately 31% and 42% with 1% and 2% carbon fiber contents, respectively, reaching 1.155 W/mK and 1.258 W/mK. It was observed that carbon fiber increases thermal conduction by providing a filling effect in the gaps thanks to its fibrous structure (Figure 12).

In crystalline materials like graphite, thermal energy is conducted by lattice vibrations termed phonons. The strongly ordered graphitic structure of CF enables efficient phonon transport in the direction of the fiber axis, leading to high thermal conductivity. Even though CF is not a metal, delocalized π-electrons within the graphitic sheets provide electronic thermal conuctivity (33).

Table 3 - Thermal conductivity values of the mixtures

Mixtures	Thermal Conductivity (W/mK)
20B-80S	0.882
20B-80S-1CF	1.155
20B-80S-2CF	1.258

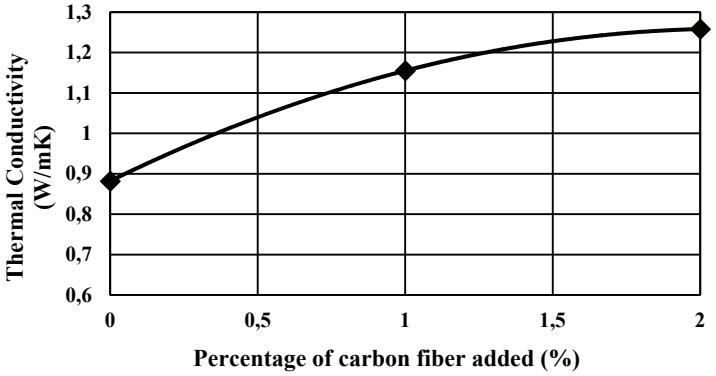


Fig. 12 - Effect of carbon fiber on the thermal conductivity of bentonite

4. CONCLUSIONS

In the present study, osmotic and matric suction pressure values of carbon fiber added sand-bentonite mixtures were measured at ambient and high temperatures. The effect of the temperature was investigated by reaching the total suction values and at the same time thermal conductivity values of the mixtures were determined under ambient temperature. The tests results showed that the carbon fiber reduced the suction pressure of the sand-bentonite mixtures at ambient temperature. It was observed that the suction pressure values decreased when the ambient temperature increased to high temperature. This is important for the energy related underground structures where high temperatures are present. The suction behavior will change under high temperatures, depending on this other properties like swelling, compressibility and shear strength of the buffer material may change.

It was determined that carbon fiber showed thermally conductive behavior by increasing the thermal conductivity of the sand-bentonite mixtures. The results have shown that 2% carbon fiber can be used in order to increase thermal conductivity and keep total suction values

unchanged under high temperatures. The positive contribution of carbon fiber to the thermal conductivity value has increased its usability as a buffer material around energy structures.

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Conflict of Interest statement

The authors declare no conflicts of interest.

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