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SOIL-WATER CHARACTERISTICS CURVE OF FIBER REINFORCED SOILS

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ABSTRACT

Soil-Water Characteristics Curve (SWCC) describes the relationship between suction and the corresponding state of wetness and has different behavior in drying and wetting conditions. The SWCC is very important to predict the hydro-mechanical behavior of unsaturated soils. To analyze the effect of fiber inclusion on SWCC, samples from a clay-silt-sand mixture with different straw contents (from 0 to 3 gravimetric percent) were made. In drying and wetting paths, the samples were subjected to a wide range of suction starting from 10 kPa to 210 MPa and vice versa. At the same suction due to the influence of reinforcement on shrinkage and swelling, the degree of saturation in samples with higher straw content was considerably smaller than that of samples with lower straw content, however, they retained almost the same amount of water. Degree of saturation and gravimetric water content were from 0.53 to 0.92 and 14% to 16%, respectively, for straw content ranging from 0% to 3% at the end of wetting paths. With an increase in fiber inclusion from 0% to 1%, the hydraulic conductivity increased from 1.6×10^{-8} to 9.1×10^{-8} cm/s. The effect of reinforcement on compaction curves and pore size distribution was also observed. Finally, the soil-fiber interaction and influence of reinforcement on pores' sizes were studied in detail using SEM photography and Porosimetry techniques.

Key words: Suction, SWCC, fiber reinforced soil, hydraulic conductivity, pore size distribution, SEM photography.

1. INTRODUCTION

Soil reinforcement is defined as the inclusion of discrete randomly distributed fibers with soil to improve the engineering characteristics of soil in order to develop the parameters such as shear strength, compressibility, density, and hydraulic conductivity. Being low cost, sustainable, and technically effective, the application of fibers -which is rooted back in the history, *e.g.,* the Great Wall of China and the Ziggurats of Elam civilization, is increasing today in rural housing projects, soil stabilizations, embankments, *etc.* Unlike most of the researches on fiber-reinforcement of soils, the selected fiber for reinforcement in this research is a natural fiber, *i.e.,* typical wheat straw, available worldwide and is a non-hazardous by-product of agriculture.

As a prerequisite to explain the unsaturated strength parameters, swelling/shrinkage behavior, as well as all other hydro-mechanical behavior of clayey soils reinforced by randomly distributed natural fibers subjected to wetting and drying paths, the water absorption of fibers, compaction and hydraulic conductivity of reinforced soil and the SWCC of such materials are investigated in this paper. For SWCC tests of this research, two methods of applying suction are employed: ATT (Axis Translation Technique) and VET (Vapor Equilibrium Technique). Moreover, in the mentioned experiments, the interaction of the host soil and the straw fibers are studied in more detail by performing SEM photography (Scanning Electron Microscopy) and Porosimetry techniques.

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The inclusion of fibers in soil considerably decreased the volumetric changes of the host soil during wetting and drying paths. Saturated samples with fiber content from 0% to 3% had initial void ratios of 0.70 to 0.77 (for 0% and 3% fiber content respectively). This phenomenon affected the SWCC curves as well. In this research, influence of fiber reinforcement with various fiber content on proctor curves, saturated hydraulic conductivity and the SWCC curves has been experimentally studied and presented.

2. BACKGROUND

2.1 Soil Reinforcement

In the modern history of soil stabilization, the concept and principles of soil reinforcement was first developed by Vidal (1969). He demonstrated that the inclusion of reinforcing elements in a soil mass increases the shear resistance of the medium. This technique is still an attractive research topic with developing field applications (Chen *et al.* 2019; Wang *et al.* 2019).

Loehr *et al.* (2000) stated that reinforcement of expansive soils with discrete polymeric fibers potentially offers an alternative method to chemical stabilization techniques and other methods of reducing swelling potential. These conventional synthetic fibers were mostly the by-products of other industries (*e.g.,* petroleum, textile, *etc.*) that are consuming non-renewable resources of the earth. As highlighted by Gowthaman *et al.* (2018), the usage of geo-synthetic products (such as plastic composites and steel straps) as soil reinforcing elements has gained popularity due to their flexibility during processing and high specific stiffness (Pujari *et al.* 2017). However, they have been grouped as a non-ecofriendly approach due to detrimental impacts on the environment. For instance, the corrosion that remained from steel reinforcing elements are very toxic to the environment (Gaw *et al.* 2011; Gowthaman *et al.* 2018). On the other hand, natural fiber reinforcement is considered as a sustainable soil strengthening techniques in geotechnical engineering due to its outstanding advantages of environmental friendliness, resource abundance, minimal energy consumption, cost-effectiveness, and high potential over other established materials (Fagone *et al.* 2017; Ibrahim *et al.* 2010; Gowthaman *et al.* 2018).

Natural fibers can be categorized into three groups in terms of their origins: (i) plant fibers (bamboo, jute, coir, hemp, straw, *etc.*), (ii) animal parts containing protein (silk, hair, wool, *etc.*), and (iii) minerals (Zakikhani *et al.* 2014). Based on the availability and compatibility for large-scale applications, plant fibers are more preferable by geotechnical engineers (Gowthaman *et al.* 2018). Such plant fibers may be originated from stem, leaf, seed, fruit, wood, cereal straw, and other remains. However, which part of the plant the fiber is taken from, the age of the plant, and how the fiber is treated, are some of the aspects which influence the durability and performance of the natural fibers (Gowthaman *et al.* 2018).

In contrary to synthetic fibers, natural fibers are prone to biodegradation due to the microorganisms living in the soil and hence less durable; further, soil's humidity provides a favorable condition for the decomposition of such fibers (Mohan and Manjesh 2017; Bordoloi *et al.* 2017; Gowthaman *et al.* 2018), although, the lignin (typically existing on the outer layer of fiber-matrix) resists the intrusion of the bacterium and protects the fibers up to a certain extent (Wei and Meyer 2015). Degradation affects the durability of natural fiber and potentially depletes the reinforcing effect of fiber, and is often regarded as a challenge that needs to be assessed. Carvalho *et al.* (2015) tested the durability of sisal, coir, and banana fibers under influence of UV rays, heat, and moisture using QUV accelerated aging effect and concluded that the studied fibers lost up to 90% of their tensile strength during the test. As to ensure the long-term durability of fibers, many treatments have been introduced in the literature and in practice, mostly by coating the fibers with chemical substances, *e.g.,* sodium hydroxide (NaOH), bitumen, paints, epoxy and polyester resins, acrylic butadiene styrene (ABS), *etc.* (Javadian *et al.* 2016; Chacko and Joseph 2016 on bamboo fibers; Fagone *et al.* 2017; Saha *et al.* 2012; Sarkar and Ray 2004 on Jute fibers; Peter *et al.* 2016 on coir fibers; Ahmad *et al.* 2010 on palm fibers).

2.2 Function of Reinforcement

Most of the published researches in the field of soil reinforcement have generally shown that strength and stiffness of the soil were improved by fiber-reinforcement (Lee *et al.* 1973; Gray and Ohashi 1983; Maher and Ho 1994; Nataraj and McManis 1997; Ghavami *et al.* 1999; Puppala and Musenda 2000; Mesbah *et al.* 2004; Tang *et al.* 2007). Several experimental studies have been carried out on the effect of fiber-reinforcement on reduction in swelling pressure, shrinkage, desiccation cracks, etc. Ayyar *et al.* (1989), Puppala and Musenda (1998), Ikizler *et al.* (2007), and Loehr *et al.* (2000) reported reduction in swelling pressure due to fiber reinforcement. Al-Wahab and El-Kedrah (1995), Cai *et al.* (2006), Illuri and Nataatmadja (2007), and Malekzadeh and Bilsel (2012a) showed that the shrinkage and swelling potential of clayey soils reduces by fiber-reinforcement.

As found by Abdi *et al.* (2008), the swelling displacement of fiber-reinforced soils appears to be less dependent on the moisture content compared to its unreinforced host soil. The effect was proportional to the fiber content. Kinjal *et al.* (2012) and Malekzadeh and Bilsel (2012b) reported that fiber inclusion reduces shrinkage tendency during desiccation. Tang *et al.* (2007) studied the behavior of lime-fiber stabilized soils, concluding the improvement in compression, and shear strength, swelling, and shrinkage. Viswanadham *et al.* (2009) examined the swelling behavior of fiber-reinforced soils, using fibers of different aspect ratios, and observed a reduction in heave.

Maher and Ho (1994), Abdi *et al.* (2008), and Chegenizadeh and Nikraz (2011a) presented that hydraulic conductivity was increased as a function of fiber content. Marandi *et al.* (2008) and Chegenizadeh and Nikraz (2011b) reported that by an increase in natural fibers, optimum moisture content increases and maximum dry density decreases. The same behavior was reported by Amir-Faryar and Aggour (2012) for silty sand and by Ikizler *et al.* (2009) for bentonite.

2.3 Unsaturated State and SWCC

Fredlund and Morgenstern (1977) described the stress state in an unsaturated soil by using two independent normal stress variables, which are the net normal stress $\sigma_{net} = \sigma_t - u_a$ and matric suction $\psi = u_a - u_w$, with the total stress σ_t, pore water pressure u_w and pore air pressure u_a. Basically, the influence of the water content on the stress state in an unsaturated soil is considered by means of matric suction, which is applicable to describe the mechanical behavior of unsaturated soils. The water content is related to matric suction via the SWCC. This curve represents the ability of soil to retain water at different suctions. The amount of water can appear as any of the parameters showing the wetness of soil (*i.e.,* degree of saturation and volumetric or gravimetric water content). The relation between the amount of water in the soil and associated suction in the pore water is described by SWCC. The matric suction increases or decreases while the soil is in drying or wetting processes, respectively (Fredlund and Rahardjo 1993). SWCC is one of the most useful characteristics in unsaturated soil mechanics and widely used to capture the effect of the water content on the behavior of unsaturated soils. Many geotechnical and hydro-mechanical properties of unsaturated soils (such as hydraulic conductivity, effective stress, and volume changes) can be explained using SWCC (Fredlund and Rahardjo 1993; Fredlund *et al.* 1995).

The specimens starting from the saturated condition lose water following the so-called drying path and those starting from the dry condition receive water following the wetting path. Due to the hysteretic behavior of SWCC, the specimens don't go through the same curve in the drying and wetting paths. For a given suction the sample started from a fully saturated condition contains more water compared to the sample started from the dry condition. Although the influence of moisture content on hydro-mechanical behavior of fiber reinforced and their SWCCs have been studied in numerous researches, the need for further studies especially on reinforced soil with natural fibers is still greatly felt.

3. MATERIALS AND METHODS

3.1 Materials

The materials used in this study were soil-straw mixtures with different dosages. Host soil itself is a composite of two types of clay, *i.e.,* Kaolin and calcium-type bentonite, called also Calcigel, silt and sand (20% Kaolin 6% Calcigel 30% silt, and 44% sand). The soil components were mixed in dry condition, then water was added to reach a uniform saturated slurry at a water content of 1.25 times the liquid limit. Manual mixing continued until a homogeneous and uniform mixture is achieved. Figure 1 shows the grain size distribution curve of the studied material. The physical characteristics of the adopted mixture were determined in accordance with DIN Standard. The adopted soil has a liquid limit of 20.5, plastic limit of 12.5, plasticity index of 9, and a specific gravity of 2.67.

In this study, straw fibers are used for reinforcing the soil, which is a natural fiber, environmentally friendly, and available worldwide. The fibers are shown in Fig. 2. The dosage of straw varies from 0 to 3 percent in samples.

The liquid limit and specific gravity of the soil reinforced with straw fibers are presented in Table 1. Figure 3 shows the chart of Atterberg limits for the adopted material. In the unified system, this soil is classified as CL.

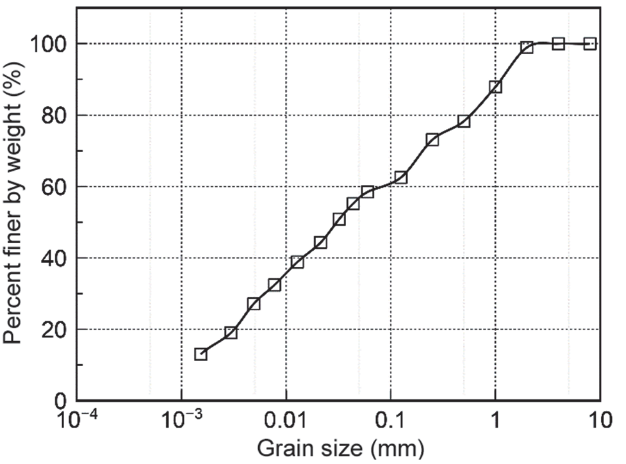

Fig. 1 Grain size distribution curve of the soil used in this study

Fig. 2 Wheat straw used in this study

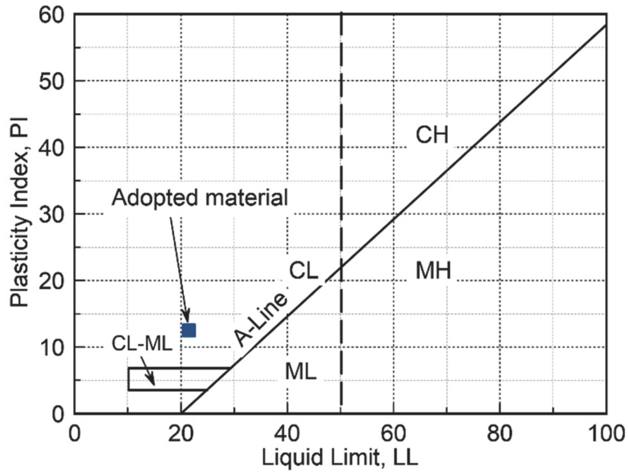

Fig. 3 Atterberg limits and values for the adopted material

Table 1 Liquid limit and specific gravity of used materials

Straw (%)	Soil (%)	Gs (g/cm^3)	LL
0	100	2.67	20.5
0.5	99.5	2.67	21.5
1	99	2.66	25
2	98	2.65	28.5
3	97	2.64	37.8

3.2 Methods

3.2.1 Compaction Test

The soil-water mixture for Proctor compaction was prepared by first mixing a measured amount of dry soil (about 2 kg for each test) with a predetermined amount of water. The dry densities and water contents of the soil samples after compaction are presented in Fig. 6. In the case of fiber addition, the weight of specific fibers content was calculated based on the weight of the dry soil. The fiber inclusion was 0%, 0.5%, 1%, 2%, and 3% of the total soil-fiber weight. The required amount of fiber was first mixed with dry soil, and then water was gradually added. Mixing continued until a uniform mixture was produced.

3.2.2 Hydraulic Conductivity

In order to measure the saturated hydraulic conductivity of unreinforced and reinforced soils, the constant head permeability test was carried out. The samples were compacted in a cylindrical mold with 120 mm height and 100 mm diameter. For this purpose, the first soil was mixed with the predetermined dosage of straw. Afterward, water was added to the mixture gradually to reach a 5% gravimetric water content. In the compaction process the void ratio of soils with various straw dosages must reach the desired void ratios for measuring hydraulic conductivity were 0.39, 0.52, and 0.57 for samples with 0%, 0.5%, and 1% straw content respectively. Afterward, samples were made and saturated under isotropic water pressure, a back pressure of 350 kPa was kept constant during the test.

3.2.3 SWCC Sample Preparation and Test Procedure

Materials with 0%, 0.5%, 1%, 2%, and 3% straw content were first mixed with 1.25 times the water content at the liquid limit (LL) of the host soil to produce a saturated uniform slurry. The slurries had the natural void ratios of 0.70, 0.705, 0.72, 0.74, and 0.77 (respectively for the unreinforced soil and four straw contents) for the predefined water contents, and were the initial points of drying paths of SWCC. To be sure that the samples were fully saturated, they were placed over-saturated porous stones and covered with nylon foil. After a few days in this condition, the samples reached constant weights. These weights were supposed to be equal to the pre-calculated weight of saturated samples, and as such, they were assumed to be fully saturated. Plexiglas rings with an inner diameter and height of 50 and 15 mm were filled with the slurries to be placed in the pressure plate or desiccators for applying controlled values of suction as explained below.

Two series of tests were performed in order to draw full SWCC of reinforced and unreinforced materials, namely ATT for suctions up to 800 kPa (Fig. 4) and VET for suctions from 2 MPa to 200 MPa or more (Fig. 5).

In ATT, matric suction is associated with the soil matrix and is defined as the difference between pore-air and pore-water pressure of the soil ($u_a - u_w$) (Hilf 1956). Both pore-air and pore-water pressures can be controlled in the Pressure Plate Apparatus in the laboratory (Fig. 4). This method is described in ASTM C1699-09. In this study, the pressure plate extractor was used to apply suction values between 10 to 800 kPa with three ceramic discs with different air-entry values used depending on the applied suction (100, 500, and 1,500 kPa discs).

Figure 5 shows the desiccators containing salt solutions for applying suction via VET in this research. Salt solutions with different salinity and molality produce various relative humidity, resulting in various suction values. Generally, the VET can be used to control almost the whole range of total suction. But the use of VET for applying total suction less than 2 MPa suffers from inaccuracies (Agus and Schanz 2005).

As mentioned before, the samples in this study were prepared in saturated slurry conditions with void ratio varying from 0.7 to 0.77 for straw contents from 0% to 3%. Then they were subjected to various suctions from 10 kPa to more than 210 MPa using ATT and VET methods, and left in the applied suction to reach the equilibrium condition. During this drying process, the samples lost water and shrank. In a separate series of tests, samples in identical conditions explained above were made and after fully drying were subjected to the same suctions as in drying paths to receive water. In the wetting process, the samples got water and swelled.

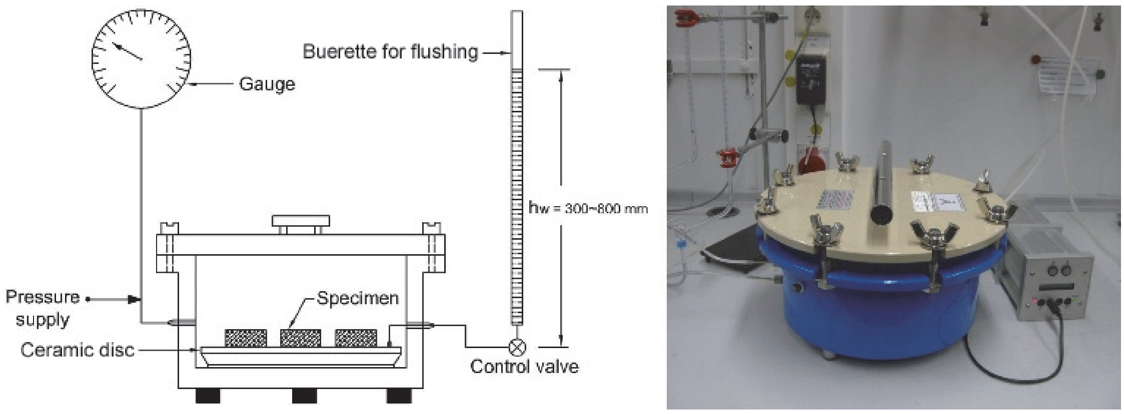

Fig. 4 Pressure plate apparatus

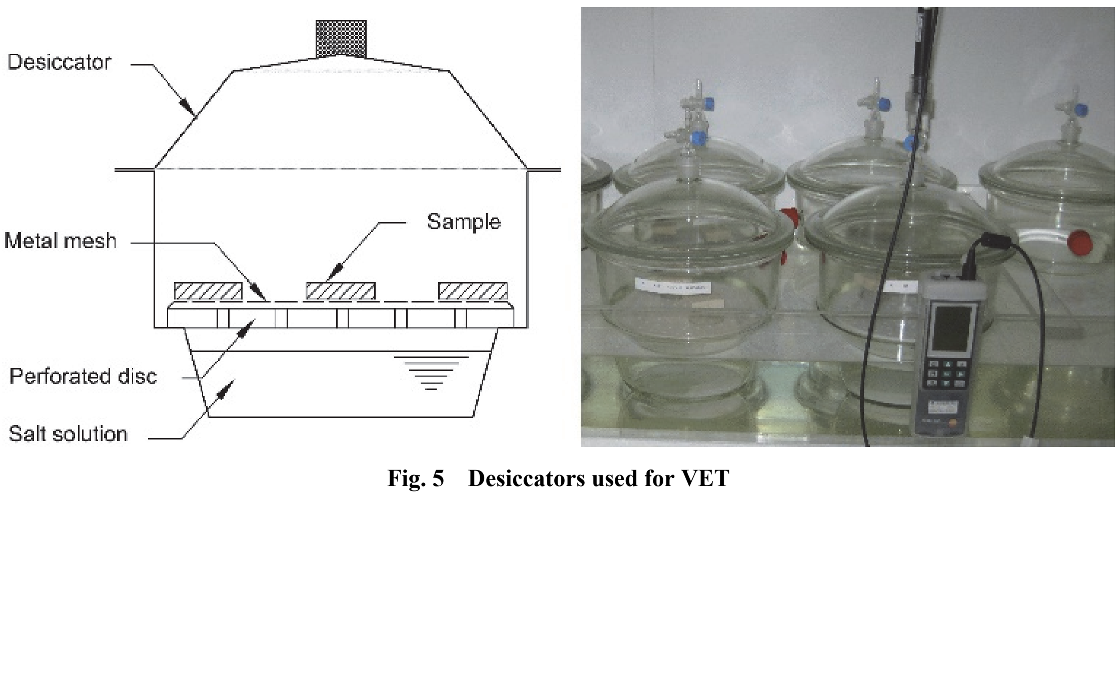

Fig. 5 Desiccators used for VET

4. RESULTS AND DISCUSSION

4.1 Compaction Test

As Figs. 6 and 7 show, after compaction of soils by an increase in fiber content, maximum dry density decreased from 1.97 to 1.64 g/cm^3 and optimum moisture content increased from 11% to 14%. In other words, for the materials used in this study, the compaction curve was shifted downward and toward the right with an increase in the fiber content.

Amir-Faryar and Aggour (2012) also reported that with an increase in fiber content in kaolin optimum moisture content increased and maximum dry density decreased. The same behavior is reported by Marandi *et al.* (2008) and Chegenizadeh and Nikraz (2011b) for silty sand, and by Ikizler *et al.* (2009) for bentonite. Similar to this study, the two former researches above used natural fibers.

The decrease in density is most likely a result of the less specific weight of fiber filaments in comparison with the soil grains and the elasticity of fibers that prevent the soil particles approach another. And the increase in moisture content is possibly a result of the greater water absorption capacity of the fibers than the base soil.

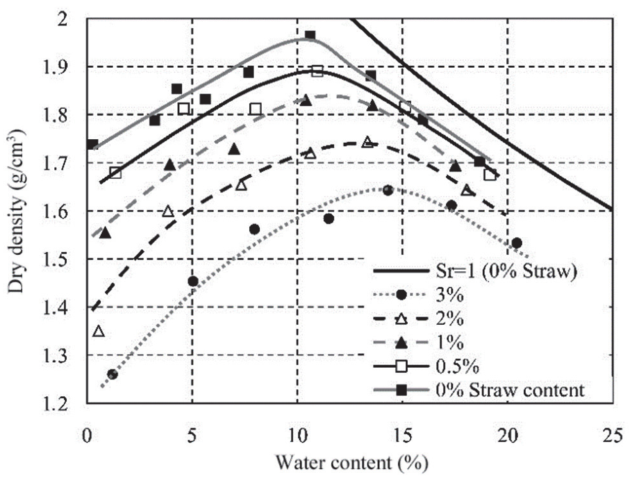

Fig. 6 Compaction curves of unreinforced and reinforced soils with various straw fibers

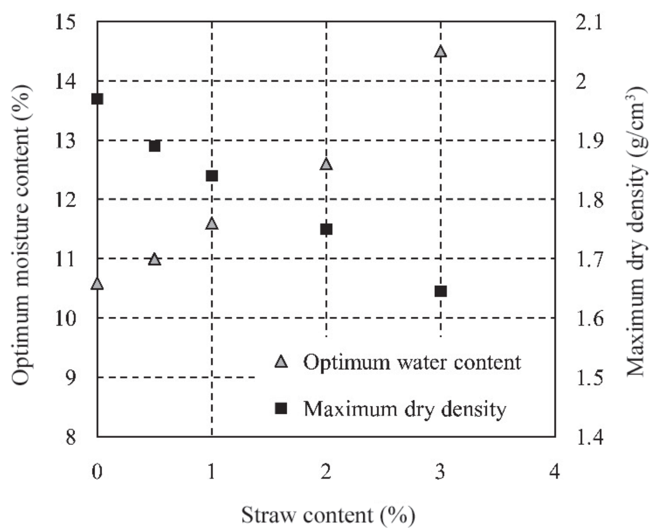

Fig. 7 The relationship between optimum moisture content, maximum dry density and straw content

4.2 Saturated Hydraulic Conductivity and Water Absorption

The effect of random fiber inclusion on saturated hydraulic conductivity of samples tested is shown in Fig. 8. Hydraulic conductivity increased from 1.6×10^{-8} to 9.1×10^{-8} with an increase in fiber content from 0% to 1%. This rapid increase might be due to two reasons; (a) porosity of fibers which can function as long pipes and transport water through the sample, and (b) higher void ratio in reinforced samples in comparison with unreinforced ones.

Abdi *et al.* (2008) presented that hydraulic conductivity was increased as a function of both fiber content and length. Chegenizadeh and Nikraz (2011a) and Maher and Ho (1994) have also proved the increase in hydraulic conductivity with an increase in fiber content.

The moisture absorption characteristics of the straw fibers were examined by submerging the fiber samples and weighing them at various times. The results, as plotted in Fig. 9, show the maximum gravimetric water content of almost 900% reached after a period of 40 ~ 50 hours. Comparing to 190% as found by Marandi *et al* (2008) for palm fiber, the water absorption of straw

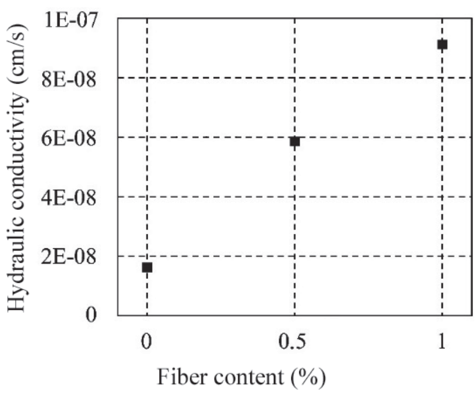

Fig. 8 The relationship between saturated hydraulic conductivity and fiber contents of tested samples

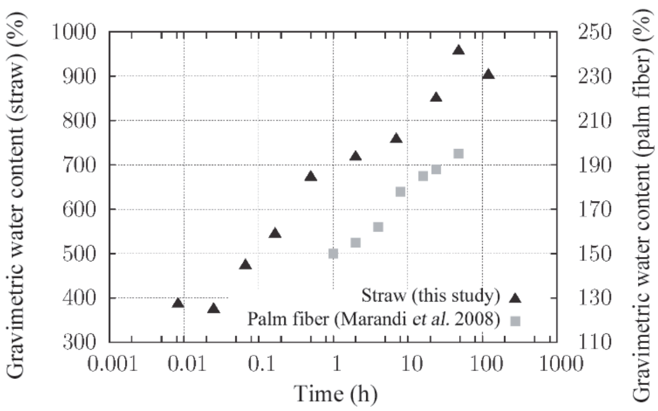

Fig. 9 Fiber water absorption (gravimetric water content) after various absorption periods

fibers is too high. This could be due to the shape of straw pieces which are like hollow tubes and can retain water inside. The initial gravimetric water content of straw was around 7%.

4.3 SWCC, Swelling, and Shrinkage

The studied range of fiber inclusions (0% to 3%) considerably affected the volumetric behavior and consequently volume-related parameters (*e.g.,* void ratio and volumetric water content), on the other hand, the mass related parameters (*e.g.,* the gravimetric water content) were not affected as much. Therefore, as shown in Fig. 10, the gravimetric water content in wetting and drying paths is almost independent of the fiber inclusion at any given suction. Due to the hysteretic behavior of SWCC, as we can see for all samples, the amount of water that samples can retain is different in wetting and drying paths. Although samples with different fiber contents could retain almost equal gravimetric water contents, at certain values of suction they had considerably different levels of shrinkage (in drying path) and swelling (in the wetting path). As it can be seen from the white markers of Fig. 11, although all samples had void ratios of 0.7 to 0.77 at their initial condition (saturated slurry), in the dry condition, as much

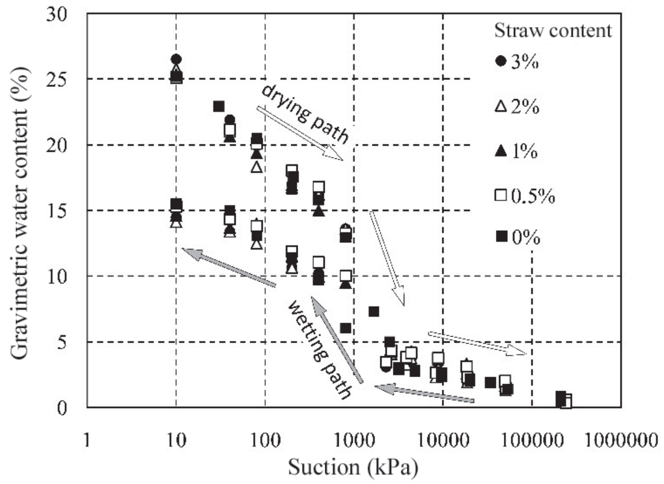

Fig. 10 Gravimetric water content in both drying and wetting paths by changing the suction

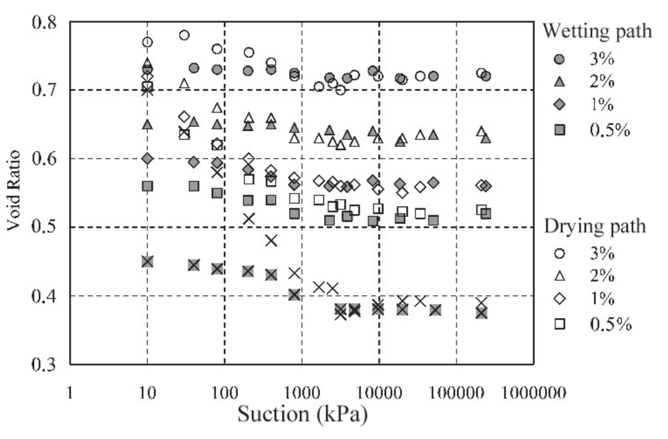

Fig. 11 Impacts of changing suction on void ratio in both wetting and drying paths (white and gray markers represent drying and wetting paths respectively)

as the straw content increased, the amount of shrinkage under the same suction decreased. Consequently, along the drying path the void ratios were ranging from 0.7 to 0.39 for unreinforced soil and from 0.77 to 0.72 for reinforced soil with 3% straw content. For other straw contents the changes in the void ratios were between these two boundaries. The presented results on shrinkage in this study are proved by other researchers. Malekzadeh and Bilsel (2012b) and Kinjal *et al.* (2012) stated that fiber reinforcing with polypropylene and polyester reduces the shrinkage tendency in expansive clay specimens.

A similar phenomenon also occurred in the wetting path (the gray markers in Fig. 11). Samples with higher dosages of straw content showed less swelling. The void ratio of samples with 3% straw content at the highest suction (end of drying path) was 0.72. During the wetting process the sample demonstrated a negligible amount of swelling and its void ratio increased only to 0.73 after completion of the wetting process. On the other hand, the void ratio of unreinforced sample showed a significant increase from 0.39 (at the highest suction) to 0.45 (after completion of wetting path). The rises observed in the void ratios of the samples with other fiber contents (*i.e.,* 0.5%, 1%, and 2%) were between these two values. Loehr *et al.* (2000), Viswanadham *et al.* (2009), and Malekzadeh and Bilsel (2012a) reported a reduction in swelling with the increase of fiber content.

The degree of saturation is the ratio of the volume of voids filled with water over the total volume of voids. As explained above in the drying process with an increase in the straw content the void ratio showed less tendency to decrease. It means that at a given suction, degree of saturation was greater for the samples with less fiber in comparison to those with higher fiber inclusion, in spite of retaining same mass of water (as shown in Fig. 10). In other words, the reinforcement caused a faster reduction in the degree of saturation. The degree of saturation for drying paths are shown in Fig. 12. In this figure, the degree of saturation of the samples with various fiber contents at the initial condition were almost 100%. During the course of drying the lower the fiber inclusion was, the faster the degree of saturation dropped.

As shown in Fig. 13, in the wetting path (although the samples didn't reach back to fully saturated condition), since the void ratio of samples was a function of straw content, as shown in Fig. 11, the degree of saturation decreased with an increase in straw

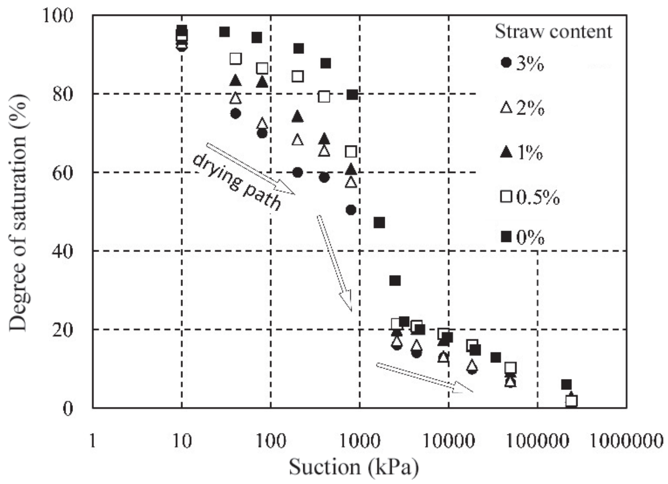

Fig. 12 The relationship between degree of saturation and suction in drying path only

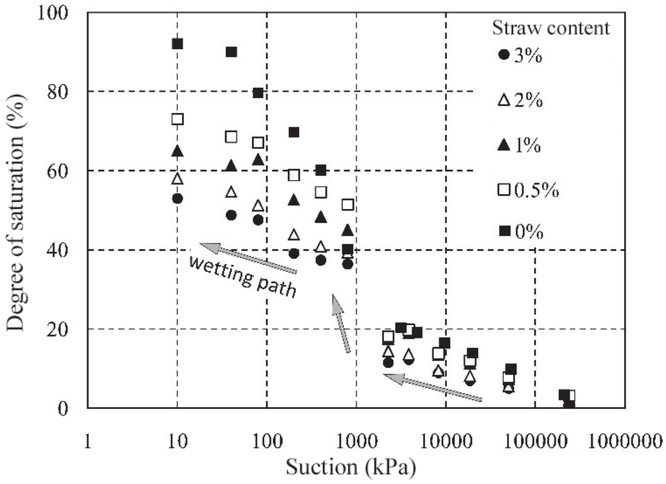

Fig. 13 The relationship between degree of saturation and suction in wetting path only

content (under a given suction), however, they contained relatively same water content. The final degree of saturation at the lowest suction of the wetting path was higher for samples with less fiber content (from 53% for 3% fiber content to 92% for unreinforced sample).

5. SCANNING ELECTRON MICROSCOPY (SEM)

SEM photos of the fiber-reinforced soil used in this study are shown in Fig. 14. As can be seen in Figs. 14(a) and 14(b), sand grains were covered with clay platelets and connected to each other via solid bridges, and no sand-sand connection was observed. Figures 14(d) and 14(e) show that the fibers' surfaces were also covered by many clay minerals which made the contribution to bond strength and friction between the fiber and soil matrix. Figure 14(e) shows that the bonding between soil structure and surface of straw was relatively strong. Moreover, as shown in Fig. 14(c), at some points clay platelets penetrated even into very thin vessels of straw, which was another reason for increasing the strength of the bonding between the soil matrix and straw filaments. Due to these connections, straw pieces limited the movement of soil particles during volume changes. This phenomenon considerably reduced swelling and shrinkage of the reinforced soil.

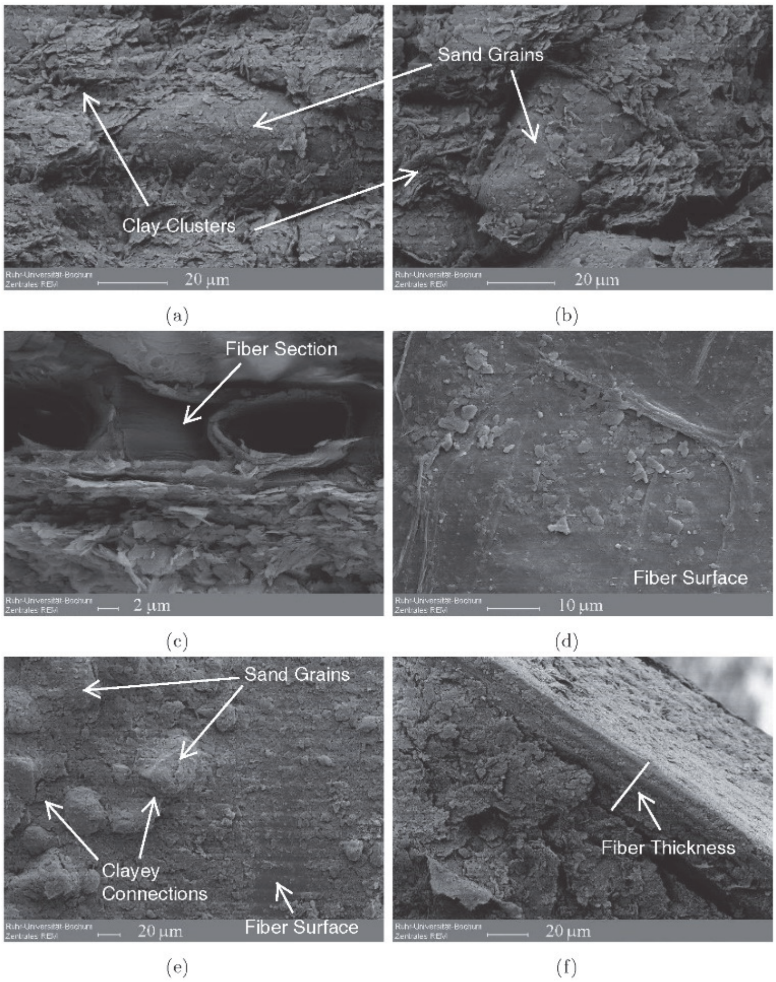

Fig. 14 Scanning Electron Microscopy (SEM) photos taken from dried sample: (a) sand grains are covered with clay platelets; (b) connection between sands are through formed clay clusters; (c) penetration of clay platelets inside vessels of straw; (d) connection between clay and surface of straw; (e) connection between sand grains and surface of straw are through clay clusters; and (f) separation between soil and straw due to shrinkage

As it can be seen in Figs. 14(e) and 14(f) the fiber surface is attached by many sand particles and clay platelets that intensified the bonding strength and friction between the fibers and the soil matrix. The distributed discrete fibers act as a spatial three-dimensional network to interlock soil grains, help grains to form a unitary coherent matrix and restrict the displacement. Consequently, the tension resistance of the reinforced soil increases.

6. POROSIMETRY

In this research, the pore size distribution obtained from the Mercury Intrusion Porosimetry (MIP) method was used to study the microstructure of dried straw-reinforced soils. In this technique a non-wetting liquid (here mercury) is intruded into a sample with various pressures in a porosimeter device. The pore size distribution can be determined from the external pressure required to push the liquid into a pore with a particular size against the opposing force of the liquid's surface tension. Details of this method have been presented in several papers (*e.g.* Delage *et al.* 1996; Agus and Schanz 2005; Thom *et al.* 2007; Arifin 2008).

Pore size distribution curve for three materials was analyzed and drawn; namely unreinforced and reinforced soils with 1% straw content, but with different lengths of 1 and 20 mm. The void ratios obtained by this observation were not the same as calculated from measuring the mass and volume of samples (the effect of straw length on the void ratio is explained below).

In Table 2 void ratios are presented and compared. Void ratios derived from porosimetry were smaller than those of mass-volume measurements. The reason for this could be due to the size of the sample which was relatively small in MIP observation (5 × 5 × 5 mm). Such a small sample might not include as many large pores as exist in larger samples. As we see in Table 2, the largest difference was found in the reinforced sample with 20 mm straw filaments. This matter was probably due to the absence of large straws thicker than 3 ~ 5 mm which could not existing in the small sample.

Table 2 Void ratios obtained from MIP and from mass-volume calculations

Material	Void ratio from porosimetry	Calculated void ratio
0% Straw	0.33	0.39
1% Straw (1 mm)	0.39	0.42
1% Straw (20 mm)	0.40	0.55

In spite of the differences in void ratios, the pore size distribution curves of the three materials mentioned above had a similar trend. Figure 15 shows the cumulative volume of voids in mm^3/g. Figure 15 shows that for all the materials the majority of pores were in the range of 0.0001 to 0.001 mm. Although the unreinforced material had a smaller void ratio, its distribution over the pore radius was similar to those of reinforced materials.

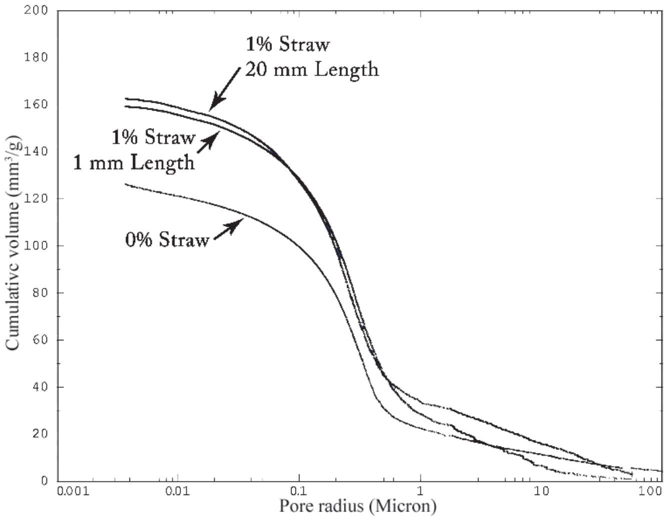

Fig. 15 Pore size distribution curves for unreinforced and reinforced soil with 1% straw content, with 1 and 20 mm length

7. CONCLUSIONS

Fiber reinforcement is a low-cost and environmentally friendly soil improvement technique that can be used in many applications, such as slope stability and rural housing. The outcomes of this work may help better understanding of hydro-mechanical properties of soil reinforced with straw fibers. In this paper, hydro-mechanical properties of fiber-reinforced soil with natural straw fibers have been analyzed. Straw fibers of varying dosages (0%, 0.5%, 1%, 2%, and 3% of the total soil-fiber weight) were mixed with the soil and tested to study the compaction behavior, hydraulic conductivity, shrinkage, swelling, and SWCC.

All unreinforced and reinforced samples of SWCC tests were prepared in slurry condition (with predefined water content of 1.25 × LL), thoroughly mixed to reach a uniform mixture, and casted inside the molds. The samples were subjected to the drying process with various suctions (applied by ATT or VAT techniques) to lose water and reach equilibrium conditions. After completion of the drying path, all samples at fully dry condition were placed under the same suctions as in drying path to received water in the so called wetting path. During both wetting and drying paths, weights and sizes of the samples were regularly measured in order to calculate the water contend, degree of saturation and void ratio.

Based on the test results and analyzes, the following conclusions are deduced:

- Increase in the straw content resulted in increase in optimum moisture content from 11% to 14% and decrease in maximum dry density from 1.97 to 1.64 g/cm^3.
- Hydraulic conductivity of the soil due to random inclusion of fibers increased from 1.6×10^{-8} to 9.1×10^{-8} cm/s as a function of straw content between 0% to 1%.
- In both wetting and drying conditions, straw inclusion had no meaningful effect on the amount of water that the samples could retain. For all samples gravimetric water content at the beginning of drying paths and at the end of wetting paths were in the range of 25% to 27% and 14% to 16%, respectively.
- Both shrinkage and swelling decreased significantly with an increase in the straw content. The void ratios of samples with 0% to 3% straw contents ranged from 0.39 to 0.72 at the end of drying paths, whereas the initial void ratios (at the beginning of drying paths) were between 0.70 to 0.77.
- Shape of SWCC (degree of saturation *vs.* suction) was in-

fluenced by straw content. In the drying paths, an increase in the straw content inclined the curve and hastened the reduction in the degree of saturation. In the wetting paths, although all the samples didn't reach back to saturated condition, but the samples with lower straw content expressed higher degrees of saturation in each value of suction.

- The swelling, shrinkage and SWCC related results presented in this paper are valid for the samples prepared as explained in Section 3.2. The sample preparation procedure highly accepts these behaviors. Any other procedure may lead to different outcomes.

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DATA AVAILABILITY STATEMENT

The data used and generated in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS' CONTRIBUTION STATEMENT

This paper is part of Ph.D. dissertation of Dr. Houman S. Fard. The main lab works, data analyses and conclusions have been made by him. Dr. Diethard König together with late Prof. Tom Schanz supervised the research. Dr. Meisam Goudarzy helped with the experiments and writing the manuscript.

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