Shear strength behavior of silty soil reinforced with basalt fiber

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ABSTRACT: To remedy the problems of civil engineering related to soils in recent years, various geosynthetic materials have been used to improve the mechanical and physical soil characteristics. Besides these geosynthetic materials, different kinds of natural fibers have also been used to improve soil characteristics. On the other hand, while a basalt fiber, which is a natural material, has been used to reinforce the concrete; it is rarely available to reach a source in literature regarding the use for soil improvement. This study is about to investigate the behavior of a silty soil reinforced with basalt fibers. To conduct this study, a series of tests of unconsolidated undrained triaxial test (UU) were carried out on both unsaturated and saturated soils. Unsaturated soils were prepared in optimum water content and maximum dry density and saturated soils were prepared by consolidating under 200 kPa. Two parameters (the length and the content of the basalt fibers) were considered in this study. The fibers of 6, 12 and 24 mm length were dispersed in silty soil at different contents (1%, 1.5% and 2%). The results of the unconsolidated undrained triaxial tests (UU) show that the addition of basalt fibers effectively improves the shear strength of silty soil without making any difference if the soil is saturated or unsaturated. For all of the lengths of the basalt fibers, the maximum improvement was obtained with a content of 1.5%. Moreover; the maximum improvement was obtained for a content of 1.5% and 24 mm of basalt fiber.

Keywords: Basalt fiber, silty soil, soil improvement, unconsolidated undrained triaxial test

1 INTRODUCTION

Fine grained soils in general and silty soils in particular may have some deficiencies of strength and stability. These deficiencies of resistance and stability are the cause of the destruction of many civil engineering structures around the world. To solve these problems, various materials such as natural and synthetic fibers, metals, geosynthetics and geotextiles have been used in the past (Gao et al. 2015). In recent years with increasing environmental problems, the use of natural fibers such as wooden plastic composites, jute fibers, coconut fibers, bamboo fibers etc. for soil reinforcement has considerably increased in the field of geotechnics (Chen et al. 2011; Fiore et al. 2015; Saygili et al. 2016; Dhand et al. 2015; Wang et al. 2017).

By looking for materials resistant to earthquakes with a high compressive strength, Binici et al. (2004) conducted a study on the mechanical properties of certain combinations of fibrous waste and certain stabilizers. By using American (ASTM) and Turkish Standard Norm (TS) Classifications, the compressive strength of the fibrous clay bricks has been considerably improved.

In order to study the durability of a soil-cement mixture treated with cellulose fibers and polypropylene (PF) fibers, Mohammad and Mohammad (2005) conducted a series of Unconfined Compression Strength Tests (UCS), Indirect Tensile Strength Tests (ITS) and Indirect Tensile Load Tests. The results showed that the mechanical characteristics of the soil-cement-fiber mixtures depended on the fiber content and the curing time. Generally, the durability, UCS, ITS, Indirect Tensile Load and modulus of elasticity of soil-cement-fiber mixtures were higher than those of soil-cement mixing.

A series of tests were conducted to investigate the effects of polypropylene fibers (PP) on the mechanical behavior of cemented and uncemented clay soil. For the smooth running of these tests, 12 soil samples were prepared with three different contents of fiber (0.05%, 0.15% and 0.25% by soil dry weight) and two different cement percentages (5% and 8% by weight of dry soil). The samples were subjected to the unconfined compressive tests and direct shear tests after curing periods of 7, 14 and 28 days. The test results indicate that Unconfined Compressive Strength (UCS), shear strength and axial deformation of cemented and uncemented soils have been improved by the inclusion of PP fibers (Tang et al. 2007).

A comparative study between the effect of basalt fibers and those of the polypropylenes was conducted by Ayothiraman and Singh (2017) on Dhanori clay. 7 groups of soil samples were mixed with four different percentages of basalt fiber and polypropylene fiber to evaluate their consistency limits, compaction characteristics, unconfined compressive strength, and consolidation properties. The test results indicate that the inclusion of basalt fiber in the Dhanori clay soil provides a significant improvement than the polypropylene fibers.

2 MATERIALS AND TEST PROCEDURE

2.1 *Materials*

The materials used in this search are basalt fibers which have respectively 6 mm, 12 mm and 24 mm long and the silty soil (Figure 1). These basalt fibers (BF) are natural fibers from a textile manufacturing company (Turkey) and the silty soil was taken in the city of Adapazarı (Turkey). Table 1 gives the physical properties of these two materials used in this study. Figure 2 shows the granulometric curve of silt soil. According to the Unified Soil Classification System (USCS) and Turkish Standard Norm (TS), the soil used is a silty soil of low plasticity (ML).

Figure 1. Basalt fibers and silty soil samples

Table 1. Physical properties of basalt fiber and silty soil samples

Fiber Basalt (BF)			Silty Soil		
Characteristics	Values	Units	Characteristics	Values	Units
Specific weight	2.60-2.65	-	-No200	88.3	%
Modulus of elasticity	70-90	GPa	Liquid limit (LL)	32	%
Tensile strength	2800-3000	MPa	Plastic limit (PL)	23.3	%
Breaking limit	3.1	%	Plasticity index (Ip)	8.7	%
Diameter	6-25	μ	Clay content	11.7	%
Temperature of application	450-550	^{0}C	Optimum water content (w_{opt})	21	%
Melting point	1350	^{0}C			

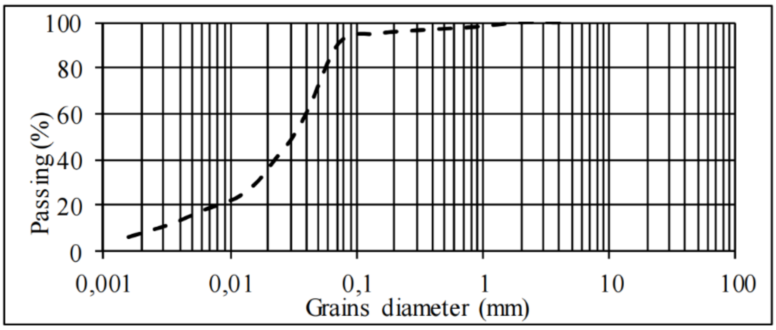

Figure 2. Granulometric curve

2.2 *Test procedure*

Two categories of silty (saturated and unsaturated) soils were used in this study. The two categories were mixed separately with basalt fibers of different lengths (6 mm, 12 mm and 24 mm) and different percentages (1%, 1.5% and 2%) by the dry weight of the soil. This study covers a total 120 unconsolidated undrained triaxial tests (UU), which 80 of them were conducted on unsaturated and 40 of them on saturated silty soil samples.

2.3 *Soil preparation*

2.3.1 *Unsaturated soil*

The process of preparing the BF-reinforced unsaturated soil samples consists firstly of uniformly mixing a certain percentage of basalt fiber (1%, 1.5%, and 2%) with a dry soil mass; secondly, to add gradually a quantity of water (100 ml, 200 ml, 300 ml, 400 ml and 500 ml) in order to have an optimum water content; thirdly, pass them to Proctor tests before submitting them to the unconsolidated undrained triaxial tests (Figure 3).

Figure 3. Unsaturated soil sample preparation

2.3.2 *Saturated soil*

The method consists of making the soil saturated and homogeneous. Once the soil is saturated, it is placed in the desiccator for about 2 hours to extract the air bubbles. After the desiccator, the soil samples were subjected to uni-axial consolidation tests under a stress of 200 kPa for at least 5 days (Figure 4). Once the consolidation is complete, the soils samples were subjected to unconsolidated undrained triaxial tests (UU).

Figure 4. Preparation of soil samples (a, b) Saturation phase (c, d) Consolidation phases (e, f) Soil extraction

2.3.3 *Unconsolidated undrained test (UU)*

Unconsolidated undrained triaxial tests were performed on two types of silty soil. They were carried out according to the Turkish Standard Norm (TS 1900-2) under initial cell pressures (σ_3) of 100 kPa, 200 kPa, 300 kPa and 400 kPa (Figure 5).

Figure 5. Unconsolidated undrained triaxial tests (UU)

3 RESULTS AND ANALYSES

3.1 *The results*

In total 120 unconsolidated undrained tests were carried out on saturated and unsaturated soils. The results of these tests can be observed and interpreted from Scanning Electron Microscopy (SEM) and the values of Undrained Unconsolidated Strength (UUS) obtained. The results of the tests carried out on the unsaturated samples were considered for optimum water content.

The effects of the two parameters, the lengths and the percentages of the BFs on the silty soil samples, were studied. The results compiled in Tables 2 and 3 were shown on the Figures 6 and 7.

Table 2. The stress-strain values of unconsolidated undrained compressive strength (UUS) for unsaturated samples

400 ml water (w_{ort}: 21.6%)		σ_3 100 kPa		σ_3 200 kPa		σ_3 300 kPa		σ_3 400 kPa	
BF Length (mm)	BF Ratio (%)	Strain (%)	$\sigma_{d,maks.}$ (kPa)	Strain (%)	$\sigma_{d,maks.}$ (kPa)	Strain (%)	$\sigma_{d,maks.}$ (kPa)	Strain (%)	$\sigma_{d,maks.}$ (kPa)
0	0	16.67	173	19.44	257	19.44	369	13.89	450
6	1.0	17.14	213	16.90	321	17.14	429	19.72	476
6	1.5	18.31	314	19.44	439	15.49	574	13.89	734
6	2.0	15.45	290	16.88	346	16.88	496	15.47	633
12	1.0	16.90	270	15.38	369	19.66	487	19.69	519
12	1.5	18.05	363	19.58	492	19.44	582	19.58	746
12	2.0	19.72	327	16.78	426	19.44	526	19.44	655
24	1.0	18.31	264	15.38	425	15.49	529	15.49	637
24	1.5	19.58	**450**	16.76	**536**	19.72	**640**	19.58	**819**
24	2.0	20.00	384	18.31	433	16.78	569	18.31	695

Table 3. The stress-strain values of unconsolidated undrained compressive strength (UUS) for saturated samples

200 kPa Vertical Stress		σ_3 100 kPa		σ_3 200 kPa		σ_3 300 kPa		σ_3 400 kPa	
BF Length (mm)	BF Ratio (%)	Strain (%)	$\sigma_{d,maks.}$ (kPa)	Strain (%)	$\sigma_{d,maks.}$ (kPa)	Strain (%)	$\sigma_{d,maks.}$ (kPa)	Strain (%)	$\sigma_{d,maks.}$ (kPa)
0	0	18.18	98	19.44	103	19.72	109	19.58	117
6	1.0	18.18	102	19.44	110	19.58	116	19.44	124
6	1.5	20.00	120	19.72	129	19.72	140	19.58	147
6	2.0	19.44	115	18.18	123	20.00	129	19.58	141
12	1.0	20.59	120	16.90	129	18.06	136	18.31	143
12	1.5	20.03	131	20.00	139	19.72	150	19.44	159
12	2.0	19.58	118	19.69	125	19.58	130	19.69	133
24	1.0	19.58	126	19.44	140	19.58	146	19.58	156
24	1.5	19.58	**140**	19.44	**147**	19.44	**152**	19.44	**162**
24	2.0	19.58	130	19.44	141	19.58	147	19.44	160

Stress - strain graphic representations at first sight show that the unconsolidated undrained compressive strength (UUS) of all (saturated and unsaturated) reinforced samples higher than those of natural soil samples regardless of the length and percentage of FBs (Figure 6 and 7). The maximum improvement was obtained for 24 mm BF - soil mixtures regardless of soil type (saturated and unsaturated).

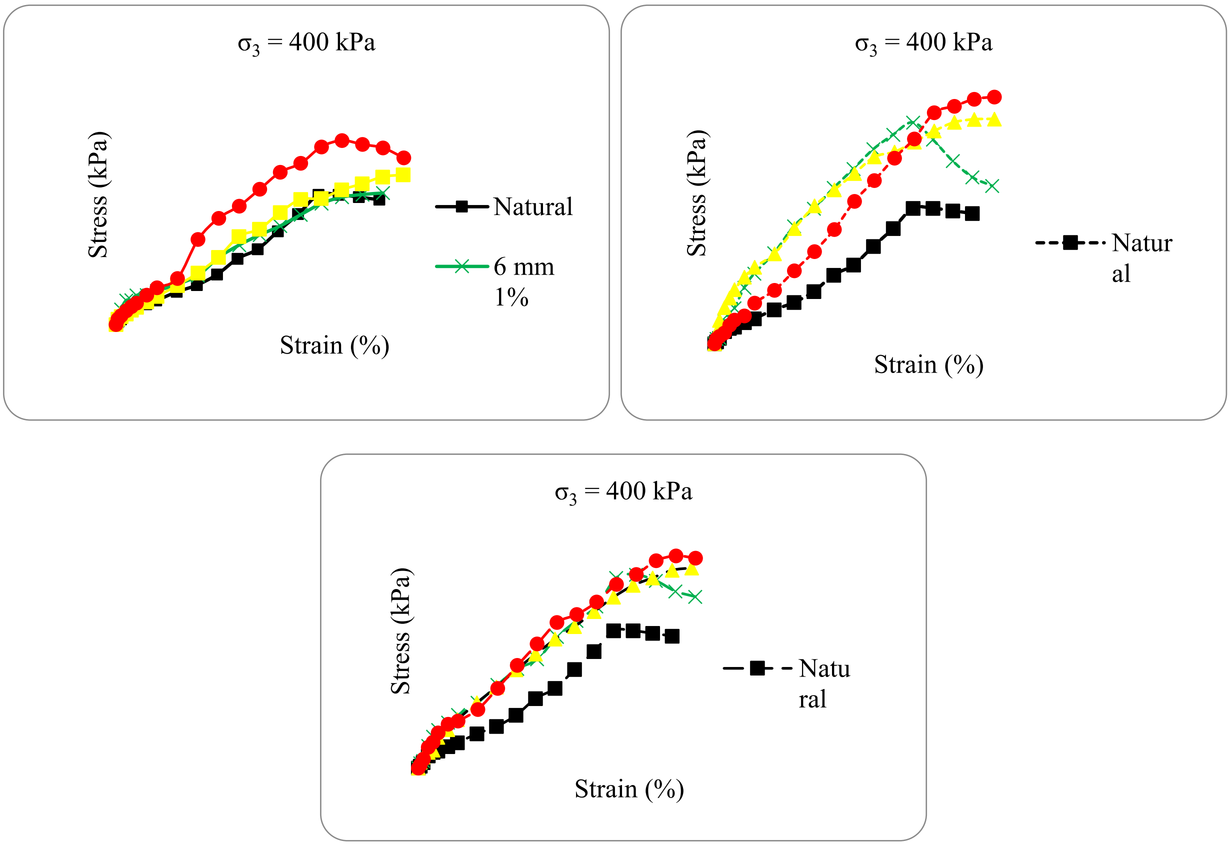

Figure 6. Effect of the BF lengths on UUS of unsaturated soils samples

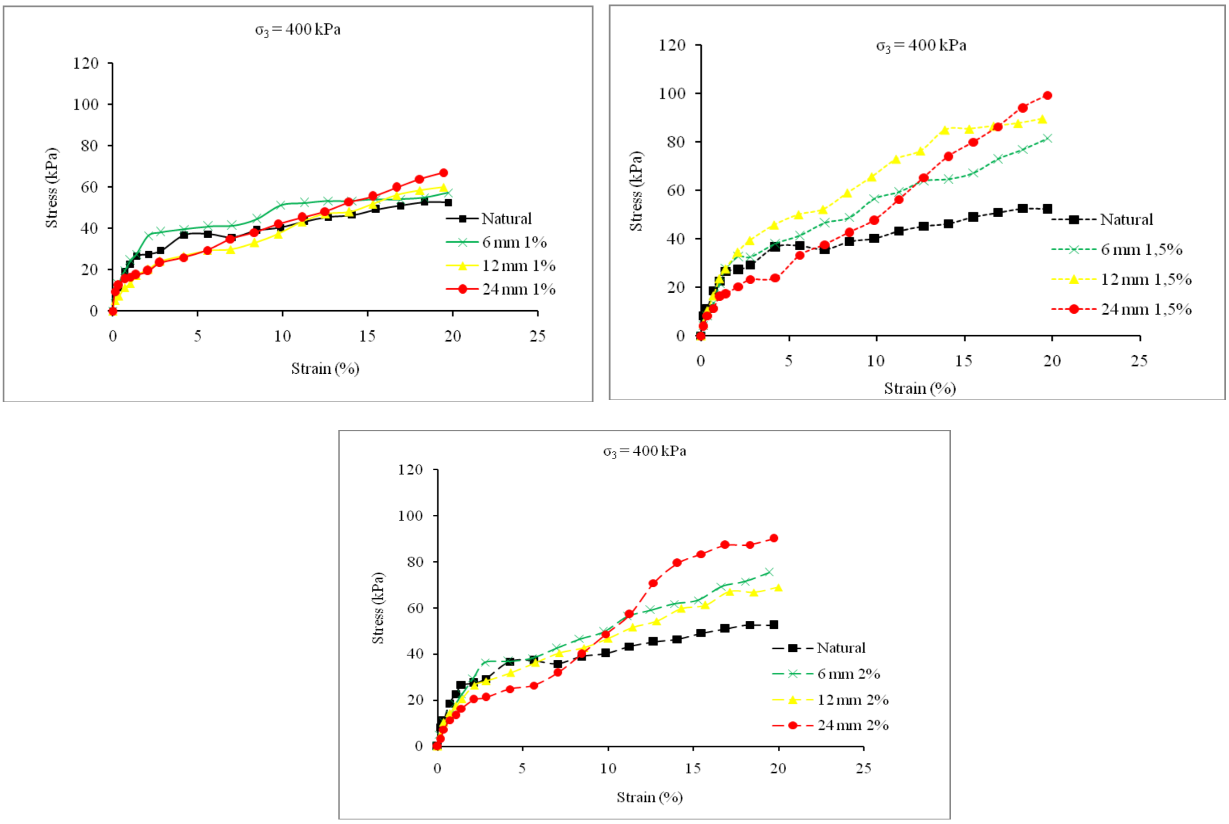

Figure 7. Effect of the BF lengths on UUS of saturated soils samples

Figure 8 and 9 show the effect of the BF content on UUS of the silty soil samples. Regardless of the type of soil (saturated and unsaturated) and the percentage of BF, there was an improvement in UUS of the soil samples reinforced compared to natural soils. The best (optimum) improvement was obtained for the BF - soil mixture of 1.5%.

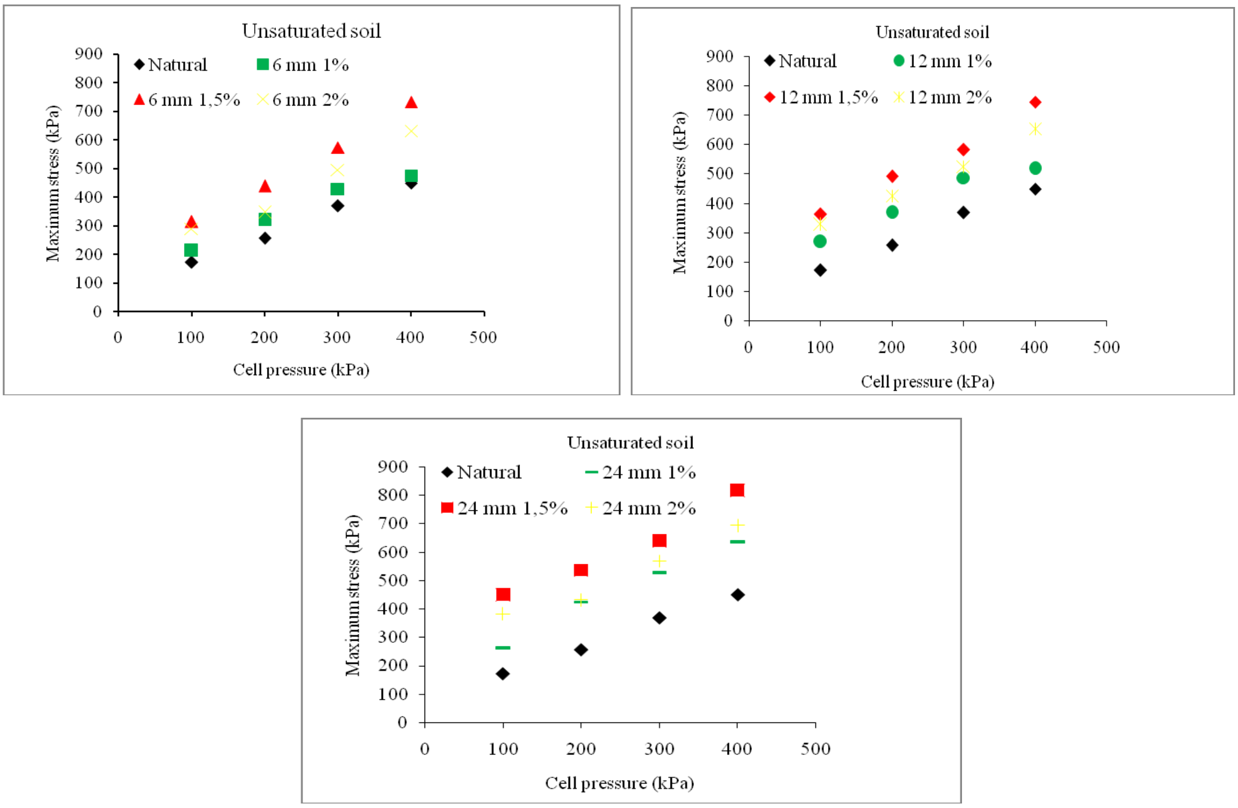

Figure 8. Effect of BF content on UUS of unsaturated soil samples

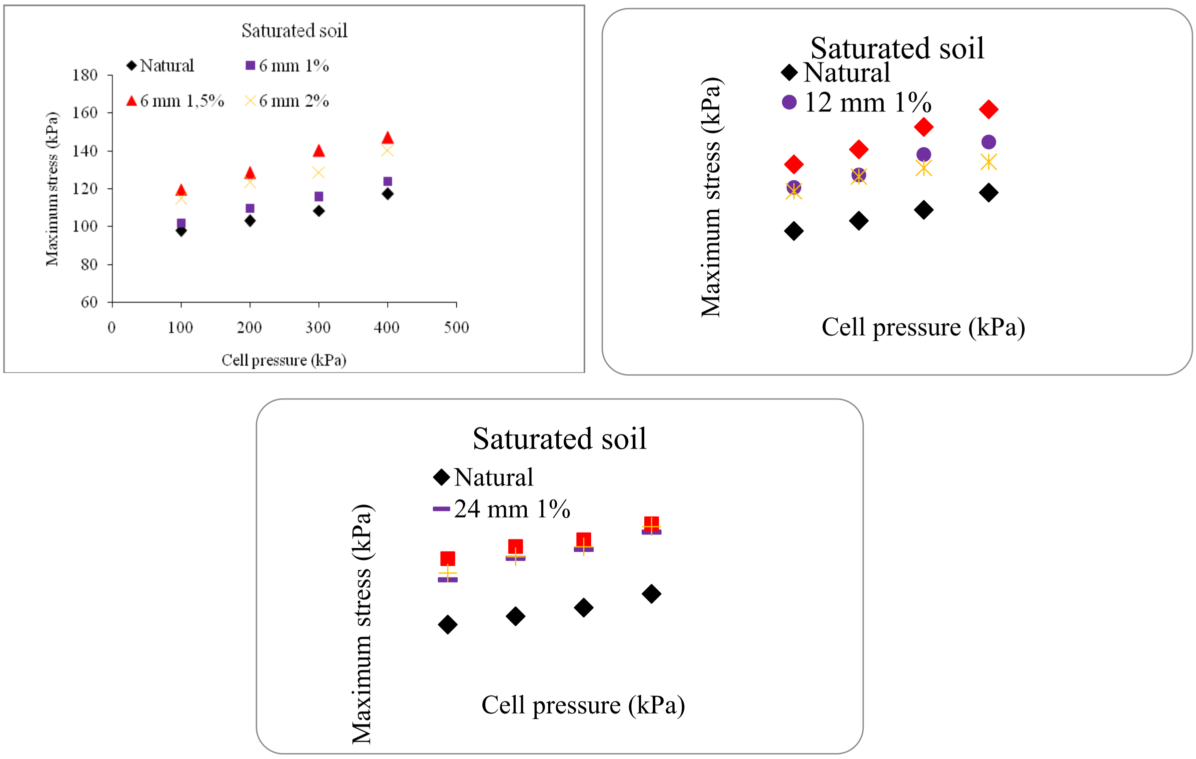

Figure 9. Effect of BF content on UUS of saturated soil samples

3.2 *Analyse and discussion (SEM)*

The results of Scanning Electron Microscopy (SEM) show a direct interaction between soil particles and basalt fibers. It can be observed on the Figure 10 (b and c) that the soil particles seek to wrap the BFs. The interfacial strength is the result of the extrusion pressure and cohesion and the adhesion strength is related to soil and to the autonomous cohesion of the silty soil particles (Tang et al. 2007).

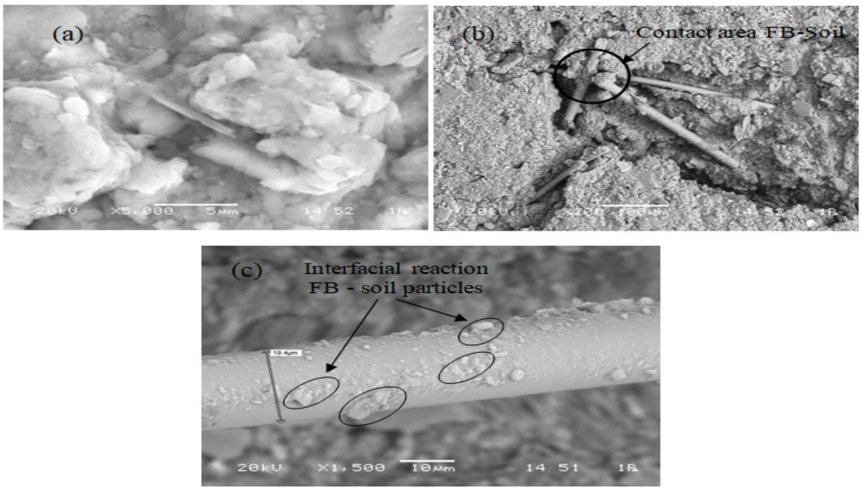

Figure 10. Scanning Electron Microscopy SEM; (a) natural soil, (b) BF-soil contact area,
(c) BF - soil column interaction.

The percentages and lengths of the BFs have a direct influence on the unconsolidated undrained compressive strength (UUS) of all silty soil samples. When the percentage of BF is fairly small (1%), there are spaces between the columns of fibers and it is difficult to establish a good intersection BF - soil. Therefore, BF - soil cannot form an effective barrier that can stop or decrease the break in the soil sample. This is explained by a progressive improvement in the unconsolidated undrained compressive strength (UUS) of all soil samples when the percentage of BF increases from 1% to 1.5% where it reaches its optimum. When the percentage of BF exceeds its optimum, there are losses of UUS resistance of the soil samples. These losses can be explained by the high quantity of BFs which interact with each other and prevent the interaction between BF and soil particles.

When the length of the BF is too short (6 mm), the BF - soil columns within the soil sample are also short. Therefore the interfacial reactions between the particles and the fibers are also small and the reinforcement is not effective. When the BFs are too long (24 mm), the contacts between the BF - Soil columns are sufficient and facilitates the transmission and the superposition of the stresses. Consequently, the fibrous barriers can be effectively formed. These are explained by the results compiled in Tables 3 and 4 and Figures 6, 7, 8, and 9.

4 CONCLUSION

The unconsolidated undrained compression strength (UUS) of all silty soil samples can be improved by basalt fiber. For all of the lengths of the basalt fibers, the maximum improvement was obtained with a content of 1.5%. Moreover; the maximum improvement was obtained for a content of 1.5% and 24 mm of basalt fiber.

When the length of the fibers is constant, a progressive improvement of UUS has been observed when the percentage of BF increases.

The length of BF plays an important role in the soil reinforcement. When the percentage of BF is constant and the length of BF is increased, there is a positive reinforcement of UUS of silty soil.

This mechanism can be explained by an interaction between the interfacial forces of the basalt fibers and the silty soil particles based on the model of the BF - Soil column arrangement.

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