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Effect of Basalt and Polypropylene Fibers on Unconfined Compressive Strength of Cement-Stabilized Clay, an Experimental Approach

Seyed Hadi Sahlabadi[a], Meysam Bayat[a,*], Mohsen Mousivand[b], Mohsen Saadat[a]

[a] *Department of Civil Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran*
[b] *Department of Civil Engineering, Gonbad Kavoos Branch, Islamic Azad University, Gonbad Kavoos, Iran*

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Abstract
So far, many studies have been done on the performance of conventional chemical stabilizers such as cement, lime, fly ash or other chemical additives. However, very limited researches were conducted on the mechanical behavior of cement-stabilized soil with fiber inclusion. Fiber-reinforcement of a stabilized soil offers new opportunities to improve ductility and strength characteristics of weak soils. The main objective of this research is considering the effects of curing time, initial moisture content, polypropylene fiber (PPF) or basalt fiber (BF) with or without addition of cement on the Unconfined Compressive Strength (UCS) of the clay soil. Different ratios of PPF or BF and/or cement were added to the soil to identify their influences on the UCS. The study finds that adding cement, PPF or BF to soil causes a remarkable increase in the strength. The strength of the PPF-reinforced specimens was observed significantly more than that of BF-reinforced ones. The strength of specimens increases gradually as the initial moisture content decreases and the cement content or curing time increases. However, the axial strain at failure for cement-stabilized specimens decreased with increasing cement content or curing time. Furthermore, it is concluded that the increase in UCS of combined PPF or BF and cement inclusions is more than the increase caused by each of them, individually.

Keywords: Polypropylene Fiber; Basalt Fiber; Cement; Unconfined Compressive Strength; Moisture Content

1.Introduction

Various soil improvement methods like cement or lime stabilization have been used to improve the mechanical behavior of weak or soft soils in practice for many years. The problems of structures on weak or soft soils are represented by differential settlements, high compressibility and low strength [1–10]. Similar to cement or lime admixtures, natural or synthetic fibers may be employed to remediate weak or soft soils to increase soil strength, enhancement of soil hydraulic properties and reduction of surficial soil erosion, swell and compressibility potential [11,12,21–25,13–20]. The choice and effectiveness of soil improvement techniques depends on the soil type (physical, chemical or engineering properties) and type of civil engineering project. Nevertheless, knowledge of physical and mechanical characteristics of stabilized and unstabilized soils has important role for selecting the stabilization parameters. Cement stabilization as a popular ground improvement technique results in soil particles bonding and reducing the pore space between soil particles. Previous studies [26–30] indicated that cementation bonds by various cementing materials such as cement can improve shear strength. In many previous studies, cement have been suggested as a good stabilizing agent for soil [31,32]. On the other hand, flexural strength of cement-stabilized soils could be improved by additives such as fibers [33,34]. A lot of studies in the literature have presented the beneficial effects of fibers on mechanical behavior [35–39], the tensile strength [40], plasticity index [41], dynamic properties [42–45] and liquefaction resistance [46–48] of soils. For example, Puppala and Musenda [16] showed that swelling potential of high plasticity soils increased as the fiber

*Corresponding Author: Email Address: bayat.m@pci.iaun.ac.ir

content was increased from 0% to 0.9%. This is because of better distribution of moisture within the soil fabric.

Polypropylene fiber (PPF) is a light weight synthetic fiber composed of 85% propylene employed in a variety of applications. PPF is produced using advanced centrifugal spinning technology which is suitable for geotextile production. So far, many researchers have studied the influence of PPF on soils stabilization. Consoli et al. [49] studied the effect of PPF on the shear strength and stiffness of an uniform fine sand using triaxial tests. They reported that an increase in the presence of PPF increased the peak strength as well as the residual shear strength, while no important effect on the stiffness is observed. Tang et al. [50] performed UCS and direct shear tests on uncemented and cemented fiber-reinforced specimens which were cured for either 7, 14 or 28 days prior to testing. Based on the results, it can be concluded that the inclusion of the PPF within the uncemented and cemented specimens improved the UCS, shear strength parameters, axial strain at failure, and ductility, significantly. They found the optimum value of fiber content equal to about 0.25 %. However, the addition of fibers to the soil specimens originates a decrease in the stiffness. Scanning electron microscopy (SEM) analysis indicated that the bond strength and frictional resistance at the soil-fiber interface are the main factors of the reinforcement improvement. Jiang et al. [51] studied some factors such as fiber length, fiber content and aggregate size in a series of UCS test to determine the engineering properties of a reinforced clayey soil. Based on the results, 0.3% fiber content by dry mass of the soil was determined as optimum value for all fiber lengths. Ding et al. [52] found that the addition of PPF increased the strength, as the strength reached the maximum with the fiber content of 0.2 %. Sharma [22] investigated the influence of cement, fly ash and fiber contents on the geotechnical characteristics of stabilized-soil using UCS tests. The results showed that the 1:6:12 cement–fly ash–dredged reservoir material composite prepared by adding 0.2% fiber is a suitable composition to be used as subbase in road pavement construction. Aryal and Kolay [29] investigated the long-term durability of stabilized kaolin soil with cement and PPF during wetting–drying or freezing–thawing cycles. They reported that the specimens containing 10% cement and 0.5% fiber have more stability and durability against wetting–drying or freezing–thawing cycles.

Basalt fiber (BF) is a new, biologically inactive, environmentally friendly material made from extremely fine fibers of basalt which is obtained from silica/alumina/other oxide basalt rock. BF has better physical properties, higher tensile strength and is more cost-effective than other fibers [53]. BF has been popular material in civil engineering practices including soil, composite materials, concrete and asphalt [45,53–60]. Ma and Gao [45] found that the addition of BF causes an improvement in dynamic properties and an increase in energy absorption capacity. Ndepete and Sert [25] reported the undrained shear strength improvement with the inclusion of BF and the optimum fiber content equal to 1.5% based on the undrained triaxial tests performed on silty-soil specimens. Lv et al. [53] indicated that inclusion of BF increased the cemented sand shear strength parameters, residual strength, and peak strain. Wang et al. [58] studied the effect of BF on the mechanical behavior and microstructure of cemented kaolinite. They found that the BF has an important effect on enhancing the strength and improving the ductility and brittleness of cemented and uncemented specimens.

The cited papers investigated synthetic fibers (i.e., polypropylene, polyester, glass and basalt) with fiber percentages varying from 0.05% to 4% by weight, and fiber lengths varying from about 3 mm to 50 mm. However, the majority of these studies are focusing on reinforced soils with less than 1% fiber by weight. Even though a great amount of efforts has been put on the stabilized-soil materials with various combinations of cementation materials and fiber, limited studies are performed to compare the mechanical behavior of stabilized-soil with various materials. Due to the low strength of clayey soils, in the current study, the PPF and PF were used to enhance the strength of cemented and uncemented soil specimens.

2. Test Apparatus, Materials and Testing Procedure

The unconfined compression test is a simple laboratory technique to determine the UCS of cohesive or stabilized-soils. In this study, a series of UCS tests were conducted on fiber reinforced, fiber-cement-stabilized and cement-stabilized specimens according to ASTM D2166 (i.e. standard test method to determine UCS of cohesive soils). Axial load increment was applied at a constant strain rate of 1% per minute. Disturbed soil specimens were loaded until peak stress was obtained.

Table 1
Geotechnical properties of soil

Liquid limit %	35
Plastic limit %	27
Plasticity index %	8
Maximum dry density, MDD (kN/m^3)	16.4
Optimum water content, ω_{opt} *(%)*	16
G_s	2.69
Passing 200 sieve (%)	98
Soil type: USCS	CL

First stage in this study is collecting the soil from the site of project located in the northwestern of Dolatabad (in the north of Isfahan, Iran). According to the USCS, the soil is defined as low plasticity soil (CL). The grain-size distribution curve and the geotechnical characteristics of soil are presented in Fig. 1, and Table 1, respectively.

The Atterberg limits of soil were measured 30 min after addition of cement according to ASTM D4318. The liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the cement-stabilized specimens versus cement content are shown in Fig. 2. As shown, initially LL increases slightly with addition of 3% cement and then drops gradually with increasing cement content. PL increases slightly with increase in cement content. Consequently, the PI increases initially followed by a decrease at higher degrees of cement content.

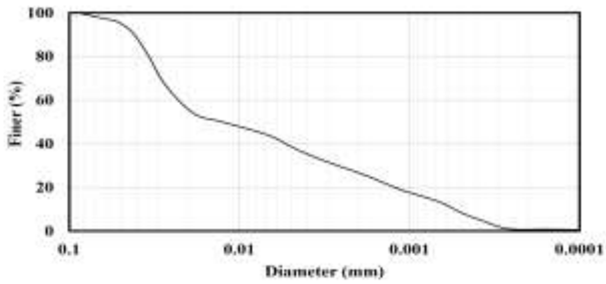

Fig. 1. Grain size distribution curve of the soil

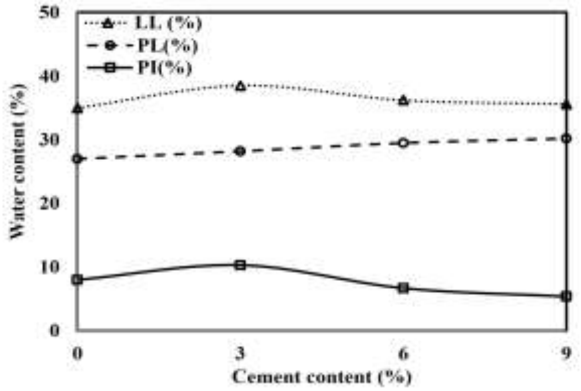

Fig. 2. Variation of LL, PL and PI as a function of cement content.

Polypropylene and basalt fibers are used in current study for the fiber-reinforced cement specimens, as shown in Fig. 3. The fiber contents denoted by PPF and BF vary from 0% to 5% by weight (the weight ratio of fiber to dry soil), respectively. The physical and mechanical characteristics of the polypropylene and basalt fibers are presented in Table 2. In this study, type II Portland cement is employed with the physical and chemical characteristics provided in Table 3. The compressive and tensile strengths of the cement were 44 and 2.8 MPa, respectively, on the 28th day according to tests conducted in accordance with ASTM 109 and ASTM 190, respectively. The cement content was defined by the ratio of weight of cement to the weight of dry soil and is denoted by C_C.

Table 2
Physical and mechanical properties of the fibers

Property	**Polypropylene fiber**	**Basalt fiber**
Cut length (mm)	12	12
Filament diameter (µm)	13	17
Density (g/cm^3)	0.915	2.61
Elastic modulus (GPa)	5.51	95
Tensile strength (MPa)	680	3000

Standard Proctor compaction tests were carried out to determine the effect of cement or fiber (polypropylene or basalt) content on the maximum dry density (MDD) and optimum moisture content (OMC). The results are shown in Fig. 4 for both cement-stabilized and fiber-reinforced specimens. According to Fig. 4, it is obvious that the MDD decreases and OMC increases as cement or fiber content increases.

Fig. 3. Photograph showing the discrete short PPF and BF.

Table 3
Physical and chemical properties of used cement

Property/composition	Value
Specific gravity	3.14
Specific surface area (m^2/kg)	320
CaO (%)	60.4
SiO_2 (%)	15.9
Al_2O_3 (%)	9.5
SO_3 (%)	6.4
Fe_2O_3 (%)	4.1
MgO (%)	0.9
K_2O (%)	0.7
TiO_2 (%)	0.1

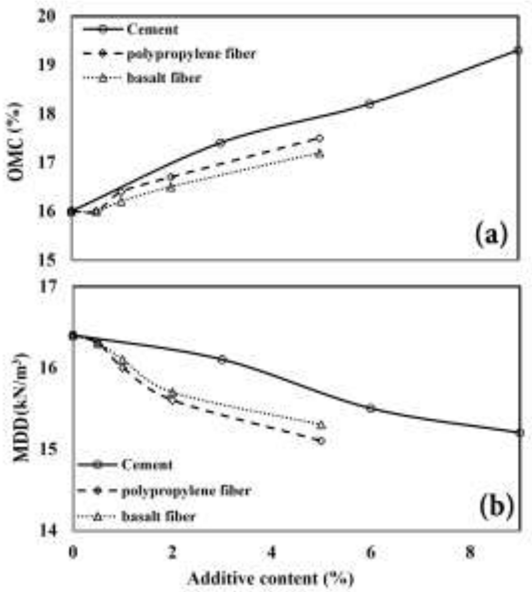

Fig. 4. Variation of OMC and MDD as a function of additive content.

In the present study, five groups of specimens were prepared as shown in Table 4. These groups include the cement-stabilized specimen which is a combination of clay, cement, and water, the fiber-reinforced specimen which is a combination of clay, the polypropylene or basalt fibers, and water, the fiber-cement-stabilized specimen which is a combination of clay, cement, the polypropylene or basalt fibers and water. For the UCS tests, cylindrical specimens were prepared with height and diameter of 100 mm and 50 mm, respectively. To prepare each specimen, the soil was first oven dried for at least 24 hours at a temperature of 110^{o}C. Afterwards, certain amounts of fiber and cement, if any, are mixed thoroughly with dry soil and the distilled water was added according to their target ratios for complete mixing. It was necessary to get a uniform distribution of the fibers in the mixture that was carefully achieved during the mixing process. The specimens in groups 1 to 3 were prepared according to obtained OMC values. The specimens in groups 4 and 5 were prepared at the OMC, 0.8 OMC or 1.2 OMC. Moist tamping fabrication technique used frequently in sample preparation in laboratory was used to prepare specimens [65–67]. It is the oldest technique which can model the soil fabric of rolled compacted reinforced soils and produce very loose to dense specimens. The materials were compacted after mixing into the split mould in five layers of equal height and each layer was compacted with a metal hammer. When set, the specimens were then taken out of the mould and the unconfined compressive tests were carried out immediately on the fiber-reinforced specimens. However, the cement-stabilized and the fiber-cement-stabilized specimens were taken out of the moulds and wrapped with thin plastic film. Afterwards, the specimens were stored in the humidity controlled chamber (temperature of 20 ± 2 °C and relative humidity of 95 ± 2%) until testing at 14, 28 or 60 days of curing.

Table 4
Summary of the tests details

Test Group	polypropylene fiber content, PPF (%)	basalt fiber content, BF (%)	cement content, C_c (%)	Curing time, CT (Days)	ω/ω_{opt}
Group-1	0	0	0, 3, 6 and 9	0, 14, 28 and 60	1
Group-2	0	0, 0.5, 1, 2 and 5	0	0	1
Group-3	0, 0.5, 1, 2 and 5	0	0	0	1
Group-4	1 and 5	0	3 and 9	28	0.8, 1 and 1.2
Group-5	0	1 and 5	3 and 9	28	0.8, 1 and 1.2

3. Tests results and discussion
3.1. UCS results

The effects of cement content and curing time on stress-strain curve of the clayey soil are shown in Fig. 5. As concluded from the results, the unstabilized specimen exhibited a ductile behavior. The stabilized specimens behaved as a brittle material and the higher axial stress were achieved at relatively small strains which is good agreement with previous studies [50,68,69]. The axial strain at failure for cement-stabilized specimens decreased with increasing curing time. Fig. 6 presents the variation in UCS versus cement content and curing time. The UCS almost increases gradually with increasing the cement content and curing time for all specimens which is consistent with previous experimental results [70–72]. The most improvement in strength is observed within the first 14 days for all stabilized specimens. As shown, by adding 3% cement to the soil, the UCS increases significantly in comparison with unstabilized soil and increases slightly with further addition of the cement content after 3%.
Figs. 7 and 8 show the UCS results with different PPF or BF contents varying between 0 and 5%. The increasing amount of PPF or BF contents results in increasing of UCS which is also reported in previous studies [22,25,50,60]. The fiber-reinforced specimens show a more ductile behavior than the soil specimen. Moreover, strength of the PPF-reinforced specimens was observed more than BF-reinforced specimens. On the other hand, BF content less than 2% has no significant influence on the improvement of compressive strength. However, PPF content of 0.5% has a significant effect on compressive strength improvement. The results show that the UCS at 5% PPF and 5% BF contents is about three and two times more than that for unreinforced specimen, respectively. Addition of PPF or BF has important effect on the behaviors of specimens and increases the axial strain at failure.

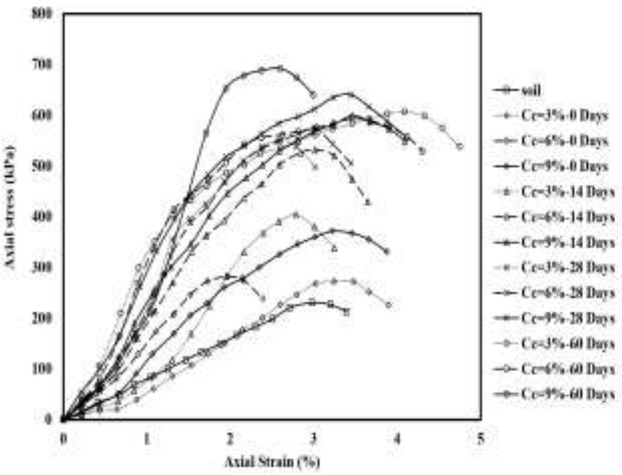

Fig. 5. Stress–strain curves of the cement-stabilized specimens at various cement content and curing time.

The results of UCS tests on the fiber-cement-stabilized with different cement, moisture and BF or PPF contents are indicated in Figs. 9 and 10. As shown in Table 4, the specimens were prepared with various initial moisture contents (i.e. OMC, 2 % more than OMC (wet side) and 2 % less than OMC (dry side)). The specimens in groups 4 and 5 were tested at 28 days of curing time. The results indicate that the UCS values of dry or wet side specimens are lower than UCS at OMC conditions for any specific additives content. The dry side specimens have greater UCS and lower axial strain at failure than the wet side specimens. Tests results show that UCS of specimens increases with increasing cement and PPF contents. As shown in Fig. 9, the highest UCS strength is achieved for the fiber-cement-stabilized specimen with 5% PPF content and 9% cement content for given initial moisture content. However, 1% BF and 9% cement content results in the highest UCS value obtained from the cement-stabilized BF-reinforced specimens. It is also showed that the cement-stabilized fiber-reinforced specimens with 5% PPF or BF content and 9% cement content have the higher axial strain at failure than other specimens.

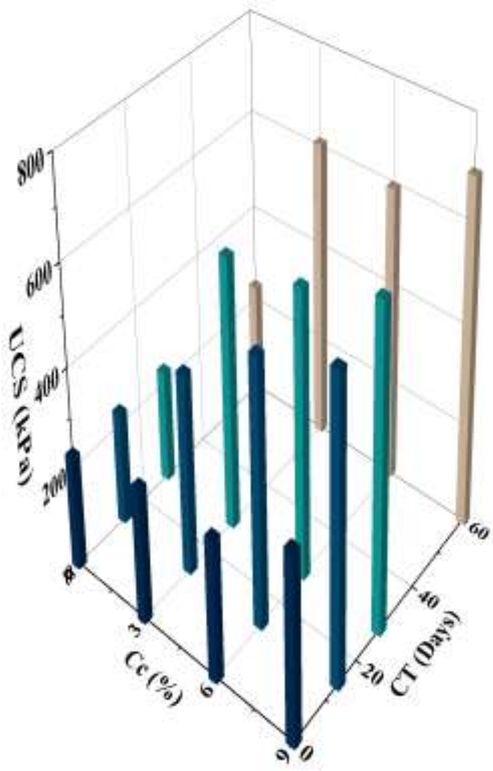

Fig. 6 UCS results of the cement-stabilized specimens at various cement content and curing time.

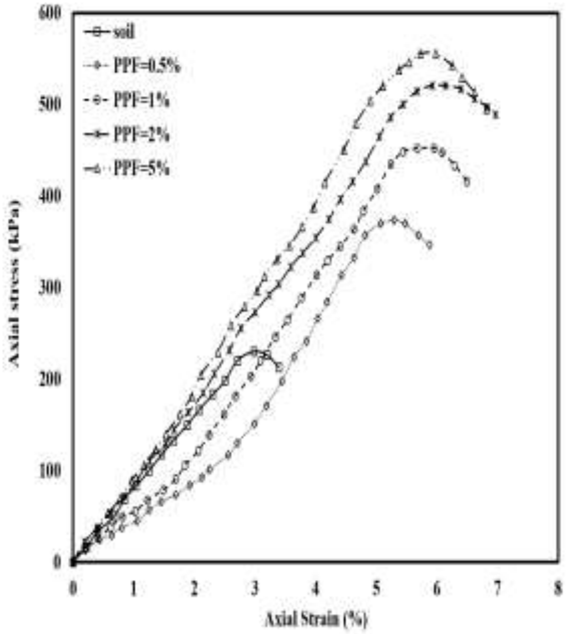

Fig. 7. Stress–strain curves of the PPF-reinforced specimens.

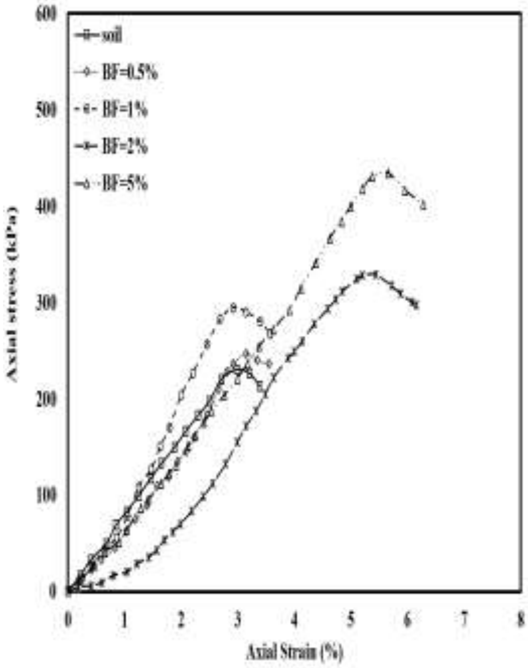

Fig. 8. Stress–strain curves of the BF-reinforced specimens.

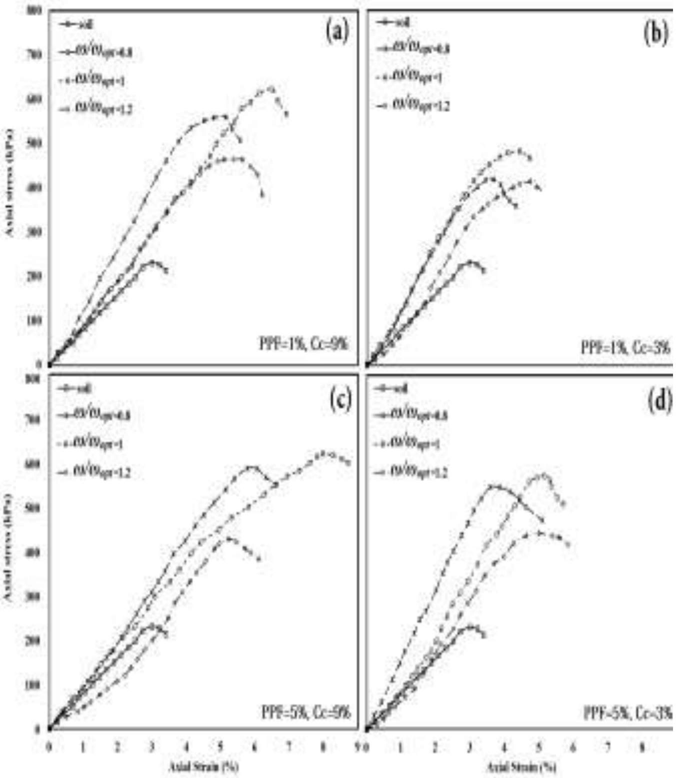

Fig. 9. Stress–strain curves of the PPF-cement-stabilized specimens.

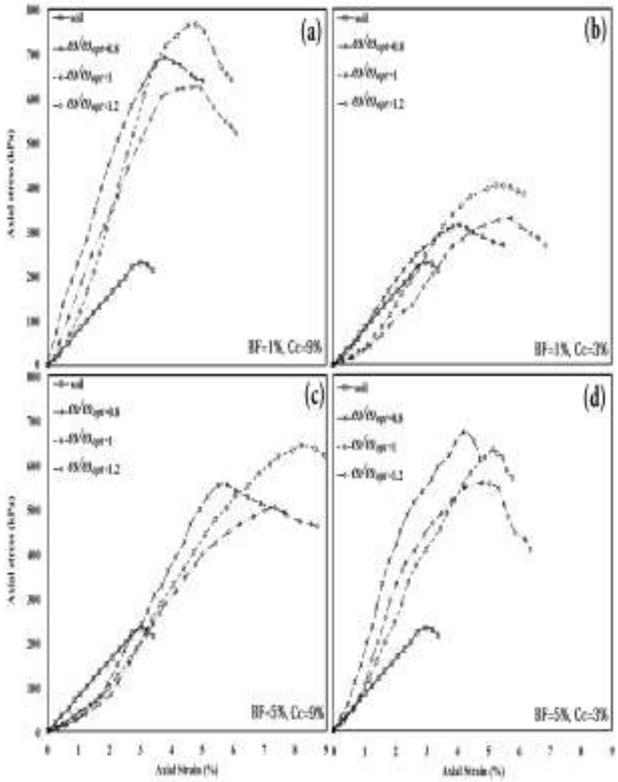

Fig. 10. Stress–strain curves of the BF-cement-stabilized specimens.

3.2. SEM Analyses

The mechanical characteristics of fiber-reinforced cement-stabilized specimens are more complicated, especially at microscopic scales. Tang et al. [50] indicated that the binding material properties, stress level, contact area and surface roughness of fibers have important effects on micro-mechanical properties of the fiber-soil interface. In other words, individual fiber inclusion alone is not an important factor in the microstructure of the soil. In fact, the soil particles which are attached to the fibers surface and bind the soil particles around fibers improve the bond strength and finally strengthen the matrix. In the current study, after shearing, four specimens including the BF or PPF-reinforced specimens (fiber content=2%), BF or PPF-cement-stabilized specimens (fiber content=2% and cement content=3%) were subjected to SEM analysis. SEM micrographs of BF and PPF specimens are shown in Figs. 11 and 12, respectively. As shown in Figs. 11 (c) and 12(c), it is observed that some cementitious particles cling to the fiber surface, constituted an interlock and improved the interactions between fiber and the soil particles. The SEM photographs indicate that the polypropylene fiber surface is more attached by many clay and cement particles than in the basalt fiber. Comparing Figs. 11(b) and 12(b) indicates that the degree of particle break-up of PPF-cement-stabilized specimen is more severe within the shear plane than outside the shear plane. As shown from SEM photographs, a stiffer cementitious matrix is developed after addition cement.

Fig. 11. SEM images of (a) BF-reinforced specimens (b) BF-cement-stabilized specimens (c) pits and grooves formed on the BF surface

Fig. 12. SEM images of (a) PPF-reinforced specimens (b) PPF-cement-stabilized specimens (c) pits and grooves formed on the PPF surface

Development of cementitious binders the soil particles and finally strengthen the soils. It is noted that fiber reinforcement effectiveness in the reinforced specimen is lower than that in the reinforced cement-stabilized specimen. In fact, the mobilized tensile strength of the fibers is mainly dependent on the level of the deformation of the soil matrix around them.

4. Conclusions

In this study, a series of UCS tests were conducted to investigate the effects of cement content, polypropylene or basalt fiber content, initial moisture content and curing time. Based on the results, the following conclusions are reached.Increasing cement content or curing time leads to a significant increasing in the UCS of cement-stabilized specimens and also changes the material behavior into a more brittle state. The results indicate that the most increasing UCS is caused after addition of 3% cement and the UCS increases slightly with further addition of the cement content after that. The results of tests on fiber-reinforced specimens indicate that PPF or BF contents play an important role in cemented or uncemented specimens. The UCS of fiber-reinforced soil is increased with increments of PPF or BF content from 0.5% to 5%. The UCS of the PPF-reinforced specimens was observed more than BF-reinforced ones for a given fiber content. The fiber-reinforced specimens show a more ductile behavior than the natural soil or cement-stabilized specimens. The inclusion of fibers within the cement-stabilized specimens reduces the brittleness of the response and increases the UCS and axial strain at failure, significantly. The increase in UCS of combined fiber and cement specimens is much more than the increase caused by fiber or cement, individually. The highest UCS strength and the axial strain at failure among the cement-stabilized PPF-reinforced specimens are achieved by 5% PPF and 9% cement for given initial moisture content. However, the UCS of the cement-stabilized BF-reinforced specimen containing 1% BF and 9% cement is the highest among the cement-stabilized BF-reinforced specimens for given moisture content. Nevertheless, the specimens containing 5% PPF or BF and 9% cement have the highest axial strain at failure. The results show that the UCS of the OMC specimens is almost more than that of the dry or wet side specimens for specific additives content. The dry side specimens have greater UCS and lower axial strain at failure than the wet side specimens. Also SEM analysis indicates that polypropylene fiber exhibited a more adhesion with the soil-cement matrix than basalt fiber.

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