Analysis of mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil

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Abstract

An experimental program was undertaken to investigate the effects of discrete short polypropylene fiber (PP-fiber) on the strength and mechanical behavior of uncemented and cemented clayey soil. In the present investigation, 12 groups of soil samples were prepared at three different percentages of PP-fiber content (i.e. 0.05%, 0.15% and 0.25% by weight of soil) and two different percentages of cement content (i.e. 5% and 8% by weight of soil), and unconfined compression and direct shear tests were carried out after 7-, 14- and 28-day curing periods. The test results indicated that the inclusion of fiber reinforcement within uncemented and cemented soil caused an increase in the unconfined compressive strength (UCS), shear strength and axial strain at failure, decreased the stiffness and the loss of post-peak strength, and changed the cemented soil's brittle behavior to a more ductile one. The interactions at the interface between fiber surface and soil matrix were analyzed by using scanning electron microscopy (SEM). It is found that the bond strength and friction at the interface seem to be the dominant mechanism controlling the reinforcement benefit. The behavior at the interface in fiber-reinforced uncemented soil was different from that in fiber-reinforced cemented soil. The micromechanical properties of fiber/matrix interface were influenced by several factors, e.g. binding materials in soil, normal stress around the fiber body, effective contact area of the interface and fiber surface roughness, etc.

Keywords: Fiber-reinforced soil; Cemented soil; SEM; Interfacial interaction; Mechanical behavior

1. Introduction

Construction of buildings and other civil engineering structures on weak or soft soil is highly risky because such soil is susceptible to differential settlements due to its poor shear strength and high compressibility. Improvement of certain desired properties like bearing capacity, shear strength (c and j) and permeability characteristics of soil can be undertaken by a variety of ground improvement techniques such as the use of prefabricated vertical drains (e.g. Abuel-Naga et al., 2006; Chu et al., 2006) or soil stabilization.

Chemical stabilization by cement or lime is a proven technique for improving the performance (strength and stabilization) of soil (Ismail et al., 2002; Aiban, 1994; Huang and Airey, 1998; Basha et al., 2005; Kolias et al., 2005; Sherwood, 1993; Al-Rawas, 2002; Tremblay et al., 2002; Lima et al., 1996; Thome, 1999). However, these chemical additives usually result in a high stiffness and brittle behavior (Wang et al., 2003; Basha et al., 2005). Incorporating reinforcement inclusions within soil is also an effective and reliable technique in order to improve the engineering properties of soil. In comparison with conventional geosynthetics (strips, geotextile, geogrid, etc.), there are some advantages in using randomly distributed fiber as reinforcement. First, the discrete fibers are simply added and mixed randomly with soil, in much the same way as cement, lime, or other additives. Second, randomly distributed fibers limit potential planes of weakness that can develop parallel to oriented reinforcement. Therefore, it has become a focus of interest in recent years. A number of triaxial tests, unconfined compression tests, CBR tests, direct shear tests on the subject have been conducted by several investigators in the last few decades (Yetimoglu and Salbas, 2003; Yetimoglu et al., 2005; Michalowski and

Čermák, 2003; Gray and Al-Refeai, 1986; Ranjan et al., 1996; Prabakar and Sridhar, 2002; Kaniraj and Gayathri, 2003; Li et al., 1995; Al-Refeai, 1991; Krishnaswamy and Isaac, 1994; Ranjan et al., 1994; Wasti and Bütün, 1996). Park and Tan (2005) studied the effects of short fiber (60 mm) reinforcement on the performance of soil wall. Miller and Rifai (2004), based on their test results, indicated that fiber inclusion increased the crack reduction and hydraulic conductivity of compacted clay soil. All these previous studies have shown that the addition of fiber-reinforcement caused significant improvement in the strength and decreased the stiffness of the soil. More importantly, fiber reinforced soil exhibits greater toughness and ductility and smaller loss of post-peak strength, as compared to soil alone. Therefore, the discrete fiber can be considered as a good earth reinforcement material, which causes significant modification and improvement in the engineering properties of soil. However, more work is necessary to comprehend the influence of fiber inclusion on the mechanical behavior of cemented and uncemented soils, especially the interfacial interactions between fiber surface and reinforced soil matrix.

The objective of this paper is to determine the strength and mechanical behavior of randomly distributed short PP-fiber (12 mm long) reinforced uncemented soil and cemented soil. A series of unconfined compression and direct shear tests were carried out on soil samples with different percentages of fiber and cement inclusion. By conducting scanning electron microscopy tests (SEM), the microstructure and the behavior of interfaces between fiber surface and soil were investigated to obtain a preliminary knowledge of the mechanism of fiber-reinforced soil.

2. Materials and experimental program

Materials

The soil samples used in the present experimental tests were obtained from the area of Nanjing, China. The soil was air dried and broken into pieces in the laboratory. The physical properties of the soil are listed in Table 1. The cement used in the test was ordinary Portland cement. Table 2 is a summary of the chemical composition and physical properties of the cement. A photograph of the short PP-fibers produced in China is given in Fig. 1. Some properties of the PP-fibers provided by the manufacturer are given in Table 3. For the preliminary investigation, only the fiber with a length of 12 mm was adopted in the tests.

Preparation of samples

The content of cement and fiber are defined herein as

$$r_c = \frac{W_c}{W}, \quad (1)$$

Table 1
Physical and mechanical properties of soil

Soil properties	Values
Specific gravity	2.7
Consistency limit	
Liquid limit	36.4%
Plastic limit	18.6%
Plasticity index	17.8
USUC Classification	CL
Compaction study	
Optimum moisture content	16.5%
Maximum dry density	1.7 g/cm^3
Grain size analysis	
Gravel	0.0%
Sand	1.7%
Silt	67%
Clay	31.3%
D_{60}	0.0117 mm
D_{30}	0.0048 mm
D_{10}	0.0011 mm
C_u	10.6
C_c	1.8

$$r_f = \frac{W_f}{W}, \quad (2)$$

where W_c is the weight of the cement, W_f is the weight of fiber, and W is the weight of air-dried soil (the final moisture content is 3.2%). The different values adopted in the present study for r_c are 0, 0.05 and 0.08 and r_f are 0, 0.0005, 0.0015 and 0.0025. All the test specimens were compacted at their respective maximum dry density (MDD) and optimum moisture content (OMC), corresponding to the values obtained in the Standard Proctor compaction tests. For the prescribed values of W, r_c and r_f, the required amount of cement and fiber are obtained from (1) and (2). Thus, 12 groups of soil samples admixed with cement and PP-fiber at different percentages were prepared for the unconfined compression and direct shear tests (GB/T 50123-1999, i.e. a national criterion for geotechnical tests in China). Table 4 gives the details of the different cement and fiber content of mixtures and the notation used for them in this paper.

In the preparation of all specimen types, if neither cement nor fiber was used, the air-dried soil was mixed with an amount of water that depends on the OMC of the soil. If the cement was used alone, considering the quick hydration of cement, the soil with the required water content was prepared first, and then the cement was added to the soil before the test samples were to be compacted. If fiber reinforcement was used alone, the prescribed content of fibers was first mixed into the air-dried soil in small increments by hand, making sure all the fibers were mixed thoroughly to achieve a fairly uniform mixture, and then the required water was added. If both cement and fiber were used, a moist fiber soil mixture was prepared as explained above and then the moist mixture was mixed

Table 2
Chemical composition and physical properties of cement

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	Specific surface, Blaine	Compressive strength, 28-day
20.3	4.3	3.5	62.4	2.8	3.3	1.6	387 m^2/kg	33.4 MPa

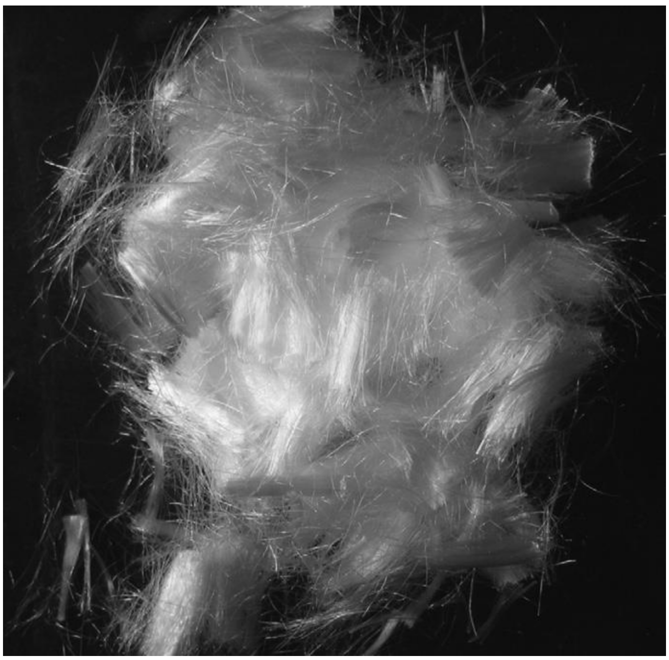

Fig. 1. Photograph showing the discrete short PP-fiber.

Table 3
Index and strength parameters of PP-fiber

Behavior parameters	Values
Fiber type	Single fiber
Unit weight	0.91 g/cm^3
Average diameter	0.034 mm
Average length	12 mm
Breaking tensile strength	350 MPa
Modulus of elasticity	3500 MPa
Fusion point	165 ıC
Burning point	590 ıC
Acid and alkali resistance	Very good
Dispersibility	Excellent

with cement. All mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. After the compaction, the samples treated with cement were wrapped with plastic membrane in the curing box for 7, 14 and 28 days, respectively until tested.

Testing program

As a prerequisite, the physical and mechanical properties (specific gravity, consistency limit, USCS classification, etc.) of soil used were determined in the laboratory according to

Table 4
Fiber and cement content of the soil mixtures

Soil no.	Cement content (%)	Fiber content (%)
S	0	0
F1	0	0.05
F2	0	0.15
F3	0	0.25
C1	5	0
C2	8	0
CF1	5	0.05
CF2	5	0.15
CF3	5	0.25
CF4	8	0.05
CF5	8	0.15
CF6	8	0.25

the pertinent tests specified in GB/T 50123-1999. Some properties of the soil are given in Table 1.

Unconfined compression tests

The conventional unconfined compression apparatus was employed in the tests. Samples were shaped in a mold with a length of 80 mm and an inner diameter of 39.1 mm, at the state of MDD-OMC. In order to ensure uniform compaction, the required quantity of material was placed inside the mold and compressed in three steps. Additionally, for the samples treated with cement, unconfined compression tests were carried out after they were socked under water for 24 h at the last day of each curing period. The loading rate was 2.4 mm/min until samples failed in the test.

Direct shear tests

The specimens for the shear tests were shaped in a cylindrical mold with 20 mm height and 61.8 mm inner diameter by static compaction at the respective MDD-OMC state of soil. The tests were performed at the vertical normal stress of s_n ¼ 50, 100, 200 and 300 kPa in order to define the shear strength parameters (*c* and j). The strain rate was 0.12 mm/min in the test.

Scanning electron microscopy tests (SEM)

The effect of additives on the soil structure and fiber reinforcement surface was observed and analyzed by SEM. Four soil samples (i.e. uncemented soil, fiber-reinforced uncemented soil, cemented soil and fiber-reinforced cemented soil) with a size of 1 cm∼1 cm∼1 cm were prepared after the unconfined compression test. The samples were kept in alcohol until the test and gold coated before examination. Finally, the SEM images were evaluated by using the image tools of geographic information system (GIS) to investigate the area porosities of uncemented soil, cemented soil and fiber-reinforced soil.

3. Results and discussions

Effect of fiber and cement inclusion on the strength behavior of soil

Effect of fiber and cement inclusion on the unconfined compressive strength (UCS) of soil

The stress–strain curves obtained from unconfined compression tests are given in Fig. 2(a) for fiber-reinforced uncemented soil and Figs. 2(b) and (c) for cemented soil and fiber-reinforced cemented soil after curing for 28 days. It can be seen from Fig. 2(a) that fiber inclusion enhanced the peak stress of uncemented soil, but the contributions of further increase of fiber content to peak stress was insignificant. It can also be seen that fiber-reinforced uncemented soil exhibits more ductile behavior and smaller loss of post-peak strength than uncemented soil. The reduction in the loss of post-peak stress is more pronounced for higher fiber content. In addition, Fig. 2(a) shows that the initial stiffness of soil appears not to be affected by the addition of fiber. While for the cemented soil specimens, as shown in Fig. 2(b), one can easily realize the effect of cementation on soil response. The peak stress increases dramatically with an increase in cement content, and the cemented soil exhibits a marked stiffness and brittleness. Its failure strain is 0.5–0.75%, which is much smaller than that of uncemented soil and fiber-reinforced uncemented soil.

The combined effect of fiber and cement inclusions on the behavior of stress–strain is shown in Fig. 2(c). It is readily observed that the peak axial stresses increase with increasing fiber content. Upon comparison with Fig. 2(b), it can be seen that the inclusion of fibers within the cemented soil reduces the brittleness of the response. The failure strain increased and ranged from 1.25% to 1.7%. The axial stress increases with an increase in axial strain until the peak value is reached, followed by a sudden drop to zero in cemented soil, but the reduction of post-peak stress is gradual when fibers are included. Furthermore, the residual strength of cement–fiber soil specimens increases with increased fiber content. Undoubtedly, one of the main advantages of fiber reinforcement when applied to soil is the improvement in material ductility.

Fig. 3 shows the effect of fiber content on the uncemented soil and cemented soil after curing for 28 days. It is indicated that fiber plays a more important role in cemented soil than it does in uncemented soil. The values of UCS for cemented soil specimens with 5% and 8% cement content increase significantly from 0.40 to 1.02 MPa and from 0.63 to 1.28 MPa after 0.05% fiber is added. However, the influence of fiber inclusion on uncemented soil is not significant. Fig. 3 also shows that,

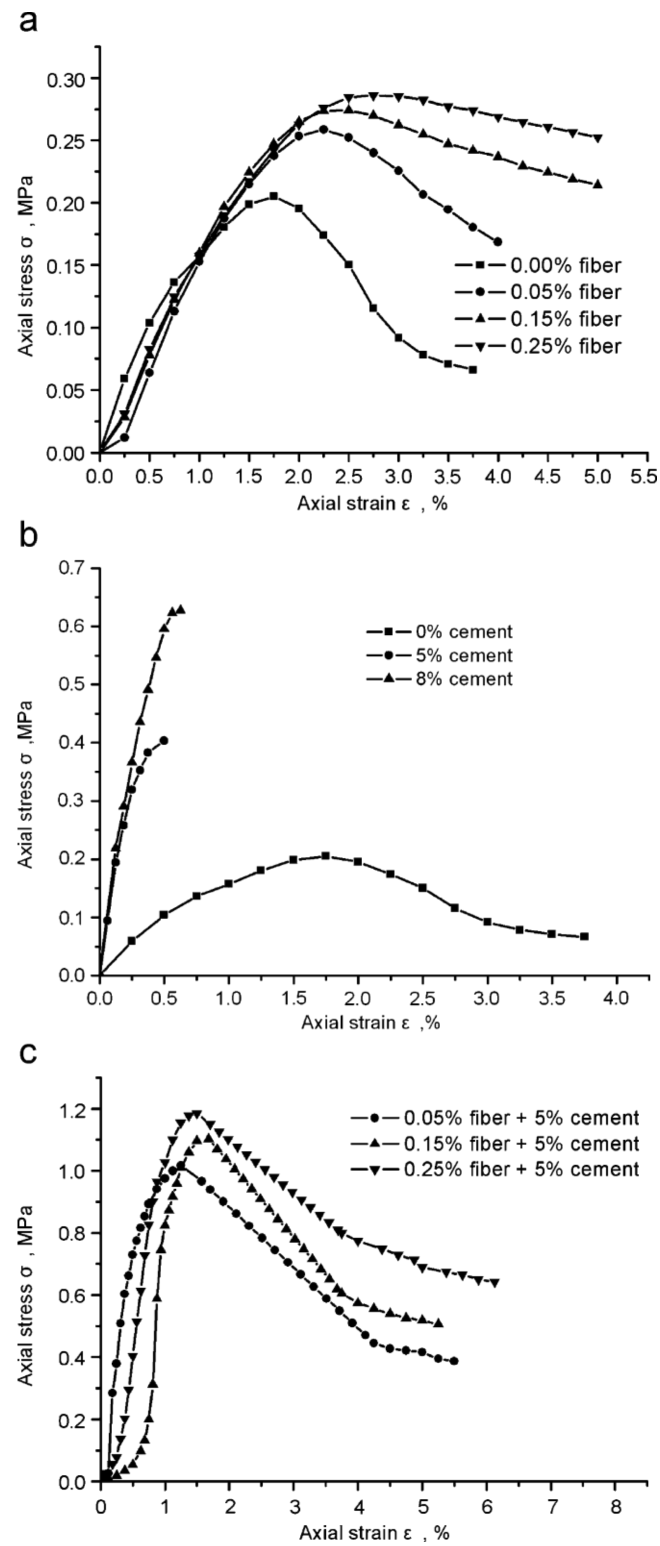

Fig. 2. Stress–strain curves: (a) fiber-reinforced uncemented soil with varying fiber content; (b) cemented soil with varying cement content after 28 days curing; (c) fiber-reinforced cemented soil with 5% cement and varying fiber content after 28 days curing.

for any particular amount of cement content, an increase in fiber content beyond r_f ¼ 0:05% induces a little increment in strength.

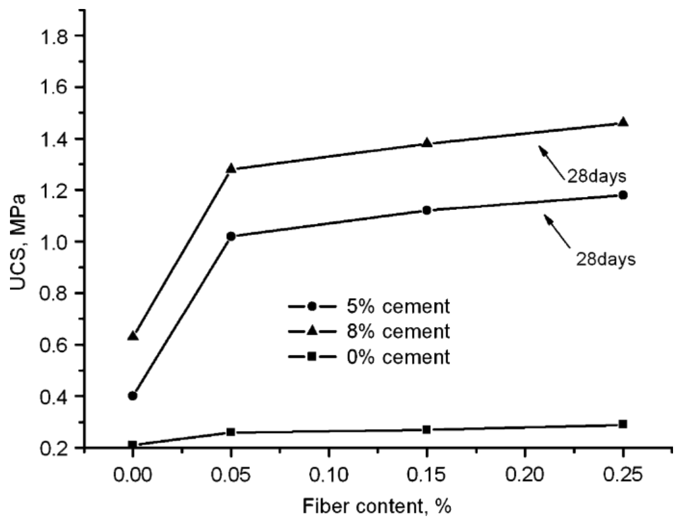

Fig. 3. The relationship between the UCS and fiber content.

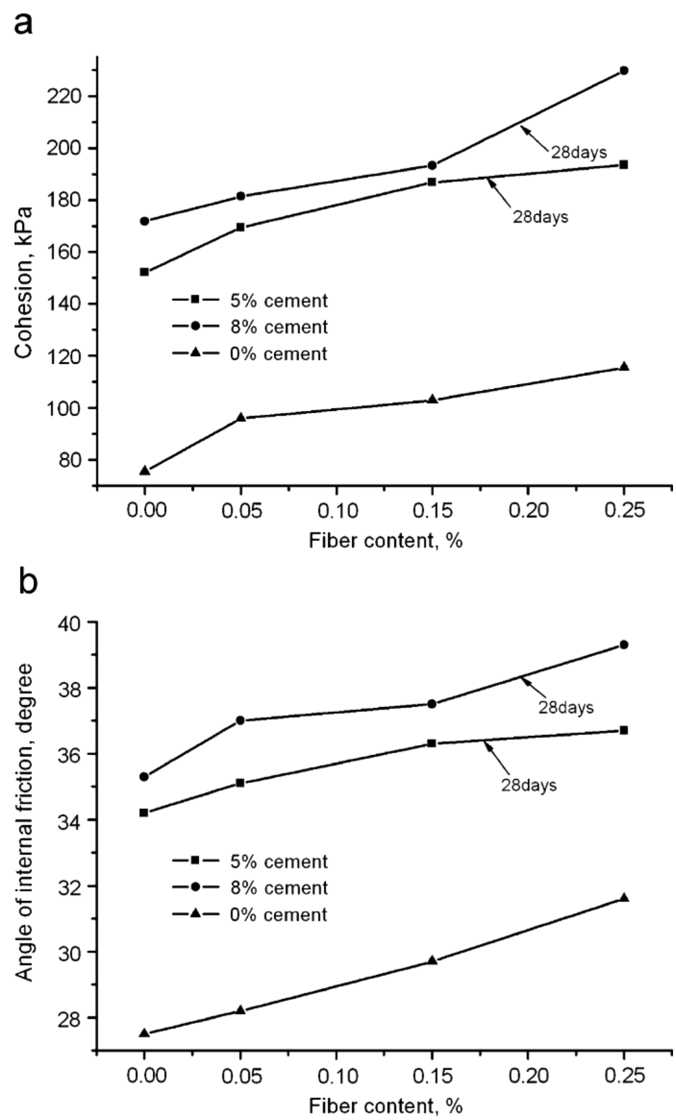

Fig. 4. The relationship between shear strength parameters and fiber content: (a) cohesion and fiber content; (b) angle of internal friction and fiber content.

Effect of fiber and cement inclusion on the shear strength parameters of soil

Fig. 4 shows the relationship between shear strength parameters and fiber content. It is indicated that the percentage of fiber and cement content play an important role in the development of the shear strength parameters *c* and j. The cohesion and internal friction angle of specimens of cemented soil increase with increasing fiber content. If the fiber content remains the same, cement inclusion significantly enhances the shear strength parameters.

The values of UCS and shear strength parameters obtained in the tests are summarized in Table 5. From these data it can be seen that the values of UCS, *c* and j of all fiber-reinforced cemented soil, like those of cemented soil, increase with increasing the curing time. The increase in strength of combined fiber and cement inclusions is much more than the sum of the increases caused by them individually.

Interface morphologies and mechanical behavior of fiber-reinforced soil

For the purpose of investigating the interfacial interactions between the fiber surface and soil matrix, several related SEM images are given and discussed in following sections.

Interface morphologies of fiber-reinforced uncemented soil

SEM images of fiber-reinforced uncemented soil and fiber surface are presented in Fig. 5. Fig. 5(a) shows that the microstructure of fiber-reinforced uncemented soil is similar to that of uncemented soil (Fig. 5(b)), the structure is not compact and the pore spaces are large. By using the image tools of GIS, the gray SEM images were transformed to binary black and white images, and the pores were represented by the black pixels. The number of the pixels is easy to calculate in GIS. Therefore, the area porosity P_a (porous area in percent of the image) can be calculated as

$$P_a ¼ \frac{N_b}{N}, \qquad (3)$$

where N_b is the number of black pixels, N is the total number of pixels in the binary image. According to (3), the area porosity of fiber-reinforced uncemented soil is 52.4% almost the same as that of uncemented soil (51.3%). It indicates that the individual fiber inclusion has no discernible effect on the microstructure of soil. From Fig. 5(c), it can be seen that the fiber surface is attached by many clay minerals which make the contribution to bond strength and friction between the fiber and soil matrix. The distributed discrete fibers act as a spatial three-dimensional network (Fig. 5(d)) to interlock soil grains, help grains to form a unitary coherent matrix and restrict

Table 5
The UCS and shear strength parameters of soil samples at different curing days

Soil no.	Cement content (%)	Fiber content (%)	UCS (MPa)			*c* (kPa)			j (degree)		
			7 days	14 days	28 days	7 days	14 days	28 days	7 days	14 days	28 days
S	0	0		0.21			75.5			27.5	
F1	0	0.05		0.26			95.9			28.2	
F2	0	0.15		0.27			103.0			29.7	
F3	0	0.25		0.29			115.6			31.6	
C1	5	0	0.30	0.32	0.40	129.4	142.3	152.1	31.8	32.4	34.2
C2	8	0	0.45	0.54	0.63	134.3	157.9	171.8	33.1	33.9	35.3
CF1	5	0.05	0.80	0.90	1.02	134.1	162.1	169.4	34.7	34.8	35.1
CF2	5	0.15	0.91	0.96	1.12	137.9	178.8	186.7	35.2	35.4	36.3
CF3	5	0.25	1.04	1.12	1.18	157.2	179.5	193.4	36.2	36.4	36.7
CF4	8	0.05	1.10	1.21	1.28	138.1	169.5	181.4	35.5	36.1	37.0
CF5	8	0.15	1.25	1.34	1.38	152.6	174.8	193.3	35.7	36.8	37.5
CF6	8	0.25	1.38	1.53	1.46	172.0	202.3	229.8	37.2	37.5	39.3

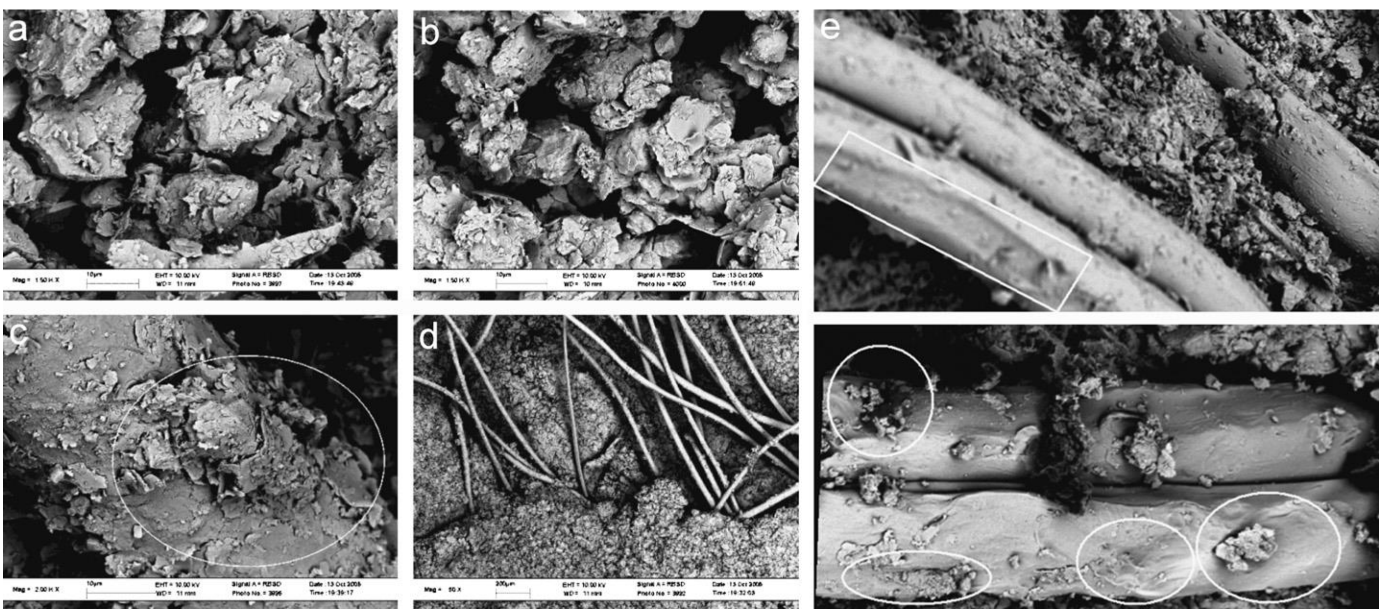

Fig. 5. SEM images of fiber reinforced uncemented soil (0.25% fiber content): (a) fiber-reinforced uncemented soil with a magnification of 1500 times; (b) uncemented soil with a magnification of 1500 times; (c) fiber surface in fiber-reinforced uncemented soil with a magnification of 2000 times; (d) fiber distribution in soil matrix; (e) pits and grooves formed on the fiber surface.

the displacement. Consequently, the stretching resistance between clay particles and strength behavior was improved. Because of the interfacial force, the fibers in the matrix are difficult to slide and they can bear tensile stress, as the sketch drawing shown in Fig. 6. When the specimens are under load, the ‘‘bridge’’ effect of fiber can efficiently impede the further development of tension cracks and the deformation of the soil (Fig. 7). As a result, the fiber-reinforced soil demonstrated a somewhat ductile behavior as shown in Fig. 2. Several researchers pointed out that the fiber sliding resistance was strongly dependent on the fiber surface roughness (Shah, 1991; Tagnit-Hamou et al., 2005; Frost and Han, 1999). As the fibers were mixed or samples were compacted, the hard particles (such as sands) of mixtures impacted and abraded the fiber surface, causing plastic deformation and even removal of part of the surface layer. As the marked area of Figs. 5(c) and (e), the pits and grooves formed on the fiber surface constituted an interlock and improved the interactions between fiber surface and the soil matrix.

Interface morphologies of fiber-reinforced cemented soil

Fig. 8(a) shows the fiber surface in cemented soil. The fiber surface is attached by hydrated products of the cement but few clay minerals in comparison with Fig. 5(c). It is known that the by-products of the cement possess higher strength and cementation than the clay grains.

Therefore, the strength at the interface of fiber-reinforced cemented soil is much higher than that of fiber-reinforced uncemented soil. Network-like crystals were wrapped around the fiber tightly and effectively restricted the fiber's relative movement and increased the reinforcement benefit

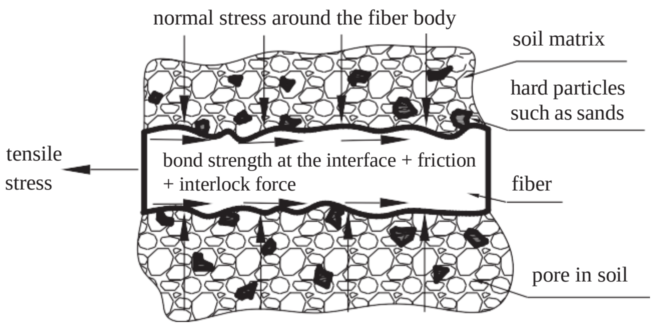

Fig. 6. Sketch of mechanical behavior at the interface between fiber surface and soil matrix.

significantly (Fig. 8(b)). The high degree of stiffness of the attached hydration crystals also toughened the distributed fibers, which act similarly to plant roots in distributing the stresses in a broader area and inhibiting fissure propagation. Therefore, the combined fiber and cement inclusions increase the efficiency of transfer of the load from matrix to fibers. Furthermore, the hydration of the cement binds soil particles together and makes the matrix compact, and causing an increase in normal stress around the fiber body and the effective contact area. As a result, the static friction coefficient between fiber and composite matrix is increased.

Effect of fiber content on failure characteristics of cemented soil

Soil stabilized with cement alone exhibits extremely brittle behavior and the failure mechanism is triggered by the formation of noticeable tension cracks. It is shown in Fig. 9(a) that the tension cracks are wide and long, and

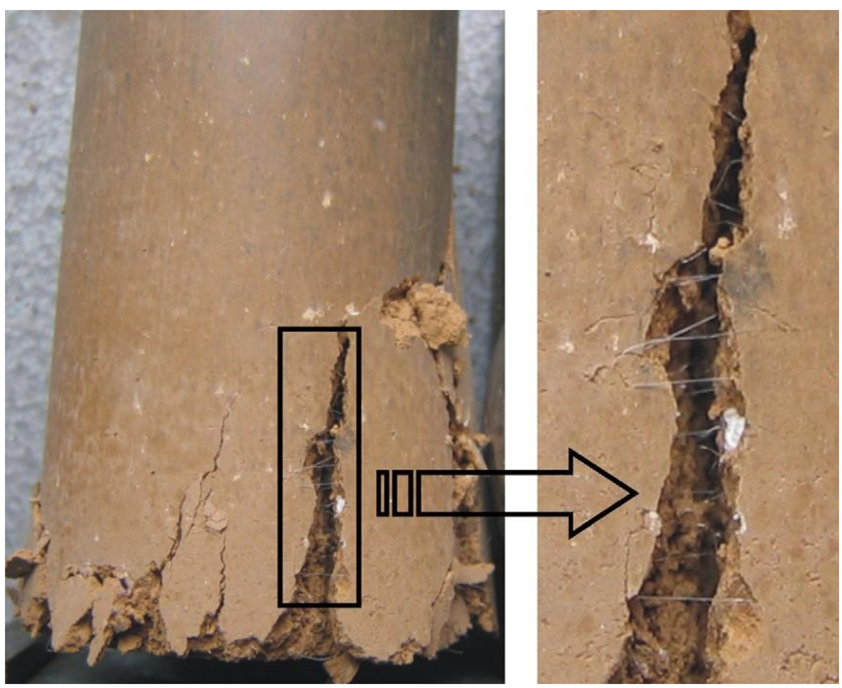

Fig. 7. The ''bridge'' effect of fiber reinforcement in soil impedes the further development of tension cracks.

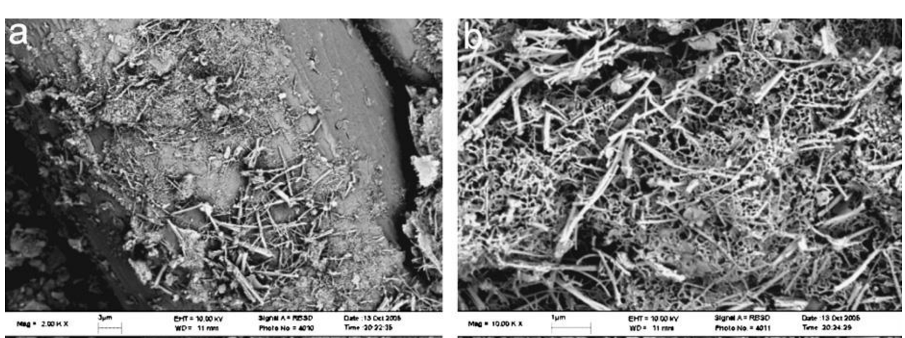

Fig. 8. SEM images: (a) fiber surface in cemented soil with a magnification of 2000 times; (b) local magnifying of hydrated products in marked area of (a).

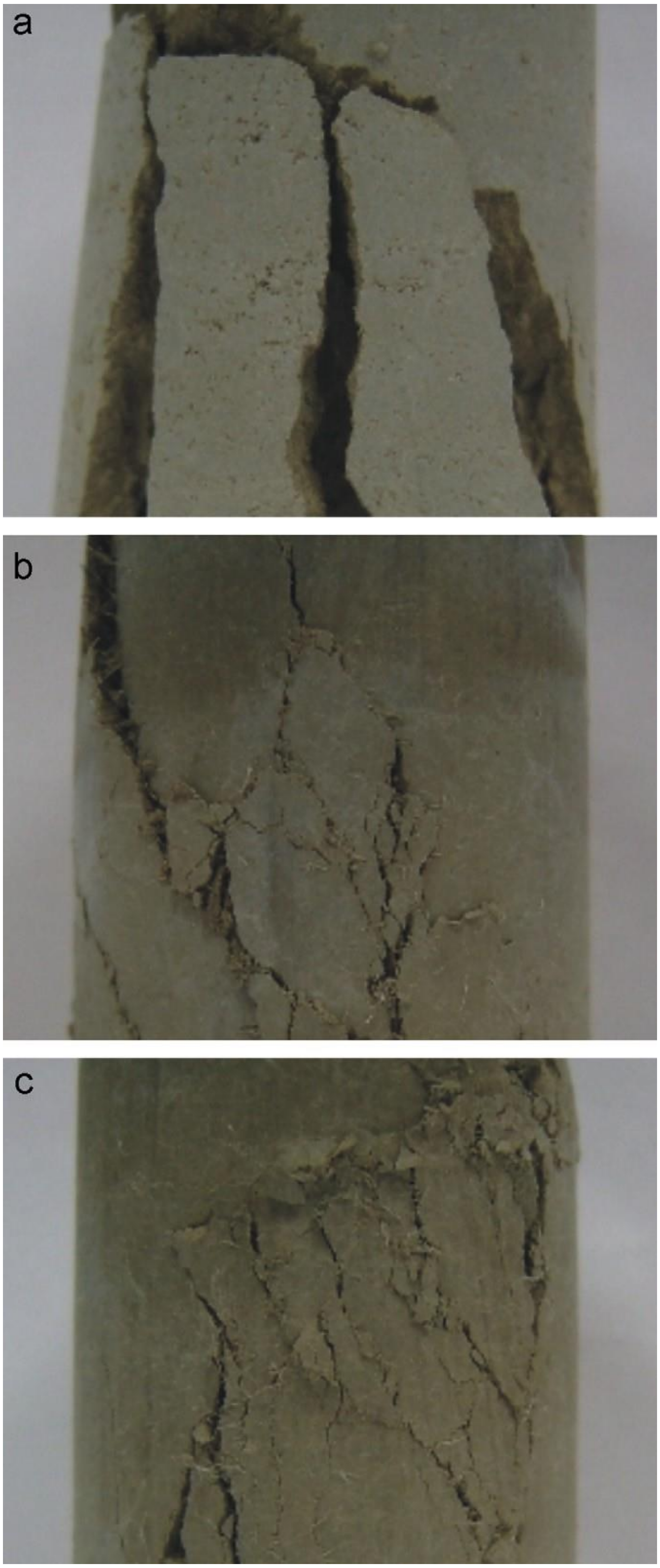

Fig. 9. Effect of fiber content on failure characteristics of cement treated soil with 8% cement content: (a) 0% fiber content; (b) 0.05% fiber content; (c) 0.25% fiber content.

spread from bottom to top of the specimen. However, fiber inclusion can change the brittle behavior to a more ductile one, and make it exhibit strain-hardening characteristics. When the tension cracks caused by loading begin to appear, the fibers serve as ‘‘bridges’’, efficiently impeding the further opening and development of cracks and accordingly preventing samples from complete failure. It is clearly shown in Figs. 9(b) and (c) that the tension cracks become gradually narrower and shorter with increasing the fiber content. These failure characteristics are consistent with the stress–strain behavior shown in Fig. 2.

4. Conclusions

A series of tests were performed to study the effects of randomly distributed short PP-fiber reinforcement on the strength and mechanical behavior of uncemented and cemented soil. The effects of fiber and cement inclusions on UCS, shear strength parameters, stiffness and ductility of soil specimens were determined. The fiber surface morphologies, interactions at the interface and mechanical behavior of fiber-reinforced uncemented soil and cemented soil were investigated by using SEM analysis. The following are the conclusions from these tests.

The inclusion of fiber reinforcement within uncemented and cemented soil caused an increase in the UCS, shear strength and axial strain at failure. Increasing fiber content could increase the peak axial stress and decreases the stiffness and the loss of post-peak strength, weakens the brittle behavior of cemented soil. The increase in strength of combined fiber and cement inclusions is much more than the sum of the increase caused by them individually. The ‘‘bridge’’ effect of fiber can efficiently impede the further development of tension cracks and deformation of the soil. Bond strength and friction at the interface seem to be the dominant mechanisms controlling the reinforcement benefit. In fiber-reinforced uncemented soil, interactions occur at the interface between the fiber surface and the clay grains play key roles in the mechanical behavior. However, in fiber-reinforced cemented soil, the interactions between the fiber surface and the hydrated products make main contribution to the strength at the interface. The micro-mechanical behavior of the fiber/matrix interface depends on binding material properties in the soil, normal stress around the fiber body, effective contact area and fiber surface roughness. It is known that the interface roughness plays an important role in reinforced soil systems. No attempt has yet been made to determine the optimum degree of the surface damage or plastic deformation caused by hard particles as the mixtures are being mixed and compacted, though of course this is an important subject.

These conclusions are of significance, both for developing methods of improving the interfacial strength, and for application in engineering projects. It could be concluded from this study that the combination of discrete fiber and cement has the virtues of both fiber-reinforced soil and cement-stabilized soil, and therefore the addition of fiber–cement to soil can be considered as an efficient method for ground improvement.

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