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Research Article

The Effect of Polymer-Fiber Stabilization on the Unconfined Compressive Strength and Shear Strength of Sand

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The mixed soil stabilizer of polyurethane organic polymer and polypropylene fiber was used to reinforce sand. The unconfined compressive test and direct shear test were carried out to evaluate the effects of polymer-fiber reinforced sand. The different contents of polymer and fiber were selected for the tests. The test results indicated that polymer-fiber mixture can improve strongly the strength of sand. The presence of polyurethane organic polymer enhances sand structural stability and the best composition of polymer and fiber was 4% and 0.2–0.3% of dry sand, respectively. Based on the test results and images of scanning electron microscope (SEM), the reinforcement mechanism was analyzed. The research results can be considered as the reference for sand reinforced engineering.

1. Introduction

Sand is usually easily destroyed due to its low strength and cohesion [1, 2]. In geotechnical engineering, most of natural sand needs to be reinforced to meet the engineering requirements. The physical and chemical reinforcement methods are mainly used in foundation, slope, and embankment. The fiber used as a physical reinforcing material has recently become a focus of intense interest [3–5]. Jiang et al. [6] introduced the engineering properties of soils reinforced by short discrete polypropylene fiber. Gao et al. [7] evaluated the unconfined compressive strength of fiber reinforced clay soil. Noorzad and Fardad [8] presented liquefaction resistance of sand reinforced with randomly distributed fiber under cyclic loading. The static liquefaction of fiber reinforced sand under monotonic loading was also studied by Ibraim et al. [9]. These results indicated that mixing of fibers with a soil mass might act as a spatial three-dimensional network to interlock soil particles to help the particles to form a unitary coherent matrix and restrict the displacement. The cohesive force of fiber reinforced soil is mainly generated by the interlock between adjacent sand particles. While the fiber is used for the loose sand, the cohesion of fiber reinforced sand is difficult to be improved strongly.

Recently, the chemical polymer materials have been used in sand reinforcement [10–15]. Liu et al. [12] evaluated effect of sand fixed with a new organic polymer sand-fixing agent. Ma et al. [13] presented sand reinforced with an eco-friendly polymer composite sand-fixing agent. Mahmoud and Attia [14] introduced the inverse emulsion polymerization for the synthesis of high molecular weight polyacrylamide and its application as sand stabilizer. Gong et al. [15] studied Kerqin sandy land of China reinforced using polymeric materials. The polymer can fill up the voids of sand and adsorbs ions on the surface of sand particle. The elastic and viscous membrane structure is formed through physicochemical bonds between molecules and sand particle to improve the sand strength and cohesion. The cohesion of polymer reinforced soil can be increased strongly. While the polymer materials are mixed with fiber to treat the sand, the cohesion of reinforced sand will be improved with the increment of connected force. Therefore, the polymer-fiber mixture can be considered as a new mixed material to reinforce the loose sand.

In this study, the polymer-fiber mixed with polyurethane organic polymer and polypropylene fiber was used as the soil stabilizer to reinforce sand. The unconfined compressive test and shear test were carried out to evaluate the effects of polymer-fiber reinforced sand. The different contents of

Table 1: Grain size distribution of sand.

Grain size (mm)	Weight percentage content (%)
2-1	0.2
1–0.5	17.1
0.5–0.25	48.9
0.25–0.1	31.7
0.1–0.075	2.1

polymer and fiber were selected for the tests. Based on the test results and images of scanning electron microscope (SEM), the reinforcement mechanism was analyzed and the best composition of polymer-fiber was obtained. The research results can be considered as the reference for sand reinforced engineering.

2. Materials

The sand used in this study was acquired from Nanjing, Jiangsu Province, China. Its property parameters are shown in Tables 1 and 2. The dominant component of the sand is the particle size between 0.5 and 0.1 mm (80%). Its specific gravity is approximately 2.65. As shown in Table 2, it has maximum dry density ($\rho_{\max}$) of 1.66 g/cm^3, minimum dry density ($\rho_{\min}$) of 1.34 g/cm^3, maximum void ratio ($e_{\max}$) of 0.970, and minimum void ratio ($e_{\min}$) of 0.590. Its particles have a mean grain size (D_{50}) of 0.30 mm, gradation coefficient (C_g) of 1.13, and uniformity coefficient (C_u) of 2.77.

The polypropylene fiber used in this study is shown in Figure 1(a). It has a length of 18 mm, diameter of 0.034 mm, specific gravity (G_f) of 0.91, tensile strength of 350 MPa, elasticity modulus of 3500 MPa, fusion point of 165°C, burning point of 590°C, and excellent dispersibility. The proportion of dry weight of sand is considered as the percentage of fiber and denoted as

$$P_f = \left(\frac{W_f}{W_s}\right) \times 100\%, \tag{1}$$

where W_f is the fiber weight and W_s is the dry sand weight.

Polyurethane organic polymer shown in Figure 1(b) was selected in this study. It has a main constituent of polyurethane resin and contains enormous amount of functional group –NCO. It is light yellow of oil liquid with a pH of 6-7, viscosity of 650–700 mPa·s, specific gravity of 1.18 g/cm^3, solid content of 85%, and coagulation time of 30–1800 s and holds water content larger than 40 times. The coagulation time decreases with the increase in the concentration. It is an environment-friendly product with no additional pollution. The proportion of dry weight of sand is considered as the percentage of polymer and denoted as

$$P_p = \left(\frac{W_p}{W_s}\right) \times 100\%, \tag{2}$$

where W_p is the polymer weight and W_s is the dry sand weight.

3. Experimental Methods

In this study, the laboratory tests of unconfined compression test and direct shear test were performed to evaluate the performance of polymer-fiber reinforced sand. In the two types of test, sand samples were first oven-dried. Four percentages of fiber (P_f) 0.1%, 0.2%, 0.3%, and 0.4% and four percentages of polymer (P_p) 1%, 2%, 3%, and 4% are considered for this investigation and the unreinforced one as a control. A moisture content of 10% was used for the mixing process of all test specimens.

In the preparation of all samples, the proposed content of fiber was first mixed with the dry sand in small increments by hand to obtain a uniform mixture. The proposed content of polymer and water were mixed to a polymer solution. The water was poured into a flask containing polymer along the flask wall gradually and the mixture was stirred continuously during the mixing process to obtain a uniform polymer dilution. After that the polymer solution was added into the fiber-sand mixture to obtain a final mixture. It is important to ensure all mixed fibers thoroughly. Finally, the mixtures were prepared for the samples of unconfined compression test and direct shear test.

3.1. Unconfined Compression Test. In unconfined compression test, samples were prepared with static compaction method based on ASTM standards. Four-layered compaction was adopted to keep the uniformity of test specimens with the diameter being 39.1 mm and height being 80 mm. After the specimen preparation, the reinforced specimens were kept in curing box with a temperature around 20°C and curing time of 48 hours. The unconfined compression tests were carried out at the loading rate of 2.4 mm/min until samples failed. Additionally, unconfined compression test was performed on specimen triplicates and average values were used.

3.2. Direct Shear Test. In direst shear test, the samples were prepared with static compaction method based on ASTM standards. Two-layered compaction was adopted to test specimens with 61.8 mm diameter and 20 mm height. After the specimen preparation, the reinforced specimens were kept in curing box with a temperature around 20°C and curing time of 48 hours. The direct shear tests were carried out at a strain rate of 0.02 mm/min under the normal pressures of 100, 200, 300, and 400 KPa in order to define the shear strength parameters (c and ψ). And the shear strength parameters were obtained on specimen triplicate and average values were used.

4. Test Results

The specimens with different percentages of fiber and polymer were tested in unconfined compression test and direct shear test. Their results are summarized in Tables 3 and 4. The detailed analysis of each test are given as follows.

4.1. Unconfined Compression Test. The results of samples in unconfined compression test are shown in Table 3. In this

Table 2: Property parameters of sand.

ρ_{max} (g/cm^3)	ρ_{min} (g/cm^3)	e_{max}	e_{min}	D_{50} (mm)	C_u	C_g	G_s
1.66	1.34	0.970	0.590	0.30	2.77	1.13	2.65


(a)

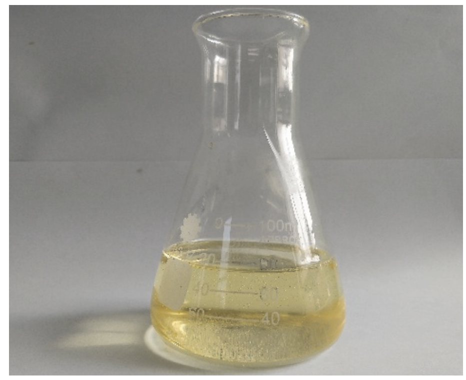

(b)

Figure 1: The polymer-fiber material: (a) polypropylene fiber; (b) polyurethane organic polymer.

Table 3: Unconfined compressive strengths of sand samples.

Serial number	Dry density (g/cm^3)	Content of polymer (%)	Content of fiber (%)	UCS (kPa)	Percentage of strength improving (%)
S1	1.5	0	0/0.1/0.2/0.3/0.4	/	/
S2	1.5	1	0	22.99	0.00
S3	1.5	1	0.1	26.28	14.31
S4	1.5	1	0.2	34.22	48.85
S5	1.5	1	0.3	41.22	79.30
S6	1.5	1	0.4	38.02	65.38
S7	1.5	2	0	41.88	0.00
S8	1.5	2	0.1	52.57	25.53
S9	1.5	2	0.2	92.05	119.79
S10	1.5	2	0.3	131.45	213.87
S11	1.5	2	0.4	129.11	208.29
S12	1.5	3	0	52.69	0.00
S13	1.5	3	0.1	65.64	24.58
S14	1.5	3	0.2	116.85	121.77
S15	1.5	3	0.3	156.69	197.38
S16	1.5	3	0.4	131.91	150.35
S17	1.5	4	0	106.14	0.00
S18	1.5	4	0.1	118.71	11.84
S19	1.5	4	0.2	157.73	48.61
S20	1.5	4	0.3	163.23	53.79
S21	1.5	4	0.4	135.13	27.31

Table 4: Direct shear strengths of sand samples.

Serial number	Dry density (g/cm^3)	Content of polymer (%)	Content of fiber (%)	Cohesion (kPa)	Angle of internal friction (degree)
S22	1.5	0	0	5.21	30.12
S23	1.5	0	0.1	8.94	30.74
S24	1.5	0	0.2	13.14	35.00
S25	1.5	0	0.3	12.21	30.54
S26	1.5	0	0.4	10.4	27.31
S27	1.5	1	0	18.27	28.37
S28	1.5	1	0.1	20.31	29.6
S29	1.5	1	0.2	21.15	30.96
S30	1.5	1	0.3	15.32	27.19
S31	1.5	1	0.4	8.65	26.66
S32	1.5	2	0	25.43	27.7
S33	1.5	2	0.1	28.98	28.12
S34	1.5	2	0.2	32.15	30.54
S35	1.5	2	0.3	30.63	26.61
S36	1.5	2	0.4	17.31	25.84
S37	1.5	3	0	40.27	25.25
S38	1.5	3	0.1	49.38	27.7
S39	1.5	3	0.2	57.59	29.1
S40	1.5	3	0.3	43.62	26.57
S41	1.5	3	0.4	29.94	24.7
S42	1.5	4	0	70.19	25.36
S43	1.5	4	0.1	75.32	26.58
S44	1.5	4	0.2	80.36	27.9
S45	1.5	4	0.3	60.85	23.75
S46	1.5	4	0.4	47.56	22.66

Figure 2: Sample of unreinforced sand.

Figure 3: Sample of fiber reinforced sand.

study, the unreinforced and fiber reinforced samples are not able to form the required samples due to their poor cohesive force. The photos of unreinforced and fiber reinforced samples after pressure molding are shown in Figures 2 and 3, respectively. But all the polymer reinforced sand can form the required samples. The unconfined compression strength of samples reinforced with polymers 1%, 2%, 3%, and 4% is 22.99, 41.88, 52.69, and 106.14 kPa, respectively. It can be seen from Table 3 that the unconfined compression strength of samples is improved by the reinforced material of polymer-fiber. The strength improving is affected by the content of polymer and fiber.

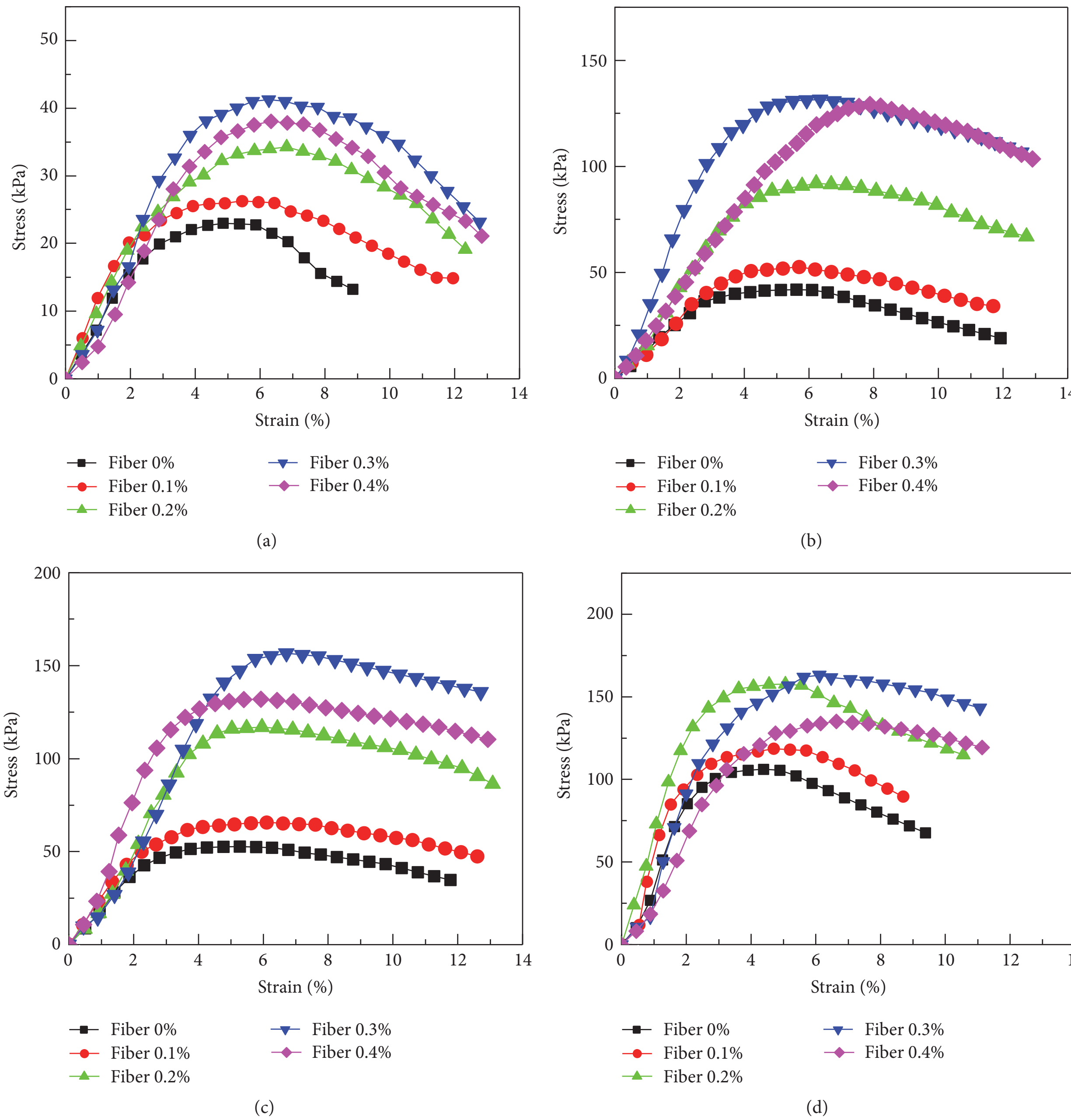


Figure 4: The strain-stress curves of unconfined compressive strengths tests. (a) Polymer 1%, (b) polymer 2%, (c) polymer 3%, and (d) polymer 4%.

The axial stress-strain curves of samples reinforced with different content of polymer-fiber are present in Figure 4. As seen in Figure 4, all the polymer-fiber reinforced samples tend to soften, with an obvious peak value, being mainly in a ductile failure state. The peak values are defined as the unconfined compressive strengths of sand samples. The axial stress increases with the increasing of the axial strain to reach the peak value and then decreases to a relative stable value. After the peak value, the axial stress decreased rate of samples reinforced with polymer 1% shown in Figure 4(a) is larger than the ones with polymers 2%, 3%, and 4% in Figures 4(b)–4(d). The samples with higher polymer content have the larger residual strength. With the same polymer content, the axial stress change paths are similar. The photos of samples before/after test are present in Figure 5. As shown in Figures 5(a) and 5(b), the samples with polymer 1% and polymer 1%-fiber 0.2% have enough cohesion to form intact required cylinders. After test, the failure shape of sample with polymer 1% is like a "petal" and the one of sample with polymer 1%-fiber 0.2% damage is along a main "sliding" surface. Based on all the failure shapes after tests, the samples only reinforced with polymer are mainly "petal" model and the ones reinforced with the mixture of polymer-fiber are mainly "sliding" model.

FIGURE 5: Photos of samples before/after test. (a) Polymer 1%-fiber 0%; (b) polymer 1%-fiber 0.2%.

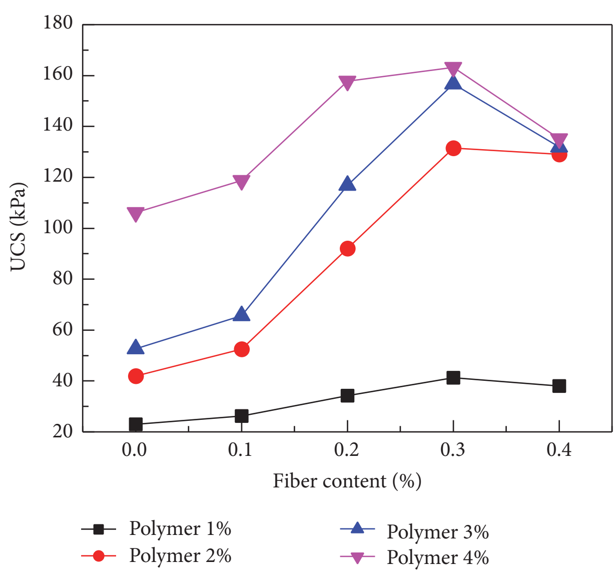


FIGURE 6: Unconfined compressive strength (UCS) of samples.

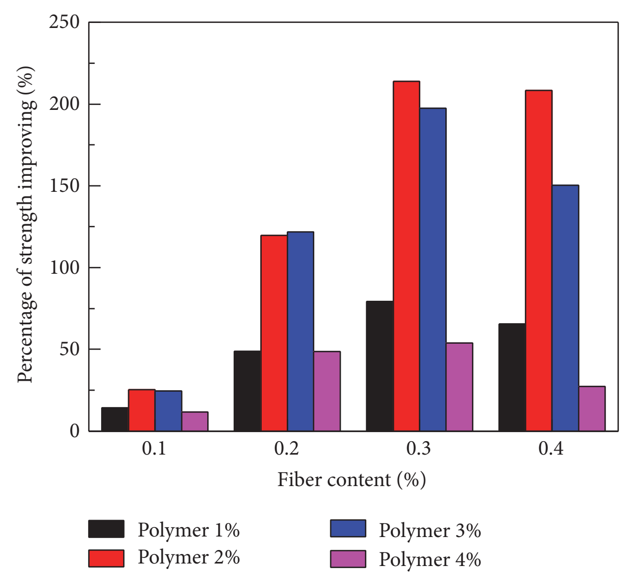


FIGURE 7: Percentage of strength improving of samples.

The unconfined compressive strength of reinforced samples is presented in Figure 6. As seen in Figure 6, the UCS of samples are affected by the different content of polymer-fiber. The UCS values of samples with the same polymer content increase with the increasing of fiber content to reach a higher value and then decrease. While the fiber content is 0.3%, four groups of samples with polymers 1%, 2%, 3%, and 4% reach the peak values 41.22 kPa, 131.45 kPa, 156.69 kPa, and 163.23 kPa, respectively. Meanwhile, the UCS of samples with the same fiber content increases with the increasing of polymer content. The highest value of sample with polymer 4%-fiber 0.3% is 163.23 kPa.

The samples reinforced with only polymer as a reference and the percentages of strength improving of samples with the different fiber content are shown in Figure 7. The UCS of samples reinforced with polymers 1%, 2%, 3%, and 4% are 22.99, 41.88, 52.69, and 106.14 kPa, respectively. As shown in Figure 7, the samples with polymers 2-3% have larger improved percentages. The improved percentages of samples reinforced with polymer 2%-fiber 0.3% and polymer 3%-fiber 0.3% are 213.87% and 197.38%, respectively.

4.2. Direct Shear Test. The results of samples in direct shear test are shown in Table 4. The unreinforced sample with a cohesion zero kPa and angle of internal friction of 30.12° is considered as a reference. The cohesion of all the reinforced samples is improved, especially for the one with higher polymer content. The sample with polymer 4%-fiber 0.2% has a higher cohesion value of 80.36 kPa. Angle of internal friction of samples is rarely affected. The samples reinforced with polymer-fiber mixture have slightly lower internal friction angle.

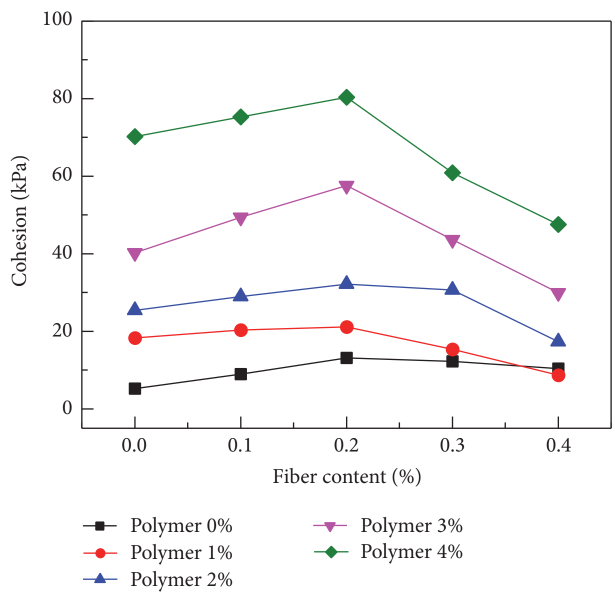


FIGURE 8: Cohesion of sand samples.

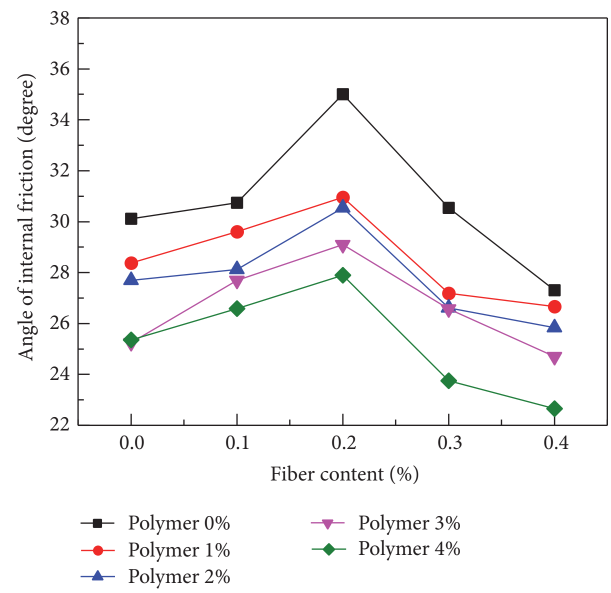


FIGURE 9: Angle of internal friction of sand samples.

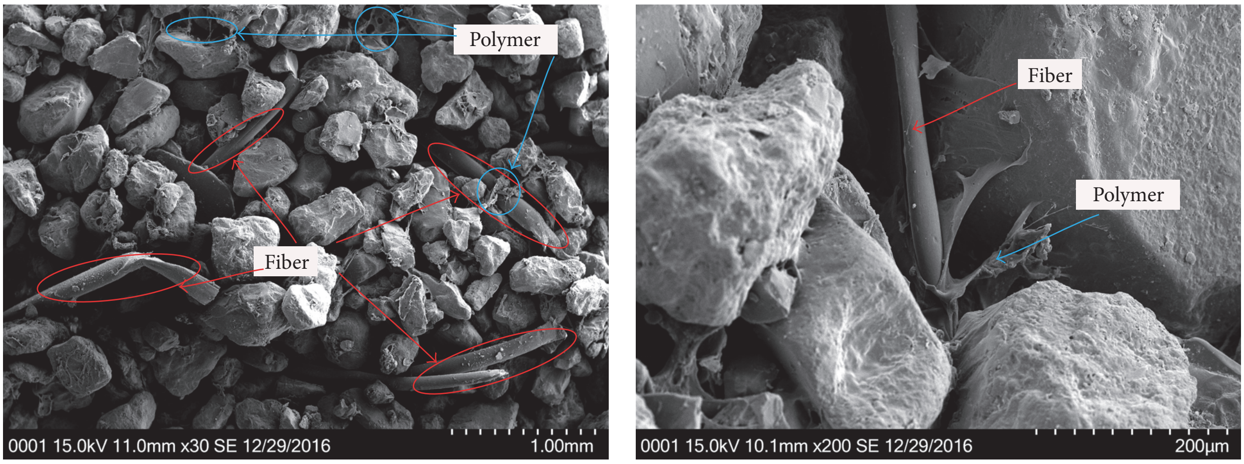
The variations of cohesion with polymer-fiber content are shown in Figure 8. As seen in Figure 8, cohesion of samples increases with increase of fiber content to reach a high value and, after that, decreases with the fiber content increasing. With the same polymer content, the samples with fiber 0.2% have the highest cohesion values. While the fiber content is 0.2%, the cohesion of these samples with polymers 0%, 1%, 2%, 3%, and 4% are 13.14 kPa, 21.15 kPa, 32.15 kPa, 57.59 kPa, and 80.36 kPa, respectively. With the same fiber content, the cohesion of samples with higher polymer content also has the higher cohesion values. The sample reinforced with polymer 4%-fiber 0.2% has a highest cohesion value of 80.36 kPa.

The internal friction angle of samples treated with different content of polymer-fiber is present in Figure 9. It is observed that internal friction angle of samples is affected by content of polymer and fiber. The unreinforced sample has internal friction angle of 30.12°. With the same polymer content, the internal friction angle of samples increases with the increasing of fiber content to reach a high value and then decreases, and the samples reinforced with fiber 0.2% have the highest value. All the samples with polymer-fiber have slightly smaller internal friction angles than the one of unreinforced sample. Therefore, the sand stabilized by polymer has higher cohesion but has slightly smaller internal friction angle. The presence of a suitable fiber content can improve the cohesion and internal friction angle.

5. Reinforcement Mechanism

The unreinforced sand has low cohesion between the soil particles resulting in its loose structure (see Figure 2). The fiber reinforcement mechanism in sand mainly includes that the fiber and sand particles constrain each other to produce interface force. This interface force is mainly caused by the extrusion pressure and in the form of cohesion and friction. In the unconfined compression test, the sample has no confining pressure result that the fiber reinforced sand has no enough cohesion to form an intact sample (see Figure 3). In the direct shear test, the fiber reinforced sand with the confining pressure is easy to form a three-dimensional fiber-sand net. When the content of fiber is rather little, the space of fiber is large resulting in the fact that it is difficult to form the effective net between fiber and sand. When the content of fiber increases gradually, the fibers have smaller space to make the adjacent fiber intersect easily to form the effective fiber-sand net to improve the cohesion and friction. But while the content of fiber is rather more, lots of fiber filaments will gather in clusters inside the sand sample to make the nonuniform distribution of fibers. It is easy to form the weak area of stress due to the excess of fibers. So all the values of cohesion and internal friction angle of fiber reinforced samples increase with the fiber content increasing and then decrease (see Figures 8 and 9).

The polyurethane organic polymer has a large amount of polyurethane resin macromolecule and isocyanate group (–NCO). The sand reinforcement mechanism of polymer includes filling, chemical reaction, and enwrapping. The polymer solution fills up the voids and adsorbs ions on the surface of sand particles and other matter to form physicochemical bonds between molecules and other matters. The elastic and viscous membrane is formed through the bands of long-chain macromolecules to interlink the sand particles. This membrane structure can increase in bonding and interlocking forces between sand particles, and the UCS and cohesion of polymer reinforced samples are improved (see Figures 6, 8, and 9). The more the polymer content is, the more the bonds are produced to form an intact membrane enwraping the sand particles, so the UCS and cohesion of polymer reinforced sand increased with polymer content. But, while the sand particle surface is enwrapped with polymer, its surface roughness will be reduced resulting in the decrease slightly of internal friction angle of polymer



(a) (b)

Figure 10: SEM images of sample reinforced with polymer-fiber: (a) 30 times magnification and (b) 200 times magnification.

reinforced sand during shearing process. Meanwhile, the internal friction angle also decreases with the increasing with polymer content because of the better enwrapping on sand particle surface (see Table 4 and Figure 9).

The sand reinforced with the mixture of polymer-fiber and the reinforcement effect is improved stronger than the ones treated with only one material polymer or fiber. The SEM images of sand sample reinforced with polymer-fiber are presented in Figure 10. As seen in Figure 10(a), while the polymer-fiber is mixed with sand, the fiber as the framework is distributed in the sand, the polymer fills up the voids and adsorbs ions on the surface of sand particles and fiber. It is seen clearly from Figure 10(b) that the sand particle and fiber surface are enwrapped fully by the polymer to from a membrane structure. The loose sand and fiber are connected by the polymer membrane thus to shape firmly together as a whole, especially for the contact area of particles and fiber. So all sand samples reinforcing the mixture of polymer-fiber can be formed to the intact columnar sample under unconfined condition (see Figure 5).

While the sample is reinforced with polymer-fiber, the different content of polymer and fiber will affect the improvement effect. With the same polymer content, the framework structure is formed more completely with the increase of fiber content. After the completely framework structure formation, the excessive content of fiber will easily gather in clusters resulting in the fact that the polymer is very difficult to enwrap each fiber surface to form a whole stable structure. So the UCS increases with the increasing of fiber content; after the fiber content larger than 0.3%, the UCS decreases with the fiber content increasing. The cohesion and friction increase with fiber content until they reach 0.2%; they decrease with the fiber content increasing. With the same fiber content, there are more polymers to enwrap the sand and fiber surface to connect them together with the increasing of polymer content. So the UCS and cohesion increase with the increasing of polymer content for the samples with the same fiber content.

6. Conclusions

In order to study the unconfined compressive strength and shear strength of sand reinforced with polymer-fiber mixture, the unconfined compressive tests and direct shear tests on sand samples with different content of polymer and fiber were carried out. The test results and reinforcement mechanism were analyzed. Based on the results of the tests presented herein, the main conclusions can be summarized as follows:

(1) The UCS of sand can be improved strongly by the polymer-fiber mixture material. While the polymer content is a constant, the UCS first increases and then has a downward trend with increasing of fiber content. With the same fiber content, the UCS increases with the polymer content increasing. The sample reinforced with polymer 4%-fiber 0.3% has a highest UCS of 163.23 kPa.

(2) The cohesion of samples increases with increase of fiber content and then decreases with the fiber content increasing. With the same polymer content, the samples with fiber 0.2% have the highest cohesion values. With the same fiber content, the cohesion of samples with higher polymer content also has the higher cohesion values. The sample reinforced with polymer 4%-fiber 0.2% has a highest cohesion value of 80.36 kPa. All the samples with polymer-fiber have slightly smaller internal friction angles than the one of unreinforced sample.

(3) About the mechanism of polymer-fiber reinforced sand, the fiber as the framework is distributed in the sand; the polymer fills up the voids and adsorbs ions on the surface of sand particles and fiber. The sand and fiber are connected by the polymer membrane thus to shape firmly together as a whole to improve the strength and cohesion of sand. The research results can be applied as the reference for practical engineering, especially for reinforcement of foundation, embankment, and landfill.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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