Research Article

Experimental Study on Unconfined Compressive Strength of Organic Polymer Reinforced Sand

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The natural sand is loose in structure with a small cohesive force. Organic polymer can be used to reinforce this sand. To assess the effectiveness of organic polymer as soil stabilizer (PSS), a series of unconfined compressive strength tests have been performed on reinforced sand. The focus of this study was to determine a curing method and a mix design to stabilize sand. The curing time, PSS concentration, and sand density were considered as variables in this study. The reinforcement mechanism was analyzed with images of scanning electron microscope (SEM). The results indicated that the strength of stabilized sand increased with the increase in the curing time, concentration, and sand density. The strength plateaus are at about curing time of 48 h. The UCS of samples with density of 1.4 g/cm³ at 10%, 20%, 30%, 40%, and 50% PSS concentration are 62.34 kPa, 120.83 kPa, 169.22 kPa, 201.94 kPa, and 245.28 kPa, respectively. The UCS of samples with PSS concentration of 30% at 1.4 g/cm³, 1.5 g/cm³, and 1.6 g/cm³ density are 169.22 kPa, 238.6 kPa, and 281.69 kPa, respectively. The chemical reaction between PSS and sand particle is at its microlevel, which improves the sand strength by bonding its particles together and filling the pore spaces. In comparison with the traditional reinforcement methods, PSS has the advantages of time saving, lower cost, and better environment protection. The research results can be useful for practical engineering applications, especially for reinforcement of foundation, embankment, and landfill.

1. Introduction

Sand material is usually difficult to meet the engineering requirements for foundation, slope, and embankment construction due to its looseness and small cohesive force. Hence, it is important to reinforce the sand. At present, chemical materials such as concrete, lime cement, and organic polymer are often chosen as the reinforcement material. Concrete, cement, and lime can all improve the sand strength [1–3]. But the reinforced sands can fracture easily due to the water loss. Furthermore, the use of lime or cement can change the pH of the sand, causing environment pollution and impact on vegetation growth [4, 5].

Recently, the organic polymer has been considered as reinforcement agent to solve the deficiencies mentioned above [6, 7]. Many types of organic polymers as reinforcement materials have been studied systematically by laboratory and

field tests [8–15]. The polymer stabilizers have been used to improve the soil to meet the engineering requirements in desert land restoration, forest road, and borehole [8–10]. The reinforced soil has shown a reduction in wind erosion and sand dune movement. The Atterberg limits, swelling potential, and swelling pressures of soil treated with polymer are reduced strongly. The excavated soil can be stabilized using the polymer to make the boreholes with larger diameter and length. The water resistance, heat resistance, unconfined compressive strength, and flexural strength of soil can also be improved by polymer material [11–15]. Therefore, the organic polymer material has more advantages in soil reinforcement.

Resin organic polymer with a macromolecule has been also widely used as soil stabilizer to improve the sandy soil [16–26]. Yang et al. [16] studied the effects of aging tests on a novel chemical sand-fixing agent, namely, polyaspartic acid resin. Naeini and Ghorbanalizadeh [17] indicated that

TABLE 1: Grain size distribution of sand.

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

the addition of epoxy resin improves significantly the compressive strength and modulus of elasticity of samples under dry condition. Sun and Lee [18] evaluated the effect of soil-conditioner in coastal sand dunes to promote the growth of vegetation, thereby reducing the price of coast erosion in coastal sand dunes. Xanthan gum is a type of environmental friendly organic polymer. Latifi et al. [19] studied the effectiveness of xanthan gum used for soil ecological reinforcement. Furthermore, other types of organic polymers such as polyacrylamides, acrylic polymer, and methylene diphenyl diisocyanate are also used to reinforce the sand [20–23]. These organic polymers can fill up void spaces and produce physicochemical bonds to enwrap the sand particles to change the loose structure [24–26]. These research results indicated that the organic polymer materials can improve the strength properties of sand.

In this study, the organic polymer was used as a polymer soil stabilizer (PSS) to reinforce the sand. A series of unconfined compressive strength tests were carried out to evaluate the effectiveness of the reinforcement. The curing time, PSS concentration, and sand density are varied in the experiment. The reinforcement mechanism is investigated using SEM images. The advantages of PSS are as follows: ① It is a type of water-soluble material to be diluted to different concentrations as required. ② Its organic component is beneficial to plant growth and forms an elastic viscous membrane structure on soil surface. ③ The cost of PSS is lower than other inorganic materials. PSS has been used to improve the engineering mechanics properties of soil effectively in previous researches [20–26].

2. Materials

The sand in this experiment is taken from Nanjing city, China. The grain size distribution of this sand is shown in Table 1 and Figure 1. The dominant component of the sand is the particle with size between 0.5 and 0.1 mm (80%). The specific gravity (G_s) is 2.64, maximum dry density ($\rho_{\max}$) is 1.66, and minimum dry density ($\rho_{\min}$) is 1.34 g/cm³. The maximum void ratio ($e_{\max}$) is 0.970, and the minimum void ratio ($e_{\min}$) is 0.590. The mean grain size (D_{50}) is 0.30 mm, gradation coefficient (C_g) is 1.13, and uniformity coefficient (C_u) is 2.77.

An organic polymer from UKC Holding Corporation in Japan is used as polymer soil stabilizer and abbreviated as PSS in this study (Figure 2(a)). The main constituent of the polymer is polyurethane resin that contains enormous amount of functional group –NCO. PSS is a light yellow oil-like liquid with a pH of 6–7, viscosity of 650–700 mPa·s, specific gravity of 1.18 g/cm³, solid content of 85%, and coagulation time of 30–1800 s and holds water content larger than 40 times. The PSS solution is prepared as follows: firstly, the PSS is placed alone in a flask while the designed amount of distilled water is put in a separate flask (Figure 2(b)). Then,

FIGURE 1: The grain size distribution of sand.

this distilled water is poured into the PSS flask along the flask wall gradually. The mixture is stirred continuously during the process. After mixing, the stirring continued for 5 minutes to obtain a uniform PSS dilution with designed concentration (Figure 2(c)).

3. Test Methods

To understand the effect of PSS on sand, the PSS concentrations, curing time, and sand density are considered as experimental parameters. With the PSS concentration less than 10%, the consolidation effect is limited and with more than 50%, the solution will solidify in a short period of time. This is not practical to site applications. Hence, five PSS concentrations of 10%, 20%, 30%, 40%, and 50% are tested for sand reinforcement and the water (0%) as a control. Different curing times of 0.5 h, 6 h, 12 h, 24 h, 48 h, and 72 h are chosen. Three dry densities of the prepared samples are 1.40 g/cm³, 1.50 g/cm³, and 1.60 g/cm³, respectively. The additive amount of PSS dilutions is taken as 10% weight of dry sand. In total, 49 groups of samples are prepared with three parallel samples for each group. The parameters of sand samples are shown in Table 2.

In the sample preparation process, the dried sand is mixed with the PSS dilution and then is prepared with static compaction method based on ASTM standards (ASTM D2166/D2166 M-16). Four-layered compaction is adopted to keep the uniformity of test samples with a diameter of 39.1 mm and height of 80 mm. After the sample preparation, it is kept in a curing box with temperature around 20°C for a specified curing time. The UCS of sand sample is then tested. The axial stress and strain are recorded, and the peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), axial strain of failure (ϵ_f), elasticity modulus

FIGURE 2: The PSS material: (a) PSS, (b) distilled water, and (c) PSS dilution.

FIGURE 3: Photo of samples after stripping mould.

(E), and failure modulus (E_f) are measured. In this study, the sample at failure is defined if the axial stress reaches the peak value. Elasticity modulus is the ratio of axial stress to its corresponding axial strain. Failure modulus is the ratio of peak strength to its corresponding axial strain. Finally, the representative sand samples are selected from the failure samples for SEM. The low-temperature baking method is used in SEM sample preparation. This is dictated by low water content and little shrinkage deformation of sand samples.

YYW-2 unconfined compressional strain control device made by Nanjing Soil Instrument Manufacturer is used in this study. The controlling strain rate is 2.4 mm/min and the test for each sample lasted for about 8 minutes. The SEM analyses are performed on Hitachi S-4800 electronic microscope, with optical, vacuum, and imaging system. It has a resolution of 1 nm.

4. Test Results

The 49 groups of samples with different PSS concentration, curing time, and sand density are tested for determining the UCS. According to the relevant parameters of sand samples in Table 2, detailed analyses are given as follows. It should be noted that the UCS gives the peak strength if the sample has demonstrated an obvious peak value. Otherwise, the strength of axial strain 15% is regarded as the UCS of the

sample. Unconfined compression test is performed on sample triplicates and the average values are summarized in Tables 3–5.

4.1. Unreinforced Sand. The unreinforced sand has a small cohesive force and it is very difficult to form a required sample to be tested in unconfined condition. The unreinforced samples with water content of 10% are prepared in a mould with static compaction to specified densities of 1.40 g/cm³, 1.50 g/cm³, and 1.60 g/cm³, respectively. After stripping the sample mould, the sample shapes are presented in Figure 3. All the samples generate disintegration somehow. The sample with density of 1.40 g/cm³ has a loose structure. The sample with density of 1.50 g/cm³ falls apart immediately after the removal of mould and it has a partly broken structure. The one with density of 1.60 g/cm³ has a rupture at the bottom and the sample barely stands. While all unreinforced samples with density of 1.60 g/cm³ are taken with great care, they were damaged immediately after the removal of mould. Consequently, the unconfined compression test cannot be carried out for those samples.

This indicated that the unreinforced sand does not have enough unconfined compression strength to sustain its own weight. They are considered to have zero unconfined compression strength.

TABLE 2: Parameters of soil samples.

Test	Number of groups	0	10	20	30	40	50	0.5	6	12	24	48	72	1.4	1.5	1.6
T1	3	✓												✓	✓	✓
T2	25		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
T3	13 (18-5*)			✓				✓	✓	✓	✓	✓	✓	✓	✓	✓
T4	8 (15-7*)		✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓

Note. * is the numbers of samples prepared in previous tests.

TABLE 3: Results of density 1.4 g/cm^3 samples with different PSS concentration and curing time.

Serial number	PSS concentration (%)	Dry density (g/cm^3)	Relative density D_r (%)	Curing time (hour)	Peak strength q_u (KPa)	Residual strength q_r (KPa)	Strength of axial strain 15% q_a (KPa)	Axial strain of failure ϵ_f (%)	Elasticity modulus E (MPa)	Failure modulus E_f (MPa)
S1	water	1.4	21.05	/	/	/	/	/	/	/
S4	10	1.4	21.05	6	1779	9.61	15.38	7.92	0.479	0.225
S5	20	1.4	21.05	6	3116	14.11	19.96	7.86	1.121	0.396
S6	30	1.4	21.05	6	42.52	16.45	20.79	4.80	1.264	0.885
S7	40	1.4	21.05	6	61.55	20.62	21.65	4.26	1.853	1.444
S8	50	1.4	21.05	6	88.89	21.98	27.74	4.18	2.326	2.125
S9	10	1.4	21.05	12	29.89	12.25	19.70	8.76	0.483	0.341
S10	20	1.4	21.05	12	36.81	17.48	28.00	7.91	1.256	0.465
S11	30	1.4	21.05	12	65.86	22.17	46.90	7.33	2.012	0.899
S12	40	1.4	21.05	12	104.70	32.25	64.95	6.73	2.917	1.555
S13	50	1.4	21.05	12	127.08	33.93	80.60	5.84	3.756	2.176
S14	10	1.4	21.05	24	36.22	18.76	23.19	10.27	0.722	0.353
S15	20	1.4	21.05	24	57.08	21.89	47.71	10.18	1.310	0.561
S16	30	1.4	21.05	24	87.24	35.89	70.61	7.65	2.144	1.140
S17	40	1.4	21.05	24	129.03	56.77	87.96	6.85	2.943	1.884
S18	50	1.4	21.05	24	196.62	86.11	130.47	5.89	3.757	3.340
S19	10	1.4	21.05	48	62.34	19.46	56.75	10.88	1.244	0.573
S20	20	1.4	21.05	48	120.83	22.52	107.44	10.75	2.594	1.124
S21	30	1.4	21.05	48	169.22	56.95	152.29	10.11	5.629	1.674
S22	40	1.4	21.05	48	201.94	75.29	168.24	8.87	8.526	2.277
S23	50	1.4	21.05	48	245.28	97.73	187.46	7.08	11.494	3.464
S24	10	1.4	21.05	72	67.85	20.39	60.23	10.92	1.251	0.621
S25	20	1.4	21.05	72	121.67	22.57	113.43	10.76	2.605	1.131
S26	30	1.4	21.05	72	172.93	57.94	153.02	10.14	5.707	1.706
S27	40	1.4	21.05	72	207.55	75.01	168.49	9.02	8.969	2.297
S28	50	1.4	21.05	72	249.18	100.85	193.31	7.31	11.352	3.391

TABLE 4: Results of PSS 20% samples with different curing time and densities.

Serial number	PSS concentration (%)	Dry density (g/cm ³)	Relative density D_r (%)	Curing time (hour)	Peak strength q_u (KPa)	Residual strength q_r (KPa)	Strength of axial strain 15% q_a (KPa)	Axial strain of failure ε_f (%)	Elasticity modulus E (MPa)	Failure modulus E_f (MPa)
S1	water	1.4	21.05	/	/	/	/	/	/	/
S29	20	1.4	21.05	0.5	29.31	12.95	17.24	7.43	0.913	0.395
S5	20	1.4	21.05	6	31.16	14.11	19.96	7.86	1.121	0.396
S10	20	1.4	21.05	12	36.81	17.48	27.13	7.91	1.267	0.470
S15	20	1.4	21.05	24	57.08	21.89	47.71	10.18	1.310	0.561
S20	20	1.4	21.05	48	120.83	22.52	107.44	10.75	2.594	1.124
S25	20	1.4	21.05	72	121.67	22.57	113.43	10.76	2.605	1.131
S2	water	1.5	55.26	/	/	/	/	/	/	/
S30	20	1.5	55.26	0.5	33.41	17.79	25.61	7.13	0.917	0.469
S31	20	1.5	55.26	6	53.22	26.89	35.29	7.49	1.188	0.710
S32	20	1.5	55.26	12	91.81	31.71	62.93	7.65	2.351	1.200
S33	20	1.5	55.26	24	143.48	34.71	100.67	7.80	3.728	1.794
S34	20	1.5	55.26	48	197.96	37.77	150.09	9.01	5.057	2.197
S35	20	1.5	55.26	72	199.24	41.06	155.34	9.03	5.131	2.206
S3	water	1.6	84.21	/	/	/	/	/	/	/
S36	20	1.6	84.21	0.5	63.95	22.54	25.77	4.44	1.538	1.439
S37	20	1.6	84.21	6	91.35	32.99	37.62	4.80	2.387	1.905
S38	20	1.6	84.21	12	125.38	43.66	64.15	6.55	2.599	1.916
S39	20	1.6	84.21	24	174.92	44.51	106.75	7.26	4.357	2.409
S40	20	1.6	84.21	48	239.25	58.67	149.21	7.63	5.227	3.136
S41	20	1.6	84.21	72	249.20	63.16	159.74	7.74	5.323	3.222

TABLE 5: Results of curing time 48 h samples with different PSS concentration and sand densities.

Serial number	PSS concentration (%)	Dry density (g/cm ³)	Void ratio e_s	Relative density D_r (%)	Peak strength q_u (KPa)	Residual strength q_r (KPa)	Strength of axial strain 15% q_a (KPa)	Axial strain of failure ϵ_f (%)	Elasticity modulus E (MPa)	Failure modulus E_f (MPa)
S1	water	1.4	0.89	21.05	/	/	/	/	/	/
S19	10	1.4	0.89	21.05	62.34	19.46	56.75	10.88	1.244	0.573
S20	20	1.4	0.89	21.05	120.83	22.52	107.44	10.75	2.594	1.124
S21	30	1.4	0.89	21.05	169.22	56.95	152.29	10.11	5.629	1.674
S22	40	1.4	0.89	21.05	201.94	75.29	168.24	8.87	8.526	2.277
S23	50	1.4	0.89	21.05	245.28	97.73	187.46	7.08	11.494	3.464
S2	water	1.5	0.76	55.26	/	/	/	/	/	/
S42	10	1.5	0.76	55.26	78.15	20.11	58.11	9.68	1.564	0.807
S34	20	1.5	0.76	55.26	197.96	37.77	150.09	9.01	5.057	2.197
S43	30	1.5	0.76	55.26	238.65	65.87	162.46	8.65	6.380	2.759
S44	40	1.5	0.76	55.26	257.92	76.63	174.63	7.72	8.722	3.341
S45	50	1.5	0.76	55.26	355.92	99.77	205.88	7.05	11.654	5.049
S3	water	1.6	0.65	84.21	/	/	/	/	/	/
S46	10	1.6	0.65	84.21	81.11	27.75	62.13	8.88	1.627	0.913
S40	20	1.6	0.65	84.21	239.25	58.67	149.21	7.63	5.227	3.136
S47	30	1.6	0.65	84.21	281.69	67.96	175.01	7.36	7.868	3.827
S48	40	1.6	0.65	84.21	298.92	77.51	202.44	7.03	10.945	4.252
S49	50	1.6	0.65	84.21	360.97	104.27	210.97	7.01	14.940	5.149

4.2. Effect of PSS Concentration and Curing Time. The results of samples with different PSS concentration and curing time are summarized in Table 3. Their respective axial stress-strain curves are shown in Figure 4. All samples take on strain-softening ductile failure. The axial stress increases with the increasing of axial strain until a peak value is reached. Then the axial strain is reduced gradually to a stable value. The stress-strain curve shape changes with different PSS concentrations and curing times. As seen, the stress-strain curve with high PSS concentrations reached peak value faster and shape of stress-strain curve is sharper. The maximum amplitudes increase with the PSS concentration and curing time.

From the axial stress-strain curves, the peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), axial strain of failure (ϵ_f), elasticity modulus (E), and failure modulus (E_f) of reinforced samples are estimated. The results are presented in Table 3 and Figure 5. As seen, for the samples with the same curing time, the peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), elasticity modulus (E), and failure modulus (E_f) increase with PSS concentration, but the one of axial strain of failure (ϵ_f) decreases with the increasing of PSS concentration. The peak strength of 88.89, 127.08, 196.62, 245.28, and 249.18 kPa are observed for 50% PSS concentration with curing time of 6, 12, 24, 48, and 72 hours, which are 5.00, 4.25, 5.43, 3.93, and 3.67 times of the ones observed at 10% PSS concentration, respectively. For curing time 72 h, the peak strength of samples at 20%, 30%, 40%, and 50% PSS concentration is 249.18 kPa which is 1.79, 2.55, 3.06, and 3.67 times of the one observed at 10% PSS concentration, respectively. For the samples with the same PSS concentration, the peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), elasticity modulus (E), and failure modulus (E_f) increase with curing time. Then all the parameters of reinforced samples reduced gradually to a stable value after curing time of 48 h. The strength of axial strain 15% of samples with 50% PSS concentration is 20.74, 80.60, 130.47, 187.46, and 193.31 kPa; the improved percentages of samples are 288.62%, 61.87%, 43.68%, and 3.12%.

4.3. Effect of Curing Time and Sand Density. The results for different curing times and sand densities are summarized in Table 4. Their axial stress-strain curves are presented in Figure 6. All the samples displayed the behavior strain-softening ductile failure. The axial stress increases with the increase in axial strain until a peak value. Then it reduces gradually with the axial strain to a stable value. The curve shape changes with the curing time, and their amplitude increases with the curing time. The axial stress curves for each density show similar tendency for curing times of 48 h and 72 h.

Based on the axial stress-strain curves, the peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), axial strain of failure (ϵ_f), elasticity modulus (E), and failure modulus (E_f) of reinforced samples are estimated. The results are presented in Table 4 and Figure 7. For all the samples with a particular sand density, all the values of peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), axial strain of failure (ϵ_f), elasticity modulus (E), and failure

modulus (E_f) increase with curing time. All the parameters converge to a stable value. The increase of strength mainly occurs in the first 48-hour curing. For example, with the density of 1.6 g/cm³, the average increment speeds of peak strength at 0–0.5 h, 0.5–6 h, 6–12 h, 12–24 h, 24–48 h, and 48–72 h are 127.9 kPa/h, 4.98 kPa/h, 5.67 kPa/h, 4.13 kPa/h, 2.68 kPa/h, and 0.41 kPa/h, respectively. For samples with the same curing time, most of the mechanical properties increase with the sand density. Only the axial strain of failure (ϵ_f) shows the opposite tendency.

4.4. Effect of PSS Concentration and Sand Density. The results for different PSS concentrations and sand densities are summarized in Table 5. Figure 8 illustrates the axial stress-strain curves for different PSS concentrations and dry densities. It is clearly observed that all the samples displayed the behavior of strain-softening ductile failure. The axial stress increases with the increase in axial strain until a peak value and then reduces gradually with the axial strain to a relatively stable value. The peak value of axial stress-strain curves increases with PSS concentrations and sand densities, and sample with densities 1.60 g/cm³ and 50% PSS concentrations has maximum peak value.

The peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), axial strain of failure (ϵ_f), elasticity modulus (E), and failure modulus (E_f) of reinforced samples are presented in Figure 9. The peak strength for each density increased with the PSS concentration. The peak strengths of 245.28, 355.92, and 360.97 kPa are observed at 50% PSS concentration which are 3.93, 4.55, and 4.45 times of the ones at 10% PSS concentration with densities 1.40 g/cm³, 1.50 g/cm³, and 1.60 g/cm³, respectively. The peak strength of each concentration sample also increases with the increasing sand density. This increase is amplified with higher PSS concentration. As seen in Figure 9(c), residual strength for each density increases with the PSS concentration and the increment of residual strength diminishes with the increase in PSS concentration. The residual strength of lower concentration sample increases with sand density. But for higher concentration, it is almost the same at the three sand densities. The residual strength of 50% PSS concentration samples with densities 1.40 g/cm³, 1.50 g/cm³, and 1.60 g/cm³ is about 40%, 28%, and 29% of their peak strength, respectively. As seen in Figures 9(e) and 9(f), both the elasticity modulus and failure modulus for each density increase with the PSS concentration. The increase for the elasticity modulus is more significant. The elasticity modulus of 50% PSS concentration samples with three densities 1.40 g/cm³, 1.50 g/cm³, and 1.60 g/cm³ is 11.49, 11.65, and 14.94 MPa, respectively. They are 9.24, 7.45, and 8.27 times of the ones at 10% PSS concentration.

4.5. Failure Model of Reinforced Sand. After the UCS tests, two different failure models of reinforced sand are observed. One model (sliding) is the sample failure along a sliding surface. The other (petal) is the sample break at the weak cross section. Photos of sample with PSS 20% and density of 1.4 g/cm³ after tests are presented in Figure 10. The pattern of failure model changes at curing time of 12 h.

FIGURE 4: The axial stress-strain curves of samples with different PSS concentration and curing time.

FIGURE 5: The parameters of reinforced samples with density of 1.4 g/cm³: (a) peak strength, (b) strength of axial strain 15%, (c) residual strength, (d) axial strain of failure, (e) elasticity modulus, and (f) failure modulus.

FIGURE 6: The axial stress-strain curves of samples with different curing time and sand density.

With shorter curing time, the reinforcement structure is not formed completely. The sample is easier to be damaged along a main sliding surface (sliding-model). With increased curing time beyond 12 hrs, the sample crouches to break around to demonstrate the petal-model in the UCS test.

Photos of sample with PSS 20% and curing time of 12 h are presented in Figure 11. As shown, the failure models for three different sand densities are almost the same; the samples all crouch to break at the weak cross section to demonstrate a “petal-model.” The “petal structure” is more developed for higher density samples.

Photos of samples with different PSS concentrations are presented in Figure 12. Two different failure models are found

for samples with curing time of 6 h and 48 h, respectively. The failure models are not affected by PSS concentration. A group of samples with curing time of 6 h damages along a main sliding surface to demonstrate a “sliding-model.” This sliding surface has some cracks and becomes stronger with the increasing PSS concentration. The group with curing time of 48 h breaks at a weak cross section to demonstrate a “petal-model.” Both ends of samples are intact after test. The samples with “petal-model” have larger peak strength, strength of axial strain 15%, residual strength, elasticity modulus, and failure modulus.

The results of UCS tests indicate that all the reinforced samples have a clearly defined value of peak strength. We

FIGURE 7: The parameters of reinforced samples with PSS 20%: (a) peak strength, (b) strength of axial strain 15%, (c) residual strength, (d) axial strain of failure, (e) elasticity modulus, and (f) failure modulus.

FIGURE 8: The axial stress-strain curves of samples with different PSS concentrations and sand densities.

defined this value as UCS of reinforced samples. All the six parameters, namely, peak strength (q_u), strength of axial strain 15% (q_a), residual strength (q_r), axial strain of failure (ϵ_f), elasticity modulus (E), and failure modulus (E_f), are suitable to evaluate the effects of PSS reinforced sand in different conditions. The suggested curing time of PSS reinforcement is 48 h. The PSS concentration can be determined according to the engineering requirement including the strength, cost, and construction.

Compared with the results of other soil stabilizer, the advantages of PSS are as follows: ① PSS can improve the unconfined compressive strength of sand effectively. Abbawi [2] presented that the increase of compressional strength

of sand with 1, 2, 3, and 4% cement is 30, 43, 59, and 150 kPa. In comparison, the sand reinforced with 1, 2, 3, and 4% PSS shows the increases of 67.85, 121.67, 172.93, and 207.55 kPa, respectively. ② The curing times of reinforced soil with $MgCl_2$, cement, and xanthan gum are more than 7 days, 28 days, and 28 days, respectively. But the curing time of PSS is only 48 hours. This is of great significance that PSS consolidation in engineering applications shortens the construction time and reduces the maintenance costs. The optimum amount and cost of sand stabilizers are presented in Table 6. The cost of PSS is lower than others. Thus, PSS should be considered as a new chemical agent to reinforce sand in constructions.

FIGURE 9: The parameters of reinforced samples with curing time 48 h: (a) peak strength, (b) strength of axial strain 15%, (c) residual strength, (d) axial strain of failure, (e) elasticity modulus, and (f) failure modulus.

TABLE 6: Costs of soil stabilizers.

Type	Polyacrylamide	Carboxymethyl cellulose	Xanthan gum	Hydroxypropyl methylcellulose	Synthetic resins	Polymer (PSS)
Unit price (\$/kg)	3.0	1.1	2.9	2.4	2.9	0.7
Cost (\$/m ³)	225	33	87	36	87	32.9

FIGURE 10: Photos of sample with PSS 20% and density of 1.4 g/cm³ after tests.

FIGURE 11: Photos of sample with PSS 20% and curing time 12 h after tests.

5. Reinforcement Mechanism

Polymer soil stabilizer (PSS) reinforces sand by forming very thin active films between sand particles. The PSS contains a significant proportion of the long-chain macromolecule of polyurethane resin and enormous amount of isocyanate group (–NCO). The different stages of sand reinforcement mechanism of PSS include filling voids, chemical reaction, and enwrapping. When the diluted PSS solution is applied to sand, a part of them fill up the voids in sand and others adsorb on the surface of sand particle. It is different from cement sand stabilizer, which is a new crystalline product in the form of lumps to fill most of the pores in the sand structure. The active groups –NCO in its molecular structure chemical react with water in voids and on surface of sand particles to form physicochemical bonds between molecules and sand particle [27, 28]. Through the bonds, long-chain macromolecules of PSS and sand particles interlink to form an elastic and viscous membrane structure to improve the unconfined compressive strength. The SEM images of sample reinforced with PSS 20% are presented in Figure 13. As seen in Figure 13, the sand particles are enwrapped and connected by the PSS to form a stable structure. This structure increases the bonding and interlocking forces between sand particles.

The sand is mixed with PSS dilution to form the elastic and viscous reinforcement structure. All the samples displayed the behavior of strain-softening ductile failure (refer Figures 4, 6, and 8). During the reinforcement process, the physicochemical reaction between polymers and sand requires enough time to get completed. The physicochemical reaction is strong in the first few hours and then weakened. So the UCS of the reinforced sand increases with curing time significantly at the first 48 hours and then increases slowly before reaching a constant value (see Figures 5(a) and 7(a)). With the increasing sand density, the void ratio reduces and the space between particles becomes smaller. This is beneficial to the formation of reinforcement structure. With the same PSS concentration, the more PSS void filling in sample with low density may lead to weakening enwrapping on sand particles and the physicochemical bond between molecules and sand particle. Therefore, the UCS of the samples increases with the increase in the sand density (Figures 7(a) and 9(a)). The formation of the void filling and physicochemical bond in reactions of reinforced sand leads to the increase in the bonding and interlocking forces between sand particles. The more amount of PSS addition can fill up more void spaces and also can produce more bonds to enwrap the sand particles and hence greater UCS properties of reinforced sand (see Figures 5(a) and 9(a)). The addition of PSS normally does not exceed 50% concentration. At this concentration, the amounts of PSS molecules are enough to fill up most of the sand void spaces to completely enwrap the sand particles.

For the PSS consolidated sand, the sand particles are quickly connected to form a stable structure through the physicochemical reaction between polymers and sand particles. In comparison with the unreinforced sand (see Figure 3), all the reinforced sand can keep structural stability after sample preparation. With the increasing reaction time, the connection of sand aggregates becomes stronger to form an elastic and viscous membrane structure. This structure leads to different failure models in UCS tests. For samples with curing time less than 12 h, the samples are mostly consisted

FIGURE 12: Photos of sample with different PSS concentration after tests: (a) curing time 6 h; density of 1.4 g/cm^3 and (b) curing time 48 h; density of 1.6 g/cm^3 .

FIGURE 13: SEM images of sample reinforced with PSS 20%, curing time 48 h, sand density of 1.5 g/cm^3 : (a) 200-time magnification and (b) 150-time magnification.

of sand aggregates; their failures occur like “sliding-model” along the sliding surface with the principal stress plane angle of approximately 60 degrees (see Figure 12(a)), while for samples with curing time more than 12 h, an elastic and viscous membrane structure is formed with the connection of sand particles. This membrane structure is formed from sample surface to the center. The sample surface is stronger than its center. This leads to the formation of “petal-model” of failure (see Figures 11 and 12(b)).

The “petal-model” bears larger axial stress with unit strain and permits the larger deformation at higher peak stress and residual strength. So the samples with “petal-model” failure mechanism have larger peak strength, strength of axial strain 15%, residual strength, axial strain of failure, elasticity

modulus, and failure modulus. The samples with the larger curing time, PSS concentration, and sand density have the better membrane structure. The peak strength, strength of axial strain 15%, residual strength, elasticity modulus, and failure modulus of reinforced samples increase with the curing time, PSS concentration, and sand density (see Figures 5, 7, and 9).

This paper is limited to evaluate the effect of UCS properties of the PSS reinforced sand. We provide guidelines for the PSS curing time and optimal concentration for practical applications. In consideration of environmental protection and cost savings, the residual PSS solution must be recycled and sunny days should be chosen for field operation to reduce polymer loss and water pollution.

6. Conclusions

The UCS tests on sand samples with different PSS concentrations, curing times, and sand densities are carried out. The test results and reinforcement mechanism are analyzed to draw the conclusions summarized as follows:

- (1) The UCS properties of sand can be effectively improved by polymer soil stabilizer (PSS). The curing times, PSS concentrations and sand densities are important factors to consider. From the unreinforced sand, it is impossible to make a sample to be tested with unconfined conditions. The strength of sand reinforced with PSS is improved significantly. The strength plateaus are at about curing time of 48 h. The UCS of reinforced sand increase with the PSS concentration and sand density. The UCS of samples with density of 1.4 g/cm^3 at 10%, 20%, 30%, 40%, and 50% PSS concentration are 62.34 kPa, 120.83 kPa, 169.22 kPa, 201.94 kPa, and 245.28 kPa, respectively. In general, when the concentration is greater than 30% and curing time is longer than 48 h, good reinforcement effect will be achieved.
- (2) All the reinforced samples displayed the behavior of strain-softening ductile failure. The failure models are mainly determined by curing time. Two failure models named as “sliding-model” and “petal-model” are discovered. The samples with “petal-model” have larger peak strength, strength of axial strain 15%, residual strength, elasticity modulus, and failure modulus.
- (3) Voids filling and physicochemical bonding in reactions lead to the increase in bonding and interlocking forces between sand particles. The research results can be applied to practical engineering applications, 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.

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