

## Research Article

# Laboratory Tests on Effectiveness of Environment-Friendly Organic Polymer on Physical Properties of Sand

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The poor water stability, high penetrability, and low antierosion of sand affect the stability of the sandy soil slope. To understand the effectiveness of environment-friendly organic polymer on these physical properties of sand, a series of laboratory tests including water stability test, penetration test, and runoff erosion test of polymer reinforced sand were performed. The results of tests indicated that the organic polymers have obvious effects on the reinforced sand. The water stability of polymer reinforced sand had been improved strongly. All the reinforced sands with polymer  $\geq 0.3\%$  remained a stable structure at immersing time of 24 hours. The penetrability of the reinforced sand decreased with the increase of the polymer. The reinforced sand with polymer  $\geq 7\%$  was impermeable. The erosion resistance of sand increased with the increase of polymer content. With the polymer  $\geq 4\%$ , the sand surface kept intact with the scouring time more than 2 hours. The results could be applied as the reference for organic polymer reinforced sand engineering, especially for surface protection of embankment, slope, and landfill.

## 1. Introduction

Sand, as a natural material, was widely used in foundation, slope, embankment, and other types of geotechnical engineering. But the sand had the characteristics of poor water stability, high penetrability, and low antierosion. The materials used in adding into sand to reduce penetrability and improve the antierosion of sand were mainly geotextile, concrete slab, plant, and others [1–5].

Soil curing agent, as a new kind of environmentally friendly soil stabilizing material, began to flourish in the developed countries such as the United States and Japan in the 1970s. In recent years, more and more researchers have begun to study the use of soil curing agent in soil reinforcement [6–12]. Mohsin and Attia [9] used polyacrylamide to reinforce sand by gel permeation chromatography and viscometer. Collins et al. [13] used polymer emulsions and fibers to study the erosion characteristics of sandy soils and analyzed their curing mechanisms. Ekwue et al. [14] used Soiltac, a new polymer, to study the antierosion properties of sand, clay loam, and clay. Telysheva and Shulga [15] introduced the silicon-containing polycomplexes for protection against wind

erosion of sandy soil. Gong et al. [16] used the amphoteric emulsion to control the impacts of blown sand in salty desert.

In this paper, the physical property of sand in the slope surface improved by the environment-friendly organic polymer was studied. Further, the water stability test, penetration test, and runoff erosion test were performed in laboratory to analyze the effects of the environment-friendly organic polymer reinforced on sand. Its reinforcement mechanism was discussed with the interpretation from scanning electron microscope (SEM) images. The results could be applied as the reference for organic polymer reinforced sand engineering, especially for surface protection of embankment, slope, and landfill.

## 2. Materials

A new type of environment-friendly organic polymer (Figure 1) was prepared for this study. It had a main constituent of polyurethane resin and contains enormous amount of functional group, NCO. It was light yellow colored oil liquid with a pH of 6–7, viscosity of 650–700 MPa·s, specific gravity of 1.18 g/cm<sup>3</sup>, solid content of 85%, coagulation

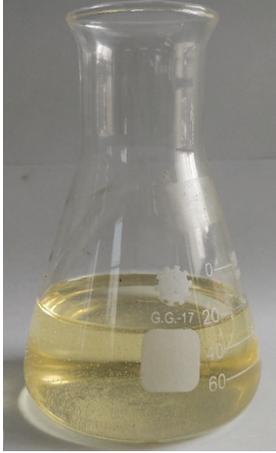


FIGURE 1: The environment-friendly organic polymer.

time of 30–1800 s, and water absorption of 40 times. The coagulation time decreased with the increase in the concentration. It was an environment-friendly product with no additional pollution. The proportion of the polymer weight to the weight of the dry sand ( $P_s$ ) was given as

$$P_s = \frac{W_p}{W_s} \times 100\%, \quad (1)$$

where  $W_p$  (g) is the polymer weight and  $W_s$  (g) is the dry sand weight.

The sand used in the laboratory experiment was obtained from Nanjing city of Jiangsu province, China. The maximum and minimum dry density of the sand were  $1.69 \text{ g/cm}^3$  and  $1.35 \text{ g/cm}^3$ , respectively. The effective particle size ( $d_{10}$ ) was 0.14 mm. The uniformity coefficient ( $C_u$ ) was 2.57 and the curvature coefficient ( $C_c$ ) was 1.05.

### 3. Experimental Methods

**3.1. Water Stability Test.** The ability to maintain stability of reinforced sand in water was important to sandy slope and sandy soil foundation. In the water stability test, three replicates were measured for its scattered area and destruction time at scouring in water for 24 h. In the case of nondestruction of reinforced sand in water, its shear strength properties (cohesion and angle of internal friction) were measured by direct shear test based on ASTM standards (ASTM D3080-98) [17]. The direct shear test was carried out with a ZJ typed strain control direct shear apparatus at a strain rate of 0.8 mm/min under the normal pressures of 50, 100, 200, and 300 kPa to obtain the maximum shear stress. The shear stress parameters ( $c$  and  $\phi$ ) were calculated based on Coulomb's law. Four shear strength values and four normal pressures were used to fit a straight line. The shear strength parameters were obtained on specimen triplicates, and average values were used.

The specimens reinforced with polymer content of 0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 1%, 2%, 3%, 4%, and 5% were prepared directly using ring-knife with diameter of 6.18 cm

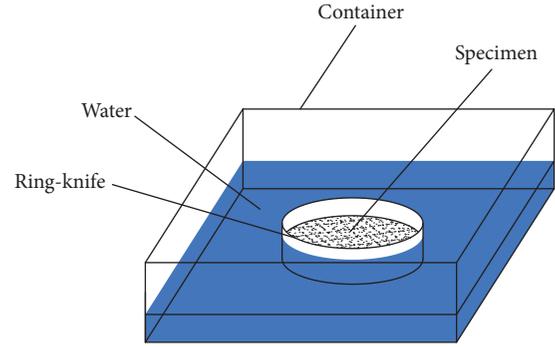


FIGURE 2: The schematic diagram of water stability test.

and height of 2 cm. Subsequently, the specimens were kept in the curing box with a temperature of around  $20^\circ\text{C}$ . After 24 h, the specimens were taken out of curing box and put in to water container for another 24 h. During this process, the water surface was maintained at 2 cm higher than that of the top surface of the specimens, as shown in Figure 2. The ring-knife was taken out to make the specimen scatter freely in water. The failure time of specimen was recorded until the main body of specimen became stable. The values of  $D_1$  and  $D_2$  of destructed specimen were recorded. The shape of the samples dispersed in water was approximately round or oval. The scattered area was calculated by the following equation:

$$s = \frac{3.14 \times D_1 \times D_2}{4}, \quad (2)$$

where the  $s$  ( $\text{cm}^2$ ) was defined as the scatter area of destroyed specimen;  $D_1$  was distance between two points through the center of a circle (ellipse) to the edge;  $D_2$  was the length perpendicular to  $D_1$ . The cross-sectional area of the specimen was  $29.98 \text{ cm}^2$ . The less the scatter area was, the more effective the polymer was.

**3.2. Penetration Test.** In the infiltration experiment, the permeability of the sand after reinforcement with the environment-friendly organic polymer was determined by using constant head permeability tests.

The TST-70 soil penetrant (Figure 3) was used to study the permeability of sand after reinforcement with the environment-friendly organic polymer. The upper part of the device was connected with a water tank whose water head was stable. And the water flowing out from the lower outlet was received by a cylinder. The device had a metal orifice plate to prevent the upper part of the soil from blocking the lower outlet. The upper part of the device was used to maintain the constant water level on the surface of the specimen during testing.

In this experiment, 3250 g of sand after air drying was divided into 13 parts. The thickness of each part of sand was about 2.22 cm after putting into the device. The wood hammer was used for compaction, so that the density of each layer was controlled at  $1.44 \text{ g/cm}^3$ . After achieving the desired density, the layers were saturated. Among these layers, the last two layers of sand were not saturated. 50 ml polymer

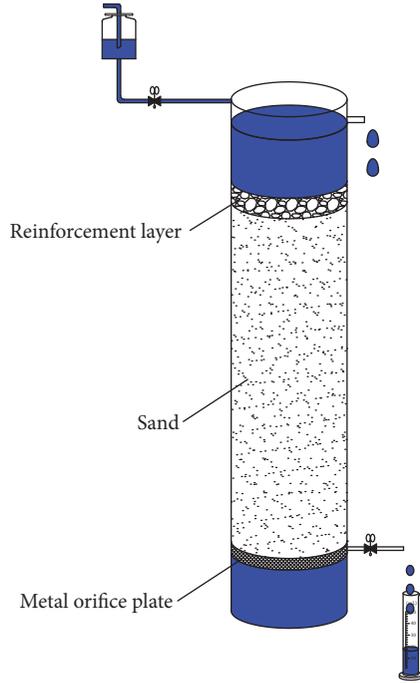


FIGURE 3: The soil penetrant used in penetration test.

solution with polymer content of 0%, 1%, 2%, 3%, 4%, 5%, 7%, and 9% was prepared and sprayed on the surface of the sand body. After spraying, the samples were incubated in a constant temperature incubator at a temperature of 20°C for 0 h, 3 h, 6 h, 12 h, and 24 h, respectively. While testing, the upper inlet and lower water pipes were opened maintaining the constant surface water level.

A water pipe with a length of 10 cm was connected at the bottom of the experimental instrument. After discharging the effluent water, the initial water discharge time and the amount of water discharge in every 3 minutes for the sand bodies with different polymer contents and different curing times were recorded until the difference was less than 3% in the two successive measurements. When the effluent gradually stabilized, the permeability coefficient of sand was measured. The permeability coefficient in this experiment was determined by the following formula:

$$K = \frac{\Delta QL}{\Delta T A h}, \quad (3)$$

where  $K$  (cm/s) was defined as the distance through the soil per unit time of the seepage in the soil;  $\Delta Q$  (cm<sup>3</sup>) was defined as the seepage flow through the sample within  $\Delta T$  (s) time.  $A$  was 78.5 cm<sup>2</sup> in this case.  $L$  (cm) was defined as the distance between two adjacent piezo-resistive tubes and at this time,  $L$  was 10 cm.  $h$  (cm) was defined as the average head difference of the adjacent piezometers and the size of  $h$  was determined by the formula (4). In (4),  $h_{12}$  and  $h_{23}$  (cm) referred to the head difference between the piezometer tube I (II) and the piezometer tube II (III).  $H_1$ ,  $H_2$ , and  $H_3$  referred

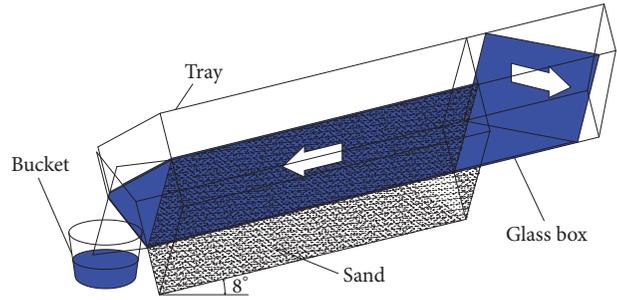


FIGURE 4: The runoff erosion device.

to the pressure tube I, pressure tube II, and pressure tube III head values.

$$\begin{aligned} h &= \frac{1}{2} (h_{12} + h_{23}) = \frac{1}{2} (H_1 - H_2 + H_2 - H_3) \\ &= \frac{1}{2} (H_1 - H_3). \end{aligned} \quad (4)$$

**3.3. Runoff Erosion Test.** In runoff erosion test, a tray with dimensions of 90 × 30 × 12 cm (length × width × height) packed with sand was subjected to the simulated slope. Relatively small trays such as this, or even smaller ones, had been used in many other studies [18–20]. The tray was set on a framework that could be inclined to give slope gradients of 8 degrees. A glass box was attached to the trays in order to simulate runoff, and a bucket was placed under the tray to collect sediment loss in the runoff (Figure 4).

The sand was divided into 3 equal parts and each part was put into the tray and compacted to a bulk density of 1.4 g/cm<sup>3</sup>. Subsequently, 0.5 L/m<sup>2</sup> of polymer solution with polymer contents of 0%, 1%, 2%, 3%, 4%, and 5% was sprayed on specimen surfaces. After spraying, the specimen was kept in laboratory for 24 h. In the runoff erosion test, the glass box simulated runoff flow rate was controlled at 3.5 L/m<sup>2</sup>. The initial time for forming sediment loss was recorded, and the sediment loss in the runoff was collected in separate buckets at every minute interval. Each runoff erosion test continued over 90–190 minutes, until the sediment loss appeared and three consecutive sediment losses had a similar weight. When the destructive pattern of specimen reached steady state under water scouring, the scour rate was given by

$$r = \frac{S_d}{s} \times 100\%, \quad (5)$$

where  $r$  (%) was defined as the scour rate of specimen;  $S_d$  (cm<sup>2</sup>) was the destruction area of specimen;  $s$  (cm<sup>2</sup>) was the area of specimen surface.

## 4. Results of the Tests

**4.1. Experimental Results of Water Stability Test.** The water stability experimental analysis results in terms of measuring scatter area, scatter time, and shear strength parameters of specimens were presented in Table 1. The failure patterns of reinforced specimens were given in Figure 5. As seen in

TABLE 1: The results of reinforced specimens in water stability test.

Number	Dry density (g/cm <sup>3</sup> )	Polymer content (%)	Scatter area (cm <sup>3</sup> )	Scatter time (s)	Cohesion (kPa)	Angle of internal friction (degree)
1	1.58	0	90.12	2	/	/
2	1.43	0	101.11	2	/	/
3	1.31	0	107.76	2	/	/
4	1.44	0.1	64.91	2	/	/
5	1.44	0.2	32.67	4	/	/
6	1.44	0.3	29.98	∞	/	/
7	1.44	0.4	29.98	∞	/	/
8	1.44	0.5	29.98	∞	8.75	25.21
9	1.44	1	29.98	∞	11.51	24.58
10	1.44	2	29.98	∞	21.09	27.35
11	1.44	3	29.98	∞	19.36	24.41
12	1.44	4	29.98	∞	13.56	23.53
13	1.44	5	29.98	∞	12.31	24.98

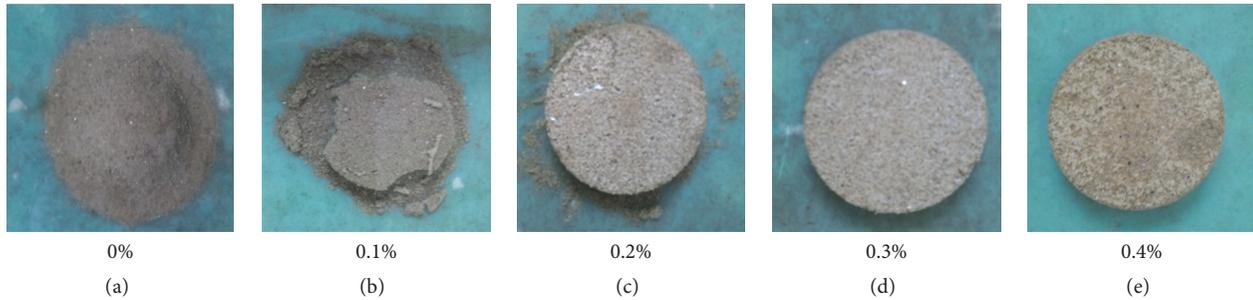


FIGURE 5: The specimen failure pattern in water stability test.

Table 1, the unreinforced specimens with different dry density totally separated immediately for its poor cohesive force, and the process of destruction continued for 2 seconds when ring-knife was taken out in water (seen in Figure 5(a)). And the scatter area of specimens decreased with the increasing dry density. The scatter area of unreinforced specimens with dry density of 1.31 g/cm<sup>3</sup>, 1.43 g/cm<sup>3</sup>, and 1.58 g/cm<sup>3</sup> were 107.76 cm<sup>2</sup>, 101.11 cm<sup>2</sup>, and 90.12 cm<sup>2</sup>, respectively. The unreinforced specimen with middle dry density was used as a control specimen. The presence of polymer decreased the specimen scatter area, and the scatter area decreased from 101.11 cm<sup>2</sup> with 0% polymer to 64.91 cm<sup>2</sup> with 0.1%. The scatter area remained at a relatively stable value while the polymer content was more than 0.2%.

As seen in Figures 5(b)–5(e), the specimens reinforced by polymer content of 0.1% collapsed immediately but not totally separated, and the process of destruction continued for two seconds when ring-knife was taken out in water (Figure 5(b)). For the specimens reinforced with content of 0.2%, small amount of agglomerates was disintegrated and fell. However, the main body of the sample-maintained integrity (Figure 5(c)). The failure process of the specimen continued for four seconds. The specimens were kept completely in water for 2 h even for longer time, while the polymer

content in the specimens was more than 0.3% (Figures 5(d)–5(e)). The samples reinforced with polymer content of 0.3% and 0.4% remained loose and could not be moved easily, although they maintained integrity. The direct shear strengths of specimens reinforced with polymer content of 0.5% and more were tested.

As seen in Table 1, the cohesion increased for all the reinforced specimens with polymer and the angle of internal friction varied with the increasing polymer content. The maximum cohesion and internal friction angle of specimens reinforced with 2% polymer content were 21.089 kPa and 27.35°, respectively. The variation of shear strength of specimens was given in Figure 6. As seen in Figure 6, the cohesion of specimens increased first and then decreased with the increasing polymer content beyond 2%. The internal friction angle fluctuated at around 25° and attained the maximum value at polymer content of 2%.

**4.2. Experimental Results of Penetration Test.** In penetration test, the specimens reinforced with polymer content of 0%, 1%, 2%, 3%, 4%, 5%, 7%, and 9% at curing times of 0 h, 3 h, 6 h, 12 h, and 24 h were considered. The initial water discharge time of the bottom outlet of each sample was recorded. At the same time, the volume of water flowing from the bottom of

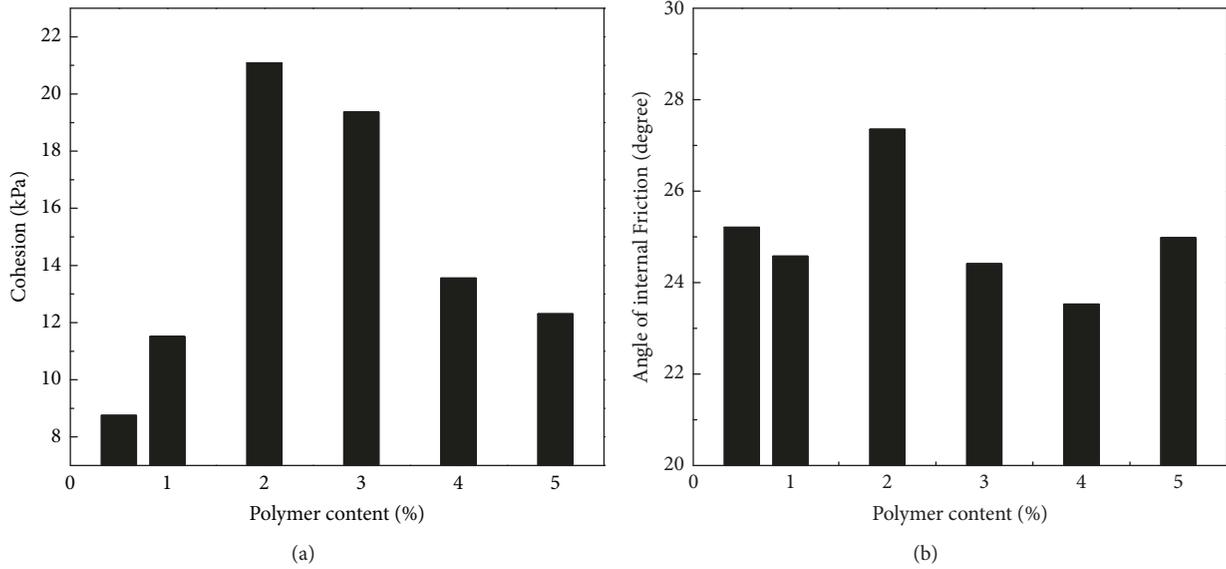


FIGURE 6: The direct shear strengths of specimens: (a) cohesion; (b) internal friction angle.

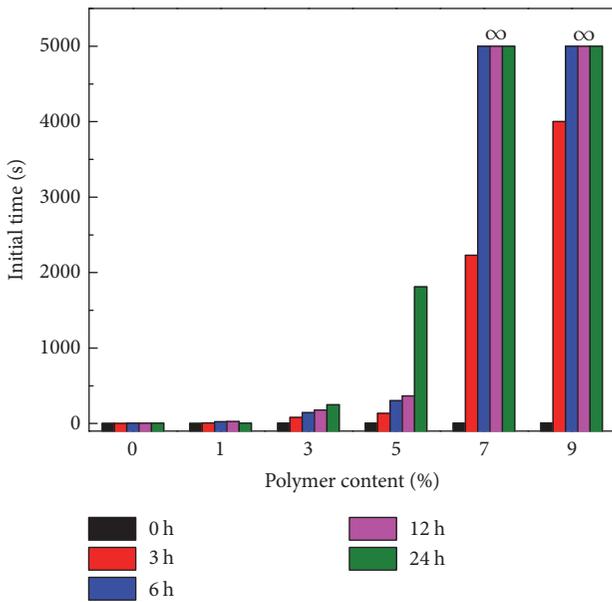


FIGURE 7: Initial time of running water from bottom outlet.

the sample at every three minutes with a number of 5 times was also recorded.

Figure 7 represented the column of the initial time. It could be seen from Figure 7 that the initial time of sand varied with the polymer content. The higher the polymer content was, the longer the initial time was. When the polymer content was 0%, the initial time was in 2-3 s or so. When the polymer content was 3% and greater, the polymer content made the initial time to increase. As the curing time increased, the initial time became longer. When the polymer content was 7% or 9% and the curing time was 0 h, the initial time of the sample was within 10 s. When the curing time was

greater than 6 h, the sample did not show the phenomenon of outflowing water. This showed that the polymer content and curing time had a great impact on the initial time.

Figure 8 showed the volume of water flowing from the bottom per every three minutes for samples, which had been cured for a certain period of time, with different polymer content. It could be seen from Figure 8 that the volume of water running out from the samples cured for 0 h, 3 h, 6 h, 12 h, and 24 h was small in the first 3 min, because the flow of water from the upper part of the infiltration instrument required a certain process and time. The volume of water gradually reached a steady state after the first 3 min. From the comparison of the volume of water in 9-12 min, it could be observed that the volume decreased with the increase in polymer content when the curing time remained same. The volume of the sample tended to be stable when the curing time of the sample exceeded 6 h. The polymer formed a relative barrier to prevent the infiltration when the polymer content was 7% or 9% and the curing time exceeded 6 h.

Table 2 was the permeability coefficient ( $K$ ) of each sample. The value of the permeability coefficient in constant head permeability test was calculated from (3). It was too small to exceed the measurement range of the constant head test when the polymer content was 7% or 9% and the curing time exceeded 6 h.

Figure 9 was a graph showing the variation of the permeability coefficient of the samples. According to Figure 9, the permeability coefficient of the sample decreased with the increase in polymer content under the same curing time in the permeability test. When the polymer content in the sample was constant, the value of the permeability coefficient of the sample decreased with the increase in curing time.

Figure 10 was the photo of reinforcement layers taken from the specimens with polymer agent 3%, 5%, 7%, and 9% and curing time of 24 h after the constant head permeability test. The reinforcement layer with polymer agent 1% was so

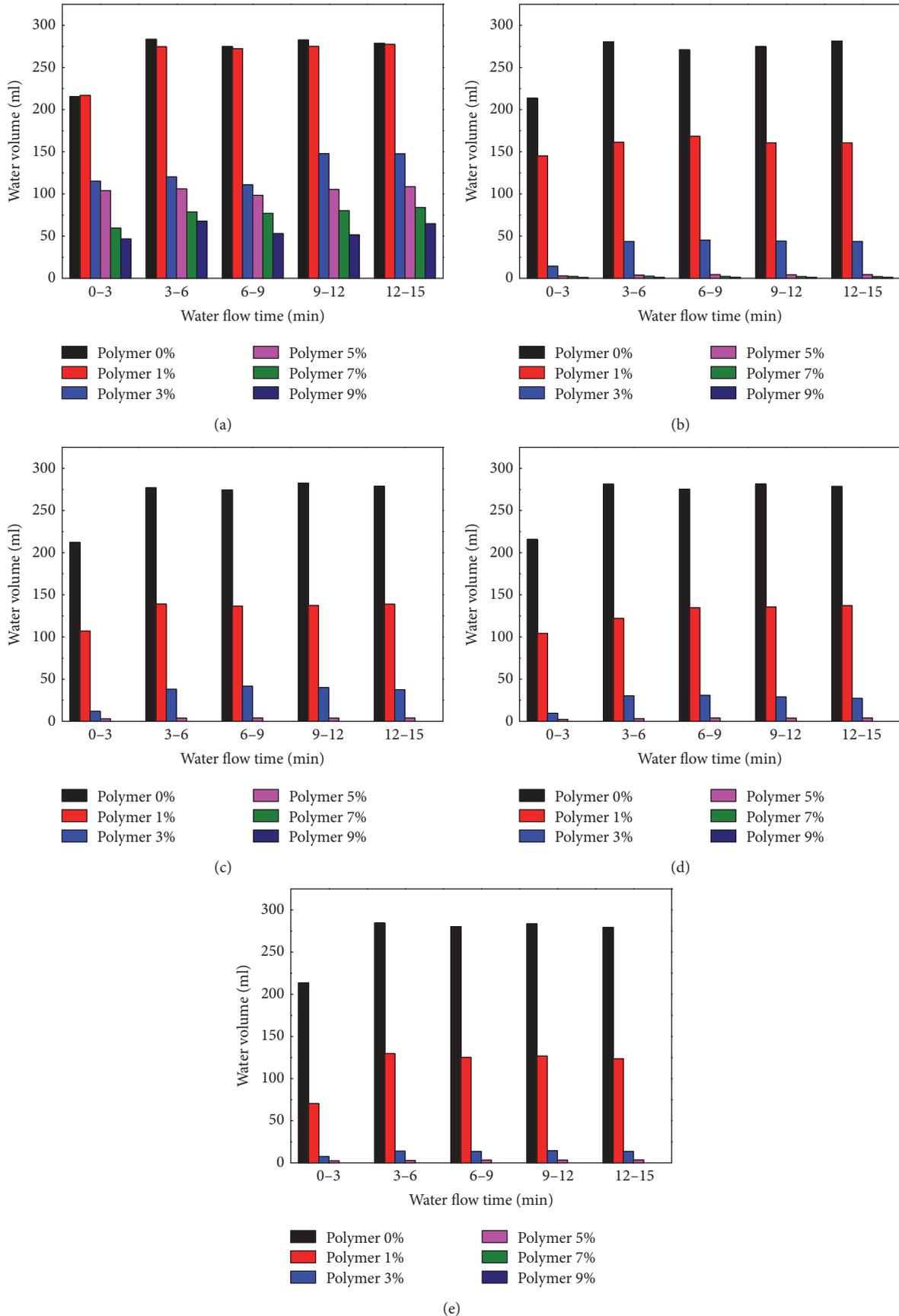


FIGURE 8: The volume of running water from bottom outlet: (a) curing time 0 h; (b) curing time 3 h; (c) curing time 6 h; (d) curing time 12 h; (e) curing time 24 h.

TABLE 2: The permeability coefficient ( $K$ ) calculated from penetration test.

Polymer content (%)	Constant head test- $K$ (cm/s)				
	0 h	3 h	6 h	12 h	24 h
0	0.0168	0.0154	0.0143	0.0132	0.0125
1	0.0129	0.0102	0.0092	0.0085	0.00749
2	0.0055	0.0043	0.003	0.0018	0.00124
3	0.0026	0.0017	$9E - 4$	$3E - 4$	$2.78E - 4$
4	$9.62E - 4$	$9.85E - 4$	$7.23E - 4$	$2.73E - 4$	$2.41E - 4$
5	$6.58E - 4$	$2.62E - 4$	$2.4E - 4$	$2.37E - 4$	$2.06E - 4$
7	$5.09E - 4$	$1.16E - 4$	/	/	/
9	$3.92E - 4$	$7.46E - 5$	/	/	/

TABLE 3: The initial time and scour rate in runoff erosion test.

Polymer content (%)	0	1	2	3	4	5
The initial time for erosion (min)	1	16	38	71	$\infty$	$\infty$
Scour rate (%)	63	54	33	14	0	0

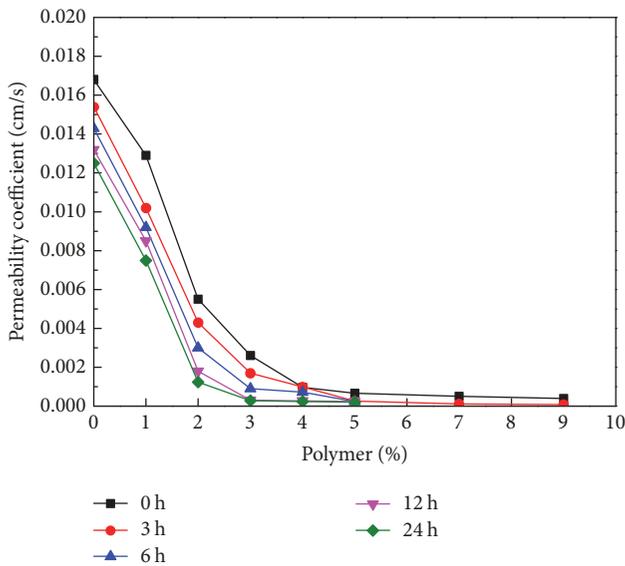


FIGURE 9: The permeability coefficient of the sample.

loose that it could not be removed. It could be seen from the Figure 10 that the thickness and integrity of the cured layer increased as the polymer content increased. The sample's curing layers with polymer content 3% and 5% were loose and complete, respectively. The samples with polymer content of 7% and 9% had a complete relative barrier layer. The hardness of the cured layer also increased with the increase in polymer content.

4.3. Experimental Results of Runoff Erosion Test. In runoff erosion test, the specimens reinforced with polymer content of 0%, 1%, 2%, 3%, 4%, and 5% at curing time of 24 hours were considered to explore the influence of polymer content on specimen surface erosion. The initial times of erosion on specimen surface were recorded. The results were shown in Table 3.

As seen in Table 3, the control specimen of unreinforced sand exhibited immediate erosional effect under runoff condition due to its little cohesive force. The presence of polymer delayed the initial time of erosional process, and the specimens reinforced with more polymer content had higher initial time values than the ones reinforced with less polymer content. The initial time of forming erosion of specimens reinforced with polymer content of 0%, 1%, 2%, and 3% were 1 min, 16 min, 38 min, and 71 min, respectively. The specimen reinforced with polymer content of 4% and 5% had greater cohesive force which was larger than the water scouring force.

The variation of sediment loss rate of specimens reinforced with polymer was present in Figure 11(a). The accumulated sediment loss of specimen under water scouring was presented in Figure 11(b). The failure pattern of unreinforced specimen for different scouring time was given in Figure 12. The failure pattern of specimen reinforced with 3% polymer was given in Figure 13. It could be seen from Figure 11(a) that the sediment loss rate of unreinforced specimens increased rapidly to a peak value and then decreased to a relative stable value. The sediment loss rate of reinforced specimens had similar trend. It also could be seen in Figure 11(a) that the time at which the sediment loss rate began to increase was influenced by the polymer content. The specimen reinforced with higher polymer content had larger time value than those reinforced with less polymer content. When there was runoff, the sediment loss occurred and increased with water flows along specimens' surface for its poor cohesive force (Figure 12(a)) and the process continued for five minutes. After that the sediment loss rate began to decrease and continued for about 45 minutes (Figures 12(b)-12(c)). Finally, the sediment loss rate tended to be stable (Figure 12(d)) and the accumulated sediment loss reached about 12500 g (as shown in Figure 11(b)). However, the specimens sprayed with polymer formed reinforcement layer on the surface.

The reinforcement layer with larger cohesive force and lower permeability coefficient was likely to act as a protective layer to prevent the erosion and infiltration of water flow (Figure 13(a)). There was no sediment loss in this case. With the increasing time, the reinforcement layer got destructed with water scouring (Figure 13(b)) and then the specimens started eroding. The destructive area of reinforcement layer

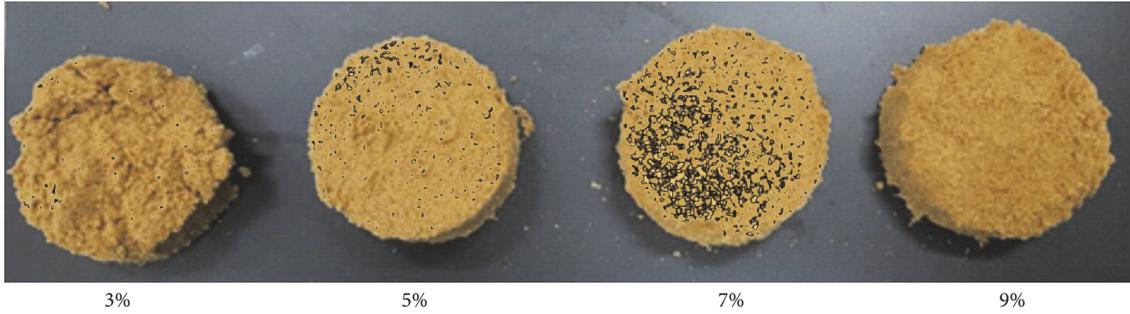


FIGURE 10: Photos of reinforcement layers taken from the specimens with curing time of 24 h after the constant head permeability tests.

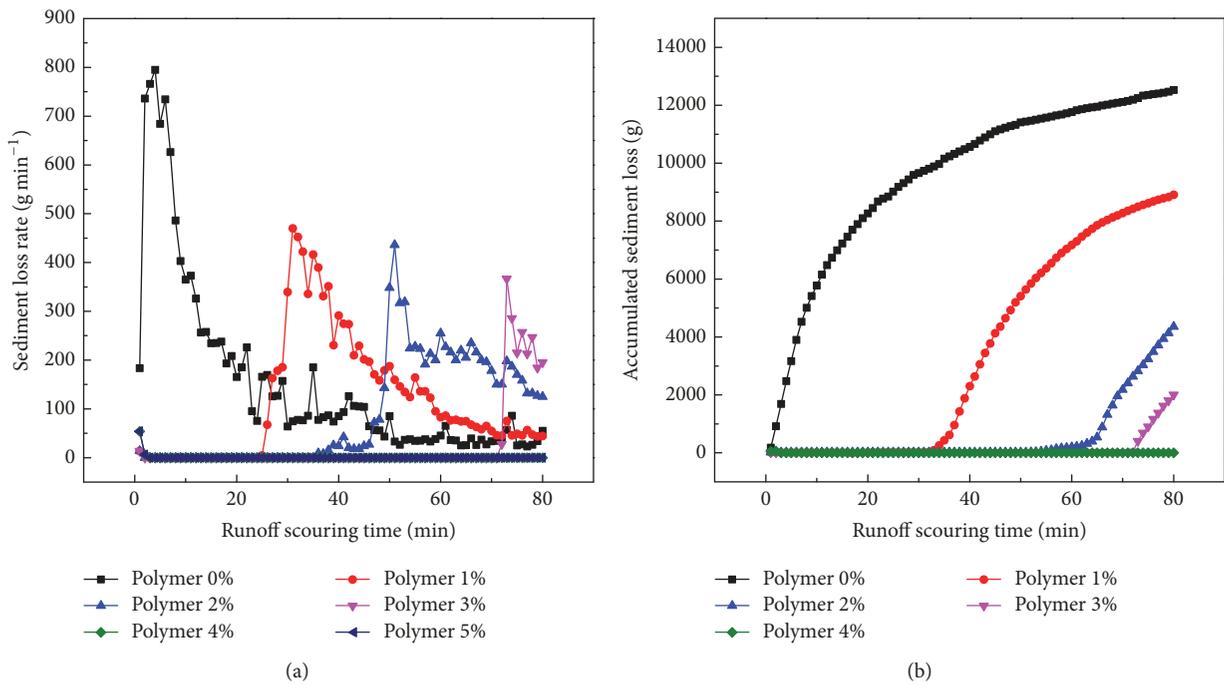


FIGURE 11: Results of runoff erosion test: (a) variation of sediment loss rate of specimens reinforced with polymer; (b) variation of accumulated sediment loss of specimens reinforced with polymer.

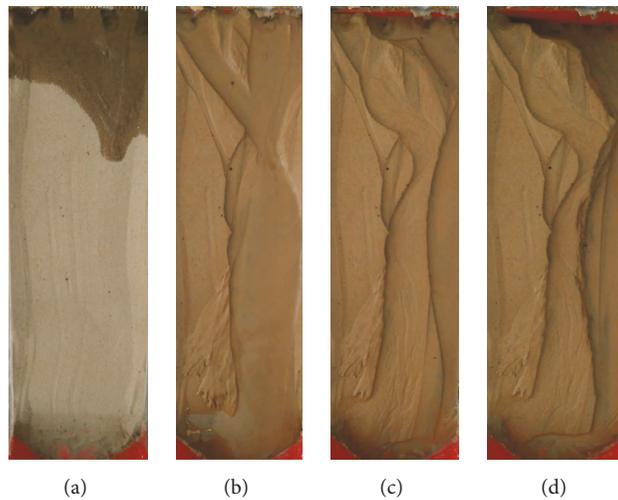


FIGURE 12: The failure pattern of unreinforced specimen: (a) development stage; (b) failure stage 1; (c) failure stage 2; (d) stable stage.

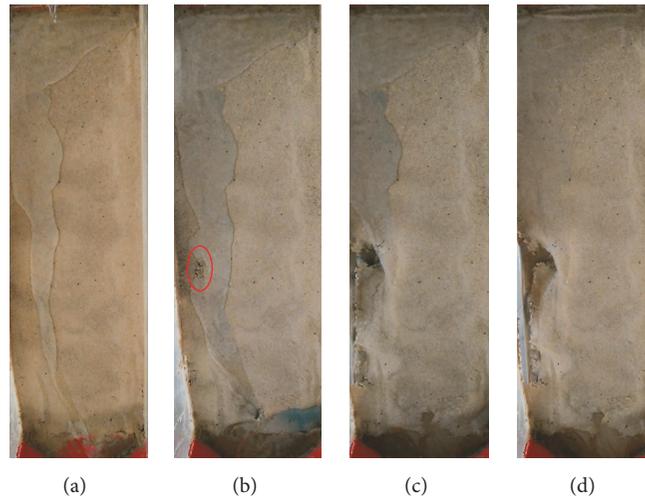


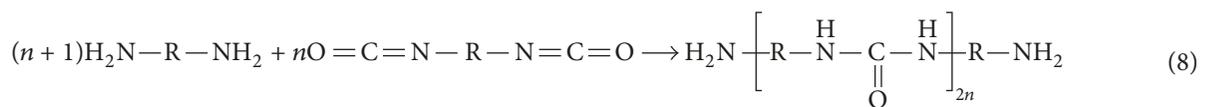
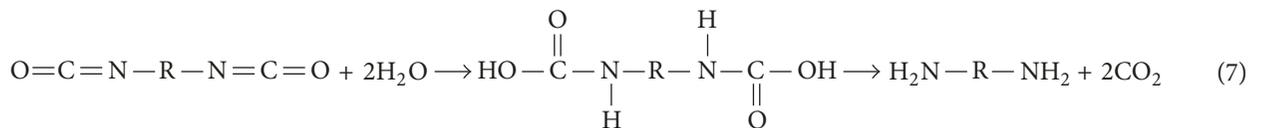
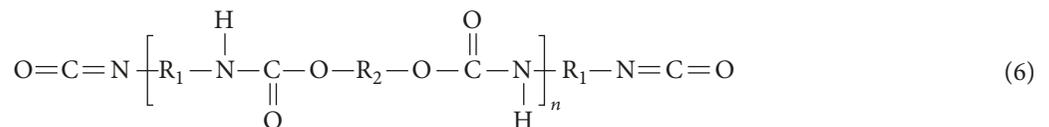
FIGURE 13: The failure pattern of specimen reinforced with polymer 3%: (a) development stage; (b) failure stage 1; (c) failure stage 2; (d) stable stage.

increased with the increasing time (Figure 13(c)). And the destruction process continued for about 50 minutes. After that the destructive pattern of specimen reached steady state under water scouring (Figure 13(d)), and the sediment loss rate tended to be stable. The destructive time of reinforcement layer was determined by the polymer content. And the accumulated sediment loss value varied with polymer content (as seen in Figure 11(b)). When the scouring time reached 80 minutes, the accumulated sediment loss of specimens reinforced with polymer content of 0%, 1%, 2%, 3%, 4%, and 5% were approximately 12500 g, 8900 g, 4300 g, 2000 g, and 0 g, respectively. While the destructive pattern of specimen reached steady state under water scouring, the scour rate was evaluated using (5). The results were given in Table 3. It could be seen from Table 3 that the scour rate decreased

rapidly with the increasing polymer content. The scour rates of specimens reinforced with polymer content of 0%, 1%, 2%, 3%, 4%, and 5% were 63%, 54%, 33%, 14%, 0%, and 0%, respectively.

## 5. Discussion

The environment-friendly organic polymer contained a significant proportion of the long-chain macromolecule of polyurethane resin and enormous amount of isocyanate group ( $-NCO$ ). Its chemical formula could be expressed by formula (6). A chemical reaction occurred when it came into contact with water. The specific reaction process was shown in formulas (7) and (8).



Polymer and water could be mixed in any proportion to dilute into different levels of polymer solution. After mixing with the soil, polymer would fill the pores of the sand. The prepolymer in polymer carried a reactive isocyanate group

$-NCO$  and it reacted quickly with water to produce a polymeric polyurea. Surfactants in the polymer, which contained other substances such as butanone, toluene, SDS, MDI, and other substances, could control the rate of solidification of the

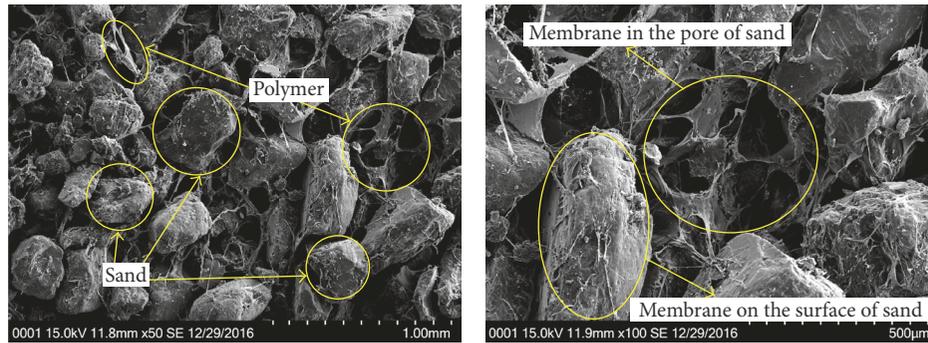


FIGURE 14: SEM images of specimen reinforced with polymer 5%.

polymer. It also maintained the homogeneity of the polymer prepolymer and increased the adhesion to the soil particles.

Figure 14 was a micrograph of a cured layer with a polymer content of 5%. As shown in the Figure 14, the polymer was filled with pores between the sand particles while being wrapped with individual soil particles and connected to adjacent soil particles to form a network structure. These reticular membrane structures were mainly formed from the prepolymer. Sand particles of various sizes could be seen in Figure 14, which were all wrapped in reticular membranes and connected by a network of membrane structures.

When the polymer came in contact with sand, the polymer changed to long chain. The active hydroxyl or carboxyl and other functional groups at the end of the long polymer chain and the chemical groups on the surface of the soil particles underwent physical or chemical reactions to bond the soil particles into a network-like structure, thereby forming a certain thickness of the cured layer on the surface of the sand. When the sand had been consolidated, some properties of the sand had changed. The stabilized sand could maintain greater stability in the water (see Figure 5). The shear strength of saturated sand had also been improved (see Figure 6).

The specimen surface was sprayed by polymer solution to form the curing layer. The curing time and polymer content were two important factors to the void ratio of curing layer on specimen surface. The permeability coefficient of the specimen reduced with the decrease in its void ratio. This decrease of void ratio was improved by the curing time or polymer content. And the permeability coefficient decreased with the increase in curing time or polymer content (see Figure 9). While there was lower polymer content or shorter curing time, there was not enough macromolecule or time to form the curing layer. The water-resisting layer on sand surface was formed when the curing time was more than 6 h and polymer content was larger than 7%. The existence of the water-resisting layer made the enhancement in the scour resistance of the sand surface to a great extent. The variation of accumulated sediment loss of specimens reduced with the increasing polymer content (see Figures 11(b), 12, and 13). In addition, the complete degree of curing layer taken from the surface of the specimens also increased with the increasing polymer content (see Figure 10). Compare with other types

of organic polymer, sand reinforced with the environment-friendly organic polymer used in this study had a better effect. It could be seen in the Tables 2 and 3 that the permeability of reinforced sand reduced 70%, but the one of sand reinforced with phenolic reduced about 10% [21]. The scour rate of sand reinforced with our polymer content 3% was only 14%, but sand reinforced with the same content of interpolymer complexes was about 40% [22].

With the increase in curing time, the cured layer prepolymer gradually stabilized to hardening. In a certain period of time, the curing layer could maintain a high toughness, water retention, and permeability. When the curing layer was exposed to oxygen, high temperature, and light conditions for a long time, the prepolymer radicals in the cured layer were aged. After aging, the elasticity of the reticular membrane structure became smaller and the toughness became weaker, but the prepolymer still had a good curing effect.

## 6. Conclusion

In order to evaluate the effectiveness of environment-friendly organic polymer on sand, the laboratory tests comprised of water stability test, the penetration test, and the runoff scouring test were conducted. The test results and reinforcement mechanism were analyzed. Based on the results of the tests presented herein, the main conclusions could be summarized as follows:

(1) After adding the environment-friendly organic polymer in the sand, the water stability of the specimen had been greatly improved. All the reinforced sand with polymer  $\geq 0.4\%$  remained a stable structure at immersing time of 24 hours. The permeability of sand decreased with the increase in polymer content and curing time. The permeability coefficient of the sample decreased with the increase in polymer content under the same curing time in the permeability test. When the polymer content in the sample was constant, the value of the permeability coefficient of the sample decreased with the increase in curing time.

(2) In runoff erosion test, the erosion resistance of sand gradually increased with the increase of polymer content. The sand surface kept intact with the scouring time more than 2 hours when the polymer content was more than 4%. The scour rates of specimens reinforced with polymer content of

0%, 1%, 2%, 3%, 4%, and 5% were 63%, 54%, 33%, 14%, 0%, and 0%, respectively.

(3) The environment-friendly organic polymer contained a significant proportion of the long-chain macromolecule of polyurethane resin and enormous amount of isocyanate group, NCO. Microscale SEM observations showed that the environment-friendly organic polymer enwrapped the sand particle and interlinked them to form a reinforcement layer on the sand surface. The environment-friendly organic polymer filled up the voids of sand and adsorbed on the surface of sand particle to reduce or block the flowing channels of water to improve the permeability resistance of sand. The research results could be used as a reference for strengthening sandy slope.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Conflicts of Interest

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

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