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Research Article

Study on Application Effect of Sand Consolidating Agent for the Slope of Highway Subgrade in Season Frozen Zone

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In deep season frozen areas, the solidified layer is easy to be destroyed due to the influence of freeze-thaw cycles after the surface layer of the sandy slope is solidified by chemical methods. In order to study the application effect of the new sand consolidating agent after solidifying sand body, the mechanism of strength formation was analyzed by scanning electron microscopy (SEM). The freeze-thaw cycle tests were carried out on sand consolidating samples. The direct shear tests and unconfined compressive strength tests were carried out before and after freeze-thaw cycles to analyze the freeze-thaw resistance of sand consolidating samples. The sand consolidation agent was tested on-site, and its strength was tested to observe its effect. The results showed that the adhesive membranes on the surface of sand particles were formed by the sand consolidating agent, which increased the cohesion and strength of sand particles. After freeze-thaw cycle tests, the cohesion, internal friction angle, and compressive strength of the solidified sand gradually decreased with increasing freeze-thaw cycles. The decreasing rate reduced from fast to slow and then tends to be stable. The failure mode of samples changed from brittle failure to plastic failure. The sand consolidating layer can effectively prevent collapse of the sandy slope. Combining with the external-soil spray seeding, the sand consolidation layer is beneficial to the growth of plants.

1. Introduction

Aeolian sand is widely distributed in the west and north of China. At natural state, aeolian sand is loose, which brings some difficulties in the construction of highway engineering in aeolian sand areas. For the aeolian sand slope, the traditional engineering protection has disadvantages of high cost, high labor intensity, and easy aging of engineering materials [1~3]. The plant protection has the disadvantages of slow construction progress and low plant survival rate. It is not easy to achieve protection effect [4~6].

Due to the limitations of engineering sand consolidation and plant sand consolidation, chemical sand consolidation technology has attracted more and more attention in recent years because of its low cost, high efficiency, and convenient construction [7]. Chemical sand consolidation is to form solidified layers on the surface of aeolian sand to enhance the surface strength. It can keep water in the lower layer so as to achieve the effect of sand consolidation [8]. Researchers have carried out comprehensive research on sand consolidating formula, spraying technology, and sand consolidating effect and achieved some results [9].

A new method for the consolidation of loose sand formations has been developed by Hafez et al. [10]. The method involves in situ precipitation of a composite calcium phosphate-polyelectrolyte salt that binds together with loose sand grains, thus resulting in their consolidation. Three different polyelectrolytes (PE) were tested, i.e., polyacrylic acid (PAA), polyallylamine hydrochloride (PAH), and polyethylenimine (PEI). Lucas et al. [11] devoted to the knowledge of the consolidation of silica sand with an alkaline solution in order to determine the mechanisms that occur during the drying of sand and various alkaline solution mixtures. The investigations concern effects of sand distribution size, dilution of sodium silicate solutions, and drying temperature of the mixtures on consolidation behaviour. A novel polymer, polyaspartic acid (PASP) resin which is used as a chemical sand-fixing agent (CSFA), was studied by Yang et al. [12] to improve the sand's antiwind erosion and compressive strength properties. Zhao and Wang [13] used the mixture of organosiloxane prepolymer and polyvinyl alcohol as the sand consolidating agent for the first time and studied the water resistance and shear strength of solidified sand. Several gradations of sands were grouted using acrylamide chemical grout and tested by Ozgurell et al. [14]. Filet et al. [15] introduced Biocalcis and its applications for the consolidation of sands. The mechanical and hydrological characteristics of compacted sand-bentonite mixtures with bentonite contents ranging from 5% to 40% were investigated in the laboratory by Haluk and Mustafa [16]. Nowadays, the research on chemical sand consolidation mainly focuses on the strength, permeability, freeze-thaw resistance, water resistance, wind erosion resistance, and so on and tends to combine with plant sand consolidation. However, the analysis of chemical sand consolidation mechanism is not in-depth. The research on freeze-thaw resistance of chemical sand consolidation is relatively single. Most of the tests are suitable for indoor, and the field conditions are not fully taken into account.

The new sand consolidating agent TD-1 has good permeability. After spraying, it can form a 20–30 cm thick consolidation layer on the surface of aeolian sand and effectively prevent the collapse of sandy slope. The potassium salt in the solidified product is beneficial to the growth of plants. Combining with external-soil spray seeding, grass planting can be carried out on the surface of the consolidation layer. Now, it has been used in the test section of Zhangjiakou area, and the effect of sand consolidation is good. Zhangjiakou area belongs to deep season frozen area. In early spring and winter, the temperature difference between day and night is large. The consolidation layer on the slope surface is liable to be destroyed under freeze-thaw cycles, which affect the stability of the slope. In order to understand the effect of solidified sand, the strength formation mechanism of solidified sand was analyzed from the microscopic aspect. Through freeze-thaw cycle tests, direct shear tests, and unconfined compressive strength tests, the changes of cohesion, internal friction angle, and compressive strength were studied. The relationship between stress and strain was studied. The sand consolidating agent was tested in Zhangjiakou area, and its effect was observed.

2. Test Material

The aeolian sand used in the test was from Zhangjiakou area, which was medium sand with poor gradation. The new sand consolidating agent TD-1 was mainly composed of potassium silicate, silicon phosphate, lithium silicate, silica sol, and water in a certain proportion.

The basic property indexes of aeolian sand are known (see Table 1).

(i) Potassium silicate: according to the application effect of engineering practice and considering the economic benefits of field use, the ratio of three different moduli (3.2, 3.3, and 3.4) of potassium silicate was studied

(ii) New silicon phosphate: the new silicon phosphate is a white powder crystal, which is soluble and can be evenly dissolved in mixed solution

(iii) Lithium silicate: the modulus of lithium silicate is 4.8, and the concentration is 0.2 g/mL

(iv) Silica sol: silica sol is alkaline (pH = 9), and the concentration is 0.3 g/mL.

3. Test Scheme and Sample Preparation

3.1. Test Scheme. Through orthogonal tests, the optimum proportion of sand consolidating agent TD-1 is known. The solid content of potassium silicate is 3% of the quality of aeolian sand. The solid content of silicon phosphate is 6% of that of potassium silicate. The solid content of lithium silicate is 2% of that of potassium silicate. The solid content of silica sol is 3% of that of potassium silicate. Three kinds of potassium silicates and silicon phosphate, lithium silicate, and silica sol were used to prepare the sand consolidating agent to prepare sand consolidation samples. Sand consolidating agent was mixed with sand to make sand consolidating samples. When the age of the samples reached 14 days, the tests were carried out. At this time, the samples reached high strength. In the future, the samples with the age of 28, 90, and 180 days will be tested to study the variation of sample parameter with time.

Scanning electron microscopy (SEM) was used to observe loose sand particles and sand consolidating samples. The strength formation mechanism of sand consolidating samples was analyzed from the microscopic aspect.

The freeze-thaw cycle tests of sand consolidating samples were carried out by the high-low temperature alternating humidity-heat test box. Samples were saturated in water and taken out after 24 hours. The surface moisture of the samples was absorbed by soft cloth. The samples were wrapped with a fresh-keeping film before freezing and thawing. In order to simulate the maximum daily temperature difference between early spring and early winter in Zhangjiakou area, the cooling temperature was set at −20°C and the melting temperature was set at 20°C. The freeze-thaw cycle time is set at 12 hours, of which the cooling time is 6 hours and the melting time is 6 hours. The samples were subjected to 0, 1, 2, 5, 10, and 20 freeze-thaw cycles, respectively. After freeze-thaw cycles, direct shear tests were carried out on sand consolidating samples under a vertical pressure of 100 kPa, 200 kPa, 300 kPa, and 400 kPa. The variation of cohesion and internal friction angle of samples after different freeze-thaw cycles were studied.

The sand consolidating agent was tested on the sandy slope of Zhangcheng Expressway, and its infiltration depth and strength of the consolidation layer were tested. After external-soil spray seeding, the effect of planting grass was observed.

Table 1: The basic property indexes of aeolian sand.

Nonuniform coefficient	Curvature coefficient	Optimum moisture content (%)	Maximum dry density ($g\cdot cm^{-3}$)	Cohesion (kPa)	Internal friction angle (°)	Permeability coefficient ($cm\cdot s^{-1}$)
4.32	1.24	12.8	1.627	0.065	35.23	3.57×10^{-3}

3.2. Sample Preparation. Samples for direct shear tests were made with cutting ring. The inner diameter and height of the ring cutter were 61.8 mm and 20 mm, respectively. The inner wall of the ring knife was coated with vaseline. The samples for microscopic analysis were cut from the samples for direct shear at the reaching age and sliced into 5 mm × 5 mm × 2 mm sections. The diameter and height of the sample for unconfined compressive strength test were 40 mm and 100 mm, respectively.

The maximum dry density, optimum water content of aeolian sand, and optimum proportion of the sand consolidation agent are known. The quality of aeolian sand, the volume of potassium silicate, the volume of lithium silicate, the volume of silica sol, the solid mass of silicon phosphate, and the quality of water added were calculated. Samples were made by mixing the materials required evenly. The samples were filled in layers. The surface of each layer was shaved, and the compactness was 97%.

4. Microscopic Analysis of Strength Formation Mechanism of Sand Consolidating Samples

The sand particles and the samples made of potassium silicate with different moduli are magnified 1000 times and imaged (see Figure 1).

As it can be seen from Figure 1, the surface of aeolian sand is relatively smooth, and there is almost no cohesion between sand particles. The sand consolidating agent forms white adhesive membranes on the surface of the sand particles. The sand particles are enclosed by the adhesive membranes, and the pores between the sand grains are filled by the adhesive membranes. The adjacent sand particles are bound together by the adhesive membranes. Because of the bonding and filling of the adhesive membranes, the loose sand particles form strength. The composition of the adhesive membranes is mainly composed of potassium silicate curing. H^+ produced after hydrolysis of silicon phosphate replaces K^+ which easily causes hydrolysis in potassium silicate and improves the water resistance and toughness of the adhesive membranes. The adhesive membranes formed by a small amount of lithium silicate and silica sol are insoluble in water, which improves the overall strength and weatherability of the adhesive membranes.

Samples made with modulus 3.2 of potassium silicate have fewer adhesive membranes between sand particles and larger residual voids. With the increase in the modulus of potassium silicate used, the adhesive membranes between sand particles increase gradually, which not only enhance the bonding effect between sand particles but also reduce the pores of sand consolidating samples and make them tend to be compact. At the same age, the higher the modulus of potassium silicate used, the greater the strength of sand consolidating samples.

When the samples are completely dried, with the increase in age, the hardness of the adhesive membranes formed by the sand consolidating agent increase and the strength of the samples increases gradually, but the adhesive membranes between the pores will produce some cracks. The main component of aeolian sand is SiO_2. As it can be seen from Figure 1, the sand consolidating agent solidifies on the surface of the sand particles without any chemical reaction with the sand particles.

5. Results and Analysis of Freeze-Thaw Cycle Tests

5.1. Changes in Cohesion, Internal Friction Angle, and Compressive Strength. The mechanical parameters, i.e., cohesion, internal friction angle, and compressive strength, were obtained via direct shear tests and unconfined compressive strength tests conducted on the three kinds of sand consolidating samples.

It can be seen that the cohesive force, internal friction angle, and unconfined compressive strength change with the number of freeze-thaw cycles (see Figures 2~4).

According to Figures 2 to 4, the cohesive force, the internal friction angle, and the compressive strength of the samples made of potassium silicate with different moduli are gradually decreased with increasing the number of freeze-thaw cycles. In the first five freeze-thaw cycles, the rate of decrease is large. After 5 freeze-thaw cycles, the rate of decrease slows. After 10 freeze-thaw cycles, it tends to be stable. After 20 freeze-thaw cycles, the cohesion of the samples made of potassium silicate with modulus 3.2 is 123.46 kPa, which decreases by 30.01%. The internal friction angle is 36.43 degrees, which decreases by 5.18%. The strength is 558.32 kPa, which decreases by 34.81%. The cohesive force of the samples prepared with modulus 3.3 of potassium silicate is 149.53 kPa, which decreases by 31.17%; the internal friction angle is 37.27 degrees, which decreases by 6.50%; and the strength is 682.32 kPa, which decreases by 35.56%. The cohesion of the samples made of potassium silicate with modulus 3.4 is 169.43 kPa, which decreases by 31.47%; the internal friction angle is 37.63 degrees, which decreases by 6.676%; and the strength is 889.96 kPa, which decreases by 36.89%.

The freeze-thaw cycles of sand consolidating samples are carried out after saturation. There are still some pores between the adhesive membranes of the samples and the water frost heaves in the pores when it freezes. During the freezing process, the external temperature of the samples decreases rapidly and gradually freezes from the outside to the inside. Under the action of matrix potential, the internal moisture migrates to the outside. During the freeze-thaw cycles, the adhesive membranes between sand particles are destroyed with the migration and frost heaving of moisture, which

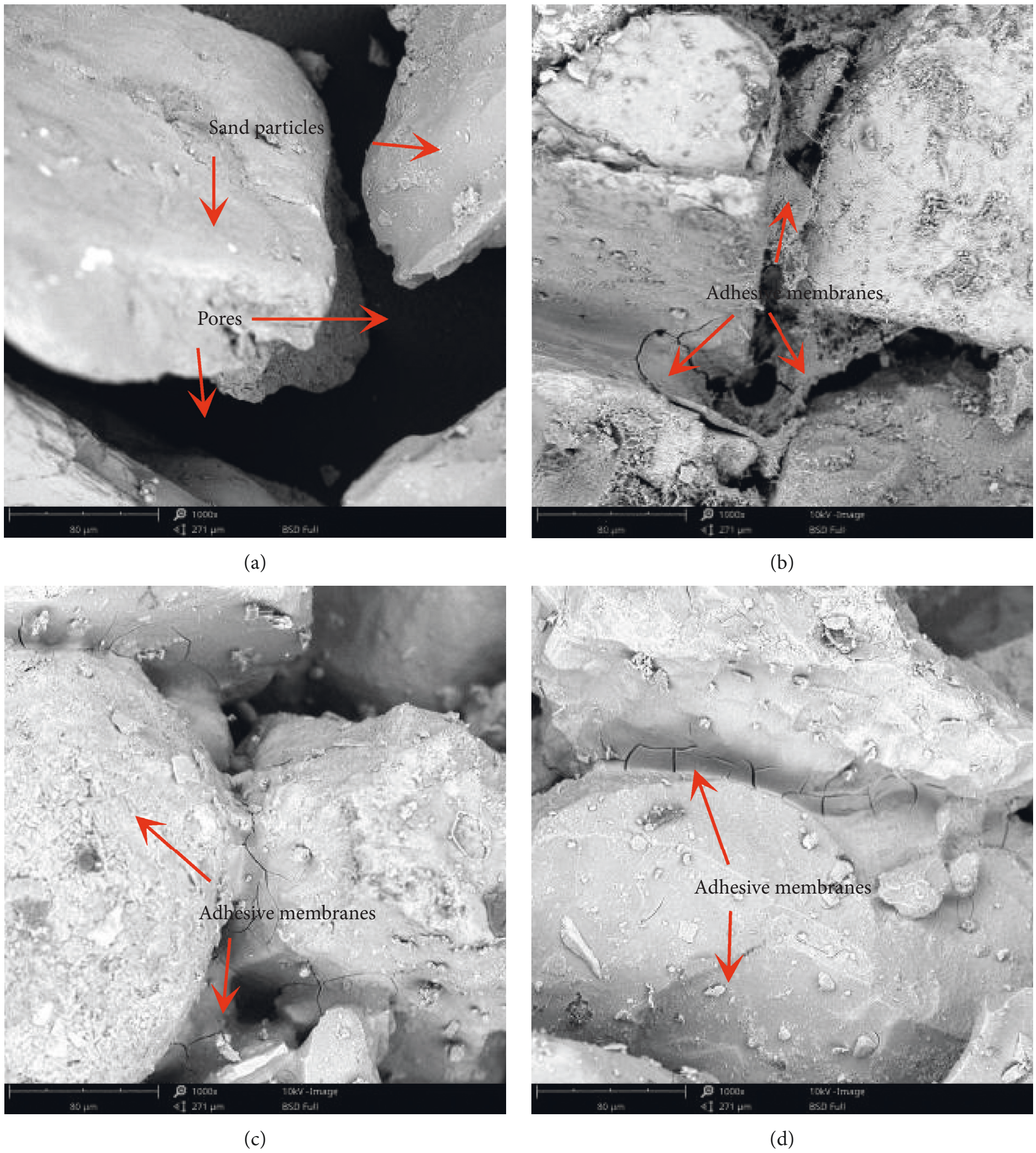

Figure 1: SEM images of sand particles and samples. (a) Sand particles. (b) Modulus 3.2. (c) Modulus 3.3. (d) Modulus 3.4.

reduces the bonding and friction between sand particles. The shear strength and compressive strength of the samples decrease with the decrease in cohesion and internal friction angle.

During the first five freeze-thaw cycles, the water-soluble and crack-prone parts of the adhesive membranes are liable to be destroyed, so the decrease rates of cohesion, internal friction angle, and compressive strength of the samples are relatively high. After 10 freeze-thaw cycles, the remaining adhesive membranes are not easy to destroy, and the cohesion, internal friction angle, and compressive strength of the samples tend to be stable. The larger the modulus of potassium silicate used in the samples, the more the bond membranes will be formed and the smaller the pores between the sand particles will be. The effect of moisture migration and frost heaving on the freeze-thaw cycles is also greater, so the reduction rate of cohesion and internal friction angle is greater than that of samples using lower modulus potassium silicate.

5.2. Stress-Strain Behaviour. The stress changes with strain in unconfined compressive strength tests of three sand consolidating samples (see Figures 5~7).

From Figures 5 to 7, it can be seen that the stress of each sand consolidating sample increases linearly with the increasing strain in the initial stage of loading. With the continuous increase of strain, the specimens without freeze-thaw cycles immediately suffer from brittle failure when the stress reaches its peak value. With the increase in freeze-thaw cycles, the slope of the stress-strain curve decreases, the failure stress decreases, and the failure strain increases. When the peak stress is reached, the stress remains unchanged or decreases with the increase of strain, and then failure occurs.

The adhesive membranes formed by the sand consolidating agent gradually harden to form hard membranes after drying. Without freeze-thaw cycles, the

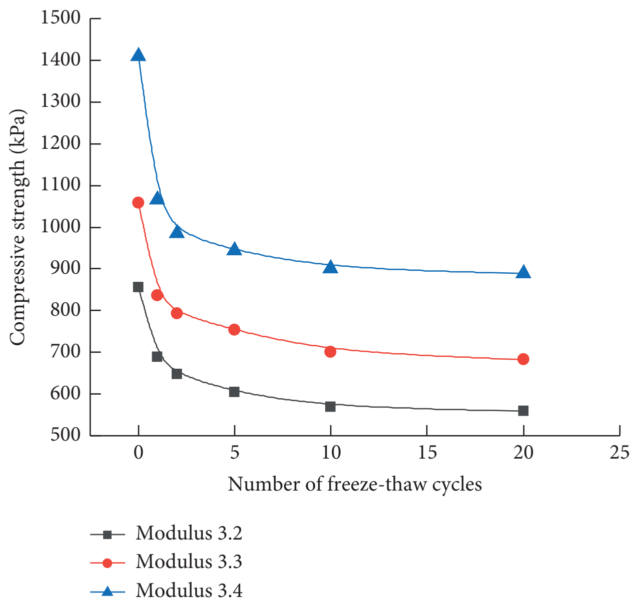

FIGURE 2: Compressive strength changes with the number of freeze-thaw cycles.

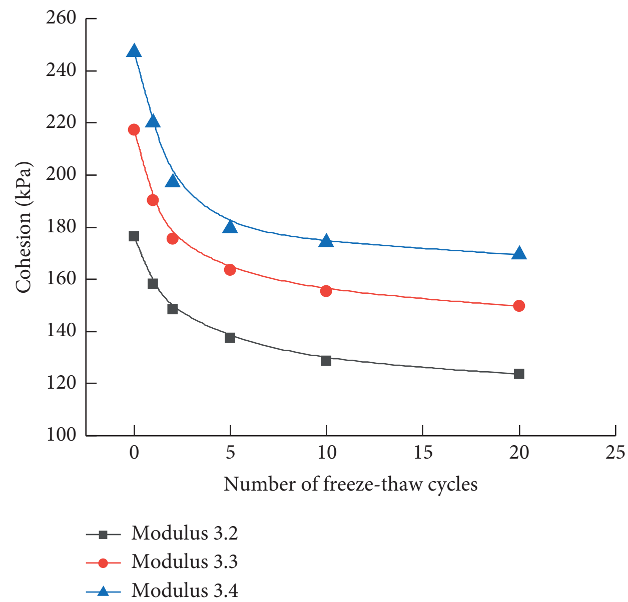

FIGURE 4: Cohesion changes with the number of freeze-thaw cycles.

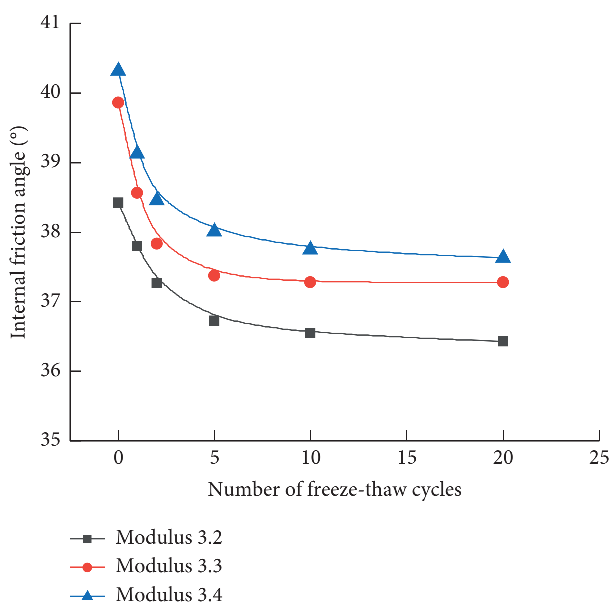

FIGURE 3: Internal friction angle changes with the number of freeze-thaw cycles.

failure of samples is brittle fracture of the adhesive membranes, so the samples are brittle failure. With the increase of freeze-thaw cycles, the adhesive membranes soften gradually under the action of water migration and frost heaving. The failure of samples transits from brittle failure to plastic failure.

6. Field Test

The sand consolidating agent was tested in the test section of Zhangcheng highway. The test slope was a sandy excavated

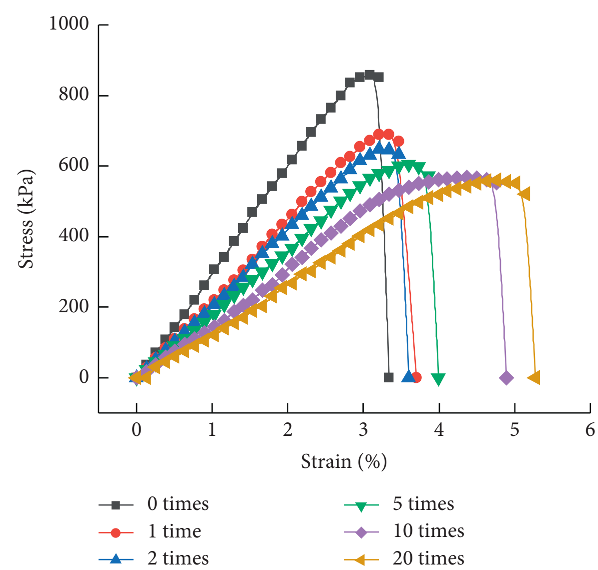

FIGURE 5: Stress changes with strain: modulus 3.2.

slope with a height of 13 m, a length of 50 m, a slope angle of 45°, and a total area of 920 m^2.

Calculate the quality of sand that needed to be solidified on the surface of the slope and prepare the sand consolidating agent on-site. The modulus of potassium silicate was 3.45, and the solid content of potassium silicate was 3% of the quality of solidified sand. The solid content of silicon phosphate was 6% of that of potassium silicate. The solid content of lithium silicate was 2% of that of potassium silicate. The solid content of silica sol was 3% of that of potassium silicate. According to the optimum water content of aeolian sand, water needed to be added was determined. The required materials were mixed and

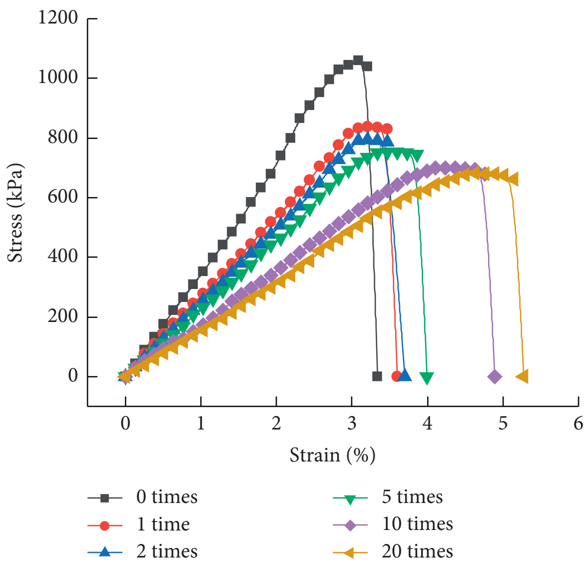

Figure 6: Stress changes with strain: modulus 3.3.

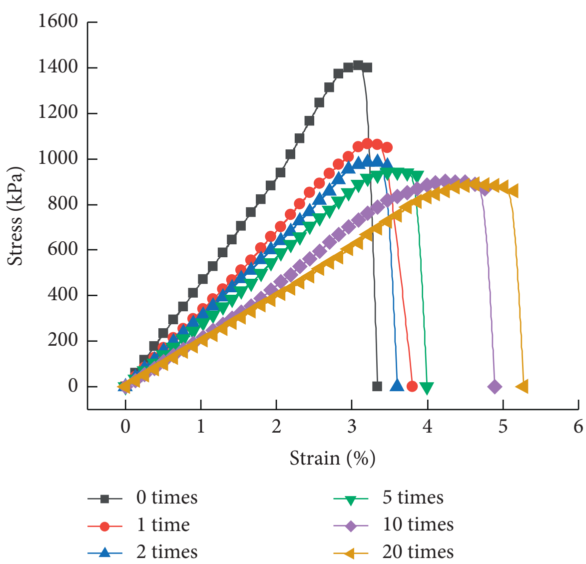

Figure 7: Stress changes with strain: modulus 3.4.

stirred evenly. Sand consolidating agent was sprayed evenly on the surface of the sandy slope by spraying equipment. The sand consolidating agent began to solidify after 2 hours and formed strength after 24 hours. The solidified layer formed by the sand consolidating agent on the surface of the slope is smooth. The effect after spraying is good (see Figure 8).

The permeability of the sand consolidating agent on the slope surface is good. Under the condition of no pressure, the depth of permeation can reach 10~30 cm (see Figure 9).

The strength of the solidified layer on the surface of the slope was tested after 7 days of sand consolidating agent spraying. One specimen per 100 m^2 was taken for strength test (for results, see Table 2).

Table 2 shows that the strength of the solidified layer is over 800 kPa after 7 days of using the sand consolidating agent in the field. The curing layer was compact and has high

Figure 8: The effect after spraying.

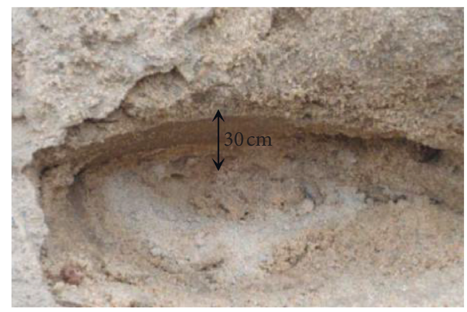

Figure 9: The depth of permeation.

Table 2: Strength of sampling at slope test points.

Sampling point	Strength (kPa)	Sampling point	Strength (kPa)
1	823.65	6	1039.19
2	1089.96	7	912.56
3	963.41	8	1036.59
4	952.86	9	996.38
5	826.35	10	886.39

Figure 10: Solidification effect of the sandy slope after two years.

strength. After that, combined with external-soil spray seeding, the grasses were planted. Two years later, the effect is good (see Figure 10).

Two years later, there were no water erosion, cracking, and collapse on the surface of the sandy slope. The curing layer had good weatherability. The solidified products of the sand consolidating agent can be used as fertilizers for plants and promoted the growth of plants on the surface of slope. After planting grasses, not only the surface of sandy slope is greened but also increased the stability of the slope.

7. Conclusion

Sand consolidation specimens were observed by scanning electron microscopy. Freeze-thaw cycling tests were carried out on sand-fixing samples. The direct shear tests and unconfined compressive strength tests were carried out before and after freeze-thaw cycles. Some conclusions are drawn.

After solidification, adhesive membranes were formed on the surface of sand grains to encapsulate the sand particles, and they were filled between the pores to form strength. The cohesion, internal friction angle, and unconfined compressive strength of the sand consolidating agent decreased with increasing of freeze-thaw cycles and tend to be stable after 10 freeze-thaw cycles. Without freeze-thaw, the sand consolidating samples showed brittle failure characteristics. With increasing freeze-thaw cycles, the samples gradually changed from brittle failure to plastic failure. After freeze-thaw cycles, the sand consolidating samples all retained large cohesion, internal friction angle, and compressive strength and had good freeze-thaw resistance. Sand consolidating agent can be applied to the protection of the sandy slope in deep season frozen areas, and it can achieve better effect in arid area.

The infiltration depth of the sand consolidating agent in the sandy slope of Zhangcheng highway was 20~30 cm. The consolidation layer formed has strength, which can effectively prevent the collapse of the sandy slope. After external-soil spray seeding, it is beneficial to plant growth and the consolidation effect is good.

Data Availability

The test data and field data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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