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Research on New Technology for Sandy Slope Safety Protection

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Abstract: The stability of sandy slopes is poor, as are the protective effects of conventional protection measures. To effectively protect sandy slopes with chemical sand consolidation technology, a new type of sand consolidation agent, TD-1, was developed. Proportion optimization tests, penetration tests, wetting-drying cycle tests, and field tests were conducted to study the effect of sand consolidation. The results show that the strength of the sand samples increases with increase in the modulus of potassium water glass when the ratios of the incorporated silica phosphate, lithium silicate, and silica sol remain the same. The optimum amount of potassium water glass added was 3% of the solidified sand. The strength of the samples containing the modifier also increases, and the permeability of the samples with low modulus potassium water glass becomes relatively better. The strength of the samples decreases gradually with increase in the wetting-drying cycle index, but tends to become stable after three cycles. TD-1 can be used with soil spraying technology for slope greening protection, while the solidified product is good for growing plants.

Keywords: sandy slope; sand consolidation agent; laboratory tests; field tests.

1 Introduction

The subgrade is one of the key road factors for ensuring normal traffic. Once the subgrade is destroyed, traffic will be blocked, and traffic safety will be endangered. The stability of slopes has a great influence on the overall performance of the subgrade structure. Engineering practice shows that geological elements are the fundamental basis for the excavation and protection of highway slopes. For sand slopes, the cohesiveness of the aeolian sand is almost zero, the stability is poor, and the slope is prone to landslides and other disasters caused by rainfall. Sand slopes generally adopt conventional protective measures, including engineering and plant protection. Engineering protection mainly involves the protection of the geosynthetics such as asphalt protection, cement concrete protection, use of pebbles and gravel, rubble type protection, soil protection, and firewood protection. Plant protection mainly involves the planting of trees, shrubs, herbaceous plants, and greenery [1,2].

There are many shortcomings associated with the use of conventional protective measures. Stone, concrete, and asphalt are prone to aging, incur higher maintenance costs as they get older and are generally not green. Firewood protection and soil protection can only be applied to low-grade highways. The use of plant protection is not stable as the slopes could get eroded under the action of rains before the plants grow, so plant protection is not always very effective [3–5].

In order to improve the protective action of sand slopes, a new safe and guaranteed technology for sand slope is studied. This technique uses chemical sand fixing method to form a sand soil solidified layer of 10–30 cm on the surface of the slope, increases the stability of the slope, and increases its resistance to wind and water erosion. Soil spray sowing is used to plant grasses

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on the slope surface, thereby enhancing the ecology. Chemical sand fixing technology has been receiving increasing attention in recent times, both at home and abroad. Li et al. [6] used sodium silicate as a sand-fixing material and used $AlCl_3$ solution as sodium silicate solidifying agent. The solid sand body formed by the solution offers better acid resistance. Jiang et al. [7] developed a sand fixing agent composed of water glass, sorbitol, lithium carbonate and so on. It showed good aging resistance and improved the stability of freezing and thawing. Dong et al. [8] extracted lignin sulfonated salts in paper waste liquid, and added formaldehyde and acrylic acid to the lignin sulfonated salt solution to make copolymerization and obtain a sand consolidation agent. The sand consolidation agent offered good resistance to wind erosion and biodegradation. Achilias et al. [9] used waste plastics to produce sand consolidating materials by dissolving waste products and plastic polymers, and then precipitating them. Thereafter, high-density polyethylene and polypropylene were extracted. After the sand consolidation is done, the solidified sand forms a high-strength layer. Most sand consolidation agents offer better characteristics during indoor tests, but the production is relatively complex, and their water resistance is relatively poor, making them unsuitable for the rough environments of the field.

To address the limitations of existing chemical sand fixing methods, a new type of sand consolidation agent, TD-1, is proposed in this paper. The raw materials for TD-1 are easy to obtain, simple to construct and can be applied to large areas in the field. The main materials for TD-1 are potassium water glass solution, new phosphate silicon, lithium silicate solution, and silica sol solution [10]. The product obtained after applying solidifying agent supports the growth of plants, and has good sand fixation properties. In addition, the authors also provide a kind of modifier to enhance the strength of the sand for use in areas where the environment is bad and where plants do not grow easily. In order to study the sand fixing effects, the authors conducted ratio optimization tests, permeation tests, and wetting-drying cycle tests. We tested the sand consolidation agent on a test section of the Zhangjiakou–Chengde Expressway, together with spray sowing grass that has good protective effects on the soil.

2 Test material and test scheme

2.1 Test material

(1) Aeolian sand: from the Guyuan area of Zhangjiakou, a medium sand with poor gradation. The optimum moisture content was 12.8%, and the corresponding maximum dry density was 1.627 $g \cdot cm^{-3}$.

(2) Potassium water glass solution: six different modulus values of potassium water glass (M = 3.20, 3.25, 3.30, 3.35, 3.40, and 3.45).

(3) Curing agent: a new type of silicon phosphate, a nontoxic and tasteless white powdered crystal that can be fully dissolved in water to promote the curing reaction.

(4) Lithium silicate solution: with modulus of 4.8 and concentration of 0.2 $g \cdot mL^{-1}$. The lithium silicate solution is self-drying and does not need the curing action of the curing agent. The combination of lithium silicate and potassium silicate can reduce costs and improve the film-forming reaction of the lithium silicate.

(5) Silica sol solution: alkaline silica sol (PH = 7.5–9) with a concentration of 0.3 $g \cdot mL^{-1}$. The silica sol solution has good dispersibility and low viscosity, and can fully be filled into the pore. The specific surface area of the silica sol particles was 50–400 $m^2 \cdot g^{-1}$, with particle size range of 10–20 nm [11]. The silica sol has larger surface area and larger surface energy, with a capability to automatically decrease the surface energy. Small particles can be condensed into larger particles, thereby forming gel and condensing into conjunctiva [12].

2.2 Test scheme

The test materials comprised potassium water glass, silicon phosphate, lithium silicate solution, and silica sol solution with water-mixed sand consolidation agent. In order to optimize the ratio of the sand-fixing agent and to study the effect of sand fixing, the following test scheme is formulated.

(1) The solid content of the potassium water glass was 2%, 3%, or 4% of the quality of the required solidified aeolian sand. The content of the added silicon phosphate was 6% of the solid content of the potassium water glass. The solid content of the lithium silicate was 2% of the solid content of the potassium water glass while that of the silica sol was 3%. The addition ratio for silicon phosphate, lithium silicate and silica sol was fixed.

(2) Making sand consolidation agent with six different modulus of potassium water glass (the solid content of potassium water glass for each modulus was 2%, 3%, or 4%). The samples were made and unconfined compression strength tests carried out. The ratio of the sand consolidation agent was optimized according to the result.

(3) Making samples of six different modulus of potassium water glass (the content of potassium water glass is 3%). A total of 5 g of modifiers was added to each sample. Unconfined compressive strength tests were conducted to study the influence of the modifier on the strength of the solid sand samples.

(4) Making samples of two different modulus of potassium water glass (M =3.20, 3.45, the content of potassium water glass is 3%). This was then used to conduct the permeation tests and wetting–drying cycle tests.

(5) The dimensions of the samples for the strength tests was 70.7 mm × 70.7 mm × 70.7 mm, with 97% degree of compaction. The samples were made in a ring knife structure, with inner diameter of 61.8 mm, height 40 mm, and degree of compaction 97%.

3 Analysis of test results

3.1 Influence of the modulus and solid content of potassium water glass on the strength of the solidified sand

The samples were made from potassium water glass with different modulus values and solid contents. The unconfined compressive strength of the specimens at 14 d was analyzed. The test results are as shown in Table 1.

The test results show the following: the aeolian sand gains certain strength under the action of the sand consolidation agent, TD-1. The strength of the sand fixation sample at 14 d was more than 700 kPa. Phosphoric acid silicon was hydrolyzed H^+ in potassium sodium silicate solution instead of the K^+ in potassium water glass that causes easy hydrolysis, and was reacted with silicate ions in potassium silicate glass to form a silicic acid two polymer. The silicic acid two polymer was further fused into polysilicic acid to form SiO_2. When the content of the formation exceeds a certain amount, a gel network structure is formed. When the gel is mixed with sand, a layer of sticky conjunctiva is formed on the surface of the sand, so that the loose sand is bonded together to produce some strength. The potassium silicate, lithium silicate, and silica sol that do not participate in the reaction will also form an adhesive conjunctiva on the surface of the sand that increases the strength of the sand fixation sample.

As shown in Fig. 1, upon addition of potassium water glass and silicon phosphate with the same solid content, the strength of the sand fixation samples increases as the modulus of the potassium water glass increases. The higher the modulus of the potassium water glass, the more the gel network structure formed in the mixed solution. The surface layer of the sand first solidifies and hardens to form a hard shell, and then hardens gradually from the outside to the inside.

As shown in Fig. 2, at 14 d, the strength of the sample with 3% potassium water glass solid content was greater than those of the sample with 2% and 4% potassium water glass solid content. When the content of the added potassium water glass is increased from 2% to 3%, the strength of the sample increases noticeably. When the solid content exceeds 3%, the sample strength growth rate not only slows down but the strength of some samples also decreases. When the solid potassium water glass content is increased, more gel network structure can be generated and the strength of the samples is increased. When the solid content of the potassium water glass is 3%, membranes are formed on the surface of the sand, and the adjacent sand particles are connected through the membranes to form a cohesive bridge. When the solid content of potassium silicate is more than 3%, the relative content of the aeolian sand aggregate decreases, and the stability of the specimen structure is affected, making it impossible to form higher strengths.

3.2 Effect of the modifier on the strength of the solidified sand

The unconfined compressive strength of the samples at 14 d was measured. The strength of the sample without the modifier is compared with its strength with the modifier, as shown in Table 2.

After adding the modifier, the strength of the samples after 14 d exceeded 1000 kPa, showing an increase of 32.5%–60.8%

Table 1. Unconfined compressive strength of samples at 14 d.

Group number	Modulus of potassium water glass	Percentage of solid content of potassium water glass (%)	Unconfined compression strength (kPa)
1	3.20	2	702.41
2	3.20	3	865.42
3	3.20	4	844.38
4	3.25	2	854.07
5	3.25	3	950.37
6	3.25	4	865.87
7	3.30	2	897.53
8	3.30	3	1 060.77
9	3.30	4	924.21
10	3.35	2	999.00
11	3.35	3	1 246.32
12	3.35	4	1 077.05
13	3.40	2	1 097.62
14	3.40	3	1 419.10
15	3.40	4	1 196.25
16	3.45	2	1 228.23
17	3.45	3	1 431.45
18	3.45	4	1 301.37

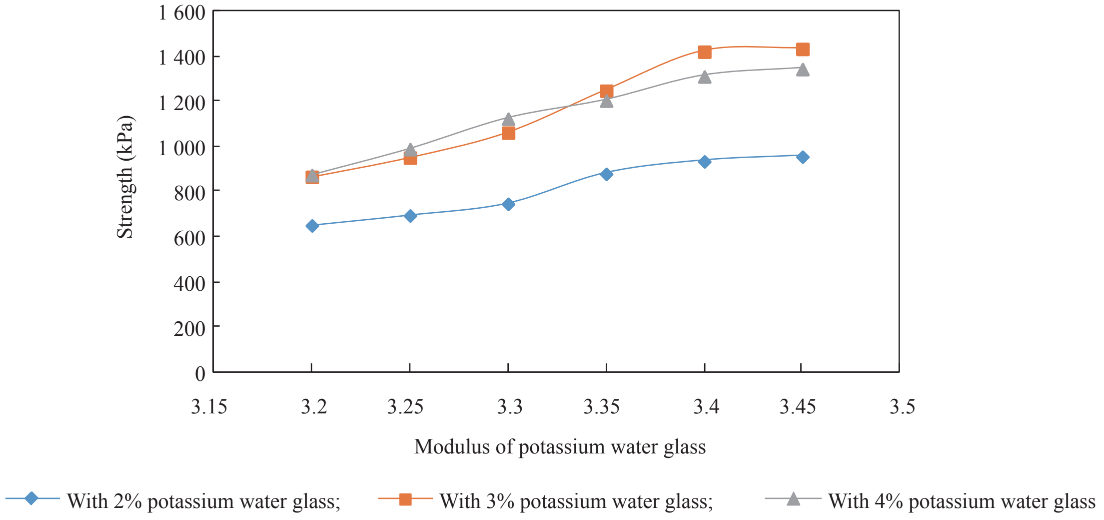

Fig. 1. Influence curve of the modulus of potassium water glass on the strength of the samples.

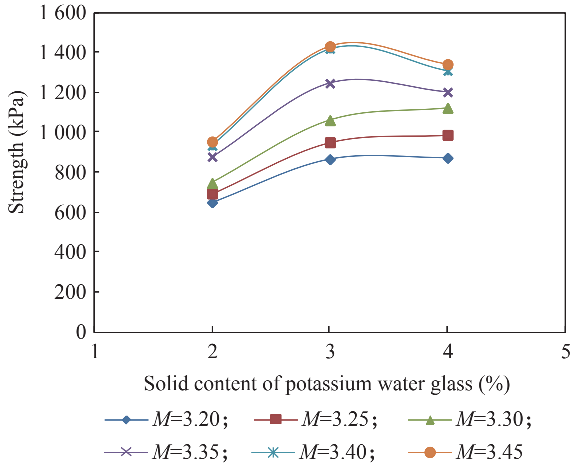

Fig. 2. Influence curve of the solid content of potassium water glass on the strength of the samples.

compared to the sample without the modifier. The added modifier can produce a compact cementitious structure similar to zeolite that enhances the bonding force between the sand particles. The produced gelation products are filled between the skeleton, which makes the pores smaller and the interface to get dense. Adding the modifier improves the acid resistance, making it non-corrosive in acidic environments.

3.3 Permeability of the solidified sand

To be used together with spraying, the solidified sand needs to be permeable. Therefore, penetration tests for the solidified sand were carried out. The samples were tested at 7 d using the variable water head method because the solidified sand formed by adding a sand consolidation agent to aeolian sand is different from aeolian sand. After the completion of the tests, there was no obvious pore in the samples. The results of the test are as shown in Fig. 3.

The permeability coefficient of the samples with a modulus of 3.20 of potassium water glass was 1.69×10^{-4} cm·s^{-1}, while that of the samples with a modulus of 3.45 of potassium water glass was 8.25×10^{-5} cm·s^{-1}. The solidified sand was permeable, and the sand consolidation agent forms membranes around the sand, with pores between the membranes. During infiltration, water passes through the pores between the membranes. The samples with high-modulus potassium water glass have more inner membranes and smaller pores than those with low-modulus potassium water glass, so their permeability is relatively lower.

3.4 Wetting-drying cycles characteristics of solidified sand

To simulate rainy conditions in the summer in the Guyuan

Table 2. Comparison of the strength of the samples with and without the modifier.

Modulus of potassium water glass	Strength of samples without modifier (kPa)	Strength of samples with modifier (kPa)	Increase in strength after adding modifier (%)
3.20	865.42	1 146.63	32.5
3.25	950.37	1 356.81	42.8
3.30	1 060.77	1 605.84	60.8
3.35	1 246.32	1 817.12	45.8
3.40	1 419.10	2 207.96	55.6
3.45	1 431.45	2 174.79	51.9

Fig. 3. Permeability test.

area and to prevent the cracking and collapse of the solidified sand on the surface of the slope after erosions from rains and natural drying, wetting-drying tests were conducted through the conventional immersion and natural drying. Sand fixation samples were employed, with 0, 1, 2, 3, 4, and 5 wetting-drying cycles, respectively. The 0 cycles of the samples were not soaked, and the strength was tested directly at 28 d. The rest of the wetting-drying cycles involved saturating the samples for 24 h by completely submerging it in water, and then drying for 48 h to test their strength. After soaking the samples for 24 h in water, the sand on the surface did not collapse. After the wetting-drying cycles, unconfined compression strength tests were performed on the samples (Fig. 4).

As shown in Fig. 4, the strength of the samples decreases with increase in the wetting-drying cycles times. After 1–3 cycles, the strength of the samples decreases rapidly. However, after the third cycle, the strength becomes stable, and then rises above 600 kPa after 5 cycles.

After a number of wetting-drying cycles, the samples gain considerable strength. When the sand consolidation agent is prepared, the structure of the gel network generated by the reaction of potassium silicate and silicon phosphate is sparingly soluble in water. The membranes formed by silica sol and lithium silicate have good water resistance. However, the membranes formed by the self-dehydration of potassium water glass are easily destroyed when fully submerged in water. During the immersion process, some membranes formed by the sand consolidation agent dissolve in the water and reduce the strength of the samples. After 3 cycles, the membranes of the remaining parts become insoluble in water and the structure is not easily destroyed, so the samples retain their strength.

4 Slope solidification tests

The sand consolidation agent was used in a test section of the Zhangjiakou–Chengde Expressway. The sandy slope was an excavation slope with a height of 13 m, length of 50 m, an angle of 45°, and a total area of 920 m^2.

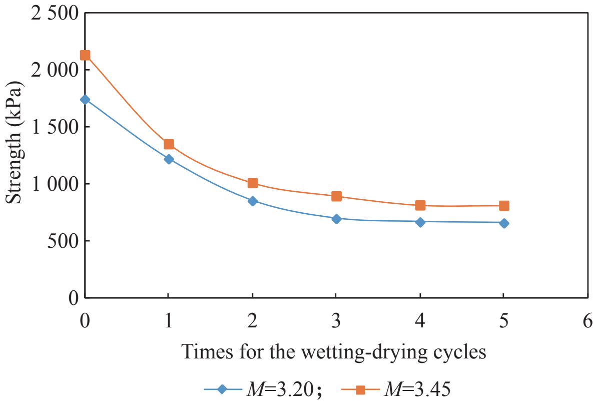

Fig. 4. Changes in the sample strength with wetting-drying cycles time.

The quality of the sand body that needed to be solidified on the surface of the slope was calculated, and the sand consolidation agent prepared on the spot. The modulus of the potassium water glass used was 3.45, with a solid content of 3% of the quality of the solidified sand body. The solid content of the lithium silicate was 2% of the solid content of potassium water glass while that of silica sol 3% of potassium water glass. The quantity of water that needed to be added was determined according to the optimum moisture content of the aeolian sand, and the material stirred evenly. The sand consolidation agent was sprayed evenly on the surface of the sand slope using a spraying equipment. The effect of the spraying is as shown in Fig. 5.

After 2 h, the sand consolidation agent began to solidify, and the strength was formed after 24 h. The surface of the solidified layer formed by the sand consolidation agent on the surface of the slope was smooth. The sand-fixing agent showed good penetrability on the surface of the slope, as shown in Fig. 6.

After spraying the sand-fixing agent for 7 d, the strength of the solidified layer on the surface of the slope was observed by taking one sample every 100 m^2 and testing the strength. The results are as shown in Table 3. It is seen from Table 3 that sand consolidation agent was used in the field. After 7 d, the strength of the solidified layer was above 800 kPa. The solidified layer

Fig. 5. Effect of spraying on the slope.

Fig. 6. Infiltration of sand fixing agent into the slope.

Fig. 7. Solidified effect of sand slope after two years.

Table 3. Sampling strength of the test point on the slope.

Sampling point	Strength (kPa)	Sampling point	Strength (kPa)
1	823.65	6	1 039.19
2	1 089.96	7	912.56
3	963.41	8	1 036.59
4	952.86	9	996.38
5	826.35	10	886.39

was dense with high strength, and was treated with soil spray sowing of grasses. The effect after two years is as shown in Fig. 7.

After two years, there was no water erosion, cracking, collapse, or other such phenomena on the sandy slope. The solidified layer showed good adaptation to the weather. The products cured by the sand consolidation agent can be used as fertilizer for plants to promote the growth of slope plants. The use of soil spray seed sowing does not only lead to green sandy slopes but also increases the stability of the slope.

5 Conclusions

The effect of sand consolidation agent was studied through proportion optimization tests, penetration tests, wetting-drying cycle tests, and field tests. A new chemical sand consolidation technology was proposed to guarantee the safety of highway sand slopes. The following conclusions are drawn:

(1) The strength of the samples increases with increase in the modulus of potassium water glass. The best solid content of the added potassium water glass was obtained at 3% of the quality of the solidified sand.

(2) After adding the modifier, the strength of the samples increased 32.5%–60.8% compared to the strength without the modifier.

(3) The samples were permeable. The samples made with low-modulus potassium water glass showed better permeability than those made with high-modulus potassium water glass.

(4) The sand consolidation agent has good water resistance. Increasing the wetting-drying cycle times led to a gradual decrease in the strength of the samples, with the strength becoming stable after 3 times.

(5) The consolidation agent together with sand spraying improved the stability of slope and slope greening when applied together with soil spray grass sowing in a test section of the Zhangjiakou–Chengde Expressway. Positive results were still obtained after two years of observation.

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