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Research Article

Stabilization of Expansive Soil with Polyvinyl Alcohol and Potassium Carbonate

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Expansive soils have great volume change potentials with water content changes, which is problematic to facilities. Great efforts have been spent on finding proper methods to stabilize expansive soils, but these stabilizers all had limitations. The Polyvinyl alcohol (PVA) and K_2CO_3 combination was proposed in this paper. Free swell tests, oedometric tests, unconfined compression tests, and direct shear tests were performed to investigate the effectiveness of the PVA and K_2CO_3 combination to control the volume change and increase the soil strength. Microstructures of the natural expansive soil and the stabilized soil were also studied with SEM photos. SEM photos showed a homogenous and dense microstructure after stabilization. In addition, a laboratory soil column model was built to study the ability of this stabilizer combination to stabilize expansive soils by directly spraying the solution on the ground surface. All these test results show that the combination of PVA and K_2CO_3 is able to effectively stabilize the natural expansive soil and increase the shear strength. It is possible to directly spray the stabilizer solution on the soil surface to form a relatively thick layer of the stabilized expansive soil.

1. Introduction

Expansive soils have large volume change potentials with water content changes, causing problems such as slope failures (e.g., [1]) and foundation damages (e.g., [2]), especially when there are wetting-drying cycles (e.g., [3]). Great efforts by previous researchers have been done on stabilizing expansive soils and increasing their strengths. Most popular methods to stabilize expansive soils are to mix natural expansive soils with different types of stabilizers. Researchers have been trying to reinforce expansive soils with natural plant fibers such as coir waste by Jayasree et al. [4]; bagasse fiber by Dang et al. [5], and jute fiber by Wang et al. [6]. Manufactured fiber products were used more often (e.g., [7–9]). Recycled fibers such as carpet waste fibers (e.g., [10, 11]) were also used as expansive soil stabilizers. In addition, Expanded Polystyrene (EPS) geofoam was used as an expansive soil stabilizer by Ikizler et al. [12].

Stabilizers involving chemical reactions with expansive soils used were more popular. Lime was very often used as an expansive soil stabilizer (e.g. [13, 14]). Cements were also commonly used as expansive soil stabilizers (e.g., [15, 16]). However, cements are typically very expensive, so affordable stabilizers are needed in practice. Fly ashes typically extracted from the furnace flue fired with coal can also provide sufficient cation exchanges when they are mixed with expansive soils, effectively stabilizing expansive soils (e.g., [17–19]). Furnace slag is another type of stabilizer (e.g., [20, 21]). There are also other rarely used stabilizers such as sulphonated oil by Soltani et al. [22].

However, these stabilizers are nonsoluble or have low solubility to water. Due to complicated site conditions in the field, other than the soil filling projects, it is hard to directly mix field soils with stabilizers as that in the laboratory. Therefore, it is necessary to find a new stabilizer with high solubility to water, and possibly, this new stabilizer solution could be directly sprayed to the ground surface to stabilize the expansive soil in a considerable depth. K^+ can be considered as a great swelling inhibitor because of the lowest hydration energy [23], but it works well only if the soil has swelled with water content increase. Polyvinyl alcohol (PVA) is soluble to water and it reacts with the ions on the crystals, forming complicated and relatively stable compound. Therefore, in order to combine the advantages of these two types of stabilizers, PVA and potassium carbonate (K_2CO_3) will be mixed and used together in this work. Yu et al. [24] proposed a mixture of PVA and KCl to stabilize expansive soils, but they only performed free swell tests, particle size distribution tests, and disintegration tests. However, more important parameters such as oedometric swelling, shear strength, and drying-wetting cyclic stability were not studied, but they will be investigated in this paper. In addition, the advantage of using K_2CO_3 instead of KCl is that CO_3^{2-} can easily react with H_2O, producing HCO_3^- and OH^- which will form weak alkaline solution. In natural expansive soils, there are often ions of Ca, Si, and Al, and these ions will react and generate gelatinous compound in the weak alkaline environment, which will finally increase the soil strength and reduce the swelling potential. Microscopic parameters of stabilized soils were studied with SEM by previous researchers (e.g., [25, 26]), and will also be studied in this paper. In addition, the effectiveness of stabilizing expansive soils by spraying this stabilizer mixture to site soil surfaces will be studied with a soil column model in the laboratory.

2. Experimental Program

2.1. Free Swell Tests. The free swell potential is a very important property of expansive soils. Three groups of free swell tests, firstly proposed by Holtz and Gibbs [27], were performed following the Chinese standard [28] with floating sample rings. In group one, expansive soil samples with the initial moisture content of 20%, the dry natural density of 1.6 g/cm^3, and the maximum dry density of 1.871 g/cm^3 were only stabilized by K_2CO_3 by weight of 1%, 2%, 3%, 4%, 5%, and 6% of the dry expansive soil, respectively; in group two, soil samples were only mixed with PVA by weight of 0.05%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, and 0.6% of the dry soil; and in group three, soil samples were improved with the mixtures with K_2CO_3 of 3% of the dry expansive soil and PVA amounts of 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, and 0.6% of the dry expansive soil.

2.2. Oedometric Swell Tests. Oedometric swell tests were conducted with vertical swelling only from the top of samples. Devices used in oedometric swell tests included the oedometer, the ring-sampler with the diameter of 61.8 mm and the height of 20 mm, and the displacement gauge with the maximum reading of 10 mm. K_2CO_3 powders having weights of 1%, 3%, and 5% of the dry expansive soil were prepared, and PVA powders having weights of 0.1%, 0.3%, and 0.5% of the dry expansive soil were prepared. Then, these powders were mixed together and dissolved into water. 16 solutions were prepared with different ratios of K_2CO_3 and PVA. Finally, these 16 solutions were mixed with expansive soil samples, and then cured for 24 hours with the water content of about 20% which was the minimum average water content in dry seasons, and the samples were collected from the ground surface to the depth of 2.5 m near the highway construction field. Therefore, the mass of the mixture (m_s) needed in the ring samples was calculated with the following equation:

$$m_s = \rho_d \cdot v \cdot (1 + \omega), \tag{1}$$

where ρ_d is the dry density of the ring samples; v is the sample volume; and ω is the water content. In order to fill the ring-samplers with the right amounts of soil samples, two rings were stacked up on a steel plate with smooth surface. Next, the soil mixture was poured into the ring-stack with a cylindrical metal plate on top with the same diameter as that of the ring-stack. Finally, a hydraulic stripping machine was used to push the cylindrical metal plate until its top surface was on the same level as the top of the top ring-sampler.

In the loaded oedometric swell tests, samples were immediately put onto the oedometer and loaded with 50 kPa from the top. Then, when the vertical strain rate was smaller than 0.01 mm per hour, distilled water was poured into the sample container on the oedometer with the water surface 5 mm higher than the sample top surface. The sample height was recorded every two hours until the difference of two adjacent readings was smaller than 0.01 mm.

In the free oedometric swell tests, ring samples were immediately put onto the consolidometer and the sample container was filled with distilled water, and the water surface was set to 5 mm higher than the sample top surface. The sample height was recorded every two hours until the swelling strain rate was smaller than 0.01 mm every 6 hours.

2.3. Unconfined Compression Tests. Because stabilized expansive soils will be used in the field construction projects, compression strength is always the most important property. Unconfined strength tests were performed to determine compression strengths of samples with different curing periods. The natural expansive soil used in tests had the dry natural density of 1.6 g/cm^3 and the maximum dry density of 1.871 g/cm^3. The samples were mixed and stabilized with PVA with the weight of 0.5% of the dry natural expansive soil and K_2CO_3 with the weight of 3% of the dry natural expansive soil. The stabilized samples and natural expansive soils were sealed in the same environment for 24 hours with the water content of approximately 20%. Then, 16 samples of stabilized soil and 16 samples of natural expansive soil were prepared by a hydraulic stripping machine with the diameter of 5 cm and the height of 5 cm. These samples were cured in wet sand for 7 days, 14 days, 21 days, and 28 days, respectively. Finally, they were compressed with the axial strain rate of 0.4 mm/min without any lateral constrains, making sure that they failed within 7–14 min.

2.4. Effects of Cyclic Drying-Wetting. The drying-wetting cycles simulate changes of water content in the field with seasonal weather changes. The stabilized soil samples had PVA with the weight of 0.5% of the dry natural expansive soil and K_2CO_3 with the weight of 3% of the dry natural expansive soil. The samples were prepared with ring-samplers with the diameter of 61.8 mm and the height of 20 mm. In the tests, the water contents were varying in the range between 19% and 25%, simulating the partial drying and partial wetting. After each drying-wetting cycle, photos of the samples were taken and the sizes of cracks were measured with a digital caliper.

The undrained shear strengths of the samples before drying-wetting cycles and after 2 and 4 drying-wetting cycles were tested with direct shear tests. During shearing, the vertical pressures were set to 100 kPa, 200 kPa, 300 kPa, and 400 kPa. Then, samples were sheared with the strain rate of 1.2 mm/min and without water drainage, so they could fail within 3–5 mins.

2.5. SEM Tests. A soil sample was scanned with the scanning electron microscopy (SEM). The SEM device model was XL-30 which was produced by the EDAX company. The soil sample had PVA with the weight of 0.5% of the dry natural expansive soil and K_2CO_3 with the weight of 3% of the dry natural expansive soil. The soil sample was cured for 7 days, and then dried and cut into small pieces with one smooth side sticking to the metal plate.

2.6. Infiltration Test. In the infiltration test, a soil column was built and shown in Figure 1. The soil column container had the height of 1 m, the length of 0.19 m, and the width of 0.13 m with cross cuttings at the heights of 10 cm, 40 cm, and 70 cm from the bottom to easily collect soil samples at these three heights. The natural expansive soil passed a sieve with 2 mm openings, and then was cured for 24 hours with the water content of about 19%. The natural expansive soil had the dry natural density of 1.6 g/cm^3 and the maximum dry density of 1.871 g/cm^3. 33.6 kg soil was filled into the container with the degree of compaction of 85.5%. The PVA stabilizer solution was prepared with PVA with the weight of 0.5% of the dry natural expansive soil, and the K_2CO_3 stabilizer solution was prepared with the weight of 3% of the dry natural expansive soil. 2000 mL of the K_2CO_3 stabilizer solution was sprayed onto the soil surface at once. Then, 723 mL of the PVA stabilizer solution was sprayed onto the top surface of the soil column every day for seven days.

3. Test Results and Discussion

3.1. Free Swell Test. Free swell tests were performed to study the soil swelling potential. Free swell index (FSI) was calculated with the following equation:

$$\mathrm{FSI} = \frac{V_w - V_0}{V_0} \times 100, \quad (2)$$

where V_w is the volume of soil after swelling and V_0 is the volume of dry soil. The FSI values in the three groups of tests are plotted in Figure 2. It can be seen that with the increase of stabilizer amounts, FSI values decrease for all the three groups of tests. Referring to the Chinese standard [28], if the FSI value is smaller than 40%, the soil will not be considered as expansive soil any more. In Figure 2(a), the amount of K_2CO_3 has to be larger than 5% of the dry expansive soil to reduce the FSI value to 39.5% which is smaller than 40%. In Figure 2(b), all values of FSI are larger than 40%. In Figure 2(c), it shows that the FSI value is reducing faster than those in Figures 2(a) and 2(b), and when the PVA amount is less than 0.5%, FSI is reduced to 33% which is even reduced by 45.5% of that with the same amount of PVA in Figure 2(b).

3.2. Oedometric Swell Tests. Free oedometric swell tests were conducted with free swell from the top, and the lateral swell of the samples was not allowed. In the loaded oedometric swell tests, the lateral swell was also prohibited, but 50 kPa vertical load was added to the top of the sample. In order to quantify the swell behavior, oedometric swell index (OSI) was calculated as follows:

$$\mathrm{OSI} = \frac{Z - Z_0}{h_0} \times 100, \quad (3)$$

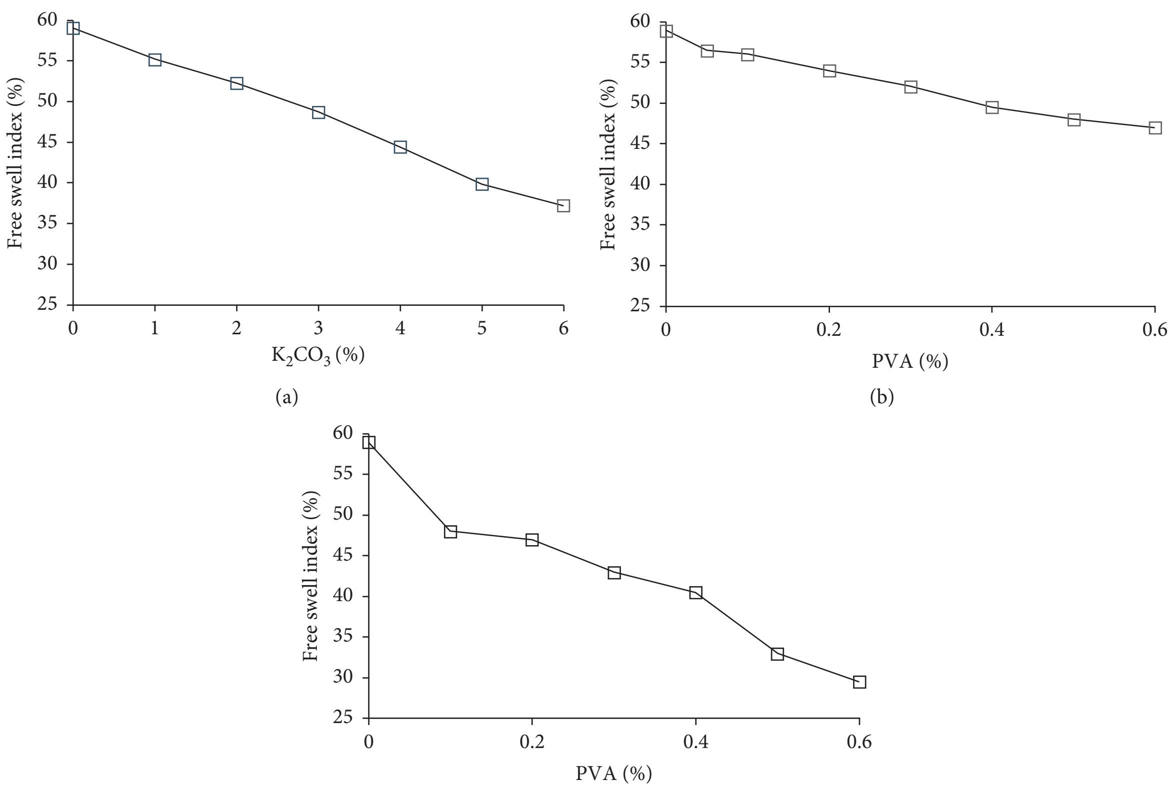
where Z is the current displacement gauge reading; Z_0 is the initial displacement gauge reading; and h_0 is the initial height of the sample. When the swell stopped, the OSI values for samples with different amounts of PVA and K_2CO_3 are shown in Figure 3. It shows that the OSI values in the free oedometric swell tests were so much larger than those in the 50 kPa loaded oedometric swell tests. It also shows that the increasing amount of PVA and K_2CO_3 effectively decreased the amount of swell in both types of oedometric swell tests, but with the same amount of PVA, the decrease of OSI values by the increase of K_2CO_3 amount was more significant than that by the increase of the PVA amount with the same amount of K_2CO_3. It can be concluded that, with sufficient amount of PVA and K_2CO_3, the oedometric swell could be controlled to a reasonable small amount.

3.3. Unconfined Compression Tests. In order to investigate the effect of PVA and K_2CO_3 on the strengths of samples, unconfined compression tests were performed. The photos of the samples before and after tests are shown in Figure 4. It is clear that with the same length of cure period, the samples stabilized by PVA and K_2CO_3 had much smaller bulging after tests than those samples with only natural expansive soil, indicating the effectiveness of the stabilizers to increase the soil strength. For samples with only natural expansive soil, there was even small bulging before compression, which was not observed in the samples with the stabilized soil.

To quantify the effect of PVA and K_2CO_3 on sample strengths, the unconfined compression strengths versus different curing period are plotted in Figure 5. It confirms that the samples stabilized by PVA and K_2CO_3 had higher values of unconfined compression strengths. With the increase of curing period length, the unconfined compression strength values for stabilized soil samples were increasing, but the unconfined compression strength values for natural expansive soil samples were almost constant with different

(a) (b)

Figure 1: Photos of the soil column: (a) side view of the soil column; (b) plan view from the top of the soil column.



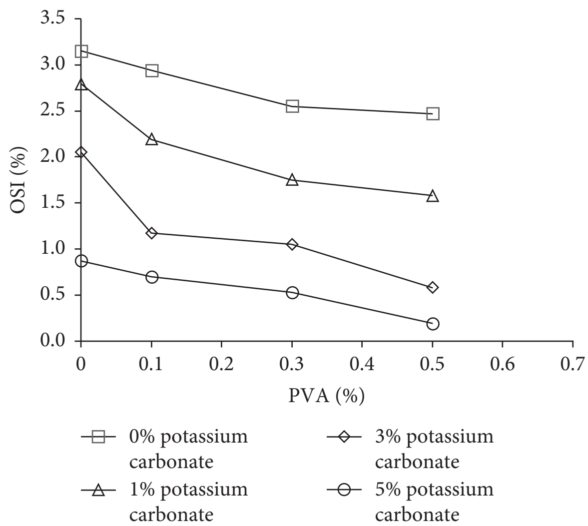
(a) (b) (c)

Figure 2: The free swell index values for samples with: (a) K_2CO_3 only; (b) PVA only; (c) 3% of K_2CO_3 and different amounts of PVA.

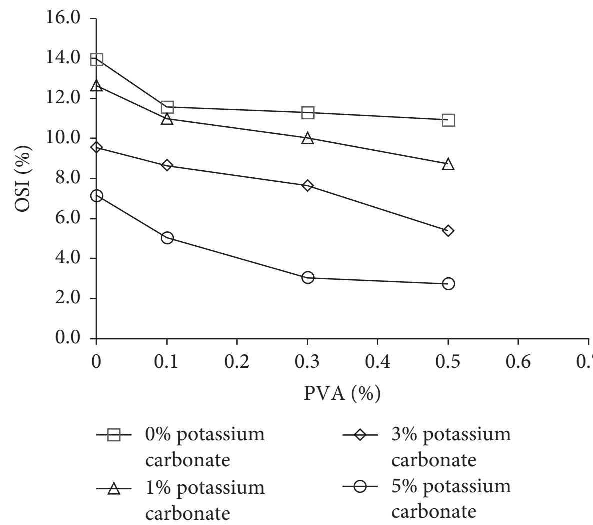
curing period lengths because natural expansive soil samples did not have any changes during the curing periods.

3.4. Effects of Cyclic Drying-Wetting. The majority of strength in expansive soil is from matric suction which is directly related to the water content [29]. Soil strength decreases with the decrease of matric suction caused by the water content increase. When the water content decreases, matric suction will increase, and soil will shrink and crack. Once there are cracks in soil body, water may easily infiltrate deeply, which will further decrease the soil strength. Thus, it is necessary to thoroughly investigate the effect of drying-wetting cycles on soil strength, and it is important to study the ability of stabilizers to reduce cracking. Figure 6 provides photos of the natural expansive soil samples after different cycles of drying-wetting. After 9 cycles, a large crack showed up going through the sample body. Figure 7 shows photos of the stabilized soil samples after different cycles of drying-wetting. Obviously, there are no through-type cracks even after 31 cycles of drying-wetting. The integrity of the sample was almost not changing after 31 cycles of drying-wetting because the samples were stabilized, and there was little volume change during drying-wetting cycles.

To quantify the effect of drying-wetting cycles on the strengths of both natural expansive soil and stabilized soil samples, direct shear tests were performed for samples



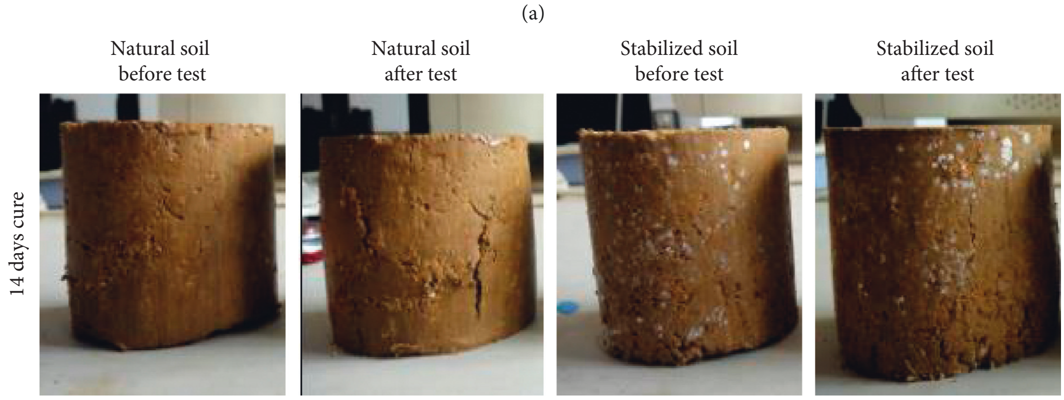
(a)



(b)

Figure 3: Oedometric swell test results (a) with a 50 kPa vertical load; (b) without vertical load.

(a)



(b)

Figure 4: Continued.

Natural soil before test | Natural soil after test | Stabilized soil before test | Stabilized soil after test

21 days cure

(c)

Natural soil before test | Natural soil after test | Stabilized soil before test | Stabilized soil after test

28 days cure

(d)

Figure 4: Photos of the samples before and after the unconfined compression tests.

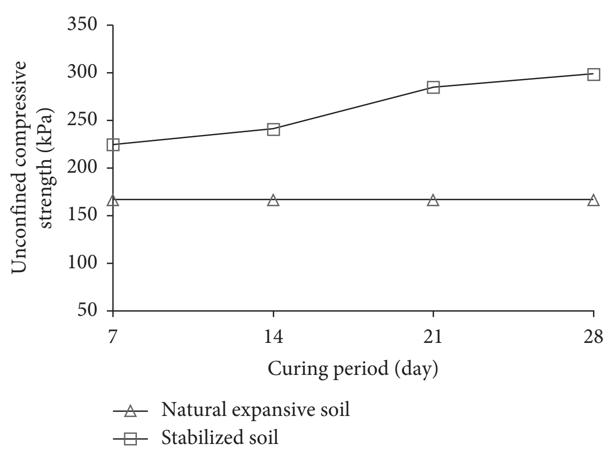


Figure 5: Unconfined compression strengths for samples with different curing periods.

Figure 6: Photos of cracks on natural expansive soil samples with different numbers of drying-wetting cycles. (a) 1 cycle. (b) 5 cycles. (c) 8 cycles. (d) 9 cycles.

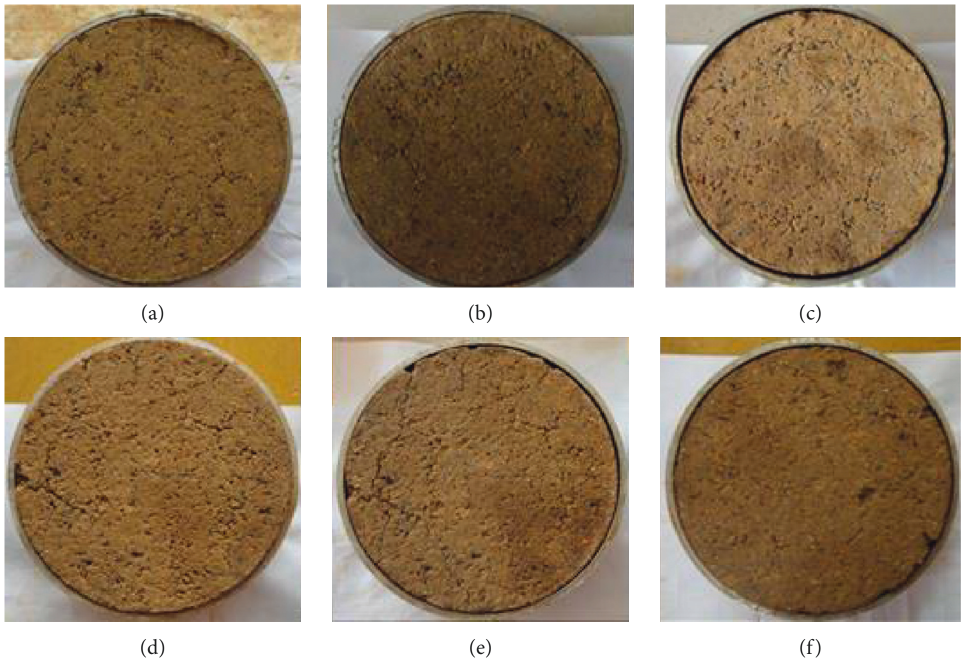


Figure 7: Photos of cracks on stabilized soil samples with different numbers of drying-wetting cycles. (a) 1 cycle. (b) 7 cycles. (c) 13 cycles. (d) 19 cycles. (e) 25 cycles. (f) 31 cycles.

before and after 2 cycles and 4 cycles of drying-wetting. Test results are shown in Figure 8. It can be seen that with the increase of vertical pressures, shear strengths for all the samples increased. The shear strengths of stabilized soil samples were larger than those of natural expansive soil samples because stabilizers reacted with the ions on the crystals, forming complicated and relatively stable compound. More importantly, for stabilized soil samples, with the increase of the drying-wetting cycles, the shear strength decreases were very limited because the stabilized samples had smaller volume changes and subsequently smaller reducing of shear strength. However, for natural expansive soil samples, the shear strength decreases were very significant.

Volume change during drying-wetting cycles is also a very important property to investigate. Figure 9 shows the vertical axial strain changes with the increase of the number of drying-wetting cycles. In Figure 9(a), the stabilized soil sample exhibited swelling-shrinking cycles with the cycles of drying-wetting, and the swelling-shrinking behavior was around a constant axial strain-4%. In Figure 9(b), the natural expansive soil sample also showed swelling-shrinking cycles, but the average values of the axial strain were increasing with the increase of the number of drying-wetting cycles. Therefore, it can be concluded that the soil stabilizer was able to well control the axial deformation even if there were many numbers of drying-wetting cycles.

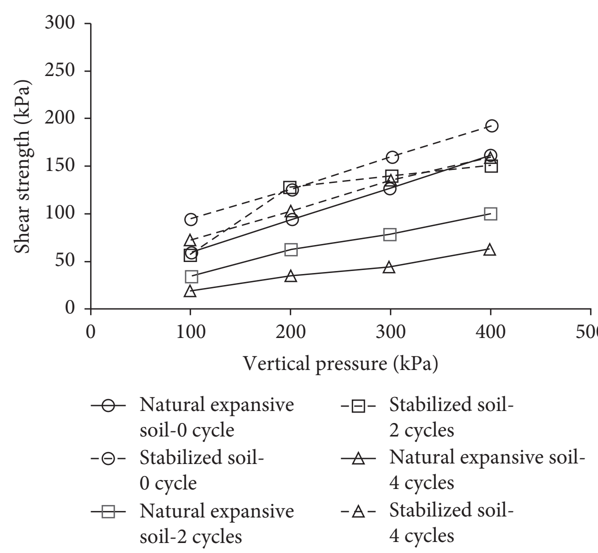


Figure 8: Direct shear strengths for samples with cycles of drying-wetting.

3.5. SEM Tests

3.5. SEM Tests. The microstructure of the natural expansive soil and the stabilized expansive soil is directly related to the macroscopic swelling potential. Therefore, the scanning electron microscopy (SEM) was used to take photos of the soil microstructures shown in Figure 10. The soil particle photos were taken at three scales: 100 μm, 20 μm, and 10 μm. It shows that blocks of clay particles with the size of about 5~10 μm spread out without any directionality. In the natural expansive soil, particles showed up as individual surface-flat blocks, loosely with large voids between particles. However, in the stabilized soil, clay particles were embedded into the PVA colloid. The soil was homogenous and very dense without large voids, which interpreted the increased soil strength from the microscale view of point. It can be concluded that the soil microstructure was completely changed by the stabilizer.

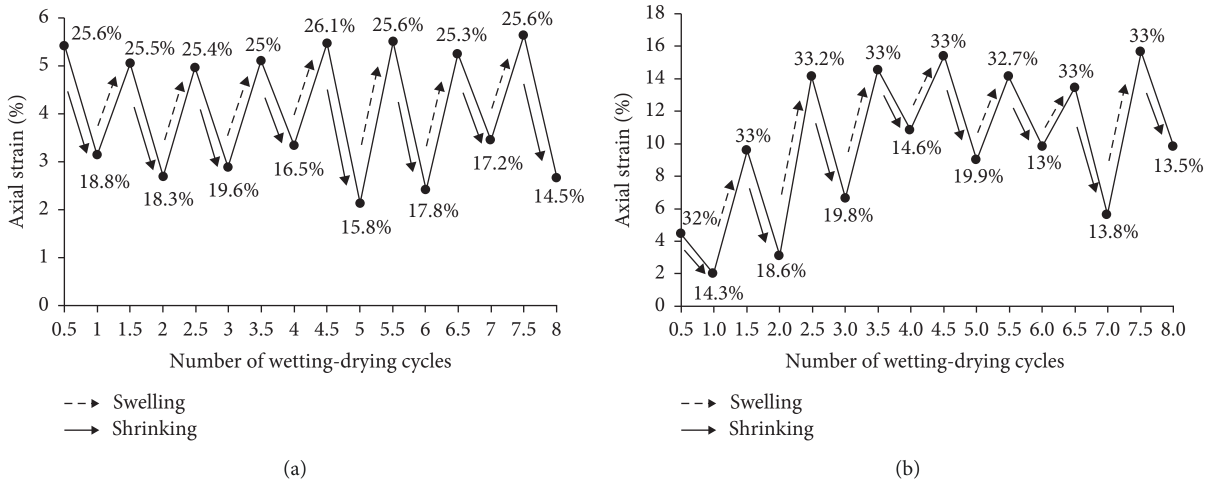


Figure 9: Axial deformations during swelling-shrinking cycles: (a) the stabilized soil sample; (b) the natural expansive soil sample.

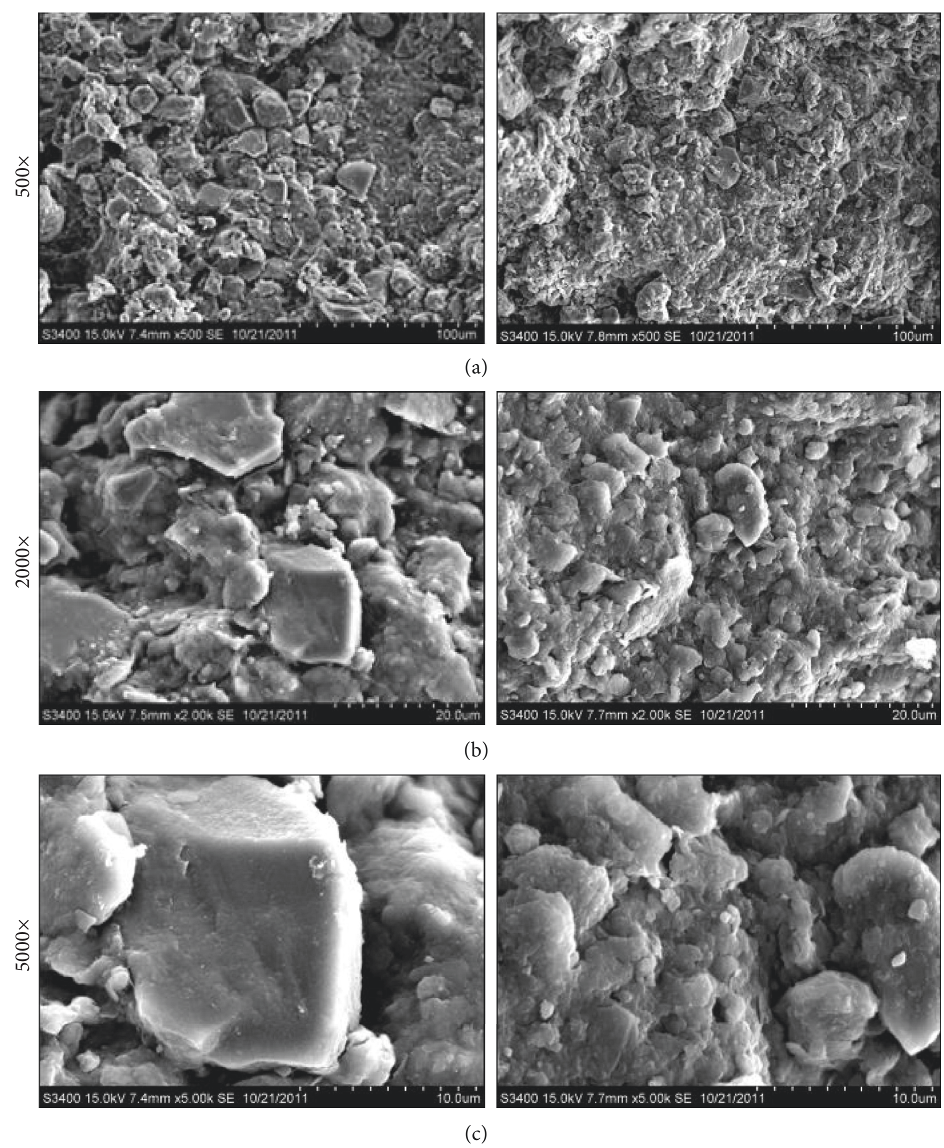


Figure 10: SEM micrographs of the samples with and without stabilization. Note: the SEM images were taken in 2011.

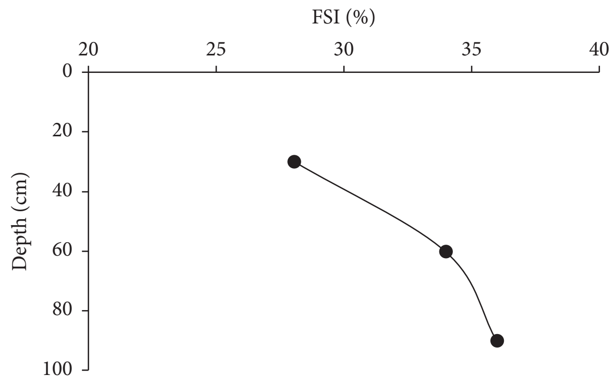


Figure 11: Free swell index at different depths.

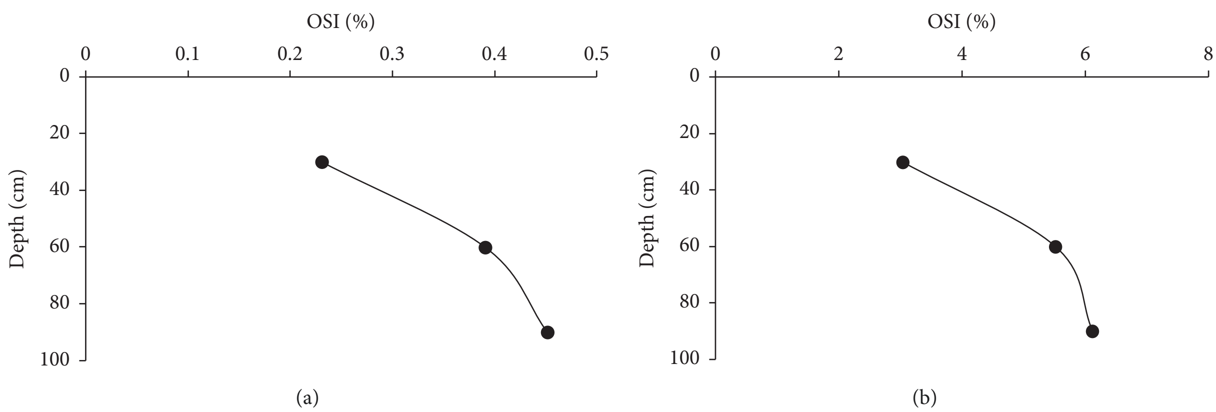


Figure 12: Oedometric swell index at different depths: (a) 50 kPa loaded oedometric swell tests; (b) free oedometric swell tests.

3.6. Infiltration Test. One of the main goals of this work is to find a stabilizer which can be directly sprayed onto the soil surface and stabilize the natural expansive soil in the field simply by infiltration vertically through the small cracks and then horizontally into soil blocks. Then, the soil in the surface layer can be stabilized as a protection layer, and subsequently, it will help to resist drying-wetting cycles and rainfall events, keeping the moisture content constant in the deeper soil layer. Finally, the soil slope stability will be increased.

After spraying, the soil samples at the depths of 30 cm, 60 cm, and 90 cm were collected, and the free swell test results are shown in Figure 11. With the increase of depth, the FSI value was increasing, but even at the 90 cm depth, FSI was still smaller than 40%, meaning that it fulfilled the requirement by the Chinese standard [28]. In addition, both loaded and free oedometric tests were performed, and the oedometric swell index values were calculated with equation (3) and shown in Figure 12. It shows that the OSI values were also increasing with the increase of soil depth, but the OSI values were always in a range which also met the field project requirements [28].

The shear strengths at the depths of 30 cm, 60 cm, and 90 cm were also tested by direct shear tests with the vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa. The test results are shown in Figure 13. It can be seen that higher vertical pressures induced higher shear strength values. However, it is more important that with the same amount of vertical pressure, the samples from deeper soil layers had smaller shear strength values, indicating more effective stabilization at the shallower soil layers.

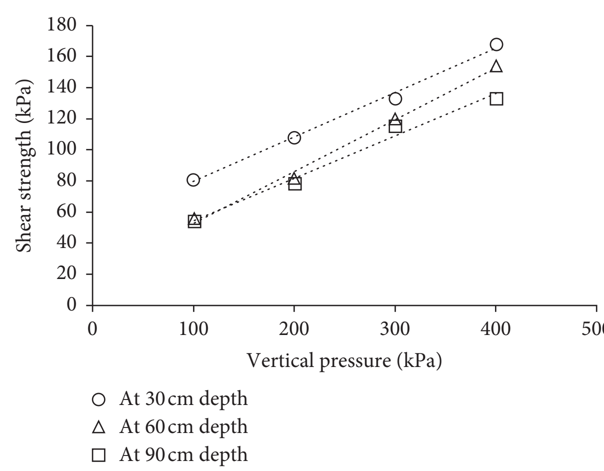


Figure 13: Shear strengths at different depths.

4. Conclusions and Recommendations

In this paper, polyvinyl alcohol and potassium carbonate were used to stabilize the expansive soil. Free swell tests, oedometric swell tests, unconfined compression tests, and direct shear tests were performed to study the swelling potential and shear strength of the stabilized soil. The microstructures of the stabilized soil were also studied with SEM photos. Finally, a laboratory model with a 1 m high soil column was built to simulate the stabilization of field soil by directly spraying the stabilizer solution onto the soil surface. Some conclusions can be summarized as follows:

(1) With the free swell test results, it shows that it is more effective to stabilize the expansive soil with the combination of PVA and K_2CO_3 than to do it with only PVA or K_2CO_3 individually.

(2) Oedometric test results confirmed the ability of the combination of PVA and K_2CO_3 to control the volume change. Unconfined compression test results showed that the stabilized soil samples had much higher strengths.

(3) After many drying-wetting cycles, the strength and volume changes of the stabilized soil samples were well controlled.

(4) SEM photos showed that the stabilized soil sample had more homogenous and denser microstructures than the natural expansive soil sample.

(5) The laboratory soil column model confirmed the ability of the stabilizer solution to form a thick protection layer to resist volume changes during drying-wetting cycles and keep the water content constant in the lower layer.

Finally, it can be concluded that the PVA and K_2CO_3 combination is able to serve as an effective stabilizer of expansive soil, and more importantly, it is possible to stabilize field soils by directly spraying the stabilizer solution on the soil surface, forming a thick protection layer.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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