KSCE Journal of Civil Engineering (2021) 25(2):417-428
DOI 10.1007/s12205-020-0341-6

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Geotechnical Engineering

Study on Properties of Expansive Soil Improved by Steel Slag Powder and Cement under Freeze-Thaw Cycles

Yankai Wu[a,b], Xiaolong Qiao[a], Xinbao Yu[c], Jiali Yu[a], and Yongfeng Deng[d]

[a]School of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China
[b]Shandong Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China
[c]Dept. of Civil Engineering, The University of Texas at Arlington, Arlington, TX 79019, USA
[d]Institute of Geotechnical Engineering, School of Transportation, Southeast University, Nanjing 211189, China

ARTICLE HISTORY

Received 28 February 2020
Revised 1st 2 June 2020
Revised 2nd 12 July 2020
Accepted 8 September 2020
Published Online 9 November 2020

KEYWORDS

Expansive soil
Freeze-thaw cycle
Steel slag powder
Unconfined compressive strength
Volume change rate

ABSTRACT

Expansive soil is considered to be an unfavorable soil due to its swelling-shrinking behavior. In order to improve the properties of expansive soil, the addition of steel slag powder (SSP) has been used to improve expansive soil that has been mixed with the cement. In this study, a series of cylindrical improved expansive soil specimens were prepared, which were improved either by the addition of cement, cement SSP, or cement SSP sodium hydroxide (NaOH). All of the specimens were prepared with an optimum water content and then subjected to a maximum of 12 closed-system freeze-thaw (F-T) cycles. The specimens were subjected to different curing times and temperatures (-5ºC,-10ºC and -15ºC) during the tests. After each freeze-thaw (F-T) cycle, the volume of each specimen was measured and an unconfined compression strength (UCS) test was performed. The results have shown that as the temperature of the F-T cycle decreased, the volume expansion rate increased with the increase of the length of the F-T cycle. As the curing time increased, the effect of the F-T cycles on the volume change rate of the specimens reduced and the UCS increased. The first F-T cycle had the greatest influence on the volume of the specimen as well as the UCS of the improved expansive soil. After the improved expansive soils had undergone more than eight F-T cycles, the volume change rate of the specimen tended to stabilize. The maximum F-T volume change rate of the improved soil was 1.93%.When the curing age was 60d and 90d, the strength of the specimen with cement SSP sodium hydroxide was 377.3 kPa and 294.7 kPa higher than the specimen with cement only (ES specimen), and its strength degradation rate was 18.737% and 9.97% lower than the ES specimen. The results have shown that the addition of SSP and cement improved the expansive soil; moreover, NaOH inhibited the degradation of the soil during an F-T cycle.

1. Introduction

Expansive soil is considered to be "catastrophic soil" or a "cancer" in engineering construction, due to the need to subject it to complex treatment (Chen et al., 2007). In order to solve this problem, many researchers have conducted long-term research on the properties of expansive soil. Its swelling-shrinking characteristics can cause significant damage to the safety of the superstructure of a building (Zheng et al., 2009; Puppala et al., 2011). As a result, many scholars have suggested various methods to improve expansive soil. Physical improvement and chemical treatment are the most significant methods of improving expansive soil. Physical improvement is mainly used to improve the engineering properties of expansive soil by mixing it with coarse materials, such as sand, gravel, slag, etc. Chemical treatment is used to improve the physical and mechanical indices of expansive soil by inducing a physicochemical reaction in the expansive soil with admixtures such as fly ash, cement, lime, etc. Many scholars and engineers have conducted detailed research on both the physical and mechanical properties of improved

CORRESPONDENCE Yankai Wu wuyankai2000@163.com School of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China; Shandong Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China

expansive soil. (Cokca, 2001; Wang et al., 2006; Zha et al., 2007; Abdullah and Al–Abadi, 2010; Kong et al., 2010; Yazdandoust and Yasrobi, 2010; Al-Mukhtar et al., 2012; Guillaume et al., 2012; Olgun, 2013; Khemissa and Mahamedi, 2014; Hotineanu et al., 2015; Soltani et al., 2018). At present, cement is the additive that is most widely used for chemical improvement of expansive soil. The addition of cement causes a large number of ion exchange reactions of the free aluminum silicon ions in the expansive soil, which results in an agglomeration reaction and the soil setting hard; this can increase the plastic limit of expansive soil, reduce the plastic index of expansive soil, and improve the expansion and shrinkage of expansive soil. However, the production of cement causes serious environmental pollution, therefore, it is necessary to find more environmentally friendly additives to chemically improve expansive soil.

After expansive soil has been chemically treated, its expanding and shrinking properties will be significantly reduced. As a result, the potential for damage to the superstructure of the system it supports will also be reduced. However, when the environmental conditions change, the physical and mechanical properties of the improved expansive soil will also change, especially for the conditions of dry-wet (D-W) cycles or freeze-thaw (F-T) cycles. At present, many studies have reported on the physical and mechanical properties of expansive soil as well as improved expansive soil when subjected to D-W cycles (Cui et al., 2002; Alonso et al., 2005; Cuisinier and Masrouri, 2005; Estabragh et al., 2015; Rosenbalm and Zapata, 2017). However, relatively few articles on research into expansive soil and improved expansive soil under F-T cycles exist. Bin-Shafique et al. (2011) compacted two types of expansive soil improved by fly ash and a man-made fiber to produce specimens for F-T tests; after the F-T cycles, the UCS, splitting tensile strength, and the vertical expansion of the specimens were measured. The test results indicated that the strength of both improved soil specimens had been significantly reduced due to the F-T cycle, but the fiber content made the strength loss less likely, and the expansion potential had been obviously reduced. Olgun (2013) used lime, chaff ash, and fiber to improve the properties of expansive soil and then conducted a UCS test and expansion tests on the soil after exposing it to F-T cycles; the results showed that F-T cycles have a significant effect on the mechanical properties of both the improved expansive soil and the unimproved expansive soil. Hotineanu et al. (2015) studied the mechanical properties of lime-improved expansive soil and kaolin soil under F-T cycles; these additives can change the cohesion force of the soil. The first F-T cycle was especially aggressive and it affected the soil's degradation the most. Yang et al. (2016) studied the shrinkage and deformation of expansive soil that had been improved by the addition of weathered sand under F-T cycles; the results showed that weathered sand can effectively inhibit the volume change rate of the soil caused by F-T cycles. Xu et al. (2017) studied the physical-mechanical properties of cement-improved expansive soil under F-T cycles; their research results indicated that the improved expansive soil displayed the characteristics of "freezing shrinkage and thawing expansion". As the ash to soil ratio increased, the maximum amount of F-T cycles and thawing expansion decreased accordingly. As the number of F-T cycles increased, the strength and elastic modulus of the soil gradually decreased and stabilized. Liang et al. (2018) through the microstructural analysis found that the influence of F-T cycle on expansive soil was concentrated in pores of more than 5 μm, when the F-T cycles exceed a threshold, the effect of F-T cycle on shear strength and volume strain was not significant. Wang et al. (2018) conducted experimental research on expansive soils that had been improved by the addition of ionic soil stabilizer under F-T cycles. The results showed that under the condition of the F-T cycles, the strength of the improved expansive soil decreased with both the increase in the water content and the number of F-T cycles. The porosity of expansive soil increased with the number of F-T cycles; this resulted in a substantial change in the strength of the expansive soil after the first F-T cycle. When the 7th F-T cycle had been completed, the strength change rate of the soil was the smallest of all the cycles and tended to be stable. Lu et al. (2019) carried out F-T cycle tests on specimens of expansive soil with different water contents for three different temperatures (-5ºC, -10ºC, -15ºC); the test results showed that the freezing temperatures had a significant effect on the volume change rate of the soil. The above research results mainly focused on the physical and mechanical properties of expansive soil and conventional improved expansive soil under the action of F-T cycles. However, no studies have investigated steel slag powder combined with cement to improve expansive soil, especially under the action of F-T cycles.

Steel slag is a by-product of steelmaking, and it has a similar chemical composition to cement and it is an industrial waste material. China's steel industry produces approximately 100 million tons of steel slag every year. At present, the utilization rate of steel slag in China is only about 40%, and the rest steel slag was mainly used for stacking treatment; this causes secondary environmental pollution. Grinding the steel slag into powder, and then using it to improve the expansive soil will not only improve the physical and mechanical properties of expansive soil but also realizes the reuse of waste.

In this study, the steel slag powder is used to replace part of cement for improving expansive soil in order to improve its physical and mechanical properties. However, due to the low activity and slow hydration of steel slag powder, According to the previous research results of the research group (Wu et al., 2017a), NaOH is used as an additive to stimulate its activity and improve its hydration rate. Both the volume change rate and UCS of the improved expansive soil have been analyzed at a temperature of -10ºC with different numbers of F-T cycles, as well as different curing times.

2. Test Materials and Specimen Preparation

2.1 Materials Used in the Test

The expansive soil that was used in this study was taken from the

Table 1. Physical and Mechanical Parameters of Expansive Soil

Specific gravity	Natural water quantity (%)	Density ($g \cdot cm^{-3}$)	Maximum dry density ($g \cdot cm^{-3}$)	Optimum moisture content (%)	Porosity (%)
2.74	29.6	1.95	1.546	28.2	45.4%
Plastic limit (%)	Liquid limit (%)	Plasticity index	Saturation (%)	Free expansion rate (%)	Void ratio
31.7	68.8	37.1	99	66.5	0.94

Table 2. Main Chemical Composition and Percentage Content of SSP and Cement

Chemical composition	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	MnO_2	SO_3	Na_2O	P_2O_5	TiO_2	K_2O
Steel slag powder	45.99	2.55	14.07	4.26	24.15	4.36	—	—	2.6	2.01	0.01
Cement	65.14	5.03	22.17	4.30	0.510	—	2.70	0.15	—	—	—

(a) (b) (c)

Fig. 1. Materials Used in the Tests: (a) Expansive Soil, (b) Cement Powder, (c) Steel Slag Powder

southern suburb of Linyi City, Shandong Province, China. The soil sample was gray-black, plastic, with high viscosity, a high natural moisture content, and its fracture surface was waxy and smooth, with the typical characteristics of expansive soil. After taking the soil samples back to the laboratory, the physical and mechanical parameters of the expansive soil were tested. The optimum moisture content and maximum dry density of the expansive soil were determined by compaction test. According the CN standard (GB/T 50123-2019, 2019), the specific parameters of the results are shown in Table 1.

The cement that was used in the test was p.c32.5r composite Portland cement. The main components of the cement are dicalcium silicate, tricalcium silicate, tricalcium aluminate and tetracalcium ferroaluminate. The steel slag powder that was used the test was ground from steel slag, which is a black powder; its chemical composition includes MgO, Fe_2O_3, Al_2O_3, MnO, etc. According to the method for chemical analysis of cement (ISO 29581-1, 2009), the main chemical components of the cement and the SSP and the percentage of each of their constituents were tested and the results have been shown in Table 2. It can be seen from the table that the SSP has a similar chemical composition to the cement. The three materials that made up the specimens that were used in the freeze-thaw tests presented in this paper, i.e., the expansive soil, the cement, and the SSP used in the test have been shown in Fig. 1.

2.2 Specimen Preparation

In this study, three methods were used to improve expansive soil, namely, cement improved expansive soil (ES-C), cement and steel slag powder improved expansive soil (ES-SSP-C), and cement and steel slag powder and an activator (NaOH) improved expansive soil (ES-SSP-C-N). According to the previous research results in the literature (Wu et al., 2017b), the specific ratios of the three improvement schemes have been shown in Table 3.

According to the ratios of the expansive soil improvement schemes shown in Table 3, the test specimens were prepared in

Table 3. Improved Ratio of Modified Expansive Soils

Test groups	Abbreviations	Cement (%)	Steel slag powder (%)	NaOH(%)
Expansive soil	ES	0	0	0
Cement soil	ES-C	10	0	0
Steel slag powder cement soil	ES-SSP-C	5	10	0
Steel slag powder cement sodium hydroxide soil	ES-SSP-C-N	5	10	1.0

Table 4. Control Parameters of Specimens

Specimen	Optimum water content ω_{op}/%	Maximum dry density ρ_{dmax}/(g/cm³)	Total density ρ/(g/cm³)
Es	28.20	1.430	1.833
Es-C	29.05	1.424	1.838
Es-SSP-C	28.71	1.442	1.861
Es-SSP-C-N	28.96	1.421	1.833

cylinders of 3.91 cm in diameter and 8 cm in height; production of the test specimens was mainly carried out according to the following steps:

1. The expansive soil was ground after outdoor natural air-drying, and it was then passed through a sieve with a mesh diameter of 2 mm (ASTM E11, 2017). The water content of the soil specimen was measured after sieving, and the specimens were put into a moisturizing tank or plastic bag and then set aside.
2. According to the optimum moisture content measured by the compaction test (as shown in Table 4), the air-dried sieved soil specimen was then weighed and then spread over the surface of an enamel pan. Water was then evenly sprinkled onto the soil and mixed well, the specimen was then put it into an earthen container and the lid was closed to ensure that the water was retained for 24 hours.
3. The compaction method was then used to prepare the specimen. The wetted soil was poured into the specimen barrel in five layers and each layer was compacted 25 times. Each layer was pressed down using the same compactor; after each layer had been compacted, it was then trimmed and then another amount of wetted soil was added. This procedure was carefully followed to produce a cylindrical soil specimen with a diameter of 39.1 mm and a height of 80 mm. After the soil specimen has been compacted for five times and the surplus soil specimen outside the mold is cut, the soil specimen was deemed to have been compacted.
4. After the specimens were taken out of the molds, they were placed in a thermostatically controlled box at a temperature of 25ºC and a constant relative humidity of 95%. During the F-T cycle test, the specimens with wrapped in cling film to reduce water dispersion loss (as shown in Fig. 2).

Fig. 2. Various Modified Expansive Soil Specimens Prepared

3. F-T Cycle Realization Process and Testing Parameters

3.1 F-T Cycle Realization Process

The method for simulating the improved expansive soil undergoing the F-T cycle process was the F-T cycle test method that was studied by Ghazavi and Roustai (2010), Lu et al. (2019), and Dagesse (2013). The specimens were frozen in a low-temperature test chamber for 12 hours and then the specimens were kept at room temperature for 12 hours. As part of the F-T test, a low-temperature test box was used in this test, as shown in Fig. 3. The temperature of the box can be reduced to -20ºC.

In the F-T cycle test, three types of improved expansive soil specimens were placed in standard curing boxes and cured for 7, 28, 60, and 90 days. When the curing time had elapsed, the specimens were placed in a low-temperature test chamber and then specimens with different curing times were subjected to F-T cycle tests with different minimum temperatures (-5ºC, -10ºC, and -15ºC). Taking the specimens that had been cured for 28d as an example, the three types of improved expansive soil specimens were prepared and cured for 28 days, and the F-T cycles with temperatures of -5ºC, -10ºC, and -15ºC were carried out. During

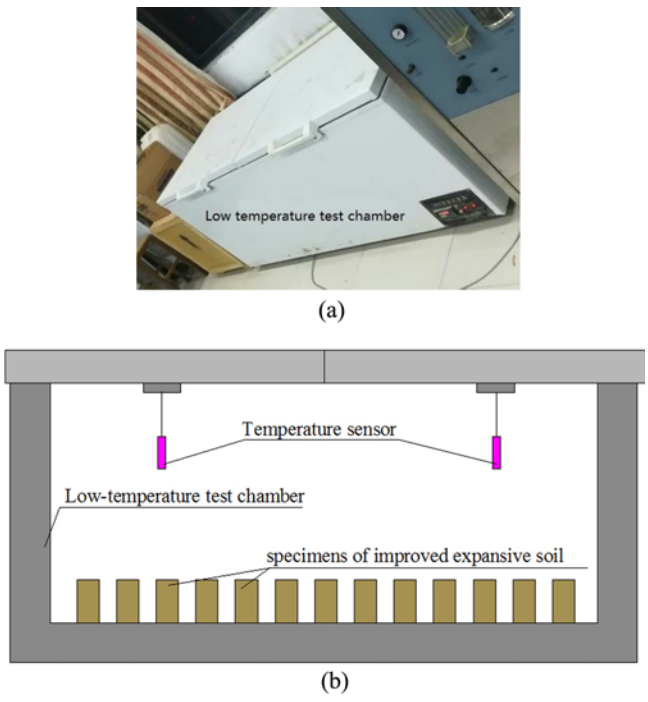

Fig. 3. Low-Temperature Test Chamber for F-T Cycle: (a) Freezer Chamber, (b) Schematic Design of F-T Test

the F-T cycle tests, the specimens were always wrapped with cling film and parallel experiments were conducted. There were three specimens in each group and the average values were taken as the final results from the tests.

3.2 Testing Parameters and Process

This study has focused on the number of F-T cycles and the curing time for the improved expansive soil. The volume change rate, the unloaded expansion rate, and the UCS of the improved expansive soil were measured during each F-T cycle. Once the testing process had been completed, the three types of improved soil were investigated using the Scanning Electronic Microscopy (SEM).

3.2.1 Volume Measurements

The diameter and height of the specimens were measured using a vernier caliper after each freeze and thaw cycle. The volume of the specimen could then be calculated from the measured data because the shape of the specimens was still a standard cylinder after the F-T cycles (as shown in Fig. 4.).

In order to reduce any errors that could occur during the measurements, the diameter and height of each specimen were measured at different locations. The average values from the three specimens were used as the final diameter and height in order to calculate the volume of the specimen.

The volume change rate of the specimens after freezing and thawing was determined by the following equations:

$$\delta_{Fn} = \frac{V_{Fn} - V_0}{V_0} \times 100\% , \tag{1}$$

$$\delta_{Tn} = \frac{V_{Tn} - V_0}{V_0} \times 100\% , \tag{2}$$

where δ_{Fn} and δ_{Tn} denote the volume change rates of a specimen after the N^{th} freezing cycle and after the N^{th} thawing cycle, respectively (a positive rate indicates expansion, a negative rate indicates shrinkage). V_{Fn} denotes the volume of the specimen after the N^{th} freeze cycle, V_{Tn} denotes the specimen's volume after the N^{th} thawing cycle, and V_0 denotes the specimen's volume prior to the F-T cycles.

(a) (b)

Fig. 4. ES Sample during the F-T Cycles: (a) ES Sample after Freezing, (b) ES Sample after Thawing

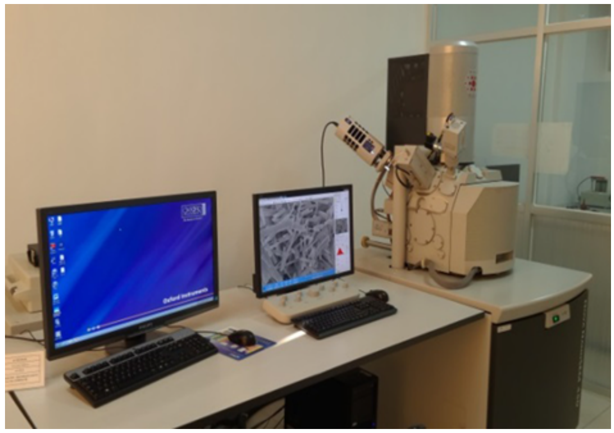

Fig. 5. Scanning Electron Microscope

3.2.2 Unloaded Expansion Rate

At any time, the expansion rate was calculated as in the following equation:

$$\delta_t = \frac{z_t - z_0}{h_0} \times 100\% , \tag{3}$$

where

h_0 = Initial height of the specimen (mm)
z_0 = Displacement reading at time 0 (mm)
z_t = Displacement reading at time t (mm)
δ_t = No load expansion rate (%) at time t

3.2.3 Unconfined Compressive Strength

The unconfined compressive strength test was performed using a WAW-1000B electro-hydraulic servo-hydraulic universal testing machine. The test machine was able to monitor the stress-strain value of the specimens during the test process, and the test strain was kept at 1.2%. The loading speed is controlled at 1 mm/min.

3.2.4 Scanning Electron Microscopy

Throughout the electron microscope scanning test, the distribution, size and other characteristics of the particles and holes as well as the other structures of the various specimens after a freeze-thaw cycle were qualitatively observed. The causes of any change in the macro strength of the specimen were analyzed, in order to combine the micro characteristics of the specimen with the change in the macro strength of the specimen. The test instruments that were used have been shown in Fig. 5.

4. Test Results and Analysis

4.1 Relationship between the Number of F-T Cycles and the Volume Change Rate of the Specimens

The specimens were prepared according to the method specified in the previous sections, and then the unimproved expansive soil and the three improved expansive soil specimens were placed in a standard curing box for 7d. The experiments were carried out using different F-T cycles with the lowest temperature set at

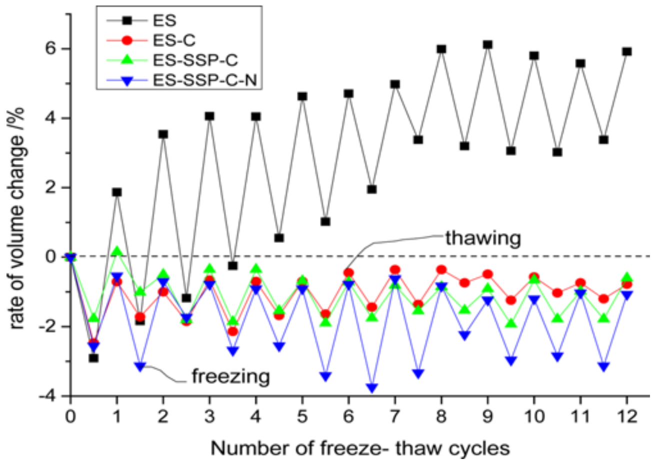

Fig. 6. The Volume Change Rate of the Specimen with the Number of F-T Cycles (0 represents the initial volume, 0.5, 1.5... represents freezing, and 1, 2... represents thawing.)

-10ºC. The volume change of the specimens were measured throughout the test process.

As can be seen from Fig. 6, regardless of whether the ES specimens were frozen or thawed, the volume change rate during the F-T cycles was very remarkable compared with the improved specimens. During the F-T cycles, the curve for the volume change in the ES specimens showed an upward parabolic trend. The ES specimens exhibited characteristics of both freezing shrinkage and thawing expansion during the first four of the F-T cycles. Lu et al. (2019) also encountered this phenomenon in expansive soil in their research. As the number of F-T cycles increased, the volume of the specimens continued to expand. After eight F-T cycles, the volume change rate of the specimen tended to stabilize. The reasons for this phenomenon are that the water in the expansive soil freezes and turns into ice; water expands when it freezes therefore the volume of the specimens also expands during the first four F-T cycles. However, a large amount of water loss occurs on the surface of the clay particles during the F-T cycles; as a result of this, the volume of the expansive soil particles appear to shrink. At this point, the shrinkage characteristics of the expansive soil plays a major role, in that the volume was shown to shrink. During the first four F-T cycles, the volume of ice reduces as it melts and turns into water; however, the volume of the expansive soil was larger than the original volume of the specimen after the cycles, this is because the granular soil swells when it encounters water. After the 8th F-T cycle, the amount of shrinkage and swelling of the ES specimens gradually stabilized. Throughout the F-T cycles, the maximum difference in the values of the volume change rate was 5.38% for the unimproved expansive soil, but it maintained a volume change rate of about 2.6% at the end of the testing (eighth cycle) when it became stable. A volume change rate like this can cause serious damage to a building's superstructure during F-T cycles.

The volume of the ES-SSP-C specimens appeared to shrink during the first F-T cycle, which follows the rules of freezing shrinkage and thawing expansion. The ES-C and ES-SSP-C-N specimens did not expand throughout the F-T tests; instead, shrinkage was the dominant characteristic. One of the reasons for this is that the hydration reaction between the SSP, the cement and the expansive soil produces a new hydrated gel; this results in the expansive soil particles becoming more compact. This finding is similar to that of Liu et al. (2019). At the same time in the process of the F-T cycles, the adsorption between the soil particles increased. Therefore the volume of the specimens appeared to shrink during both freezing and thawing cycles.

The volume change rates of the ES-C and ES-SSP-C specimens displayed a good linear steady-state tendency. In the first F-T cycle, the volume change rates of the ES-C and the ES-SSP-C specimens were the largest. The reason for this is that the hydration reaction of the cement and SSP had not fully completed as there was insufficient water; therefore, the cementation of the newly formed hydrates and particles was not satisfactory. Therefore, during the first F-T cycle, the characteristic of freezing causing shrinking and thawing causing expansion was very obvious for the improved expansive soil. After the second thawing process, the volume change rate of the ES-SSP-C was negative, which means that its volume had shrunk. After the third F-T cycle, the improved expansive soil reached a dynamic stable state, and there was no swelling phenomenon. The maximum F-T volume change rate of the improved soil was 1.93%, which indicates that mixing the expansive soil with SSP and cement was able to substantially reduce both the expansion and shrinkage of the specimens.

4.2 The Relation between F-T Cycles and the Volume Change Rate of the Improved Soil for Different Curing Times

After the various specimens were cured for 7d, 28d, and 90d before undergoing a different number of F-T cycles at a minimum temperature of -10ºC, the diameter and height of the specimens were measured so that the volume could be calculated.

After the ES-C specimen had been cured for 7d and 28d, the volume change rate was relatively large after each F-T cycle (Fig. 7(a)), which showed that the change in the volume of the specimens has little to do with the number of F-T cycles. After the specimens had been cured for 90d, the volume change rate reduced as the number of F-T cycles increased before finally stabilizing. The change in volume of the ES-C specimen indicates that the curing time of the specimen had a controlling effect on the expansion potential of the expansive soil.

After the ES-SSP-C specimens had cured for 7d and 28d, the volume change rate of the specimens was also relatively large after each F-T cycle (Fig. 7(b)), but the volume change rate was smaller than that of the ES-C specimen. After the ES-SSP-C specimen had been cured for 90d, the volume change rate fluctuated slightly around 0. The ES-SSP-C volume change rate was smaller than that of the ES-C, which has shown that the degree of damage caused by the F-T cycles can be reduced by adding SSP to the expansive soil. As the curing time increased,

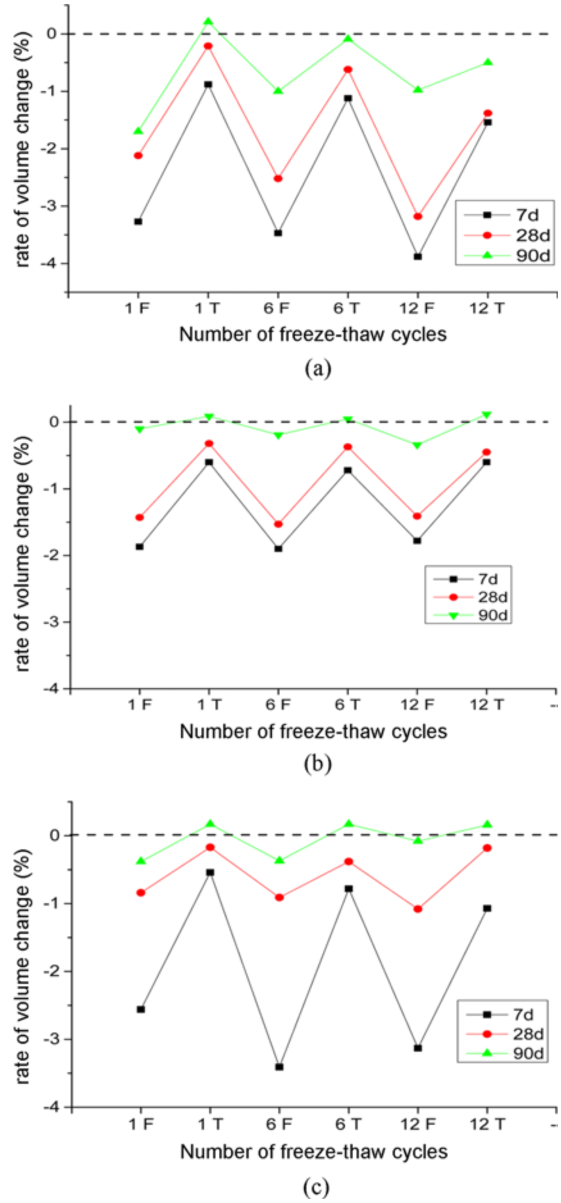

Fig. 7. The Curve of the Volume Change Rate of Different Curing Times: (a) ES-C, (b) ES-SSP-C, (c) ES-SSP-C-N

the volume change rate during the freezing and thawing cycles gradually decreased, which indicated that the expansion potential of the expansive soil was under control.

After the ES-SSP-C-N specimen had cured for 28d and 90d, the volume change rate fluctuated between -1% and 0.5% during all of the F-T cycles (Fig. 7(c)). The volume change ranged between -3.5% and -0.5% after the specimens had been cured for 7d. This phenomenon has shown how the addition of NaOH was able to accelerate the SSP and cement hydration reaction, thereby stabilizing the expansive soil. After the ES-SSP-C-N specimen had been cured for 28d, the expansion potential of the specimen had stabilized. The difference in the volume change rate of the specimens was similar after the 1st, 6th and 12th F-T cycle, according to each of the curves, indicating that the number of F-T cycles had little effect on the expansibility of the ES-SSP-C-N specimen. The hydration reaction of the cement caused the volume of the specimen to shrink. At the same time, the adsorbed water on the surface of the clay particles was consumed due to the hydration reaction, which then caused drying, shrinking, and cracking of the specimen.

The above test results have shown that the addition of SSP to expansive soil can effectively restrain the characteristics of volume expansion in the process of F-T cycles. As the curing time was increased, the volume expansion of the improved expansive soil decreased. As the number of F-T cycles was increased, the rate of volume change stabilized. The addition of the NaOH activator was able to effectively shorten the curing time, reducing the expansibility of the improved expansive soil and stabilizing it in a relatively short time.

4.3 Unloaded Expansion Rate

The curves of the unload expansion rate of the three improved soil specimens after 28 days of curing with different F-T cycles with a lowest freeze-thaw temperature of - 10°C has been shown in Fig. 8.

It can be seen from Fig. 8 that, under different F-T cycles, the change in the curve of the unloaded expansion rate of the specimens could generally be divided into two types. The first type is the typical change graph of the unloaded expansion rate curve of the expansive soil, as shown in Fig. 8(a); the curve is divided into three stages; the expansion stage, the slow expansion stage and the stable stage. The second type is the unload expansion rate curve of the improved expansive soil after the freezing and thawing cycles; the curve is divided into three stages: the short expansion stage (a-b), the fast shrinkage stage (b-c), and the constant shrinkage stage (c-d), as shown in Fig. 8(b). When the unimproved expansive soil and the improved expansive soil are not put through the freeze-thaw cycle, their unload expansion rate curves belongs to the first type, while the improved expansive soil shows the second type of curve changes after undergoing F-T cycles. The reason for this was then analyzed; on the one hand, when the improved soil was subjected to F-T cycles, the growth of ice crystals will cause expansion of the soil mass, which would destroy the connections between the particles; on the other hand, the formation of negative pore water pressure and the mixing with the cement would caused an increase in both the effective stress and the compression of the soil. When the source of cold was removed and the specimen begins to melt, the effective stress of the specimen suddenly decreases greatly, at which point unloading rebound occurs; this results in short-term expansion of the soil, which then displays an obvious “melt expansion” phenomenon in the early stages of melting.

After the soil had cured for 28 days, the unload expansion rate of the ES-C specimen started after the source of cold was removed; the volume of the soil first briefly expanded, then continued to significantly contract and finally tended to a stable state. The ES-SSP-C specimen exhibited an overconsolidation state in the first and sixth F-T cycles. The specimen briefly

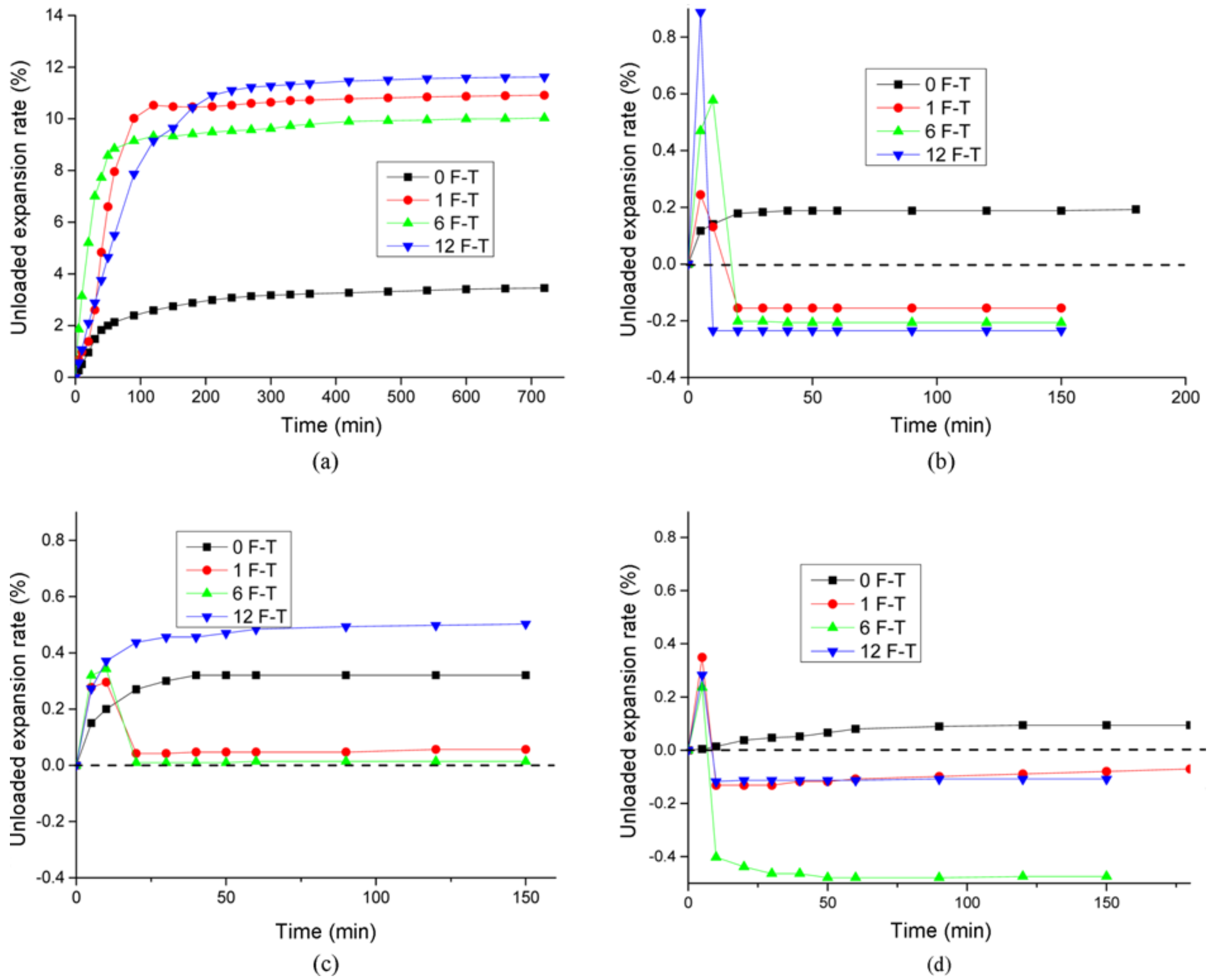

Fig. 8. Unloaded Expansion Rate of Modified Soil under Different Freeze-Thaw Cycles: (a) ES Sample, (b) ES-C Sample, (c) ES-SSP-C Sample, (d) ES-SSP-C-SH Sample

expanded shortly after the cold source was removed and then shrank rapidly. The structure of the soil changed after the 12th F-T cycle as a result of the repeated freeze-thaw cycles. After the specimen had cured for 28d, the ES-SSP-C-N specimens displayed characteristics of overconsolidated soil under the various cycles, and the shrinkage rate was the largest in the 6th F-T cycle. Among the three kinds of improved soil, the ES-SSP-C-N has obvious advantages for the specimen that was not subjected to freeze-thaw cycles, but under freeze-thaw cycles, the ES-SSP-C specimen was slightly stronger than the other two; The results has shown that the addition of steel slag powder is beneficial to expansive soil in resisting the deleterious effects of freeze-thaw cycles.

4.4 Unconfined Compressive Strength

The strength of the improved expansive soil changed with both the curing time and the number of F-T cycles. The values of the UCS changed with the number of F-T cycles, as shown in Fig. 9. In the unconfined compressive strength test, the F-T cycle test was carried out at a lowest temperature of -10°C.

Figure 9 has clearly shown that the UCS of the ES was very low compared with the other three improved soils, and the first three F-T cycles had a great influence on the UCS. After 3rd F-T cycles, the UCS was less affected by the F-T cycles.

The values of the UCS were very close to each other after a different number of F-T cycles for the ES-C and ES-SSP-C, while the UCS value of the ES-SSP-C-N was the highest. The strength of the improved expansive soil was obviously reduced after the first F-T cycle; similar results were reported in the literature by Wang et al. (2006) and Ali et al. (2015). After the ES-SSP-C-N specimens had been cured for 60d and 90d, the F-T cycles were then carried out. The results have shown that the effect of the first F-T cycle on the strength of the specimen was significantly reduced, and the degradation rate of the strength of the specimen was significantly lower than that of the ES-C and ES-SSP-C specimens. It can be seen from the figures that the longer the curing time, the higher the resulting strength of the improved expansive soil. Furthermore, the degradation of the strength of the specimens was lower after the F-T cycles had been carried out.

Figure 10 shows a histogram of the UCS of the specimens

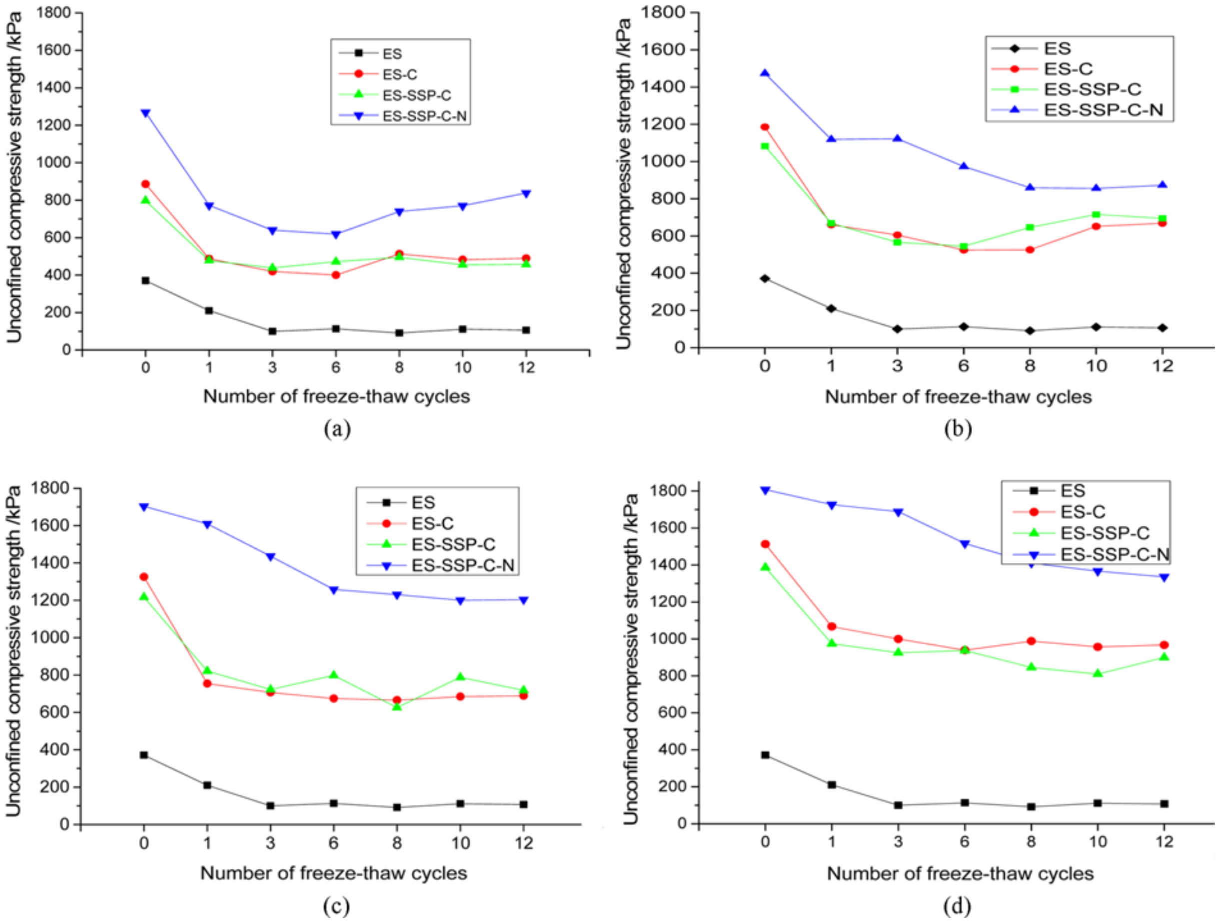

Fig. 9. UCS Curves Showing Improved Expansive Soil under F-T Cycles: (a) Curing for 7 Days, (b) Curing for 28 Days, (c) Curing for 60 Days, (d) Curing for 90 Days

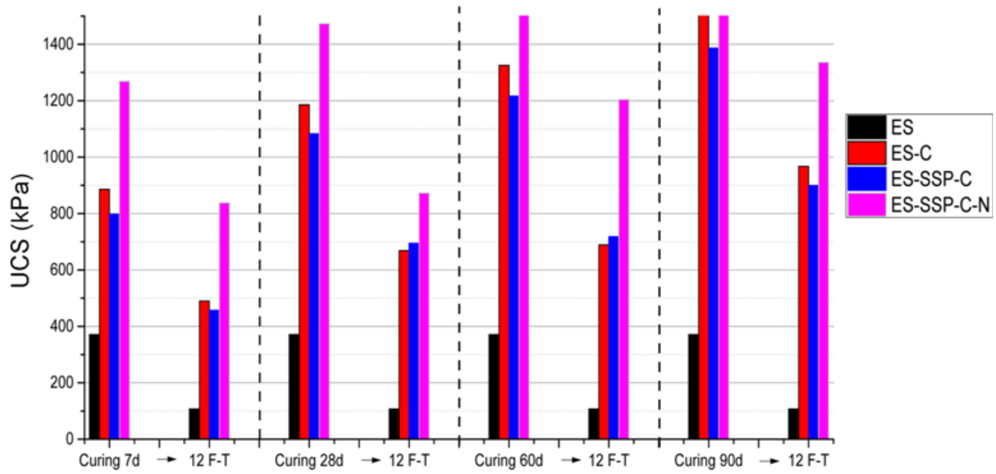

Fig. 10. The Histogram of Unconfined Compressive Strength

that had been cured for 7, 28, 60, 90 days, both before and after 12 F-T cycles. The variation in the UCS values for the unimproved expansive soil and the improved expansive soil was quite obvious after the F-T cycles. The degradation in the strength of the ES-SSP-C-N specimens was the smallest when the specimens were subjected to 12 F-T cycles. Taking the ES-C and ES-SSP-C-N specimens as an examples, when the curing age was 60d and 90d, the strength of the ES-C specimen was 1,325.4 kPa and 1,512.8 kPa, and the strength of the ES-SSP-C-N specimen was 1,702.7. kPa and 1,807.5 kPa; after 12 F-T cycles, the strength of the ES-C specimen was 689.03 kPa and 967.35 kPa, and its strength degradation rate were 48.014% and 36.055%; the strength of the ES-SSP-C-N specimen was 1,204.2 kPa, 1,336.1 kPa, and its strength degradation rate were 29.277% and 26.082%. The results have indicated that SSP can be used to replace cement and that the addition of NaOH can activated the SSP and accelerate the hydration reaction. As a result of this, more hydration products will be produced and the strength of the improved expansive soil will be greater by cementing the clay particles into a more compact form. The longer the curing time of the specimens, the better the resistance to the strength degradation of the improved expansive soil under the F-T cycles.

4.5 Microstructure Analysis

Figure 11 has shown the SEM image of the improved expansive soil specimen after 90 days of curing and 12 F-T cycles. With the passage of time, the hydration of the cementitious materials in the specimen would continue to improve the performance of the expansive soil. The increasing quantity of the hydration products would not only compensate for the strength defects of the expansive soil itself, but also improve the weak points, such as cracks in the soil's structure; this is also a key factor in improving the strength of the material and of its ability to resist the repeated action of F-T cycles. The specimens were cured for 90 days; prior to the freeze-thaw cycles, the integrity of the improved soil specimens was better, the cementitious materials were completely hydrated, and the soil particles were enveloped with calcium silicate gel, and the density was higher. After the specimen had been subjected to 12 F-T cycles, the surface of each improved soil specimen was thin and loose, and cracks had developed fully. It can be seen that the freeze-thaw cycles damaged each specimen of the improved soil. Among them, the ES-SSP-C specimen still retains the micro image from before the freeze-thaw cycle, but there were many small cracks. This is because the steel slag powder has the characteristics of resisting low temperature cracking and good volume stability.

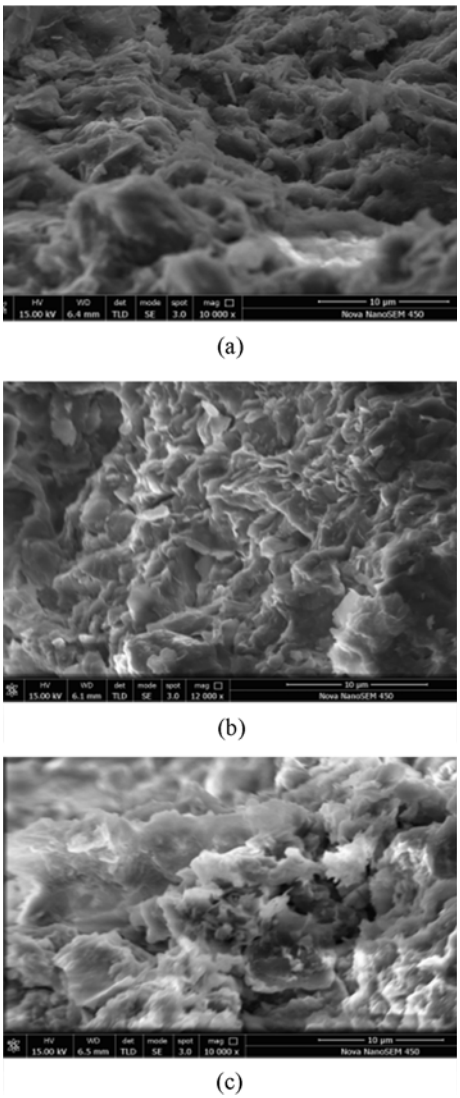

Fig. 11. Microstructure Chart of Modified Soil Samples after 12th F-T Cycle (90 days): (a) ES-C (×3,000), (b) ES-SSP-C (×3,000), (c) ES-SSP-C-SH (×3,000)

5. Conclusions

In this paper, both laboratory tests and analyses of the test data have been used to show how the volume change rate and the UCS of the improved expansive soil were affected by the number of F-T cycles, the freezing temperatures and the curing time. The primary results of this research are as follows:

1. Compared with unimproved expansive soil, after the hydration of the cement and the addition of SSP, it was found that new cementitious substances had formed in the improved expansive soil; this resulted in the greater compactness of the expansive soil particles as well as a decrease in the soil's water content. Therefore, the volume change rate of the improved expansive soil significantly decreased during the F-T cycles.
2. The characteristic expansion of the expansive soil that had been enhanced by the addition of cement and SSP was effectively reduced under the action of F-T cycles. As the curing time of the specimens was increased, the expansibility of the improved expansive soil decreased. As the number of F-T cycles increased, the volume change of the improved expansive soil stabilized.
3. The lower the temperature of the F-T cycles that the specimens were subjected to, the greater the volume change rate that was produced by the F-T cycles. The volume change rate of the expansive soil that has been improved by the addition of cement was much larger than that of the soil that had been improved by the addition of cement and SSP. The addition of the SSP had an obvious effect in improving the volume change rate of the expansive soil undergoing F-T cycles at a lower temperature.
4. The UCS of the expansive soil that had been improved by the addition of cement as well as the addition of cement combined with SSP displayed a close relationship with the curing time of the specimens. As the curing time increased,

the F-T cycles had less effect on their compressive strength.

The expansive soils that had been improved by the addition of cement as well as cement combined with SSP displayed a close relationship between their UCS value and the curing times after undergoing different freeze-thaw cycles. When NaOH was added to the cement and the SSP used to improve the expansive soil, the effect of this on the specimen's resistance to the freezing and thawing cycles was most obvious, and the UCS was the least affected by the F-T cycles. It can be concluded that the methods introduced in this paper have served to improve expansive soil that is subjected to F-T cycles.

Acknowledgments

This research was supported by SDUST (Shandong University of Science and Technology) and the SDUST Research Fund (grant number 2015KYDT104).

ORCID

Yankai Wu https://orcid.org/0000-0002-3147-663X
Xiaolong Qiao https://orcid.org/0000-0002-3715-7146
Xinbao Yu https://orcid.org/0000-0002-5681-0390
Yongfeng Deng https://orcid.org/0000-0002-8223-8711

References

Abdullah WS, Al-Abadi AM (2010) Cationic-electrokinetic improvement of an expansive soil. *Applied Clay Science* 47(3):343-350, DOI: 10.1016/j.clay.2009.11.046

Al-Mukhtar M, Khattab S, Alcover JF (2012) Microstructure and geotechnical properties of lime–treated expansive clayey soil. *Engineering Geology* 139:17-27, DOI: 10.1016/j.enggeo.2012.04.004

Ali AF, Mohd R, Tanveer AK (2015) The influence of freeze-thaw cycles on unconfined compressive strength of clay soils treated with lime. *Jurnal Teknologi (Sciences & Engineering)* 76(1):107-113, DOI: 10.11113/jt.v76.4127

Alonso EE, Romero E, Hoffmann C, García-Escudero E (2005) Expansive bentonite–sand mixtures in cyclic controlled–suction drying and wetting. *Engineering Geology* 81(3):213-226, DOI: 10.1016/j.enggeo.2005.06.009

ASTM E11 (2017) Standard specification for woven wire test sieve cloth and test sieves. ASTM E11-17, ASTM International,West Conshohocken, PA, USA, DOI: 10.1520/E0011-17

Bin-Shafique S, Rahman K, Azfar I (2011) The effect of freezing-thawing cycles on performance of fly ash stabilized expansive soil Subbases. *Geo-Frontiers 2011:Advances in Geotechnical Engineering* 2011:697-706, DOI: 10.1061/41165(397)72

Chen L, Yin ZZ, Zhang P (2007) Relationship of resistivity with water content and fissures of unsaturated expansive soils. *Journal of China University of Mining & Technology* 17(4):537-540, DOI: 10.1016/S1006-1266(07)60141-2

Cokca E (2001) Use of class C fly ashes for the stabilization of an expansive soil. *Journal of Geotechnical and Geoenvironmental Engineering* 127(7):568-573, DOI: 10.1061/(ASCE)1090-0241(2001)127:7(568)

Cui YJ, Yahia-Aissa M, Delage P (2002) A model for the volume change behavior of heavily compacted swelling clays. *Engineering Geology* 64(2):233-250, DOI: 10.1016/S0013-7952(01)00113-2

Cuisinier O, Masrouri F (2005) Hydromechanical behavior of a compacted swelling soil over a wide suction range. *Engineering Geology* 81(3):204-212, DOI: 10.1016/j.enggeo.2005.06.008

Dagesse DF (2013) Freezing cycle effects on water stability of soil aggregates. *Canadian Journal of Soil Science* 93(4):473-483, DOI: 10.4141/CJSS2012-046

Estabragh AR, Parsaei B, Javadi AA (2015) Laboratory investigation of the effect of cyclic wetting and drying on the behavior of expansive soil. *Soils and Foundations* 55(2):304-314, DOI: 10.1016/j.sandf.2015.02.007

GB/T 50123-2019 (2019) Standard for geotechnical testing method. GB/T 50123-2019, China Planning Press, Beijing, China

Ghazavi M, Roustai M (2010) The influence of freeze-thaw cycles on the unconfined compressive strength of fiber-reinforced clay. *Cold Regions Science and Technology* 61(2):125-131, DOI: 10.1016/j.coldregions.2009.12.005

Guillaume S, Olivier C, Farimah M (2012) Multi-scale analysis of the swelling and shrinkage of a lime-treated expansive. *Applied Clay Science* 61:44-51, DOI: 10.1016/j.clay.2012.04.001

Hotineanu A, Bouasker M, Aldaood A (2015) Effect of freeze-thaw cycling on the mechanical properties of lime-stabilized expansive clays. *Cold Regions Science and Technology* 119:151-157, DOI: 10.1016/j.coldregions.2015.08.008

ISO 29581-1 (2009) Method for chemical analysis of cement. Cement-test methods - Part 1: Analysis by wet chemistry. ISO 29581-1, The International Organization for Standardization, Geneva, Switzerland

Khemissa M, Mahamedi A (2014) Cement and lime mixture stabilization of an expansive overconsolidated clay. *Applied Clay Science* 95:104-110, DOI: 10.1016/j.clay.2014.03.017

Kong LW, Zhou BC, Bai H, Chen W (2010) Experimental study of deformation and strength characteristics of Jingmen unsaturated expansive soil. *Rock and Soil Mechanics* 1(10):3036-3042, DOI: 10.16285/j.rsm.2010.10.018 (in Chinese)

Liang T, Cong SY, Ling XZ, Xing WQ, Nie Z (2018) A unified formulation of stress-strain relations considering micro-damage for expansive soils exposed to freeze-thaw cycles. *Cold Regions Science and Technology* 153:164-171, DOI: 10.1016/j.coldregions.2018.05.006

Liu L, Zhou A, Deng YF, Cui YJ, Yu Z, Yu C (2019) Strength performance of cement/slag-based stabilized soft clays. *Construction and Building Materials* 211:909-918, DOI: 10.1016/j.conbuildmat.2019.03.256

Lu Y, Liu SH, Eduardo A, Wang LJ, Xu L, Li Z (2019) Volume changes and mechanical degradation of a compacted expansive soil under freeze-thaw cycles. *Cold Regions Science and Technology* 157:206-214, DOI: 10.1016/j.coldregions.2018.10.008

Olgun M (2013) The effects and optimization of additives for expansive clays under freeze-thaw conditions. *Cold Regions Science and Technology* 93:36-46, DOI: 10.1016/j.coldregions.2013.06.001

Puppala AJ, Manosuthki T, Nazarian S, Hoyos LR (2011) Threshold moisture content and matric suction potentials in expansive clays prior to initiation of cracking in pavements. *Canadian Geotechnical Journal* 48(4):519-531, DOI: 10.1029/2004JB003596

Rosenbalm D, Zapata CE (2017) Effect of wetting and drying cycles on the behavior of compacted expansive soils. *Journal of Materials in Civil Engineering* 29(1):04016191, DOI: 10.1061/(ASCE)MT.1943-5533.0001689

Soltani A, Deng A, Taheri A (2018) Swell-compression characteristics of a fiber–reinforced expansive soil. *Geotextiles and Geomembranes*

46(2):183-189, DOI: 10.1016/j.geotexmem.2017.11.009

Wang FH, Wei X, Corey T, Tian-Chyi JY, Yuan YF (2018) The influences of freeze-thaw cycles on the shear strength of expansive soil treated with ionic soil stabilizer. *Soil Mechanics and Foundation Engineering* 55(3):195-199, DOI: 10.1007/s11204-018-9525-1

Wang BT, Zhang FH, Zhang WH (2006) Study on construction techniques and characteristics of lime-stabilized expansive soil. *Chinese Journal of Rock Mechanics and Engineering* 25(S1):3157-3161, DOI: CN/Y2006/V25/IS1/3157

Wu YK, Hu XS, Hu R, Han T, Yu JL (2017a) Study on the application of an activator for steel slag powder–cement in muddy soil. *European Journal of Environmental and Civil Engineering* 7:1-13, DOI: 10.1080/19648189.2017.1357872

Wu YK, Hu R, Zhao WY, Li YB (2017b) Study on expansive soil properties improved by steel slag powder admixture. *Journal of Henan Polytechnic university (Nature Science)* 36(1):136-143, DOI: 10.16186/j.cnki.1673-9787.2017.01.023 (in Chinese)

Xu L, Lu Y, Xue Y, Song YJ, Yang Q (2017) Physico-mechanical properties of cement-modified expansive soil under freeze-thaw cycles. *Journal of Yangtze River Science Research Institue* 34(4):87-91 (in Chinese)

Yang J, Liu SY, Zhang GD (2016) Study on influence of freeze-thaw cycles on shrinkage of weathered sand-improved expansive soil. *Journal of Hydroelectric Engineering* 35(2):75-81

Yazdandoust F, Yasrobi SS (2010) Effect of cyclic wetting and drying on swelling behavior of polymer–stabilized expansive clays. *Applied Clay Science* 50(4):461-468, DOI: 10.1016/j.clay.2010.09.006

Zha FS, Liu SY, Du YJ (2007) Experiment on improvement of expansive clays with fly ash. *Journal of Southeast University(Natural Science Edition)* 37(2):339-344, DOI: 10.3969/j.issn.1001-0505.2007.02.031

Zheng JL, Zhang R, Yang HP (2009) Highway subgrade construction in expansive soil areas. *Journal of Materials in Civil Engineering* 21(4):154-162, DOI: 10.1061/(ASCE)0899-1561(2009)21:4(154)