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Research Article

Improving Carbonate Saline Soil in a Seasonally Frozen Region Using Lime and Fly Ash

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In this study, carbonate saline soil in the Duerbote of Songnen Plain was improved by adding lime and fly ash. The improved soil was exposed to 0, 30, and 60 freeze-thaw cycles, and ordinary triaxial compression tests (UU) were conducted under confining pressures of 100, 200, and 300 kPa. The effects of freeze-thaw cycles, lime content, fly ash content, and confining pressure on the peak deviatoric stress, cohesion, and internal friction angle on the lime-ash improved carbonate saline soil were analysed. The incorporation of lime and fly ash in carbonate saline soil transformed the stress-strain curves from the strain hardening type to strain softening type and also changed the strain corresponding to the peak deviatoric stress of the soil. The effect of lime on the shear strength of the soil was the most significant, and it significantly increased the peak deviatoric stress, cohesion, and internal friction angle of the soil. Similarly, the effect of fly ash on the peak deviatoric stress and internal friction angle of the soil was significant, but the effect on cohesion was very limited. A small amount of fly ash increased the peak deviatoric stress and internal friction angle of carbonate saline soil, but an excessive amount had the opposite effects. The freeze-thaw cycles cause the shear strength of the carbonate saline soil to decrease, but the incorporation of lime and fly ash alleviated this decrease.

1. Introduction

There are 7.66×10^4 km^2 of saline soil in the Northeast China, of which 39.3% is located on the Songnen Plain [1]. Influenced by climate, topography, geology, hydrology, and human factors, the salinization of the Songnen Plain is serious, and the area of carbonate saline soil now exceeds 3.2×10^4 km^2 [2, 3]. For these carbonate saline soils, the main cation is Na^+, and the main anion is HCO^{3-}, with pH > 7.5 [4, 5], making its natural state alkalic or strongly alkalic [6]. The mineral compositions of the carbonate saline soil in Songnen Plain are mainly montmorillonite, illite, and kaolinite [7].

Presently, research on saline soil has mainly focused on sulfuric saline soils and coastal saline soils, and study for carbonate saline soils is relatively rare. Carbonate saline soil greatly influences engineering. It is hard when dry, but has poor stability and drainage after being soaked with water. The pavement often becomes seriously damaged in the severely salinized areas [8, 9]. The collapsibility of carbonate saline soils also causes the damage of water conservancy projects and reduces the stability of water channel slopes [10]. The Songnen Plain is located in a seasonally frozen region, so the soil undergoes freeze-thaw cycles at least once a year [11]. The surface soil even experiences freeze-thaw cycles once a day in spring and autumn. The periodic freeze-thaw cycles can weaken the mechanical properties of carbonate saline soil [12]. Due to the influences of temperatures, salt contents, water contents, and compactions, carbonate saline soils in seasonally frozen regions also exhibit obvious frost heave, which can seriously damage buildings, roads, and bridges [13]. The shallower soils located in the Songnen Plain area are frozen for a long period each year. During frozen periods, repeated loading and unloading by traffic on roads will damage the frozen saline soil, thus reducing the strength of the soil [14]. In order to reduce the hazard of carbonate saline soil in seasonally frozen regions, it is especially important to seek an efficient and practical method to control carbonate saline soil in seasonally frozen regions.

Saline soil usually cause damage in engineering structures. Replacement or improvement for saline soils is the most reasonable methods for preventing engineering disasters. Replacement method increases a large amount of work and high transportation costs, which make it infeasible for the control of carbonate saline soil on a large scale. Therefore, improvement technology is the more reasonable method to control carbonate saline soil. Lime is rich in CaO and is often used to improve poor soils [15–17]. By mixing lime into the soil, the soil strength can effectively be improved [18, 19], along with its volume characteristics [20, 21] and shear strength [22]. Similarly, the dynamic characteristics of clay can also be improved by adding lime into the soil [23]. Although lime efficiently enhances the strength properties of soil, it is slightly less capable of suppressing the loss of soil strength due to freeze-thaw cycles [24, 25]. Fly ash, a product of coal combustion, has fine particles and is often used as a partial substitute for concrete cementitious materials [26, 27]. Many studies have been showed that fly ash can effectively enhance the freeze-thaw resistance of concrete materials [28, 29]. Therefore, in this paper, fly ash is used to compensate for the strength loss of carbonate saline soils due to the increasing freeze-thaw cycles.

Most previous studies on carbonate saline soils have focused on improving shear strength. However, in cold region engineering, the hazards associated with freeze-thaw cycles are also very seriously. Based on the previous research on improving carbonate saline soils and improving the frost resistance of concrete, lime and fly ash were used to improve the carbonate saline soil in the Songnen Plain. The effects of freeze-thaw cycles, lime content, fly ash content, confining pressure, and their interactions on the strength properties of improved carbonate saline soils were investigated. The damage to soil during freeze-thaw cycles was analysed along with mechanical properties, and freeze-thaw resistance of the lime-ash improved carbonate saline soils in a cold region environment.

2. Experimental Materials

In this paper, carbonate saline soils in the Duerbote of the Songnen Plain (Figure 1) were selected, and soils were sampled from a depth of 60-80 cm below the surface. In order to reduce the influence of changes in salt content on the test results, the studied soil was desalted. After desalting, the particle size distribution of the samples was measured using laser particle analyzer (Figure 2). The average specific surface area of the soil was 0.081 m^2/g. The liquid and plastic limits of the soil were 20.2% and 11.3%, respectively. Through a light compaction test (Figure 3), the maximum dry density of the soil was determined to be 1.835 g/cm^3, and the optimal water content was 15.0%. According to *the Engineering Classification Standard of Soil GB/T50145-2007* issued by the Ministry of Water Resources of the People's Republic of China, the soil samples were classified as silt after desalting.

The main chemical components of the lime and fly ash selected for improving the carbonate saline soil are shown in Table 1.

3. Sample Preparation and Test Methods

3.1. Sample Preparation. Based on the results of the compaction test, the water content and dry density of the soil samples were 15.0% and 1.84 g/cm^3. Based on the carbonate content of the carbonate saline soil in the study area, the content of carbonate in the prepared soil sample was set to 1.5%. After thoroughly mixing the soil sample, lime, fly ash, and sodium bicarbonate, distilled water was added and evenly mixed; then, the prepared soil samples were sealed and left to stand for 24 h. Standard triaxial specimens were prepared by the compaction method (φ39.1 mm × 80 mm). In order to reduce the hydration heat generated by the reactions of fly ash and lime with water, which would damage the soil structure and result in strength loss, the specimens were placed in a 25°C and 95% humidity environment for curing for 28 d after preparation. After the maintenance was completed, the specimens were subjected to freeze-thaw cycles, freezing in an industrial grade freezer and thawing in a constant temperature maintenance room. According to the climatic conditions in the Duerbote area and the weakening effect of ground temperature change with ground depth, the temperature was cycled between -20°C and 20°C during the freeze-thaw cycles (FT), and each freeze-thaw cycle was completed within 24 h, that is, 12 h of freezing and 12 h of thawing. Figure 4 shows sample preparation and freeze-thaw cycle process.

There is an upper limit of lime content for improving soils, beyond which the improvement effect is reduced. In a study of lime curing of carbonate saline soils in the Songnen Plain, the soil reached an optimal level of frost heaving resistance and stabilized strength when the lime content was 12% [19, 30]. As an additive, fly ash is often incorporated into concrete materials to improve the frost resistance. In the study of concrete materials, it is presented that the compressive strength and frost resistance of concrete will be optimal when fly ash is blended at less than 25% [31, 32]. Based on the study of lime cured soil and with reference to the study of fly ash concrete, the effects of four factors, including number of freeze-thaw cycles (FT = 0, 30, and 60), lime content (L = 0, 6%, and 12%), fly ash content (FA = 0, 12%, and 24%), confining pressure (CP = 100, 200, and 300 kPa), and their interactions on the mechanical properties of soil were considered. The detailed test scheme is shown in Table 2. For this purpose, we prepared 81 specimens.

3.2. Test Method. The triaxial compression test was carried out using a high-precision triaxial test apparatus (Figure 5) developed by the GDS, U.K. The range of axial force of this triaxial test apparatus was 0–16 kN with an accuracy of 0.1 N. The range of axial displacement was 0–100 mm with an accuracy of 35 μm/50 mm, and the range of confining pressure was 0–2 MPa with an accuracy of 1 kPa. The test apparatus is shown in Figure 5. The rate of shear was 0.8 mm/min, and the termination condition of shear was axial strain reaching 20%. The test type was unconsolidated undrained (UU).

3.3. Data Processing Methods. In engineering, the strain hardening curve takes the value of deviatoric stress at 15%

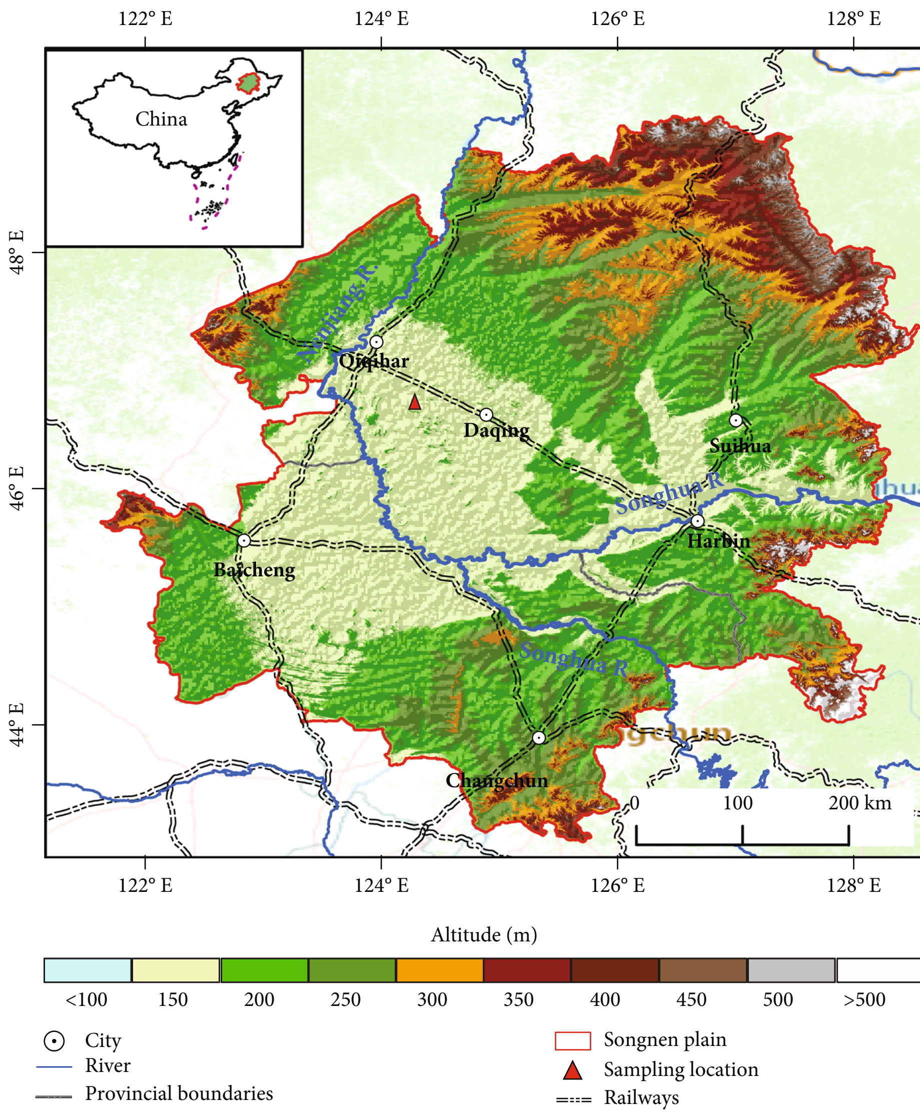

Figure 1: Location of carbonate saline soil sampling site.

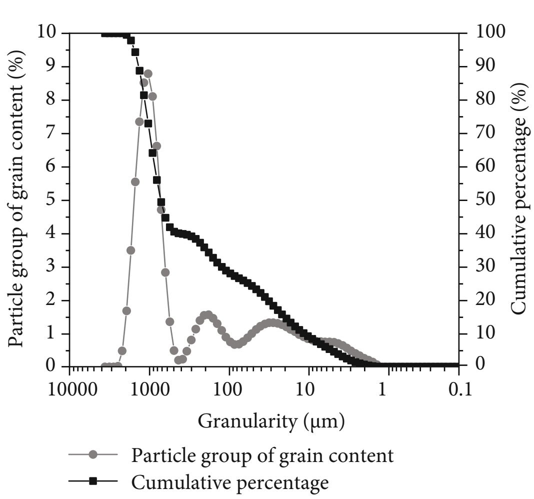

Figure 2: Grain-size distribution.

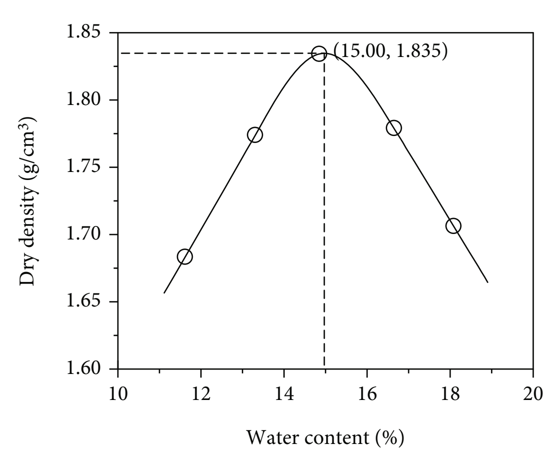

Figure 3: Compaction curve of soil after desalting.

Table 1: Main chemical components of lime and fly ash.

Component	SiO_2 /(%)	Al_2O_3 /(%)	Fe_2O_3 /(%)	CaO /(%)	MgO /(%)	SO_3 /(%)	Loss on ignition /(%)
Lime	3.445	—	—	82.40	7.28	0.62	2.02
Fly ash	51.75	32.30	7.56	3.87	0.93	0.60	1.44

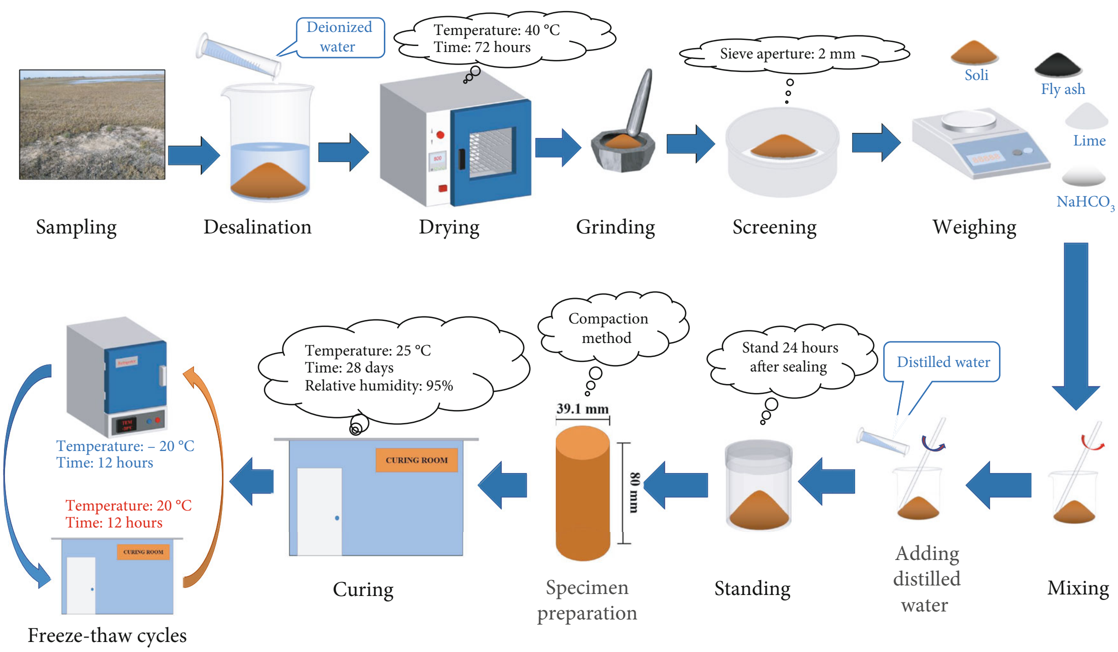

Figure 4: Sample preparation process and freeze-thaw cycle experiment.

Table 2: Testing conditions.

Freeze-thaw cycle	Lime content /(%)	Fly ash content /(%)	Confining pressure /(kPa)
0, 30, 60	0, 6, 12	0, 12, 24	100, 200, 300

strain as the peak deviatoric stress, and the strain softening curve takes the maximum value of the deviatoric stress as the peak deviatoric stress.

To measure cohesion and internal friction angle of soil in this study, three peak deviatoric stresses were obtained by triaxial tests at three confining pressures (100 kPa, 200 kPa, and 300 kPa), and the cohesion and internal friction angles (Equations (1)–(4)) were obtained by the relationship between the strength envelope (τ_f) and the failure principal stress line (K_f) (Figure 6).

$$r = O'A \bullet \tan \alpha = O'A \bullet \sin \varphi, \tag{1}$$

$$\varphi = \arcsin (\tan \alpha), \tag{2}$$

$$O'O = \frac{a}{\tan \alpha} = \frac{c}{\tan \varphi}, \tag{3}$$

$$c = \frac{a}{\cos \varphi}. \tag{4}$$

4. Results and Discussion

4.1. Stress-Strain Curve. Figures 7–15 show the experimental stress-strain curves. It can be seen that when the fly ash mixture was increased from 0% to 12% without the adding lime, the fly ash filled the interstices between soil particles, but did not result in the soil reaching the compactness when it was transformed into strain softening. The hydration reaction with the CaO in the fly ash increased the peak deviatoric stress of the soil, so the stress-strain will be strain hardening, but the peak deviatoric stress increased slightly. When the content of fly ash was increased from 12% to 24%, substances such as SiO_2 in the fly ash filled the interstices between soil particles and made the soil denser, so the stress-strain curve changed from strain hardening to strain softening. When no fly ash was added, and lime content was increased from 0% to 6%, the lime reacted with water to produce a large amount of cementitious material, which tightened the connection between soil particles, so the stress-strain curve changed from strain hardening to strain softening and the peak deviatoric stress increased significantly. When

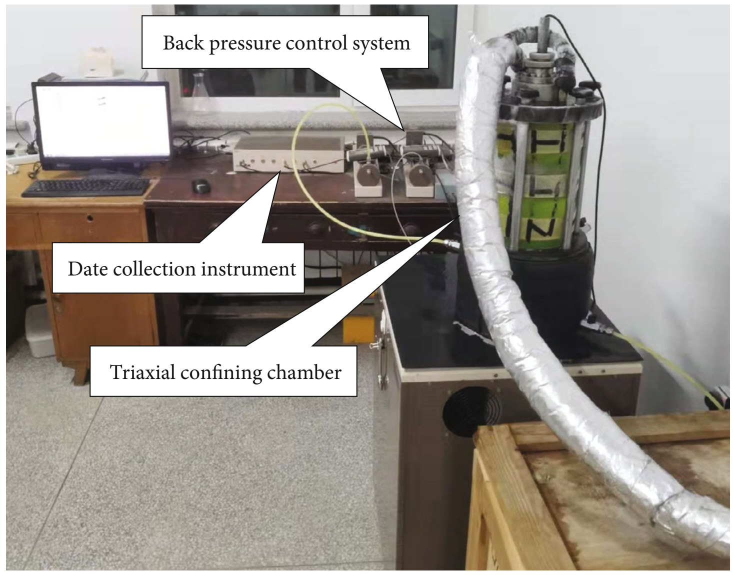

Figure 5: GDS triaxial test apparatus.

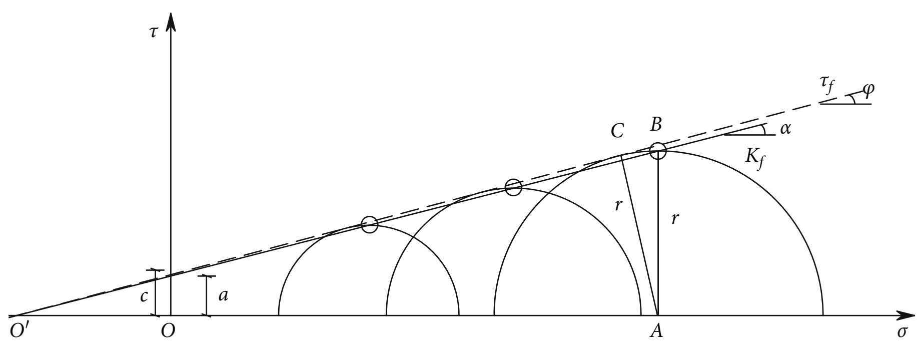

Figure 6: The strength envelope (τ_f) and the failure principal stress line (K_f).

the content of lime increased from 6% to 12%, without adding fly ash, the stress-strain curves were strain softening, and the peak deviatoric stress still increased substantially. However, the lime reacted with water and produced a large amount of cementitious material, which made the soil more brittle, so the strain corresponding to the peak deviatoric stress decreased. The strain corresponding to the peak deviatoric stress decreased significantly in the experimental groups with 0 and 30 freeze-thaw cycles. When fly ash and lime were mixed together, with 12% fly ash, the peak deviatoric stress of the soil increased slightly, but when 24% fly ash was mixed, the peak deviatoric stress was weakened, and the strain corresponding to the peak deviatoric stress increased. The effect of freeze-thaw cycles on the stress-strain curve of the soil was also obvious, and the stress-strain curve decreased with increasing the number of freeze-thaw cycles. The effect of envelope pressure on the stress-strain curve was similarly obvious, and with increasing of confining pressure, the stress-strain curve increased.

4.2. Significance Analysis. In order to investigate whether the freeze-thaw cycles (FT), lime (L), fly ash (FA), and confining pressure (CP) had significant effects on peak deviatoric stress, cohesion, and internal friction angle of the improved carbonate saline soil, the level of the effects of each factor on the peak deviatoric stress, cohesion, and internal friction angle of the improved carbonate saline soil was assessed along with the contributions of various factors and interactions.

In this paper, four factors, each with three levels, were considered to determine their influence on peak deviatoric stress: FT, L, FA, and CP. The test results obtained for each group (FT_i, L_j, FA_k, CP_l) are referred to using the notation x_{ijkl}.

$$R = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} x_{ijkl}^2, \tag{5}$$

$$\mathrm{CT} = \frac{1}{81}\left(\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} x_{ijkl}\right)^2, \tag{6}$$

$$Q_{\mathrm{FT}} = \frac{1}{27}\sum_{i=1}^{3}\left(\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} x_{ijkl}\right)^2. \tag{7}$$

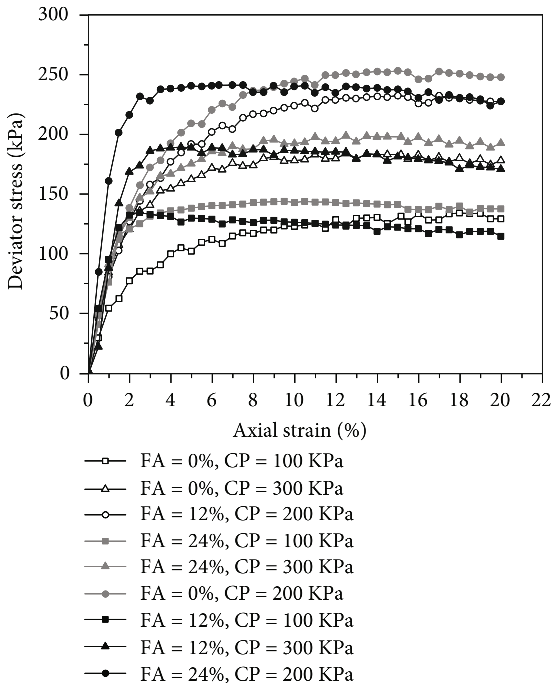

Figure 7: Stress-strain curves (FT = 0, $L = 0\%$).

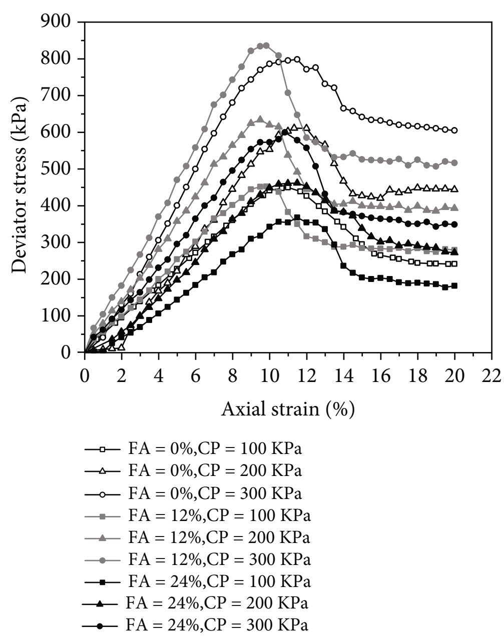

Figure 8: Stress-strain curves (FT = 0, $L = 6\%$).

Note: Q_L, Q_{FA}, and Q_{CP} were calculated in the same way as Q_{FT}.

Total variance sum of squares and variance sum of squares for each factor:

$$S_T = R - \mathrm{CT}, \quad (8)$$

$$S = Q - \mathrm{CT}. \quad (9)$$

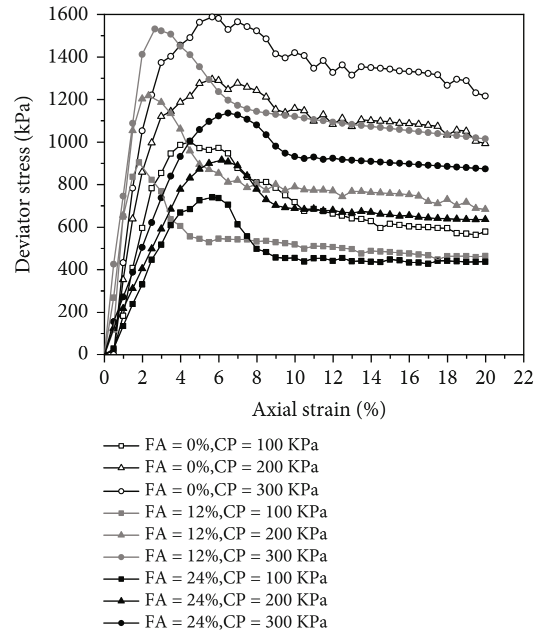

Figure 9: Stress-strain curves (FT = 0, $L = 12\%$).

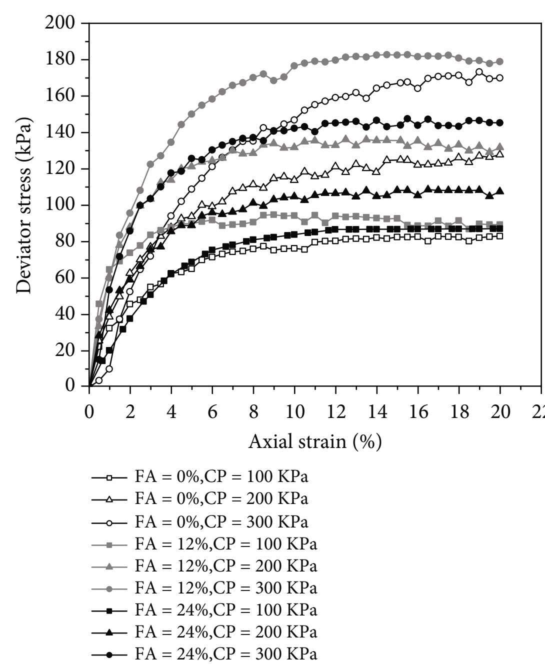

Figure 10: Stress-strain curves (FT = 30, $L = 0\%$).

When considering the interaction of two factors, the significance analysis was performed as follows:

$$Q_{FT-L} = \frac{1}{9}\sum_{i=1}^{3}\sum_{j=1}^{3}\left(\sum_{k=1}^{3}\sum_{l=1}^{3}x_{ijkl}\right)^2. \quad (10)$$

Note: Q_{FT-FA}, Q_{FT-CP}, Q_{L-FA}, Q_{L-CP}, and Q_{FA-CP} were calculated in the same way as Q_{FT-L}.

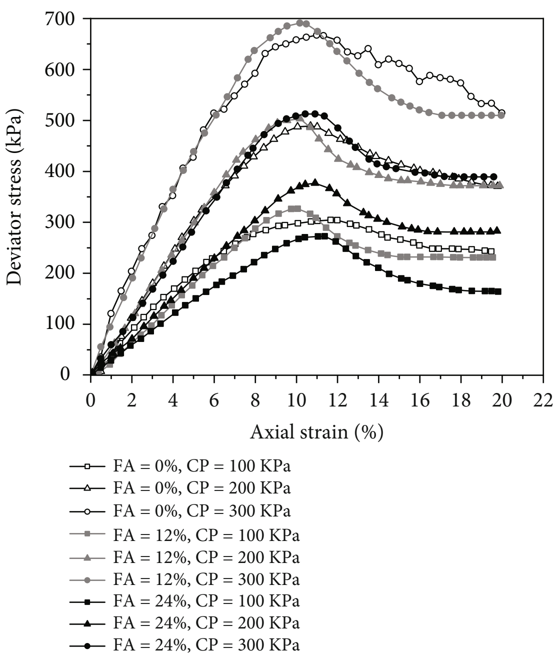

Figure 11: Stress-strain curves (FT = 30, $L = 6\%$).

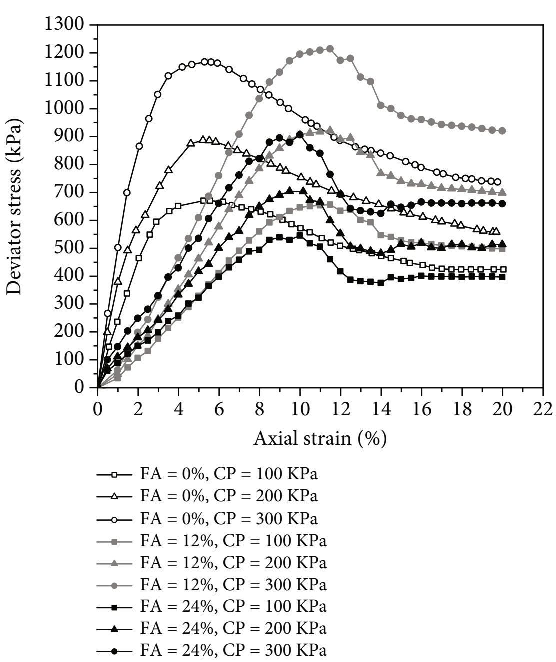

Figure 12: Stress-strain curves (FT = 30, $L = 12\%$).

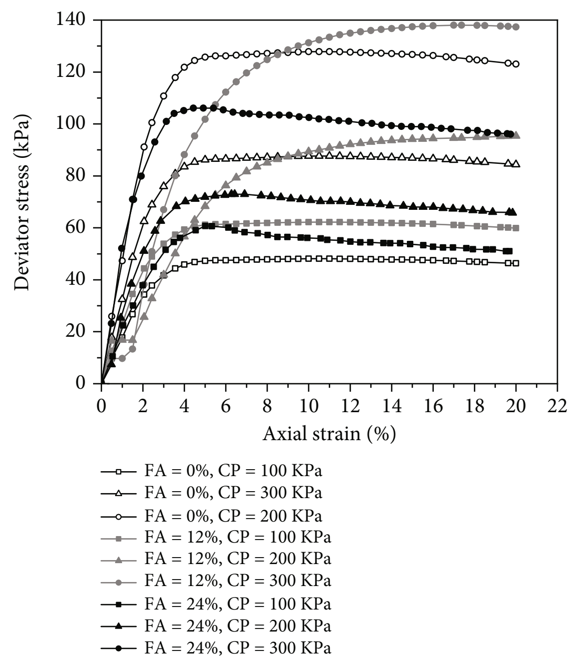

Figure 13: Stress-strain curves (FT = 60, $L = 0\%$).

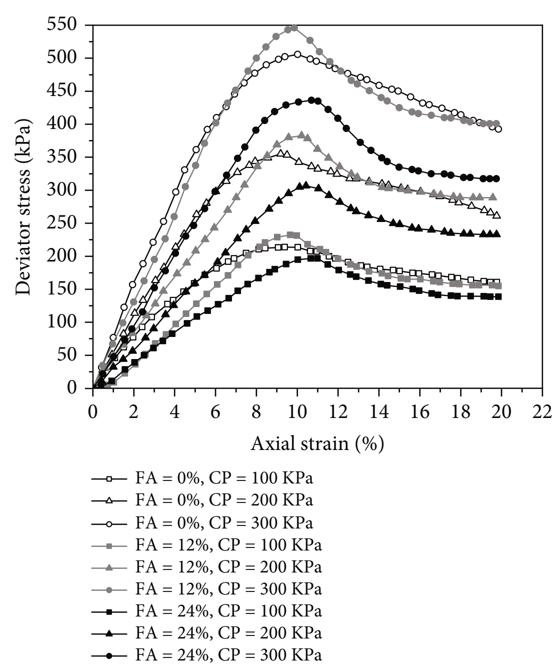

Figure 14: Stress-strain curves (FT = 60, $L = 6\%$).

Sum of squared variance of the interaction effect of the two factors:

$$S_{FT-L} = Q_{FT-L} - Q_{FT} - Q_L + CT. \quad (11)$$

Note: S_{FT-FA}, S_{FT-CP}, S_{L-FA}, S_{L-CP}, and S_{FA-CP} were calculated in the same way as S_{FT-L}.

Significance analysis when considering the interaction of three factors:

$$Q_{FT-L-FA} = \frac{1}{3}\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\left(\sum_{l=1}^{3} x_{ijkl}\right)^2. \quad (12)$$

Note: $Q_{FT-L-CP}$ and $Q_{L-FA-CP}$ were calculated in the same way as $Q_{FT-L-FA}$.

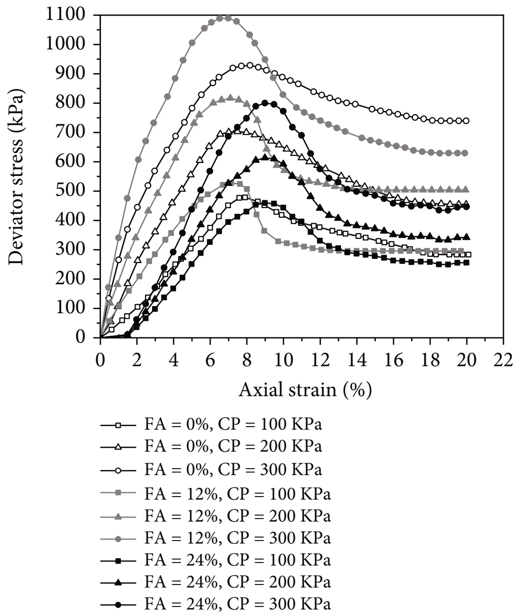

Figure 15: Stress-strain curves (FT = 60, L = 12%).

Sum of squared variance of the interaction effect of three factors:

$$S_{FT-L-FA} = Q_{FT-L-FA} - Q_{FT} - Q_L - Q_{FA} + CT. \quad (13)$$

Note: $S_{FT-L-CP}$ and $S_{L-FA-CP}$ were calculated in the same way as $S_{FT-L-FA}$.

Variance estimates for each factor and when interacting with multiple factors:

$$F = \frac{(S/f)}{(S_E/f_E)}, \quad (14)$$

where f is the degree of freedom at single-factor and multi-factor interactions, respectively; f_E is the degree of freedom of error.

In this paper, only three factors (FT, L, and FA), each with three levels, were considered when examining their influence on cohesion and internal friction angle. Their significance analysis was conducted similarly to that of peak deviatoric stress, so it is not repeated here.

The significance analysis of the effects of FT, L, FA, and CP and their interaction on the peak deviatoric stress of the lime-ash improved carbonate saline soil is shown in Figure 16. The effects of FT, L, FA, CP, $FT \times L$, $FT \times FA$, $FT \times CP$, $L \times FA$, $L \times CP$, $FA \times CP$, $FT \times L \times FA$, and $L \times FA \times CP$ on peak deviatoric stress were all significant ($P < 0.001$). The effects of $FT \times L \times CP$ ($P = 0.091$) and $FT \times FA \times CP$ ($P = 0.843$) on the peak deviatoric stress were not significant. The strength of effects of the factors and their interactions on peak deviatoric stress were, in descending order: $L > CP > FT > FA > L \times CP > FT \times L > L \times FA > FT \times FA > FA \times CP > FT \times L \times FA > L \times FA \times CP > FT \times CP$.

The significance analysis of the effects of FT, L, FA, and their interactions on the cohesion of lime-ash improved carbonate saline soils is shown in Figure 17. The effects of FT, L, and $FT \times L$ on cohesion were significant ($P < 0.001$). The effects of FA ($P = 0.075$), $FT \times FA$ ($P = 0.108$), and $L \times FA$ ($P = 0.054$) on cohesion were not significant. The strengths of effects of the factors and their interactions on cohesion were, in descending order: $L > FT > FT \times L$.

The significance analysis of the effects of FT, L, FA, and their interaction on the internal friction angle of the lime-ash improved carbonate saline soil is shown in Figure 18. The effects of FT, L, FA, $FT \times L$, and $L \times FA$ on the angle of internal friction were significant ($P < 0.001$). The effect of $FT \times FA$ ($P = 0.174$) on the angle of internal friction was not significant. The strengths of effects of the factors and their interactions on the angle of internal friction were, in descending order: $L > FT > FA > L \times FA > FT \times L$.

4.3. Effect of Fly Ash. Fly ash particles are small and heavy and can fill the pores between soil particles and increase the density of the soil while maintaining the same volume, thus making the soil more compact. However, with excessive fly ash, the ratios of clay particles and cementitious materials to other substances decrease, leading to decreased soil strength. The influence of fly ash content on the peak deviatoric stress of the improved carbonate saline soil under different freeze-thaw cycles is shown in Figures 19–21.

The dispersion of soil particles in soil samples without lime or with low lime contents increased with increasing fly ash content, resulting in a small increase and then decrease in its peak deviatoric stress. However, when the lime content was 12% and the soil was not exposed to a freeze-thaw cycle, the peak deviatoric stress decreased gradually with increasing fly ash content. This was because lime reacts with water in the soil in a priority manner, and the increased strength due to fly ash will not fully develop in the short-term curing process. However, the smaller particle sizes of fly ash increase the dispersibility of soil particles and reduce the soil strength. When the number of freeze-thaw cycles increases, the peak deviatoric stress initially increased and then decreased with increasing fly ash content in the test groups with lime contents of 12%. This was because, during the freeze-thaw cycles, the fly ash had time to undergo hydration and generate gelling material, which increased the peak deviatoric stress, but excessive fly ash content still resulted in overall reductions in the peak deviatoric stress of soil.

Figure 22 shows the effect of fly ash content on the internal friction angle. With increased fly ash content, the internal friction angle of the soil showed an initial increase and then decrease, but the effect of fly ash on the internal friction angle was small. The fly ash particles are fine and do not easily chemically react with the materials in the soil, so adding fly ash into the soil is equivalent to adding fine particulate matter to the soil. Mixing a small amount of fly ash can increase the inhomogeneity of the soil, leading to an increase in the internal friction angle. However, a large amount of fly ash can play a role similar to that of a lubricant, reducing the internal friction angle.

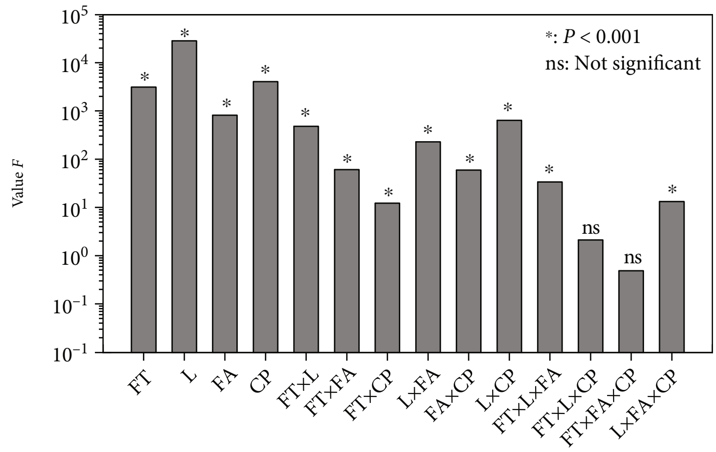

Figure 16: Significance tests of peak deviatoric stress considering interactions.

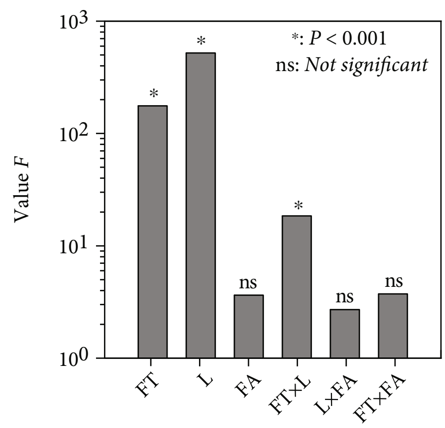

Figure 17: Significance test of cohesion considering interactions.

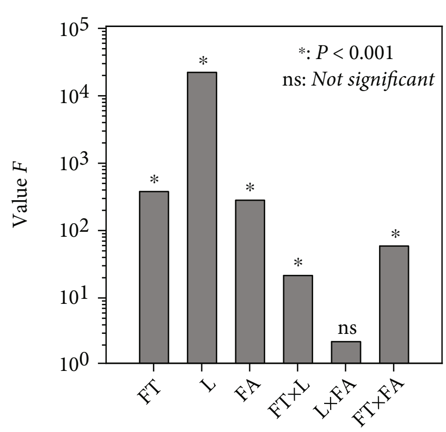

Figure 18: Significance test of internal friction angle considering interactions.

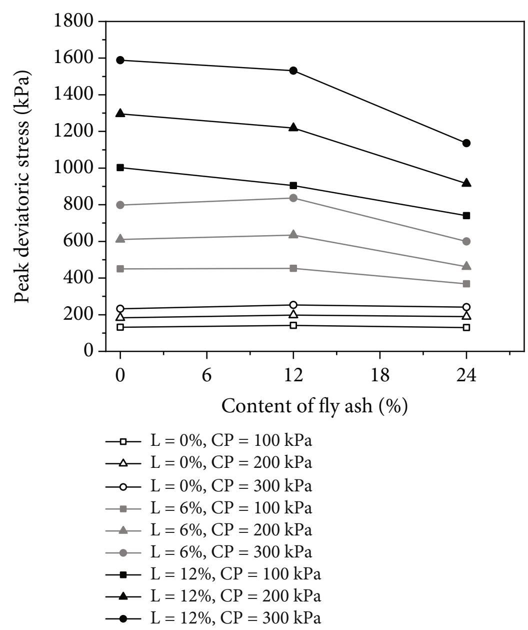

Figure 19: Peak deviatoric stress due to different content of fly ash (FT = 0).

4.4. Effect of Lime. When lime is mixed into soil, the CaO and MgO in the lime react with the Na^+, K^+, H_2O, CO_2, SiO_2, Al_2O_3, and other substances in the soil via ion exchange, crystallization, volcanic ash reaction (Equation (15) and Equation (16)), and carbonization (Equation (17) and Equation (18)) to form new substances [33, 34].

$$x\mathrm{Ca(OH)_2} + \mathrm{SiO_2} + n\mathrm{H_2O} \longrightarrow x\mathrm{CaO}\bullet\mathrm{SiO_2}\bullet(n+1)\mathrm{H_2O}, \tag{15}$$

$$x\mathrm{Ca(OH)_2} + \mathrm{Al_2O_3} + n\mathrm{H_2O} \longrightarrow x\mathrm{CaO}\bullet\mathrm{Al_2O_3}\bullet(n+1)\mathrm{H_2O}, \tag{16}$$

$$\mathrm{Ca(OH)_2} + \mathrm{CO_2} + \mathrm{H_2O} \longrightarrow \mathrm{CaCO_3} + \mathrm{H_2O}, \tag{17}$$

$$\mathrm{Mg(OH)_2} + \mathrm{CO_2} + \mathrm{H_2O} \longrightarrow \mathrm{MgCO_3} + \mathrm{H_2O}. \tag{18}$$

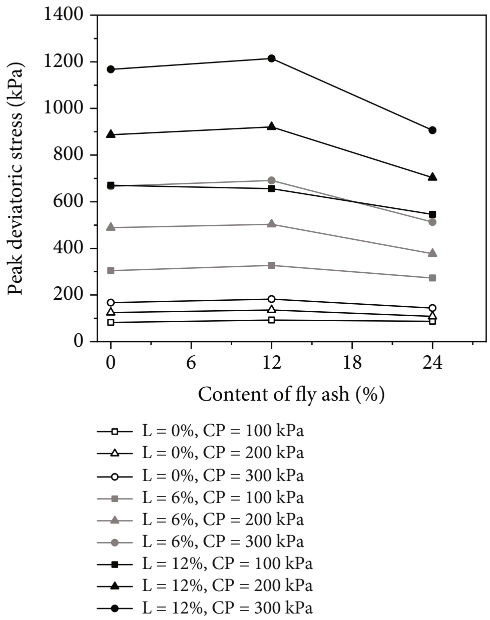

Figure 20: Peak deviatoric stress due to different content of fly ash (FT = 30).

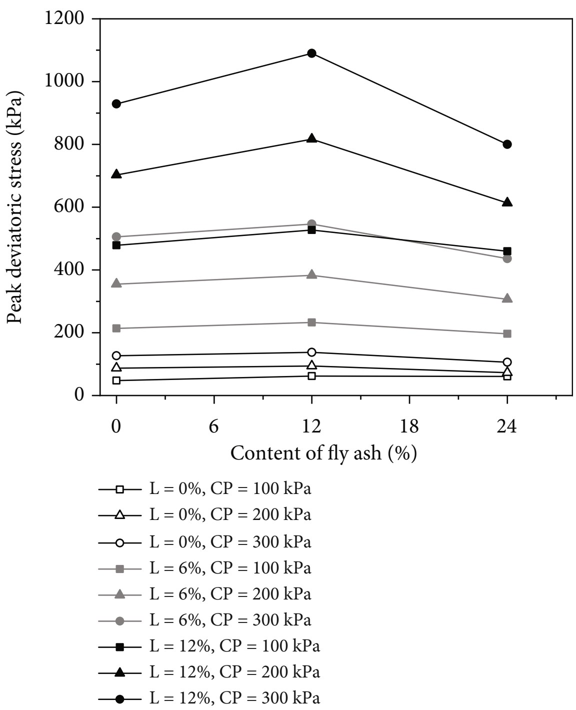

Figure 21: Peak deviatoric stress due to different content of fly ash (FT = 60).

The above reactions and new materials strengthen the soil structure, reduce the number of pores between soil particles, increase the density of soil, and substantially improve the strength of the soil. The influence of lime content on the peak deviatoric stress of the improved carbonate saline soil under different freeze-thaw cycles is displayed in Figures 23–25.

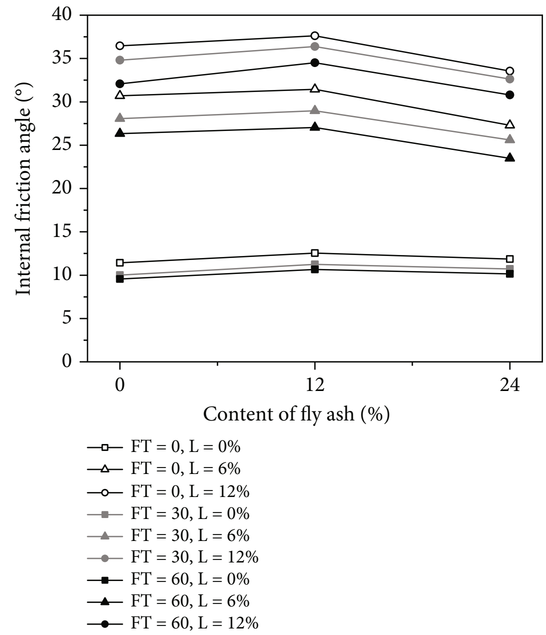

Figure 22: Internal friction angle due to different fly ash contents.

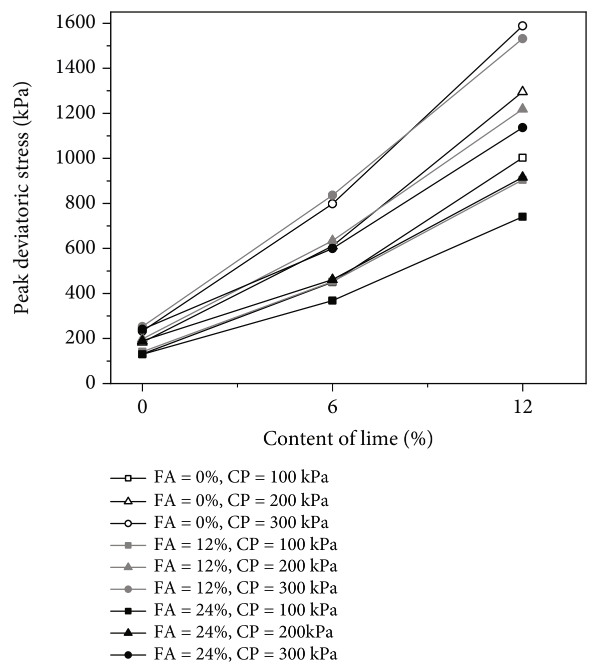

Figure 23: Peak deviatoric stress at different lime contents (FT = 0).

With all other conditions held constant, as lime content increased, the peak deviatoric stress of the soil significantly increased, and the growth rate of peak deviatoric stress increased. Due to the compressive hardening deformation characteristics of the soil, its peak deviatoric stress will be controlled by the confining pressure when other conditions are held constant. With increased confining pressure, the peak deviatoric stress increased. Moreover, the addition of excessive fly ash and increasing number of freeze-thaw

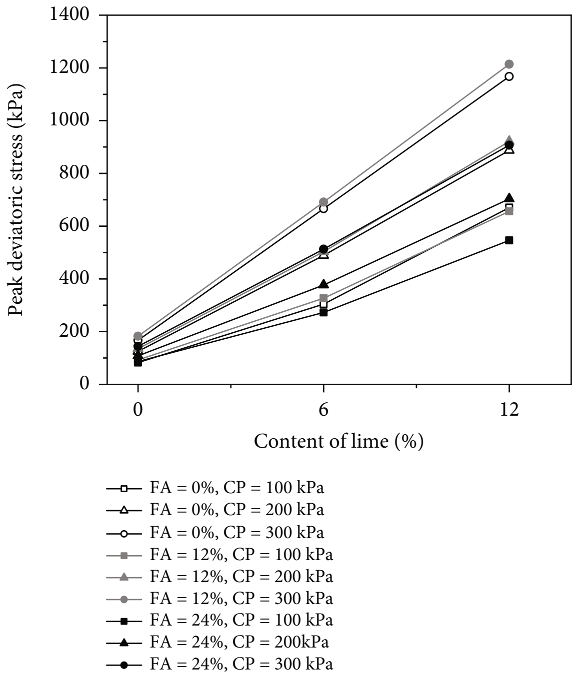

Figure 24: Peak deviatoric stress at different lime contents (FT = 30).

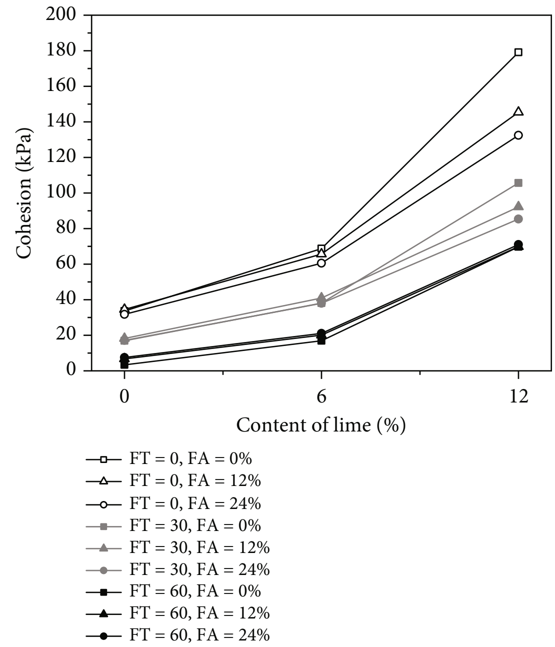

Figure 26: Cohesion at different lime contents.

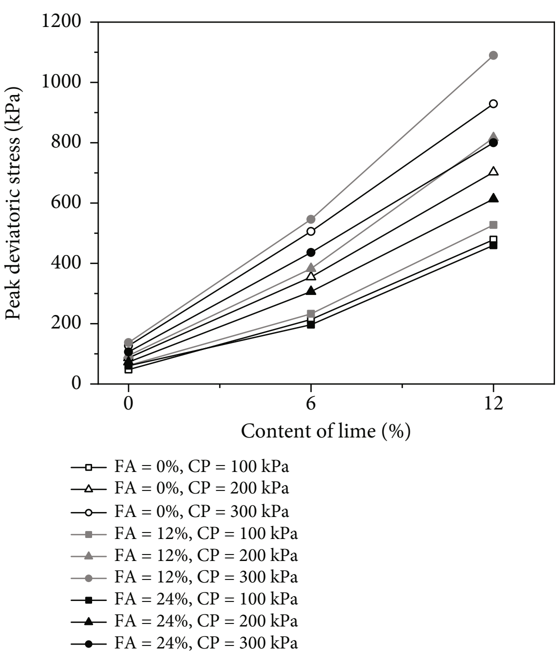

Figure 25: Peak deviatoric stress at different lime contents ($FT = 60$).

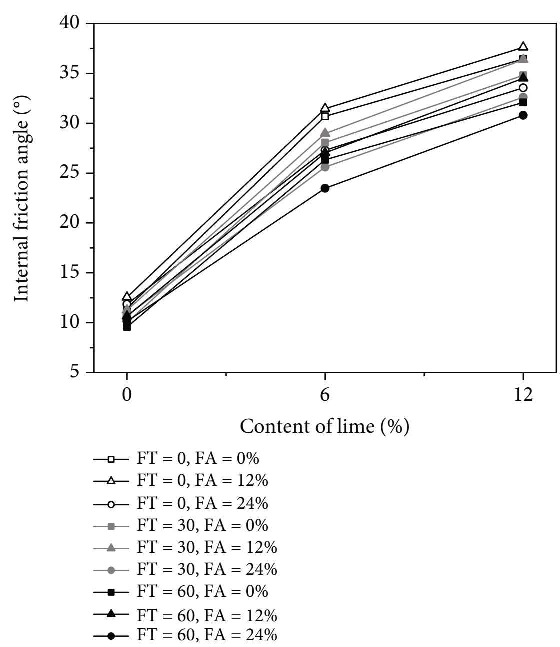

Figure 27: Internal friction angle at different lime contents.

cycles, both had negative effects on the peak deviatoric stress of the soil improved by lime, but the positive effect of lime on the peak deviatoric stress of the soil was still significant.

Figure 26 shows the effect of lime content on the cohesion of carbonate saline soil. The effect of lime on cohesion was similar to its effect on peak deviatoric stress. The CaO and MgO in lime easily react with Na^+, K^+, H_2O, CO_2, SiO_2, Al_2O_3, and other substances in the soil to produce binding materials, so lime increases the cohesion of the soil. With increased lime content, this phenomenon became increasingly obvious, and the increase in cohesion also increased with increasing lime content.

Figure 27 shows the effect of lime content on the internal friction angle of the carbonate saline soil. The incorporation of lime obviously increased the internal friction angle of carbonate saline soil. However, the rate of increase in the internal friction angle decreased with increasing lime content.

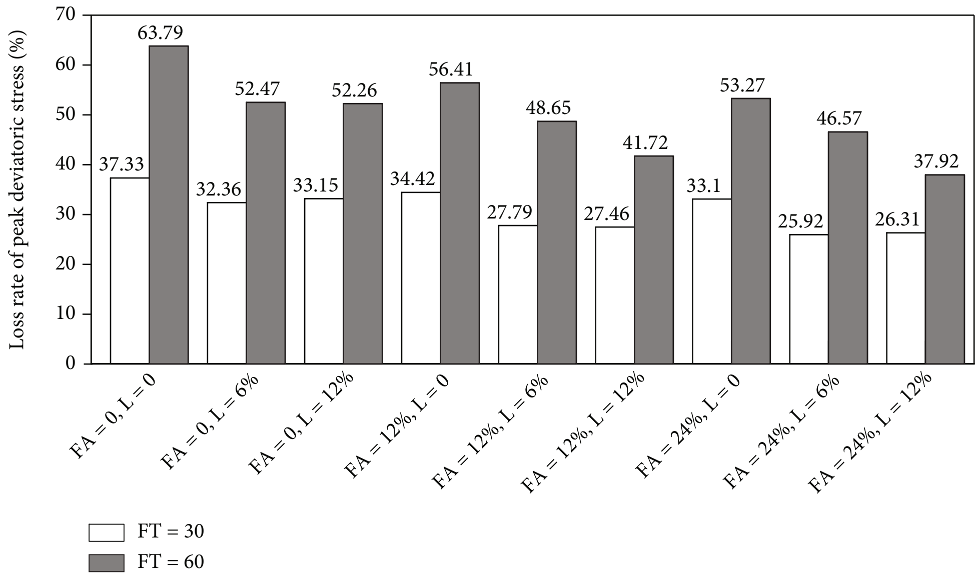

Figure 28: Loss rate of peak deviatoric stress after freeze-thaw cycles.

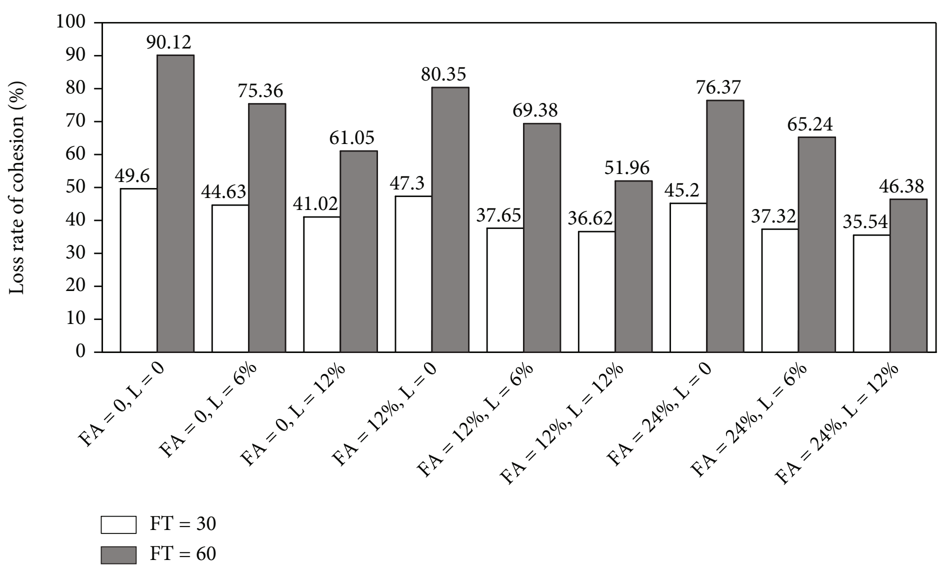

Figure 29: Loss rate of cohesion after freeze-thaw cycles.

4.5. Effect of Freeze-Thaw Cycles. Soil strength is generally reduced by freeze-thaw cycles [35]. Loosely bound water and free water are the main forms of water within coarse grain soils. In low temperature environments, the free water within the coarse grain soil expands in volume as it freezes, resulting in cracks developing in the coarse grain soil. During freeze-thaw cycles, free water freezes and thaws repeatedly, which intensifies the cracking in the coarse grain soil and breaks the soil particles into smaller sizes. The water in fine grain soils exists in the form of bound water and remains unfrozen at low temperatures. Therefore, it is less likely for fine grain soil particles to break during freezing, but it is easier to generate larger soil particles via extrusion of coarse grain soil. After repeated freeze-thaw cycles, moderately sized soil particles become more easily generated in the soil.

In the Songnen Plain, the carbonate saline soil is distributed in the seasonally frozen soil region. Due to the temperature differences between day and night, repeated freeze-thaw cycles occur in the surface soil throughout the year, so it is reasonable to conduct experiments exploring the effects of repeated freeze-thaw cycles on soil. In this test, soil was exposed to 0, 30, and 60 freeze-thaw cycles. The peak deviatoric stress loss rates of the improved carbonate saline soil after freeze-thaw cycles are shown in Figure 28.

The resistance of carbonate saline soil in the Songnen Plain to the loss of peak deviatoric stress from freeze-thaw cycles increased significantly after adding fly ash and lime. With increased lime content, the peak deviatoric stress loss rate of the carbonate saline soil with freeze-thaw cycles initially decreased and then stabilized. When fly ash was added alone, the peak deviatoric stress of the carbonate saline soil

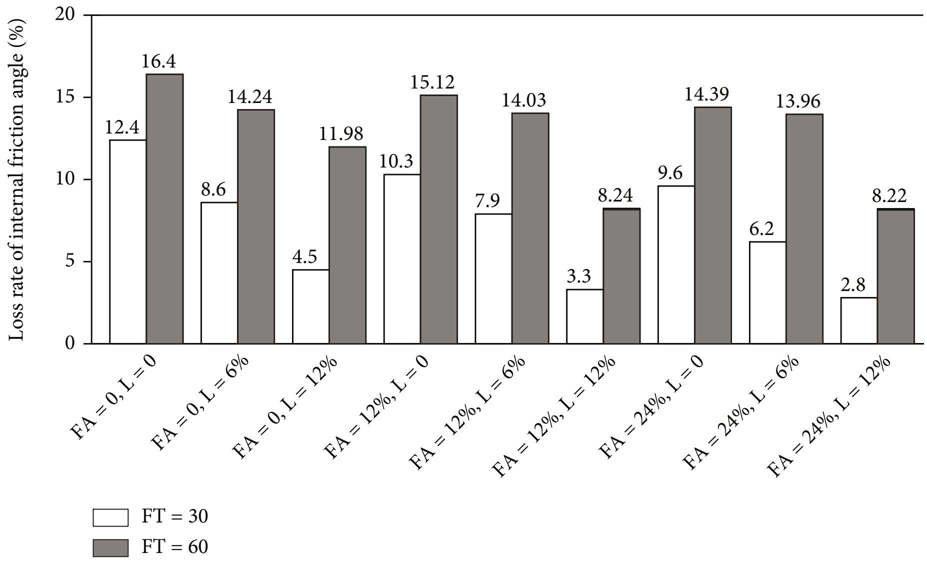

Figure 30: Loss rate of internal friction angle after freeze-thaw cycles.

decreased gradually with increasing fly ash content, but the decrease was small. When lime and fly ash were added together, at 6% and 24%, respectively, exposure to 30 freeze-thaw cycles resulted in a minimum peak deviatoric stress loss rate value of 25.92%. This peak deviatoric stress loss rate was 11.41% lower than that of carbonate saline soil without improvement (37.33%). When the number of freeze-thaw cycles was increased to 60, the peak deviatoric stress loss rate of the experimental group with 24% fly ash content and 12% lime content reached the minimum value of 37.92%. Compared with the unimproved carbonate saline soil (63.79%), this decrease in peak deviatoric stress was 25.87%. Comparing the two tests, the fly ash content was 24%, which indicated that the effect of fly ash weakening the freeze-thaw cycles effect on the peak deviatoric stress was more significant.

Figure 29 shows the effect of freeze-thaw cycles on the cohesion of lime-ash improved carbonate saline soil. The number of freeze-thaw cycles decreased the cohesion of the soil. The greater the number of freeze-thaw cycles, the greater the magnitude of the decrease in cohesion. Comparing the test groups with lime alone and fly ash alone, both lime and fly ash inhibited the loss of cohesion of carbonate saline soil due to freeze-thaw cycles, but lime had a stronger effect. However, lime and fly ash mixed together suppressed cohesion loss due to freeze-thaw cycles even more.

Figure 30 shows the effect of freeze-thaw cycles on the internal friction angle of the lime-ash improved carbonate saline soil. The effect of freeze-thaw cycles on the internal friction angle of lime-ash improved carbonate saline soils was smaller than the effect of freeze-thaw cycles on the peak deviatoric stress and cohesion of lime-ash improved carbonate saline soils. The loss rate of the internal friction angle increased with increasing number of freeze-thaw cycles. The ability of fly ash to suppress the loss of internal friction angle due to freeze-thaw cycles in lime-ash improved carbonate saline soil was weaker than that of lime. The incorporation of both fly ash and lime was more beneficial to suppressing the loss of internal friction angle due to freeze-thaw cycles.

5. Conclusions

The following conclusions were obtained from the analysis and test results:

(1) With the increase of lime and fly ash content, the stress-strain curve of carbonate saline soil changed from strain hardening to strain softening. At the same time, the strain corresponding to the peak deviatoric stress of the soil was altered

(2) The significance analysis method can clearly reflect the degree of influence of multiple factors and their interactions on the shear strength of the improved carbonate saline soil in seasonally frozen soil regions. Among the factors and their interactions involved in this study, the effects of the $FT \times L \times CP$ interaction and the $FT \times FA \times CP$ interaction on peak deviatoric stress were not significant; the effects of fly ash, the $FT \times FA$ interaction and the $L \times FA$ interaction on cohesion had limited effect, and the effect of the $FT \times FA$ interaction on internal friction angle had piccaninny influence. The effects of other factors on peak deviatoric stress, cohesion, and internal friction angle were all significant

(3) The experimental results showed that a small amount of fly ash could improve the peak deviatoric stress and internal friction angle of carbonate saline soil; the incorporation of lime could greatly improve the peak deviatoric stress, cohesion, and internal friction angle of carbonate saline soil. Lime played a dominant role when incorporating lime and fly

ash to improve the shear strength of carbonate saline soil

(4) The study showed that the incorporation of lime and fly ash suppressed the damage of freeze-thaw cycle on peak deviatoric stress, cohesion, and internal friction angle of carbonate saline soil. Fly ash weakened the effect of freeze-thaw cycle on peak deviatoric stress more significantly, but lime weakened the effect of freeze-thaw cycle on cohesion and internal friction angle of carbonate saline soil more significantly. The experiment, after adding 12% lime alone, the loss of cohesion of carbonate saline soil decreased by 8.58% and 29.07% after 30 and 60 freeze-thaw cycles, respectively, and the loss of internal friction angle decreased by 7.9% and 4.42%. After adding 24% fly ash alone, the loss rate of peak deviatoric stress of carbonate saline soil decreased by 4.23% and 10.52% after 30 and 60 freeze-thaw cycles, respectively

(5) Our proposed incorporation of lime and fly ash to improve carbonate saline soil in seasonally frozen soil regions can improve the shear strength and freeze-thaw resistance of carbonate saline soil, but the optimal incorporation amount for both to improve carbonate saline soil will need to be optimized in future research

Data Availability

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

Conflicts of Interest

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

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