



Effect of Freeze-Thaw Cycle on Shear Strength of Lime-Solidified Dispersion Soils

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Abstract

The freeze-thaw cycle of saline soil in the seasonal frozen area will produce diseases such as frost heave and thaw settlement, road frost boiling, collapse and uneven settlement. In order to reduce the occurrence of these undesirable phenomena, it is often necessary to improve the saline soil in engineering. In this paper, the typical carbonate saline soil in the west of Jilin Province, China is taken as the research object. By adding different content of lime (0%, 3%, 6%, 9%, 12%, 15%), the change of mechanical strength of lime solidified saline soil under different freeze-thaw cycles (0, 1, 3, 6, 10, 30, 60 times) is studied. The mechanical analysis is carried out by combining particle size analysis test and SEM image. The test results show that although repeated freeze-thaw cycles make the soil structure loose and the mechanical strength greatly reduced, the soil particles agglomerate obviously after adding lime, its dispersion is restrained by the flocculation of clay colloid, and the shear strength of soil is improved by the increase of the cohesive force between clay particles, and the optimal lime mixing ratio of the saline soil in this area is 9%.

Keywords: Saline Soil; Freeze-Thaw Cycle; Lime Improvement; Particle Size Analysis; SEM Image.

1. Introduction

The western part of Jilin Province is located in the southwestern part of China's Songnen Plain. It is one of the world's three major soda alkaline soil distribution areas, and is also the largest area of soda alkaline soil in China [1-4]. In the past 20 years, not only the total area of saline soil has expanded rapidly, but also the degree of soil salinization has increased greatly, and the ecological environment is very fragile [5, 6]. In order to alleviate land degradation and improve the ecosystem, Jilin Province has started the water diversion project of the lower Nenjiang River and the second Songhua River to wash the salinized land to achieve the purpose of restoration of cultivated land, grassland and wetland environment [7, 8]. Because of the high content of Na⁺ in the soil of this area, its dispersity is relatively large, which has been fully proved in many scholars' research. Xudong et al. (2015) verified the dispersion of shallow soil in Qi'an area by means of pinhole test, particle test and double gravity meter [9, 10]. Yan Han studied the initial freezing point of dispersive saline soil in this area [11]. At the same time, because the soil in this area is highly dispersed, and often develops a large number of macro-micro fissures, obvious structure and large non-uniformity of mechanical properties, it is often easy to cause bank collapse, slope instability and other engineering accidents, so it is necessary to improve the engineering properties of saline soil in this area. In the early stage of soil improvement, the research is mainly limited to the observation of its macro properties, and the research on its indicators and improvement mechanism is less. After the 1990s, with the development of micro equipment, the micro research of improved soil began to be common, and the exploration of improved mechanism gradually became the mainstream direction. Ambarish G and Chillara S study the

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physical and chemical reactions and microstructure changes of modified soils mixed with lime and fly ash by XRD, SEM, X-ray energy spectroscopy, differential thermal analysis and other testing techniques [12]. Yarbasi et al. compared the compressive strength, ultrasonic, CBR and resonance characteristics of saline soil after adding lime, fly ash and cement in different freeze-thaw cycles. It was found that the freeze-thaw resistance and durability of the improved saline soil were greatly improved [13]. Bin-Shafique et al. (2010) tested and studied the long-term performance of two kinds of fine-grained soil subgrade stabilized by fly ash. It was found that the effect of dry wet cycle on the stability of soil was negligible, while the loss of strength by freeze-thaw cycle was as high as 40% [14]. Cuisinier et al. (2011) carried out relevant experiments on the micro-structure, hydraulic conductivity and so on of compacted lime-treated soil [15]. Ziaie-Moayed et al. (2011) used cement and polymer, through direct shear test and unconfined compression test to explore the shear strength of saline soil before and after immersion [16]. Liu and Bin (2012) adopt slag cementitious material to mix into saline soil, reduce the soluble salt content of saline soil, increase water stability and improve soil strength [17].

In recent years, more and more scholars began to use more advanced instruments and new solidifying materials, starting from the material composition, microstructure, physical mechanics and other aspects, to test the improved soil from the perspective of quantitative and qualitative, macro and micro combination. Arvind Kumar and Sivapullaiah (2016) carried out consolidation test after gypsum soil was treated with lime, and analyzed its microstructure by XRD, SEM and EDAX, which proved the rationality of the formation of ettringite crystal by ion exchange reaction, and explained that the expansion reduction caused by the increase of curing period was due to the continuous growth of ettringite and cementite [18]. A series of undrained cyclic triaxial compression tests and hollow cylinder torsional shear tests were carried out on saturated sand with and without fiber by Ye et al. (2017). It was proved that the randomly distributed fiber-reinforced samples can bear more loading cycles before liquefaction than the samples without fiber, that is, the incorporation of fiber can effectively improve the liquefaction resistance of sand [19]. Zhang et al. (2017) used self-designed experimental equipment to study the electroosmotic chemical treatment of marine cohesive soil and established an empirical formula for its reinforcement treatment (2017) [20]. Ta'negonbadi and Noorzad (2018) used a new material, lignin-sulfonate (LS) as a curing agent, and evaluated the long-term behavior of unstabilized soil and stabilized soil by direct shear and triaxial tests [21]. Choobbasti et al. (2018) have verified that nano-mud can significantly improve soil brittleness behavior through static and cyclic triaxial tests [22]. Badv and Lonbar (2018) demonstrated the application of cement kiln dust (CKD) as an additive of pozzolanic ash in stabilizing Urian peat, and concluded that compared with natural peat, CKD treated peat samples have higher cohesion, internal friction angle, CBR and UCS [23]. Sujatha et al. (2018) believe that coconut fiber and lime mixed solidified material can improve soil-fiber interaction, increase the occlusion between fiber and soil, and thus improve soil strength [24]. In addition, microbial induced calcite precipitation technology has realized the interdisciplinary field of bioengineering and civil engineering, which is a new development direction of bio-soil materials. Kalantary et al. (2019) used microbial induced calcite precipitation method to increase the compressive strength of samples with 30% salt content by 5 times [25]. Wei and Zhang (2018) reviewed and prospected the improvement of soils from the separation of halophilic fungi, gene of salt and alkaline resistant fungi, macromolecular degrading enzyme, and application of halophilic fungi in the repair of fungi in saline alkali soil [26]. Hoang et al. (2019) extracted a new microbial catalyst from sand and muddy soil, which can replace the traditional microbial enzyme to induce calcite precipitation, making new improvements in biosafety and geotechnical engineering [27]. In the past, most of the research focuses on simply discussing the change rule of the mechanical properties of soil by solidifying agent. There is little analysis on the mechanism of the strength change under the double influence of freeze-thaw cycle and solidifying agent. Therefore, it is necessary to study the shear strength change of lime-solidified soil during freeze-thaw cycle and analyze the mechanism.

The research object of this paper is saline soil in the excavation test section of Qian'an water diversion canal. There are a lot of macro-micro cracks on the surface and inside of the soil in this area, which have obvious structure and uneven mechanical properties. In this paper, based on the characteristics of strong dispersion of soil in this area, the direct shear test method was used to study the shear strength and related mechanical parameters of lime-solidified soil under different conditions of ash-adding and different freeze-thaw cycles. The mechanism of the change of strength of saline soils was analyzed by particle test and SEM image observation.

2. Experimental Scheme

2.1. Basic Physicochemical Properties of Soil Samples

This paper focuses on the lime improvement of saline soil in the experimental section of channel excavation in Qian'an County. The sampling points are shown in Figure 1. Sampling points are selected on the peripheral flat land about 50 meters away from the canal. During the excavation process, the ground temperature is measured and sampled at 20 cm intervals, and the depth is 160 cm underground.

Natural density of soil samples ranged from 1.864 to 2.056 g.cm⁻³; The natural moisture content is at least 11.31%, up to 21.58%; Except for 100 cm depth, the content of fine grains (< 0.075 mm) in soil samples at all depths is more

than 75%, which is silty light clay; The highest content of organic matter is 0.40%, which can be judged as non-organic soil; The soluble salt content in each layer ranged from 0.28% to 0.71%, and HCO_3^- and Na^+ were the main anions and cations in the soil. The content of Na^+ is more, which not only improves the dispersion, plasticity and expansibility of soils, but also weakens the permeability and shear strength of soils. In the test of soluble salt content, the turning point and maximum point of soluble salt in soil layer are at 40 cm. This is because the shallow soil is mainly leached by rainwater, which makes the salt move downward. Because of the poor permeability of the soil in this area, the leaching effect of rainwater gradually weakens with the increase of depth. From 40 cm down, the soluble salt mainly comes from the rising of capillary water in the lower part of soil in spring and autumn and the migration and accumulation of structural water in winter. With the increase of depth, the content of soluble salt in the lower part of soil gradually decreases [7]. Therefore, this layer of soil is selected as the experimental soil to study the shear resistance of saline soil in Qian'an County, and physical and chemical experiments are carried out. The experimental results are as follows: Table 1 and Table 2. The optimum moisture content and maximum dry density of soil at 40cm are 15.6% and $1.781\text{g}\cdot\text{cm}^{-3}$ respectively.

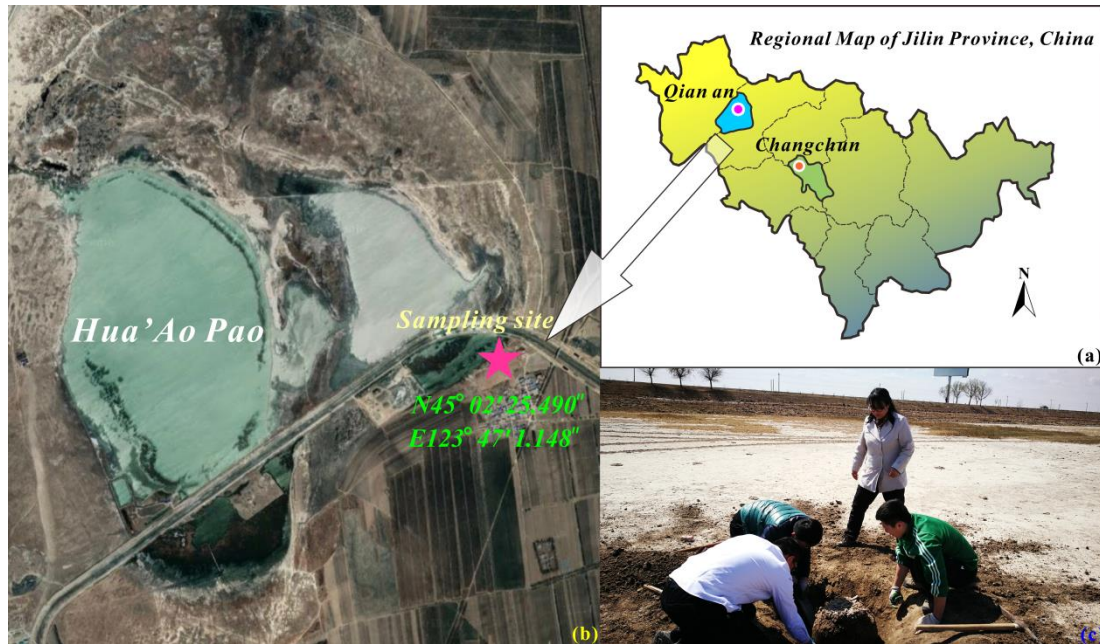


Figure 1. Research areas and sampling sites: (a) regional map of Jilin province, China; (b) sampling site; (c) sampling scene

Table 1. Basic physical and hydraulic properties of 40cm soil samples

Natural density $\rho/\text{g}\cdot\text{cm}^{-3}$	Natural moisture content $\omega/\%$	Plastic limit $\omega_p/\%$	liquid limit $\omega_l/\%$	Plasticity index I_p	Liquid index I_l	Consistency state
1.909	21.58	19.00	45.75	26.75	0.10	Hard plastic

Table 2. Basic chemical properties of 40cm soil samples

Total Soluble Salt (%)	Various ion components/mmol/kg					
	K^+	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}
0.71	1.48	32.26	0.87	3.04	3.88	0.58

2.2. Control of Freeze-Thaw Cycle

Freeze-thaw cycle is a kind of strong weathering action, which makes the water state in soil change repeatedly, causes frost heave and thaw settlement, and destroys the structure of soil, thus changing the mechanical properties of soil. In this test, it was carried out by the research team's self-made "super-cold environment rock-soil freezing and thawing experiment simulation platform". As shown in Figure 2, the control precision is 0.1°C , which can simulate the low temperature environment from 0°C to -45°C . The device consists of four parts, namely, temperature control system, refrigeration system, heat dissipation system and thermal insulation system.

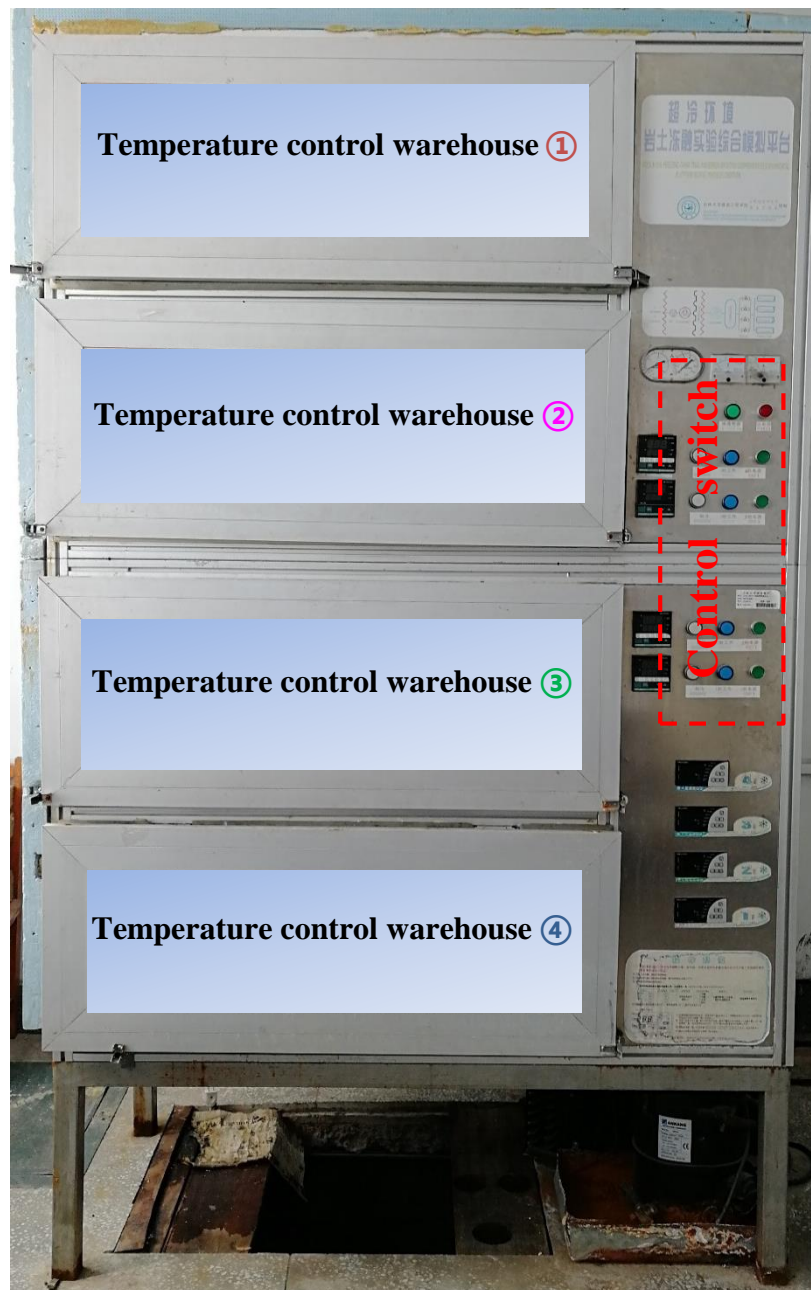


Figure 2. Comprehensive simulation platform for freeze-thaw test of rock and soil in ultra-cold environment

According to the range of temperature change in the permafrost region in the Qian'an season, the core temperature of soil samples during freeze-thaw is controlled as follows: the core decreases to -20°C and then rises to 20°C , which is a complete freeze-thaw cycle. The freezing temperature of this freezing-thawing cycle is set to -25°C , and the time of freezing and thawing is 12 hours at room temperature of 25°C , that is, 24 hours at a freezing-thawing cycle. The freeze-thaw cycles of 0, 1, 3, 6, 10, 30 and 60 times were selected to study the effect of freeze-thaw cycles on shear resistance of solidified saline soil.

2.3. Lime Content and Curing Period

In the study of the solidification mechanism of lime soil, Rao and Shivananda (2005) considered that the solidification effect of lime was mainly due to the combination of aluminite hydrate and calcite hydrate formed by the reaction of lime and clay minerals, which played a cementing role [28]. Broms (1986) suggested that the optimum yield of lime-improved soil was 12%, and its strength was about 50 times that of plain soil [29]. Ciancio et al. (2014) improved the soil with two different solidifying agents, Portland cement and lime, and put forward the optimum lime content [30]. Based on the previous research experience, and in order to explore the improvement effect of saline soil with higher lime content, six kinds of lime content were selected to study the effect of lime content on solidified saline soil, which were 0, 3, 6, 9, 12 and 15% respectively.

In this experiment, YH-40C standard constant temperature and humidity curing box was selected for maintenance. The tightly wrapped samples were put into the curing box with 20°C and 95% relative humidity for maintenance. Liu et al. (2019) [4] has carried out mechanical experiments on lime-stabilized soil under freeze-thaw cycles and analyzed its mechanism. Sun (2017) [31] carried out mechanical tests on unsaturated saline soil and lime-stabilized soil under freeze-thaw cycles. According to the team's experimental conclusion, after 28 days of curing at room temperature, lime can give full play to the role of cementation, and its mechanical properties are basically stable. Therefore, 28 days of curing age is chosen for this experiment.

2.4. Sample Preparation Process

The natural saline soil is dried by air, then the dried soil sample is passed through a 2 mm sieve, and quicklime is also sifted through a 2 mm screen for standby use. According to the amount of lime, the quality of dry soil and lime needed to be added to each sample was calculated, and then they were stirred evenly. Calculate the quality of water according to the formula of water content. The spray pot is used to add water evenly and mix well so as to ensure the uniform moisture content of soil samples. After that, the soil samples were put into the fresh-keeping bag and sealed, and then put into the wetting cylinder to stand for 24 hours.

In this direct shear test, four strain-controlled direct shear apparatus and unconsolidated undrained test are used. In practical engineering, soil compaction of 100% is only ideal, even 95% is difficult to control. Therefore, in this test, the water content of samples is 15.6% of the optimum moisture content of natural saline soil, 0.71% of the salt content of natural saline soil and 90% of the compactness. The diameter of ring cutter is 61.8 mm, the height is $H=20$ mm, the loading grade is 100, 200, 300 and 400 kPa, and the shear rate is 0.8 mm/min, which makes the specimen destroyed in 3-5 minutes. Considering the effects of six different lime dosages and seven different freeze-thaw cycles, the total number of samples is $6 \times 7 \times 4 = 168$.

Combined with the above two different control variables of freeze-thaw cycle times and lime content, the main research contents of this paper are as follows:

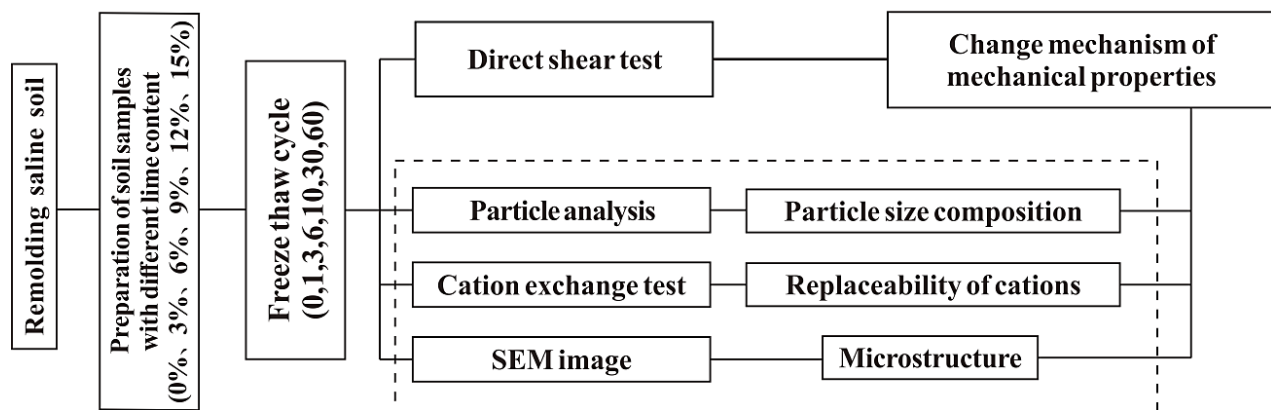


Figure 3. Experiment flow chart

3. Experimental Result

3.1. Effect of Freeze-Thaw Cycles on Cohesion and Internal Friction Angle

The cohesion decreases with the increase of freeze-thaw times, as shown in Figure 4. The decay rate of cohesion is the fastest at low freeze-thaw times (0~3 times), slower at 3~10 times than before, and slowest at high freeze-thaw times (more than 10 times). Therefore, the variation of cohesion can be roughly divided into three stages: rapid decline (0~3 times), slow decline (3~10 times), and structural failure (10~60 times). After the 10th freeze-thaw cycle, the cohesion of plain saline soil and low ash content (3, 6%) solidified soil hardly changed, while the cohesion of high ash content (9 to 15%) solidified soil still decreased significantly, and it can be predicted that it may continue to decrease after 60 freeze-thaw cycles according to the image, therefore, it can be seen that the lime-solidified soil with high ash content requires more freeze-thaw cycles to make the cohesive force stable, this shows that the addition of lime in saline soil can enhance its freeze resistance to a certain extent, and make its freeze-thaw stability stronger.

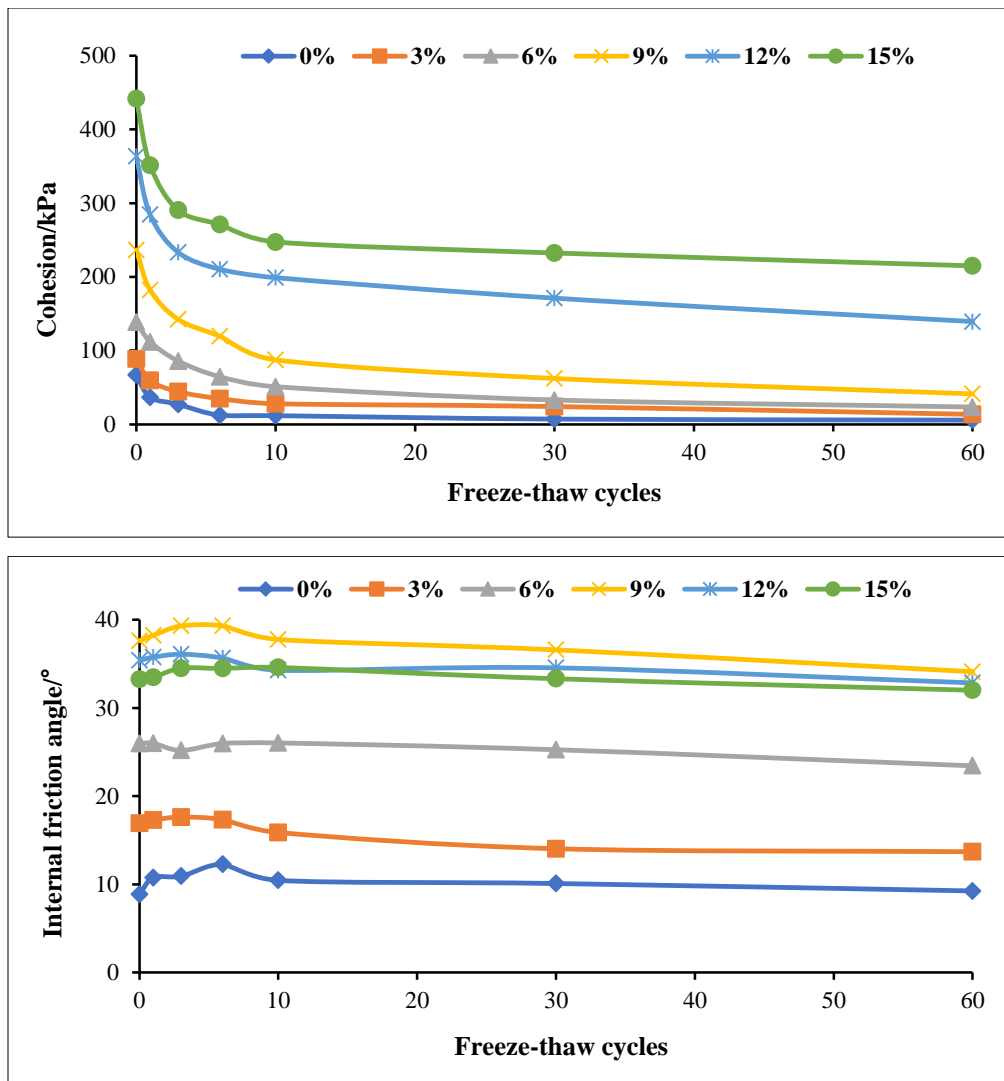
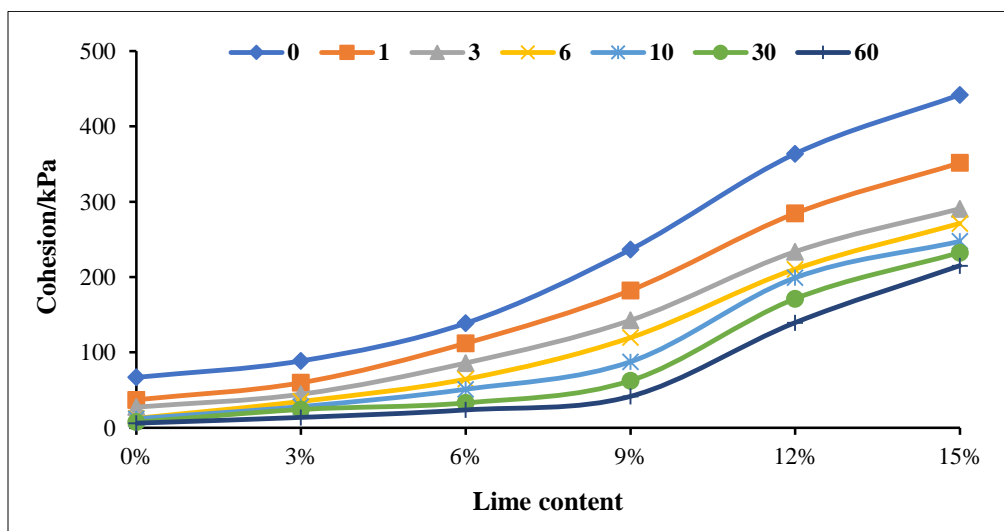


Figure 4. Effect of freeze-thaw cycles on strength parameters

The internal friction angle increases first and then decreases with the increase of freeze-thaw times, but the degree of change is not obvious. Among them, the internal friction angle of plain saline soil is the smallest, while the internal friction angle of lime solidified soil increases with the increase of lime content. The internal friction angle of lime solidified soil with 9% lime content is the largest. It can be seen that this ratio of lime content may make the cementation and encapsulation effect between soil particles the most fully. At the same time, the internal friction angle of plain saline soil is almost the same as that of solidified soil with different amount of lime, which shows that the effect of freeze-thaw cycle on plain soil and lime-stabilized soil is similar.



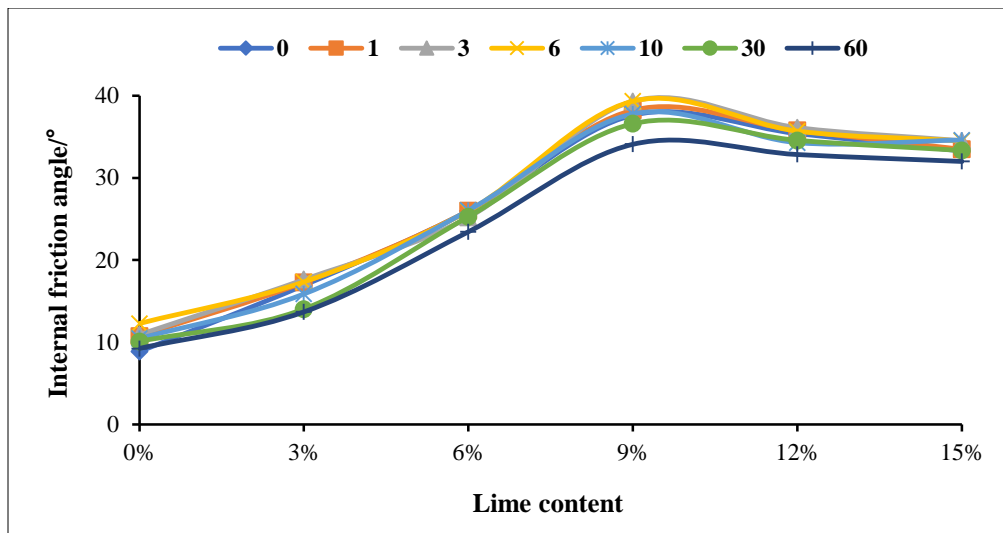


Figure 5. Effect of lime content on strength parameters

As shown in Figure 5, as the amount of lime added increases, the cohesive force gradually increases. When the low lime content (3 to 9%), the cohesive force increases slowly, but when the high lime content (9 to 15%), the cohesive force sharply increases. Therefore, it can be inferred from the image that when the lime content is more than 15%, the cohesion may continue to increase.

The internal friction angle increases firstly and then decreases slightly with the increase of lime content. When the content of lime is low, the internal friction angle increases rapidly, and when the content of lime reaches 9%, the internal friction angle reaches the maximum value. However, with the continue increase of the content of lime, the internal friction angle decreases obviously. When the content of lime exceeds 12%, the internal friction angle almost remains unchanged.

Therefore, it can be seen that the lime in the saline soil has a great influence on the shear strength. When the blending amount is very low (<3%), the cohesion, internal friction angle and shear strength increase slowly, but as the blending amount increases to 6%, the shear strength index of lime solidified soil increases rapidly. At the same time, the internal friction angle decreases obviously when the lime content is higher than 9%, which indicates that under the same freeze-thaw cycles, it is not the higher the lime content, the more obvious the effect of improving the shear strength of saline soil, but the existence of an optimum mixing ratio. From the above test results, it can be inferred that the optimum lime incorporation ratio of saline soil in this area is 9%.

4. Factors Affecting Mechanical Parameters and Mechanism Analysis

4.1. Effect of Lime Curing Agent

The cumulative distribution curves of soil particle size of each layer are obtained from hydrostatic settlement test and sieving test as shown in Figure 6. By comparing the particle distribution curves of soil samples before and after adding dispersant, it can be found that the content of fine particles in soil samples before and after adding dispersant has been higher, and the change of the content of fine particles in soil samples before and after adding dispersant is not obvious, so dispersant has little influence on the particle size composition of soil samples in Qian'an area, and the layer soil itself has strong dispersion.

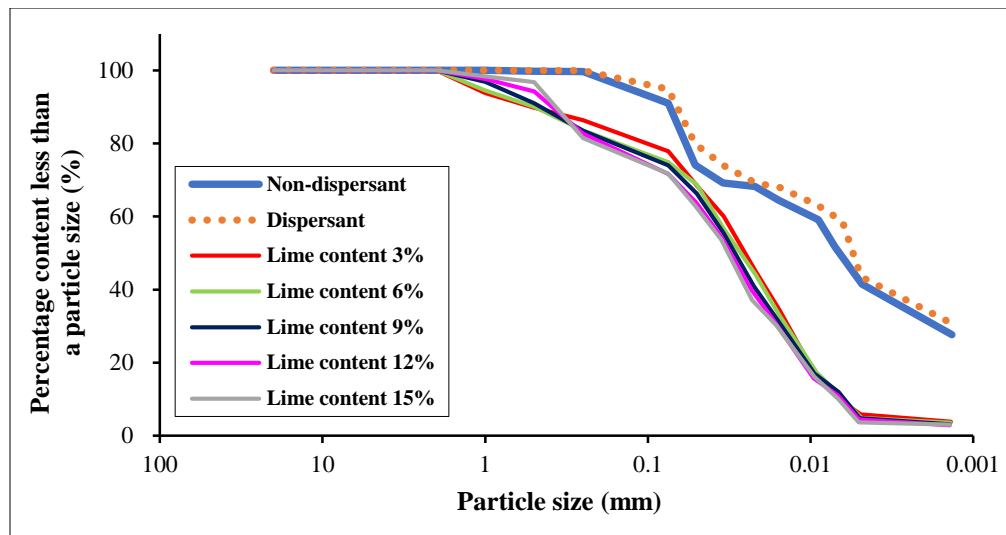


Figure 6. Cumulative Distribution Curve of Diameter Size

The cumulative curve becomes smoother after adding lime into soil, which indicates that the content distribution of each grain group in soil is more uniform, the size of particles is mixed, and the gradation is better. The cumulative distribution curves of particle size with different ash content are similar: the curve of clay ($< 0.005\text{mm}$) part slows down, while the curve of sand ($2-0.075\text{mm}$) and silt ($0.075-0.005\text{mm}$) part steepens obviously, which indicates that the clay content decreases, while the sand content and silt content increase. It can be seen from this that lime is added to saline soil, and the particles have obvious "agglomeration" effect.

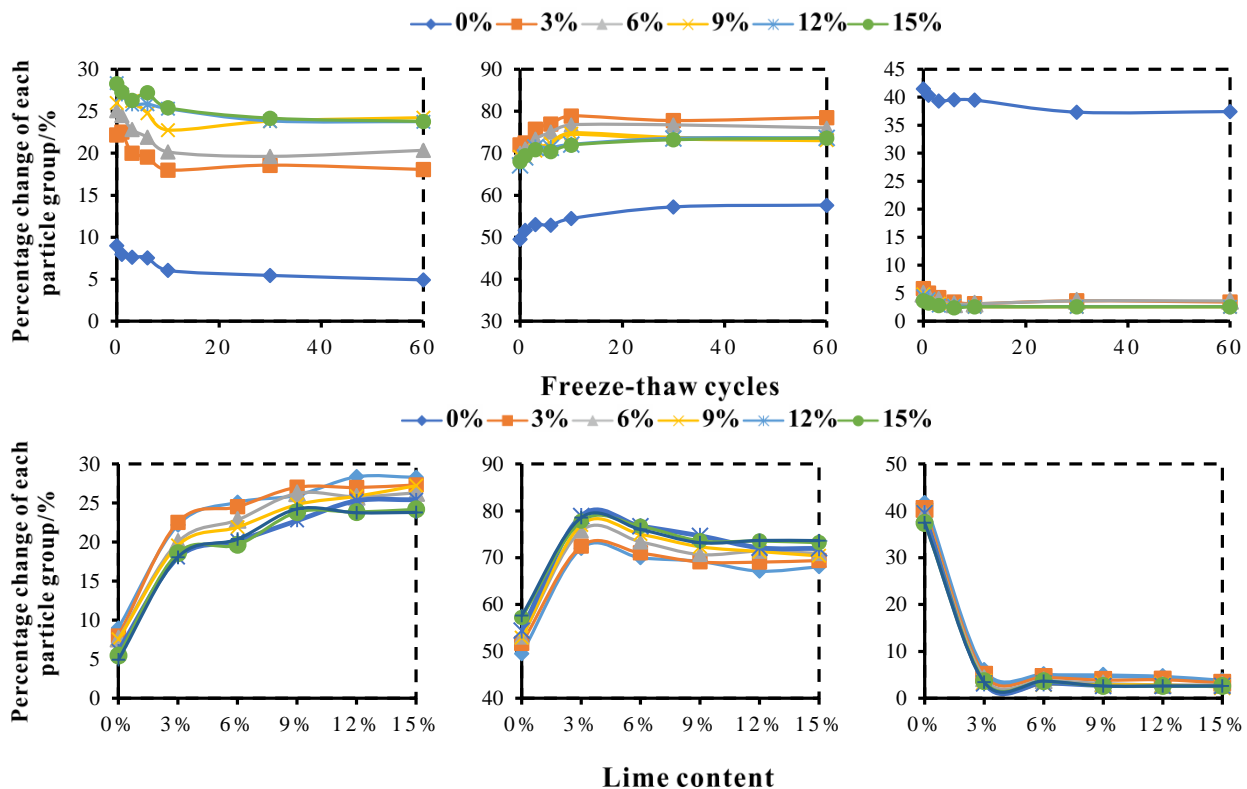


Figure 7. Effect of freeze-thaw cycle number and lime content on the change of particle percentage: (a) sand group (b) silt group (c) clay group

As shown in Figure 7, after lime treatment, the grain size composition of saline soil changed significantly, the content of clay group decreased, and the content of sand group and silt group increased. Among them, the change of granularity percentage content is particularly significant when the ash content is less than 3%, but with the increase of the ash content, the change of granularity composition tends to be stable. For example, the clay content in saline soil without freeze-thaw cycle is 41.49%, and the content decreases sharply to 5.81% when only 3% lime is added, but with the

increase of the ash content, the change of granularity composition tends to be stable. With the increase of lime content, the content of clay fraction decreases only slightly, which indicates that lime cannot change the size composition of saline soil indefinitely, but has a reasonable amount of lime.

At the same time, when the lime content exceeds 3%, the content of silt group decreases slightly, while the content of the sand group continues to increase, which indicates that the increase of the amount of lime will make the agglomeration of small particles in the soil more significant, and more it is even understood that agglomerates into sand group instead of silt group, and it is even understood that some of the silt group are also agglomerated into sand group at this time.

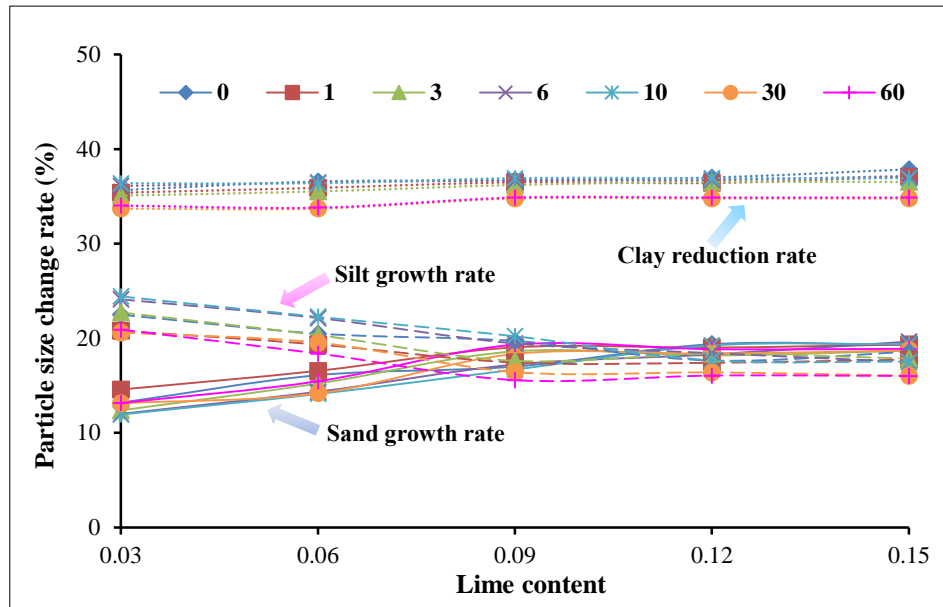


Figure 8. Particle size change rate with different lime content

As shown in Figure 8, it is more obvious from the grain size change rate curve that when lime is added into the soil, the degree of change of clay group is the most obvious, followed by silt group, and finally sand group. The former is greatly reduced, while the latter two are increased. With the increase of ash content, the clay group always decreases at a slower rate, while the content of silt group decreases slightly, and the content of sand group increases continuously. When the content of ash exceeds 9%, the change rate of both groups tends to be the same, and even the grain size growth rate of silt group is slightly smaller than that of sand group, this proves that when the lime content reaches 9%, the particles have already undergone a relatively good agglomeration. At this time, the best effect of improving the particle composition is almost achieved. Therefore, a reasonable amount of ash may be around 9%.

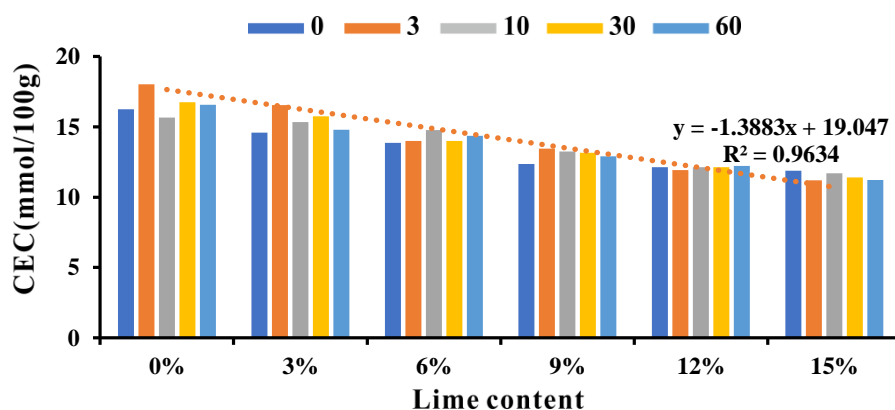


Figure 9. Effect of lime content on total cation exchange

As shown in Figure 9, the lime in the saline soil is mixed, and the cation exchange amount is approximately linearly related to the ash content. The regularity of the cation exchange is: the more the lime content, the smaller the total cation exchange, which indicates that the ion exchange will take place when lime is added into soil, and Ca^{2+} generated after $\text{Ca}(\text{OH})_2$ ionization by hydrolysis can replace Na^+ which is replaceable on the surface of the soil particles, and the more

the amount, the more sufficient the ion exchange effect. Because the end of the curve of the image is much smoother than that of the front part, the trend of the image predicts that with the increase of the amount of ash, the total cation exchange amount may approach a fixed interval rather than decrease all the time.

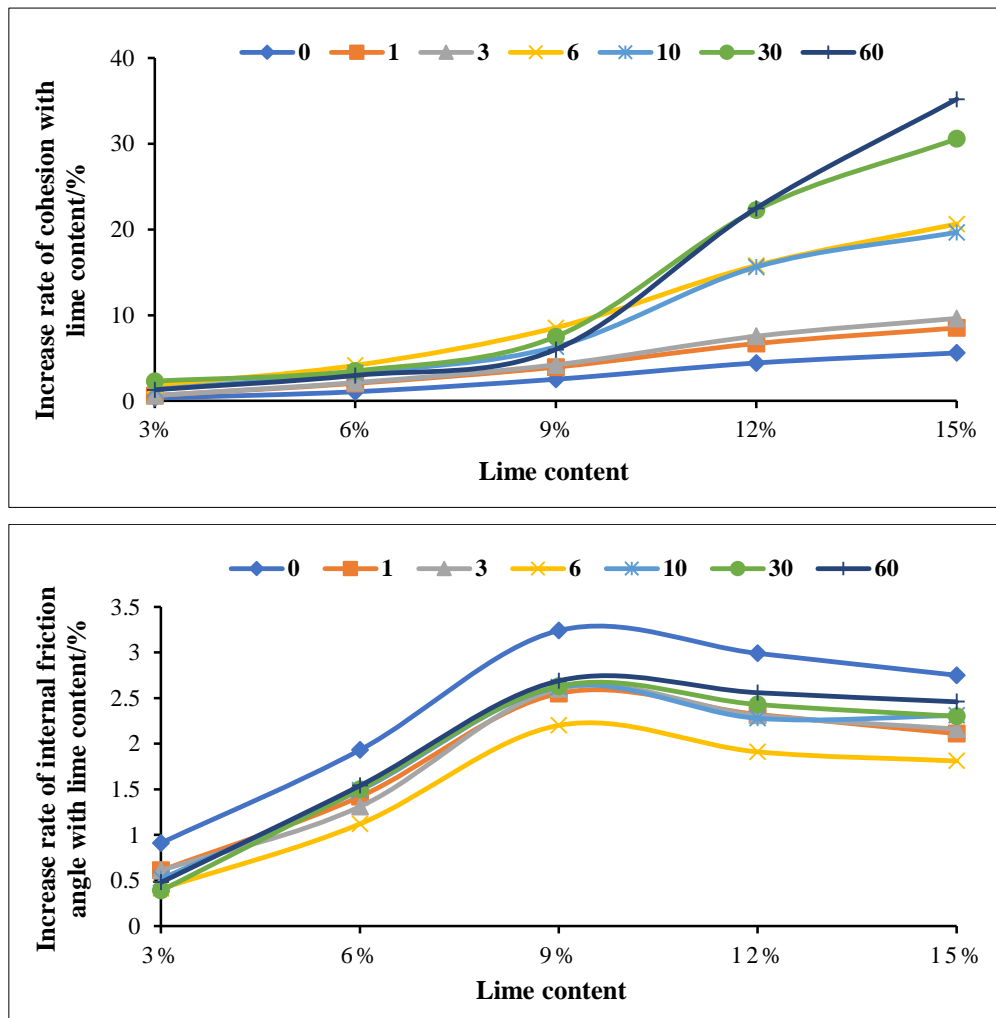


Figure 10. Change rate of strength parameters with different lime content

Figure 10. With the increase of lime content, the change rate curves of cohesion and internal friction angle of saline soils with different freeze-thaw cycles are very similar to those obtained by experiments. The change rate of cohesion increases gradually, and the change rate of internal friction angle increases first and then decreases slightly, and reaches the maximum when the ash content is 9%.

According to the above experimental rules, the mechanism of the change of cohesion and internal friction angle of saline soil mixed with lime is as follows: when lime is mixed into soil, a series of physical and chemical reactions will occur, such as thermal reaction of water absorption and expansion, ion exchange, crystallization reaction of $\text{Ca}(\text{OH})_2$, carbonation reaction of $\text{Ca}(\text{OH})_2$ and pozzolanic reaction. $\text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$, $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ and solid CaCO_3 formed in the reaction wrap up the soil particles, making the particle size composition and material composition of the soil change significantly, so that its strength is improved. In structural connection, the reaction products of lime play a cementing role on soil particles in the crystallization process. With the increase of lime content, the more crystals, the stronger cementing effect, and greatly enhance the overall strength of soil. During the ion exchange process, Ca^{2+} replaces the exchangeable Na^+ on the surface of the particles, so that the thickness of the electric double layer becomes thinner, the combined water is reduced, and the bonding force between the soil particles is enhanced. In the process of agglomeration of soil particles, while forming large particles, fine particles in the soil will be filled in the pores of the soil, reducing the size of the pores, enhancing the bonding force of the soil skeleton and improving the strength of the soil.

The change of internal friction angle is mainly due to the addition of lime in saline soil, and clay particles form larger aggregates because of the encapsulation and agglomeration of reaction products. At the same time, the formation of crystalline calcium silicate, crystalline calcium aluminate and calcium carbonate will make the outer surface of soil particles rougher, resulting in the increase of internal friction angle of soil particles. When the amount of lime is too

high, the fine lime particles in the soil can fill the voids of the soil particles, which weakens the friction force between the soil particles, thus the internal friction angle decreases slightly.

4.2. Effect of Freeze-Thaw Cycles

It can be seen from Figure 7 that as the number of freeze-thaw cycles increases, the sand group content curve first decreases and then tends to be gentle. The curve of the silt group first rises and then stabilizes, and the clay group curve first decreases and then flattens. Therefore, the mode of action of freeze-thaw cycles on each group of saline soils is as follows: On the one hand, the larger particles are broken up, on the other hand, the smaller particles are agglomerated and the size of particles tends to be uniform, which also reflects the duality of the effect of freeze-thaw cycles on the grain size composition of soils.

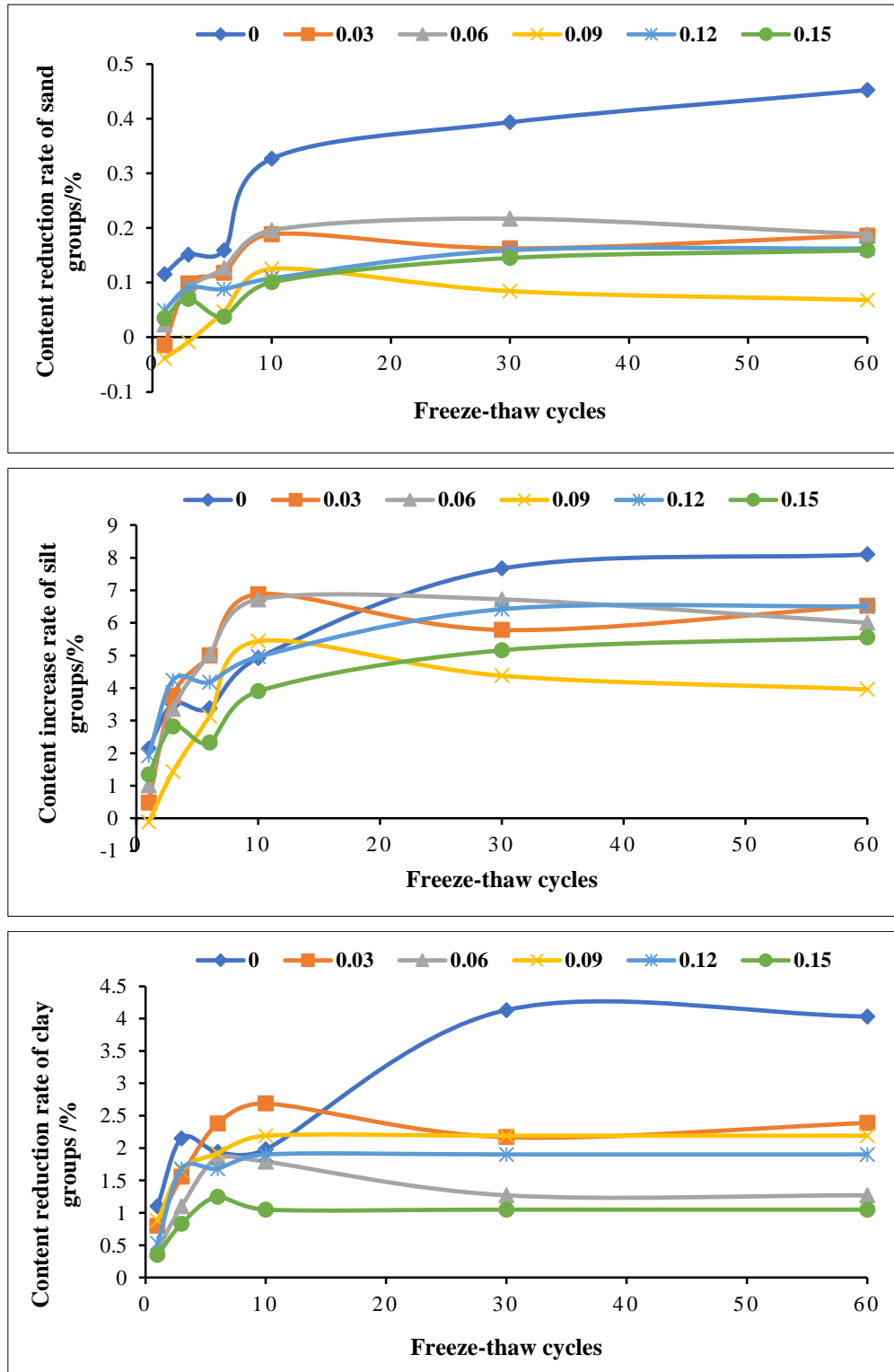


Figure 11. Change rate of percentage content of each particle group by freeze-thaw cycles

As shown in Figure 11, the change rate curve of percentage content of each grain group at different freeze-thaw cycles shows the following rules: With the increase of freeze-thaw cycles, the change rate of grain percentage of plain soil in different particle size ranges is always greater than that of lime solidified soil in general, which indicates that adding lime into saline soil may improve its frost resistance correspondingly. Whether sand, silt or clay, the percentage content of each grain group will change dramatically at low freeze-thaw times (< 6 times), but after more than 10 freeze-thaw times, the change rate of each grain group tends to be flat, which may be due to repeated freeze-thaw cycles which may lead to the destruction of soil structure, so that no significant changes in particle size will occur. At the same time, the change rate curves of solidified soil with different lime content after different freeze-thaw cycles are roughly the same, which indicates that freeze-thaw cycles may only change the percentage content of each grain group in the soil, but cannot change the material composition of the soil.

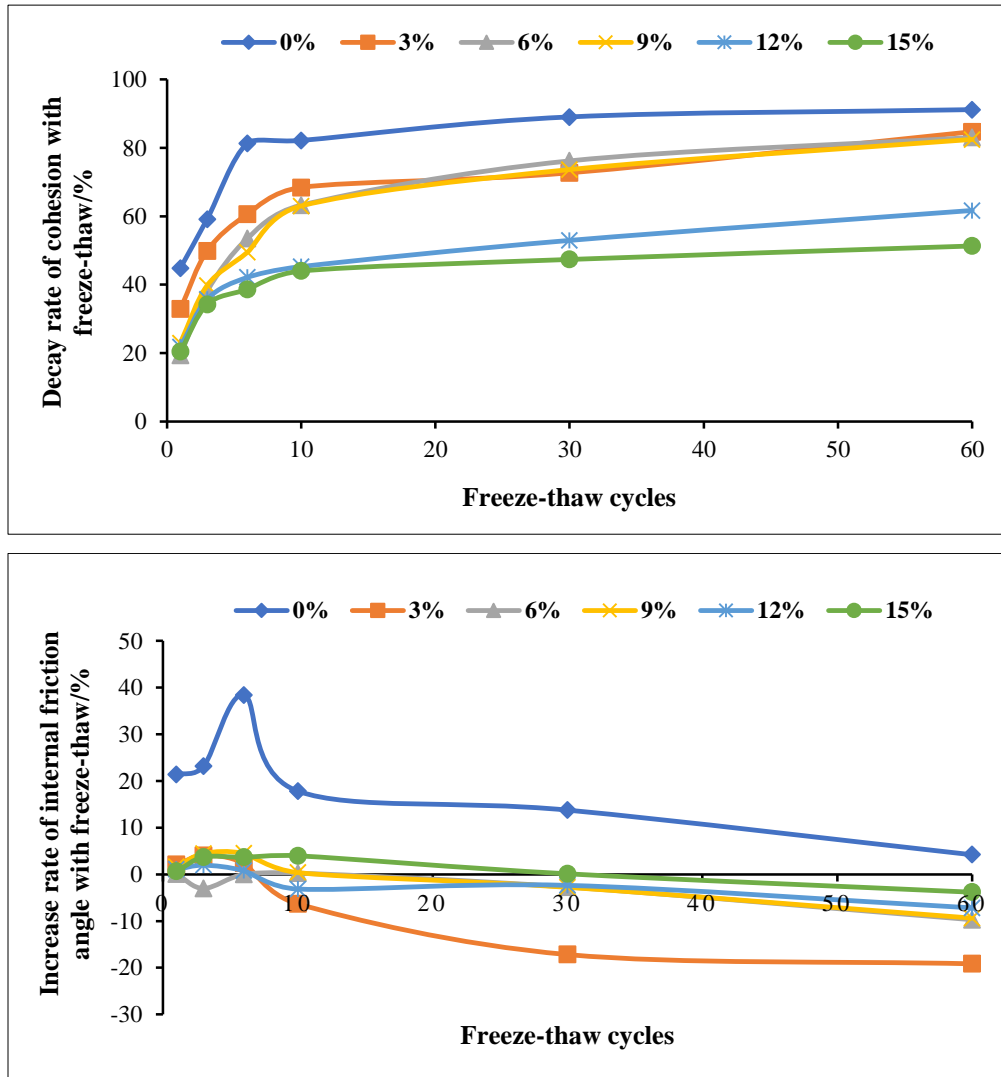


Figure 12. Change rate of shear strength parameters with freeze-thaw cycles

Figure 12 with the different freeze-thaw times, the change trend of shear strength parameters curve of plain soil and lime solidified soil is very similar, but the change degree of the former is always greater than that of the latter, especially the change rate of internal friction angle at low freeze-thaw times (< 6 times), which is much more than that of lime solidified soil. In addition, the shear strength parameters change dramatically at low freeze-thaw times (< 6 times), but at high freeze-thaw times (> 10 times), the change degree of both is gradually flat. From the curve, it can be seen that the change rate of low lime content soil is generally less than that of high lime content soil. For example, the change rate of cohesion and internal friction angle of 3% lime content soil is always less than 15% lime content soil, which proves that the addition of lime in soil can reduce the "deterioration" of the soil structure by the freeze-thaw cycle, and the mechanical strength of the soil is improved.

Combined with the above experimental rules, the mechanism of the change of cohesion and internal friction angle of plain saline soil and lime solidified soil is as follows: Recurrent freeze-thaw cycles will make the soil moisture move and freeze continuously, resulting in frost heave deformation of the soil, the extrusion between soil particles and the

original degree of cementation will be greatly weakened, the soil particles rearranged or even broken into deformation, the soil becomes more loose porous, the cracks in the soil increase, and the structural strength will be greatly reduced. Therefore, the cohesion C value decreases gradually with the increase of freeze-thaw cycles.

The change of particle size makes the strength of soil structure change, so the internal friction angle also changes. During low freeze-thaw cycles (1 to 6 cycles), the reconstructed saline soil is compacted, which makes loose saline soil compact, reduces clay content, almost unchanged sand content, increases silt content, and decreases the orderliness of the arrangement of soil particles. Small particles agglomerate into larger particle size due to freeze-thaw cycles, resulting in smaller specific surface area of soil particles, less contact points between particles, so the internal friction angle between soil particles increases. High freeze-thaw cycles (10 to 60 cycles), the soil loses its original structure, the bonding between soil particles is destroyed, and the particles become more fragmented, which makes the fragmentation of large particles far exceed the agglomeration of fine particles. At the same time, a large number of small particles will be embedded between large particles, so the internal friction angle value of the soil particles is reduced.

4.3. Microstructural Characteristics

The microstructural changes are closely related to the macroscopic mechanical properties. The following are the microscopic images of the number of different freeze-thaw cycles and different lime content.

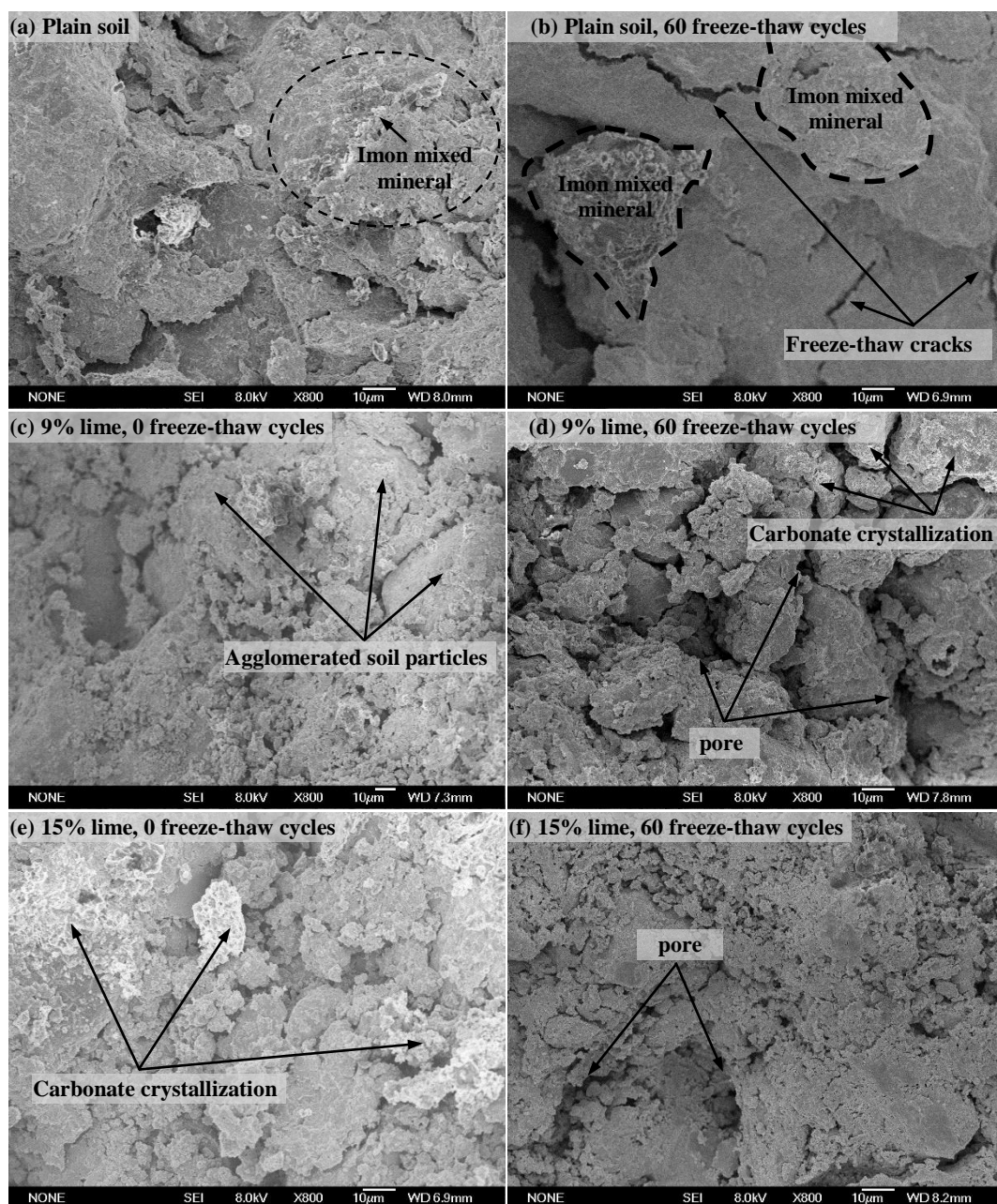


Figure 13. SEM image of saline soil with different lime content and freeze-thaw cycles

Figure 13 from (a) it can be seen that the saline soil in Qian'an area is a relatively compact flocculant structure, and the structural connection is mainly cemented connection and combined water connection. Fine grains are dominant, only a small amount of coarse grains or aggregates exist, and the overall particles are relatively dispersed. The pore is mainly medium and small pore, and the macropore is less, which has good connectivity. The clay mineral content in the soil is relatively high, and the main mineral is the mixed layer of illite and montmorillonite, with partial crystallization. With the increase of freeze-thaw times, the original cementation structure of soil gradually destroys and the soil gradually breaks up. The structure type of soil changes from compact flocculation to loose flocculation-aggregation. When the freeze-thaw times reach 60 times, the cracks develop obviously, as shown in Figure 13(b).

When lime is added into saline soil, as shown in Figure 13(c), the fine particles in the soil are "agglomerated" into aggregates, and the content of silt particles increases, which makes the soil more compact and smooth, the macropore and extra-macropore decrease obviously, the small pore transforms into the micro-pore, the intragranular pore increases, the intergranular pore only exists a little, and the fracture development decreases significantly. Soil samples are mainly flocculent and aggregated, some fine particles are covered by membrane on the surface of coarse particles, and some fine particles are filled in the pore or at the contact point of powder particles in the form of individual particles. After repeated freeze-thaw cycles, as shown in Figure 13(d), the soil becomes loose and fragmented, the structure type of the soil changes from compact flocculation to loose flocculation-aggregation, and the macropore between particles increases significantly. Although under the same freeze-thaw cycles, the microstructural characteristics of 9% Lime-mixed reinforced soils are better than those of plain saline soils, but they are still seriously damaged. At this time, carbonate crystals can be seen locally covering illite and montmorillonite mixed minerals, which also plays a role in supporting the soil skeleton and increasing the friction between particles to a certain extent.

When the lime content is too high, the phenomenon that the soil particles are wrapped during the crystallization process is more obvious, as shown in Figure 13(e). Because the products produced by lime-soil interaction have cementation effect, they are filled in the intergranular pore, and the cementation degree of intergranular particles is strengthened, thus forming new microstructural characteristics. Thus it can be seen that the strength of lime-stabilized soil is higher than that of saline soil. Comparing with the Figures 13(d) and 13(f) of the same freeze-thaw cycles of the solidified soil with 9% and 15% ash content, it is obvious that the structure damage of the solidified soil with 15% ash content is smaller after the same freeze-thaw cycles, while the microstructure of the solidified soil with 9% ash content changes greatly during the high freeze-thaw cycles, the cracks are more developed and the soil structure is more loose during the 60 freeze-thaw cycles.

5. Conclusions

Lime can improve the soil. Therefore, according to the above test results, the following conclusions can be drawn:

- Recurrent freeze-thaw cycles "deteriorate" the structural strength of the saline soil, which reduces the shear strength of the soil. As the number of freeze-thaw cycles increases, the cohesion decreases gradually, and the internal friction angle increases first and then decreases.
- The frost resistance of lime-stabilized soils is significantly higher than that of plain saline soils. With the increase of lime content, the cohesion of soils increases greatly, and the internal friction angle increases first and then decreases slightly. When the lime content is 9%, the shear strength value of the soil is greatly improved, and it can be inferred that the optimum lime content of the saline soil in this area is 9%.
- The effect of freeze-thaw cycle on the grain size composition of plain soil and lime solidified soil has duality, which causes large particles to break up, small particles agglomerate, and generally develop towards homogenization; The microstructure of soil particles and pores is changed by a series of physical and chemical reactions between lime soil. The reaction products play a strong role in cementation of soil particles, resulting in obvious "agglomeration" effect. The content of clay group is greatly reduced, while the content of silt group and sand group is increased, and the cohesion and internal friction angle of saline soil are improved.
- Freeze-thaw cycles loosen the structure of plain saline soil, increase the cracks and weaken the intergranular bonding force, but it has little influence on the particle composition and microstructure characteristics of the lime solidified soil. It can be seen that the influence of the freeze-thaw cycle on the lime solidified soil is far less than that of the plain soil, which shows that the frost resistance of the soil is enhanced after adding lime.

It is preliminarily believed that these conclusions have certain reference value for evaluating the mechanical properties of saline soil in a certain area. The higher amount of lime and more freeze-thaw cycles will contribute to the generalization of the conclusion.

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8. Conflicts of Interest

The authors declare no conflict of interest.

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