Journal of GeoEngineering, Vol. 16, No. 4, pp. 133-144, December 2021
http://dx.doi.org/10.6310/jog.202112_16(4).2

MECHANICAL BEHAVIOR OF UNSATURATED CHLORINE SALINIZED SOIL-CONCRETE INTERFACE CONSIDERING FREEZING-THAWING CYCLE

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ABSTRACT

The mechanical behaviors of unsaturated chlorine saline soil-concrete interface were studied by direct shear tests with freezing-thawing cycles. The results indicate that the interface strength parameters (c and φ) has a threshold value of salt content, *i.e.*, interface strength will firstly decrease and then increase with the increase of salt content. When freezing-thawing cycles increase, interface strength parameter c decreases and φ has no obvious change. The matric suction of saline soil, significantly affects the shear strength of soil-concrete interface, *i.e.*, parameters decrease and then increase as the salt content increasing. The shear stress-displacement curve of the interface is divided into four stages: linear elasticity, non-linear hardening, strain softening and flowing segment. In view of this, the applicability of the shear stress-shear displacement modes of the interface is evaluated. The statistical damage model match well with the experimental results. Finally, the mechanical model of unsaturated chlorine salinized soil-concrete interface considering freezing-thawing is established and its reliability is verified by the experimental data.

Key words: Chlorine saline soil, direct shear test, freezing-thawing cycle, unsaturated chloride saline soil-concrete interface, mechanical model.

1. INTRODUCTION

Saline soil is extensively distributed all over the world, especially distributed widely in northwestern China, belonging to seasonally frozen area, where the complex climatic environment including repeated freezing-thawing cycle, evaporation and rainfall has significant influence on the physico-mechanical properties of the saline soil and the soil-structure interface. Under the action of loads, the mechanical properties of interface produced by the soil-structure interaction are different from not only structure characteristic but also soil property. Furthermore, the differences of strength and deformation properties between soil and structure are great, so the shear failure such as relative slippage or dislocation damage and other engineering hazards often occurs along the contact interface. As a medium for transmitting stress and deformation, the soil-structure interface has a major influence on the interaction between structure and soil. Especially in cold regions, many engineering failures have been attributed to seasonal freezing-thawing of ground. As a result, the mechanical behavior of the saline soil-structure interface considering freezing-thawing action is of great importance in analyzing the performance of geotechnical engineering projects, such as foundations, tunnels, dams, embankments, retaining walls and canal works.

So far, direct shear tests and simple shear tests have been the most commonly methods used for experimental researches on soil-structure interface (Liu *et al.* 2014). Potyondy (1961) applied stress-controlled and strain-controlled direct shear apparatus to study on mechanical properties of the contact surfaces between various soils (sand, silt and clay) and different construction materials (steel, wood and concrete), respectively. Clough *et al.* (1971) did research on mechanical characteristics of soil-concrete interface by direct shear test and arrived at a conclusion that the relationship between shear stress and relative displacement of interface could be described as a hyperbola. Based on tests conducted at a constant rate of shearing, Acar *et al.* (1982) respectively established the mechanical models of the interface between quartz sand and concrete, as well as wood and steel, and the actual behavior of the stress-displacement relationship of soil-material interface could be closely approximated by the hyperbolic model. Desai *et al.* (1985) described a new device for cyclic testing of large size interfaces between structural and geologic materials and rock joints, and the constitutive behavior of the sand- concrete interface was expressed as nonlinear elastic and simulated loading-unloading-reloading response by using a modified Ramberg-Osgood model. Uesugi *et al.* (1988) expressed a method for observing the particle behavior near the interface in sand-steel friction tests, and the sand-steel interface showed a small amount of sliding before the peak in the frictional resistance. Also, many researchers have studied the shear behavior of the interface between various soils and structures made of different materials, and established constitutive models of the interface (Yoshimi *et al.* 1981; Uesugi *et al.* 1986; Yin *et al.* 1994; Evgin *et al.* 1996; Fakharian *et al.* 1997; Shahrour *et al.* 1997; Zhang *et al.* 1998; Gao *et al.* 2000; Hu *et al.* 2001, 2002; Zhang *et al.* 2005; Giuseppe *et al.* 2007; Liu *et al.* 2008; Feng *et al.* 2009, 2012, 2018).

Manuscript received May 15, 2021; revised August 10, 2021; accepted August 11, 2021.
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In addition, the study of the interaction between soil and structural surface in special environment has a good guidance for the design of related projects and is one of the main directions for future research. For instance, in cold regions, the mechanical behavior of the soil-structure interface is also a crucial factor for assessing the bearing capacity and long-term stability of infrastructure and engineering structure. A self-developed, large-scale multi-functional cycle direct shear apparatus (DDJ-1) was applied to frozen soil-structure interface for the first time, and experimental work was conducted under conditions of constant normal stiffness, normal stresses, constant frozen temperature or a rising temperature (Zhao *et al.* 2013; Zhao *et al.* 2014). Sun *et al.* (2015) systematically studied the monotonic shear mechanical properties of contact layer between artificial frozen clay and rough steel plate by using newly developed experimental apparatus specially developed for the contact surface between frozen soil and structure. In order to describe the shear characteristics of frozen soil-structure interface reasonably, Wen *et al.* (2013) and Chen *et al.* (2016) performed a series of laboratory direct shear test of the interface between frozen Qinghai-Tibetan silt and glass fiber reinforced plastics, and established a stress-displacement-temperature constitutive equation of the interface. To explore shearing mechanical characteristics of the interface between thawing soil and structure, Wang *et al.* (2017) performed a series of direct shear tests by using an improved DRS-1. DRS-1 is a super-high pressure direct/residual shear testing system developed by the author's affiliation (National Key Laboratory of Deep Geotechnical Mechanics and Underground Engineering of China Mining University), which consists of a host, control system, measurement system and data acquisition system, high-pressure direct shearing system, and the results showed that the normal stress and the thawing temperature presented remarkable effects on the shear strength of contact surface under high pressure. In order to study the mechanical properties of the frozen contact surface between soil and structure, Sun *et al.* (2018) performed a series of direct shear tests for frozen interface between saline soil and concrete lining under the conditions of different salt species, different salt contents and different water contents. He *et al.* (2020) investigated the freezing-thawing cycling impact on the shear behavior of a frozen soil-concrete interface by direct shear tests, and the findings can be used to simulate the performance of engineered geotechnical structures such as pile foundations, retaining walls, and earth dams or irrigation channels with concrete linings in cold regions.

Above all, there are few documents that can be consulted in mechanical properties and constitutive model of chloride saline soil-concrete interface considering freezing-thawing cycles. Nevertheless, with the economic development in western China, the direct-current networking project (±500 kV) of Qinghai-Tibet is constructed, which will pass through permafrost regions and seasonally frozen soil areas. In some certain areas where saline soils are distributed widely, the repeated freezing-thawing cycle will cause engineering damages to the tower base of the power transmission project. And concrete is widely used as the foundation material in the Qinghai-Tibet transmission line project. Therefore, relevant researches are expected to provide a scientific basis for the design and safety assessment of saline soil foundation projects. The main research purposes are: (1) studying the influence of freezing-thawing action on the mechanical properties of unsaturated chloride saline soil-concrete interface, and explore the effect of soil matric suction on the strength of the interface; (2) establishing the mechanical model of the chloride saline soil-concrete interface considering freezing-thawing action and validate the applicability of the model.

2. EXPERIMENTAL METHOD

The chlorinated soil samples are prepared manually by reshaping loess and NaCl. The loess is taken from a foundation pit engineering in Lanzhou City, China, and the depth of soil obtaining is between 6.0 m and 9.0 m under ground surface. The basic physical properties of loess are shown in Table 1, and the information about normally natural salt content of Lanzhou loess is listed in Table 2 (Zhang *et al.* 2008). The concrete blocks, prepared by a uniform size mold with a diameter of 61.8 mm and a height of 20 mm, are made according to the strength grade C25 (water 175 kg/m^3, cement 398 kg/m^3, sand 565 kg/m^3, stone 1262 kg/m^3) with the mixing ratio of 0.44:1:1.42:3.17. And the particle size of the stones is between 1 mm to 10 mm with better particle grading. The concrete blocks are cured in the curing room for 30 days after the completion of their production. All the concrete blocks are polished by sandpaper to keep their surfaces the same roughness. Chlorine salt soil samples with the same water content and different salt contents are prepared in a certain proportion, and the salt content refers to the ratio of salt mass to dry soil mass. The preparing method of soil samples is as follows: (1) The loess taken from the project is naturally air-dried and crushed, and then passed through a 0.5 mm sieve. The soil material with a certain water content of 17% (near plastic limit) and a pre-configured ratio of salt content is prepared, then mixed thoroughly and sealed for 7 days at room temperature, which benefits the full mixing and the full exchange and absorption of salt and soil; (2) After 7 days, the distilled water is added to the soil with fully absorbed salt, and the soil material is sealed for 2 days at room temperature in order to enable the distilled water can be completely soaked and the salt can be further exchanged for adsorption, then put in the natural state for air drying; (3) The dried soil material is ground by a wooden hammer, and the crushed soil is passed through a standard sieve of 0.5 mm. The soil with a water content of 17% is further disposed to fully exchange and adsorb salt, and the chlorine salt soil disposed by the above steps can meet the test requirements. Therefore, the salt content of the configured soil samples are 0% (plain soil), 2%, 6%, 8%, 10%, and 12%, respectively, and the configured chlorine saline soil is sealed with plastic bags to prevent water from loss.

Table 1 Basic physical properties of loess

Soil	Liquid limit	Plastic limit	Plastic index	Particle size distribution (%)				Maximum dry density (g/cm^3)	Optimum water content (%)
				> 1 mm	1 ~ 0.5 mm	0.5 ~ 0.075 mm	< 0.075 mm		
Loess	29.86	16.75	13.11	12	3	54	31	1.74	16.79

Table 2 Normally natural salt content of Lanzhou loess (Zhang *et al.* 2008)

Region	Cl^- (g/kg)	SO_4^{2-} (g/kg)	Ca^{2+} (g/kg)	Mg^{2+} (g/kg)	K^+ (g/kg)	Na^+ (g/kg)
Lanzhou	0.487	0.503	0.262	0.032	0.193	0.193

Herein, an adjustable temperature refrigerator is adopted to simulate freezing-thawing cycle. The number of freezing-thawing cycles was set as 0, 1, 3, 6, 8, and 10 times, respectively. The shear boxes (the concrete block is in the lower box, and the upper box is filled with chlorine salt soil sample) wrapped by plastic wrap are put into the refrigerator and frozen for 12 hours (the temperature in the refrigerator is set as −17°C). After freezing, the shear boxes are removed from the refrigerator and thawed at room temperature (20°C to 23°C) for 12 hours to complete a whole freezing-thawing cycle. The shear boxes are completely sealed during the freezing-thawing process, so the weights of the samples are basically unchanged after freezing-thawing. Figure 1 gives the concrete block and sealed samples. The direct shear instruments used in the experiment are the four-unit controlled direct shear apparatus produced by Nanjing Soil Instrument Factory in China. The vertical load is set as 100 kPa, 200 kPa, 300 kPa, and 400 kPa, respectively. The unconsolidated and undrained direct shear test is adopted, and the shear rate is set to 0.8 mm/min.

Nowadays, different techniques are available for measuring the matric suction of unsaturated soils. It remains, however, difficult to measure the matric suction with high accuracy. Theoretically, the filter paper method can be used to determine the total suction as well as the matric suction, which has these advantages: (1) Filter paper is currently the cheapest suction sensor, and there is no need to repeatedly calibrate; (2) The measurement range is very large, theoretically full range; and (3) The requirements for the environmental temperature are not high (Xu *et al.* 2000). Therefore, parallel samples are prepared to measure the matric suction of the unsaturated soil by using the filter paper method. According to contact degree between the filter paper and the soil, the filter paper method can be divided into contact method and non-contact method. Herein the contact method is adopted. In order to ensure that the matric suction of the parallel soil sample is the same as that of the shear plane of soil sample during the direct shear test, the process of manufacturing samples is very important. The dry densities of all soil samples are set to 1.68 g/cm^3 by using standard compactor, and sampling is performed by a standard ring cutter (61.8 mm in diameter and 20 mm in height). The samples for measuring matric suction prepared by the ring cutter are tightly wrapped together by the cling film, and placed in the refrigerator for 12 hours (the temperature is set as −17°C) and then thawed at room temperature (20°C to 23°C) for 12 hours. So the parallel soil samples for measuring matric suction are under the same conditions as the samples for the direct shear test. According to the related theory of unsaturated soil mechanics, the water migration between soil and filter paper will reach an equilibrium state after 7 days (Fredlund *et al.* 1993). Therefore, the samples for measuring matric suction are placed in a sealed box for 7 days, and the weight of filter paper is measured by using an electronic balance (precision: 0.0001 g). The Whatman's No.42 gray-free quantitative filter paper is adopted, as well as Eqs. (1) and (2) give the calibration curves between matric suction and water content of filter paper under equilibrium state, respectively. In the following study, water content and dry densities of all soil samples are respectively set to 17% and 1.68 g/cm^3.

$$\log s = 4.945 - 0.0673 w_f, \quad w_f < 47\% \tag{1}$$

$$\log s = 2.909 - 0.0229 w_f, \quad w_f \geq 47\% \tag{2}$$

where, s represents the matric suction, kPa; w_f represents the equilibrium moisture content of the filter paper.

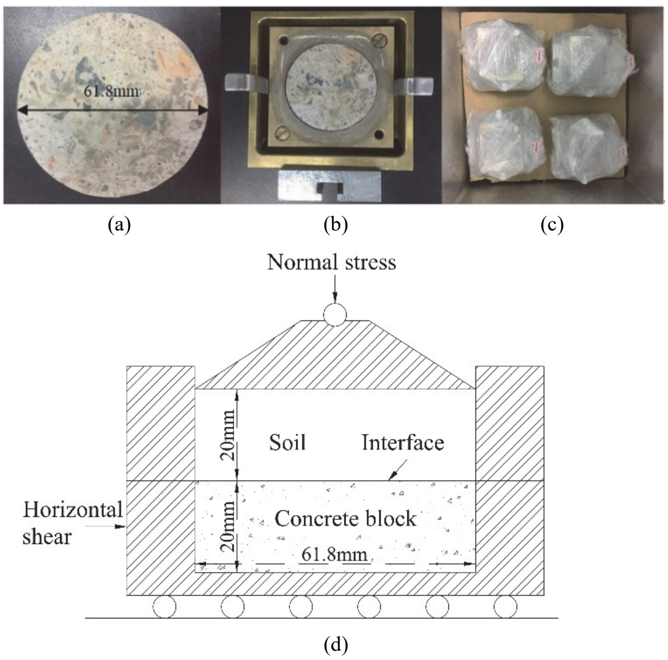


Fig. 1 The concrete block and samples: (a) concrete block; (b) concrete block in shear box; (c) sealed samples in shear box; (d) schematic diagram of the direct shear testing system

3. EXPERIMENTAL RESULTS

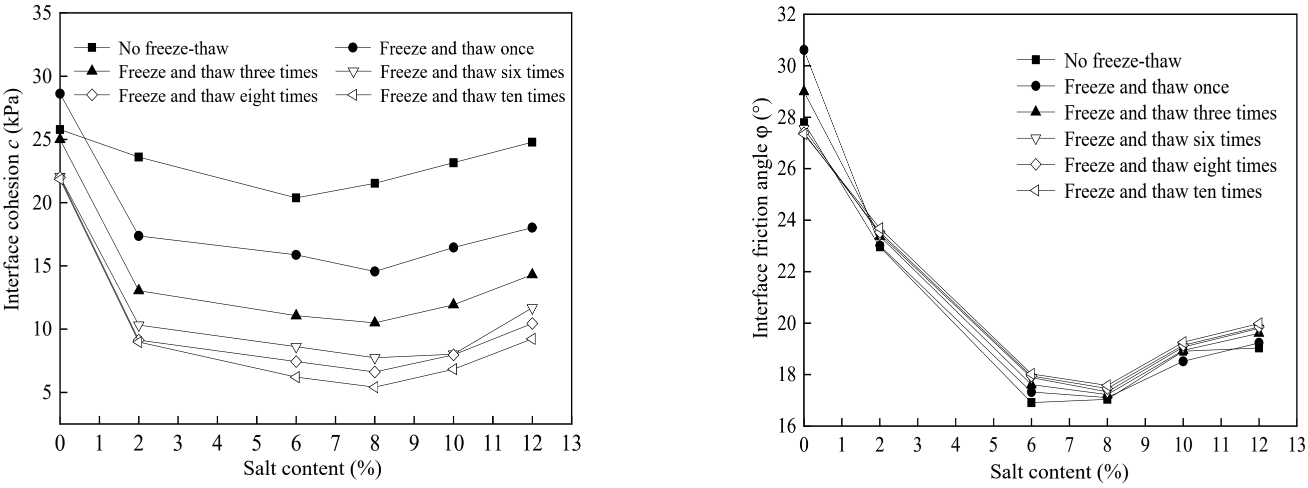
3.1 Influence of Salt Content on Mechanical Property of Interface

The interface mechanical properties produced by the interaction between soil and structure are different from not only structure characteristic but also soil property under the action of loads, and the structure surface with large deformation modulus will constrain the soil around it and also change the mechanical properties of soil. During the process of loading, the contact surface of the soil-structure system acts as a medium for transmitting stress and deformation, and plays an important role in the deformation of the structure and the soil. Salt content is an important factor affecting the mechanical properties of the unsaturated chlorinated soil-concrete interface. Figure 2 shows the influence of salt content on the mechanical strength parameters of the interface under different freezing-thawing times (including non-freezing and thawing). As far as the strength parameters including cohesion and internal friction angle of unsaturated chlorinated soil-concrete interface are concerned, the samples have their own threshold values of salt content before and after freezing-thawing action, respectively. Before freezing-thawing, when the salt content is less than 6%, the interfacial cohesion and internal friction angle both decrease with the increase of salt content. This is mainly because when the salt content is low, the Na^+ is hydrated in the salt solution, and the chloride salt is completely dissolved in the water. The surface of the soil particle in the chloride saline soil is thickened by the water film, and the lubrication effect is enhanced, which weakens the gravitational force and sliding friction between the soil particles. Hence, the occlusal force and friction force of the contact surface are both reduced, which will result in a decrease in the interface mechanical parameters. On the contrary, when the salt content is more than 6%, the salt solution in chlorinated soil reaches the supersaturated state and the excess salt is precipitated out in the form of crystals. At this time, the phase properties of saline soil are four phases, namely solid phase, salt solution phase, gas phase and crystalline salt phase. The cementation of crystalline salt strengthens the connection between soil particles, meanwhile the crystalline salt among soil particles acts as the soil skeleton, which enhances the structure of soil and increases its strength (Chen *et al.* 2006). With the increase of salt content in soil, the decrease of sliding friction is less than the increase of occlusal friction, so when the salt content is greater than the threshold (6%), the interface mechanical parameters will increase with the increase of salt content.

After freezing-thawing cycle, the friction angle and cohesion of the contact surface first decrease and then increase with the increase of salt content, but the salt content threshold is about 8% (some data overlap or cross perhaps due to measurement errors) and the number of freezing-thawing has a little effect on the threshold value. That is to say, the first freezing-thawing has the biggest impact on the threshold value. The water movement and salt migration both occur inside the chloride saline soil during the freezing-thawing cycle. Due to the temperature gradient of the soil, the moisture in the soil migrates to the cold end during the experiment. When the soil is frozen, the water moves upward under the action of temperature gradient. And when the soil thaws, the water moves downward under the action of gravity. However, the amount of water moving upward in the frozen state is less than that moving downward in the thawing state, so the moisture content of soil near the concrete block gradually increases. This makes the soil near the contact surface dissolve more salt under the action of freezing-thawing cycle, which leads to the increase of the salt content threshold of the contact surface between chlorinated soil and concrete blocks.

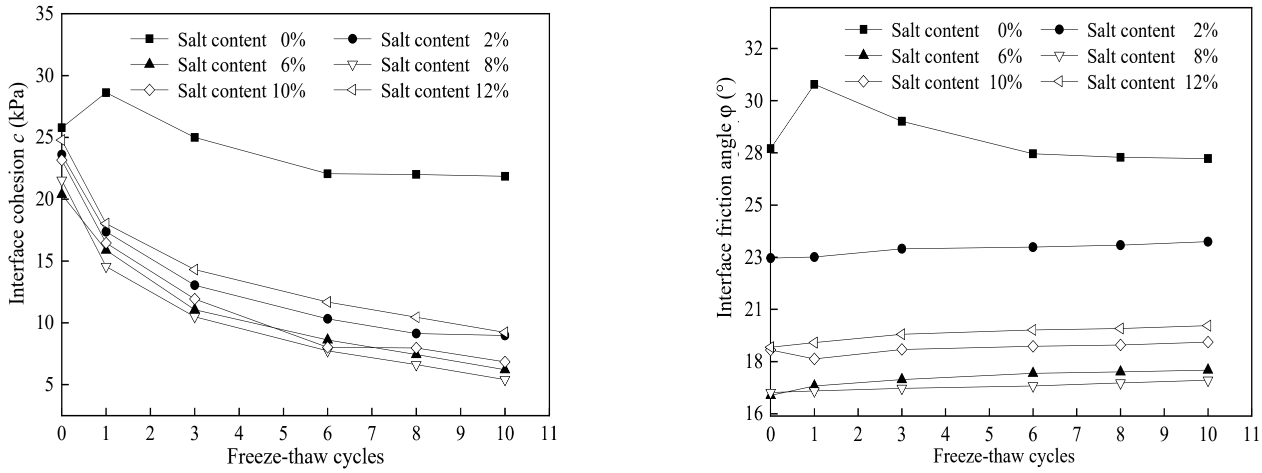
3.2 Influence of Freezing-Thawing on Mechanical Property of Interface

After the freezing-thawing cycle, the unsaturated chlorinate saline soil-concrete interface not only changes the internal structure of chlorinate saline soil, but also alters the connection relation between the chlorinated soil and concrete surface, thus affecting the mechanical behavior of contact surface. Figure 3 shows the changing curves of cohesion and internal friction angle on the interface between chlorinate saline soil and concrete blocks with the number of freezing-thawing cycles, respectively. For chlorine saline soil samples with different salt contents, they have the following characteristics: (1) When the salt content is 0%, the cohesion and internal friction angle first increase because the first freezing-thawing causes the soil to expand and has a compacting effect on the interface, which increases the bite force between the chlorinated soil and concrete; and then the cohesion and internal friction angle decrease with the increase of freezing-thawing cycle due to the fact that as the number of freezing-thawing cycles increases, a part of the large-diameter soil in the soil is decomposed into small-sized soil, and the pore structure in the soil changes. The water migration in the soil has a certain influence on the soil skeleton, which changes the internal structure of the soil and the redistribution of soil particles (Qi *et al.* 2003). Therefore, the bite force of the interface between the soil and the concrete block gradually decreases with the increase of the number of freezing-thawing cycles; (2) When the salt content is greater than or equal 2%, the thawing settlement and salt expansion both occur during the freezing-thawing cycle. Because the freezing-thawing process is incredibly complex, the trend of contact surface friction between the chloride saline soil and the concrete block is not obvious. What's more, the sliding friction between the chloride saline soil and the concrete block as well as the internal friction angle has no significant change with the increase of the number of freezing-thawing cycles. With the increase of freezing-thawing cycle, the volume of chlorinated soil keeps changing, the internal structure of chlorinate saline soil is damaged, the connection strength is reduced, and the interface cohesion decreases. The internal friction angle mainly reflects the mutual movement and occlusion between



(a) Interface cohesion (b) Interface friction angle

Fig. 2 The effect of salt content on interface shear strength parameters under freeze-thaw cycle



(a) Interface cohesion (b) Interfacial friction angle

Fig. 3 The effect of freeze-thaw cycle on interface shear strength parameters under different salt contents

particles, while the cohesive force reflects various physical and chemical forces among soil particles, including Coulomb force, van der Waals force and cementation force. The freezing-thawing action mainly changed the physical and chemical forces among soil particles, but has little effect on the mutual movement and occlusion of particles. Therefore, the effect of freezing-thawing cycles on cohesion is more significant. During the freezing-thawing cycle, water and salt migration occurs again and again in the chlorinated soil mass. After six freezing-thawing cycles, the water and salt migration reaches a new dynamic equilibrium, so the mechanical properties of the contact surface tend to be stable.

3.3 Relationship between Soil Matric Suction and Shear Strength of the Contact Surface under Freezing and Thawing

Referring to the unsaturated chlorinate saline soil-concrete interface, the soil matric suction is one of the main factors affecting the interface strength. The salinity has a certain influence on the matric suction of unsaturated chlorinate saline soil. In this test, the contact filter paper method is used to measure the matric suction of the unsaturated chloride saline soil in contact with the concrete block under the same experimental conditions. As the number of freezing-thawing cycles increases, the matric suction of the unsaturated chlorinate saline soils under the same salt content gradually decreases and eventually stabilizes (Fig. 4(a)). The main reasons for this phenomenon are: (1) freezing-thawing action affects the capillary water rise of the chloride saline soil, which leads to the phenomenon of thawing subsidence and frost heaving. After the freezing-thawing of the chloride saline soil, the volume of the soil and the pores increase, and the strength of the chloride saline soil decreases, thereby reducing the capillary suction; (2) the presence of salt in chlorinated soil will have a certain impact on the formation of pores and the structure of soil mass under different freezing-thawing cycles, which will increase the distance among the particles of chlorinated soil, reduce the Van der Waals force and electric charge force, and promote the reduction of short-range adsorption. After multiple freezing-thawing cycles, the distance among the particles of chloride saline soil is basically unchanged, and the soil reaches a new balance.

Salt content is another major factor affecting the matric suction of unsaturated salty soil. Under the same number of freezing-thawing, the matric suction decreases first and then increases as the salt content increases, and the salt content threshold is about 8% before and after freezing-thawing (Fig. 4(b)). When the salt content is not more than 6%, the matric suction changes greatly with the salt content. This is mainly because during the freezing-thawing cycle, both water and salt will migrate. With the increase of salt content, the salt solution concentration in the soil will gradually increase, which leads to the reduction of matric suction. When the salt content threshold is reached, sodium chloride gradually saturates and precipitates out, and some of the pores in the soil mass will be occupied by sodium chloride in the form of solid. This could make the difference between pore water potential energy and free water potential energy gradually increase. Therefore, as the salt content increases, the matric suction increases.

All the factors that influence the properties of unsaturated salty soil must have an effect on the shear strength of soil-concrete interface. Certainly, the matric suction is no exception. In order to better explain the relationship between the matric suction and the shear strength at the contact surface, Fig. 5 shows how the shear strength under the vertical load of 200 kPa changes with matric suction of the samples with different salt contents. Although there is no obviously quantitatively relationship between the matric suction and the shear strength of interface, the matric suction of unsaturated chloride saline soil apparently affects the interfacial shear strength. When the salt content is 0%, the shear strength of contact surface increases first and then decreases with the increase of freezing-thawing cycle and with the decrease of matric suction after freezing-thawing cycle. The main reason is that the shear strength of the contact surface is proportional to the area of the matric suction. After the first freezing-thawing cycle, the amount of meniscus water film at the interface is maximized due to the migration of water, and the maximum area of the matric suction is formed. With the increase of the number of freezing-thawing cycle, the water migration becomes more intense, and the pores and volume of soil increase, which makes the connection strength of soil decrease. The crescent-shaped water film at the contact surface shrinks and disintegrates, leading to a decrease in the area affected by the matric suction, so that the shear strength of the contact

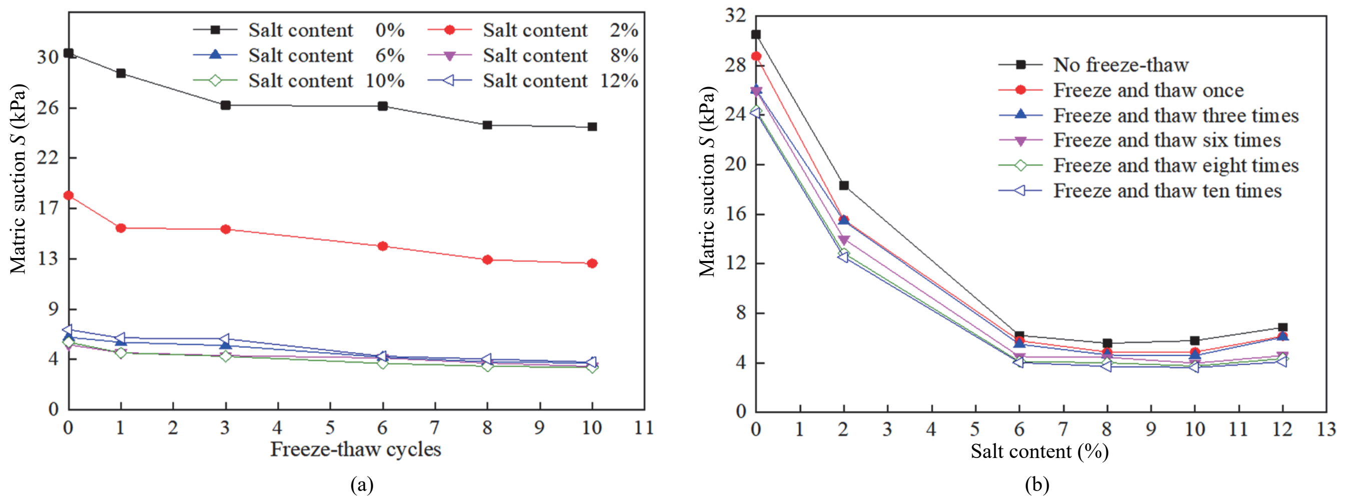


Fig. 4 The matric suction changing with freeze-thaw and salt content: (a) freeze-thaw cycle; (b) salt content

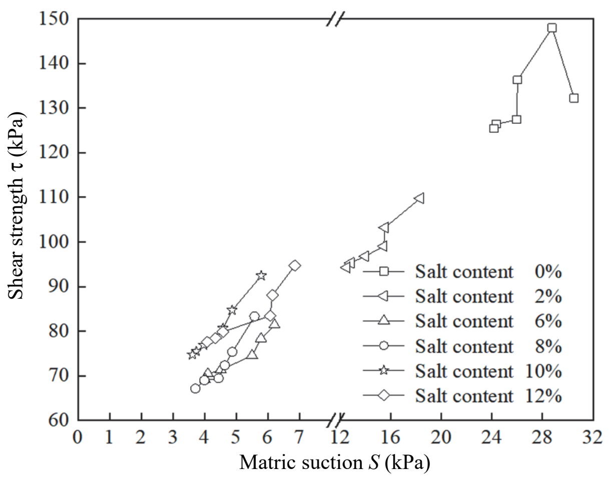


Fig. 5 The interface shear strength changing with matric suction of unsaturated salty soil

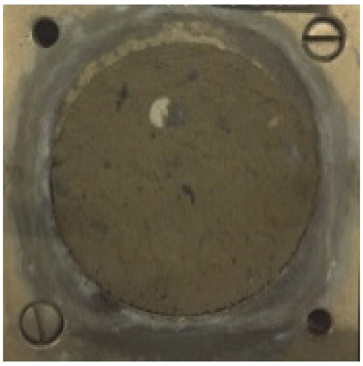
surface increases first and then decreases with the decrease of the matric suction. When the salt content is more than 2%, the interfacial shear strength decreases with the decrease of matric suction. The main reason is that the matric suction area is positively correlated with the number of lunar-shaped water films between soil particles at the contact surface (Feng *et al.* 2017). Before freezing and thawing, there were the most meniscus water films at the contact surface, and the area of matric suction at the contact surface was the largest, so the shear strength was the greatest. As the number of freezing-thawing cycle increases, water migration will drive salt migration, and the meniscus film at the contact surface will shrink and disintegrate, which results in a decrease in the number of water films. In turn, this will reduce the area of the substrate suction and reduce the shear strength at the contact surface, so the shear strength decreases as the matric suction decreases.

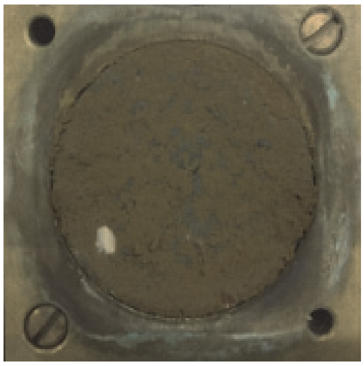
3.4 Effect of Freezing-Thawing on Shear Stress-Displacement of Contact Surface

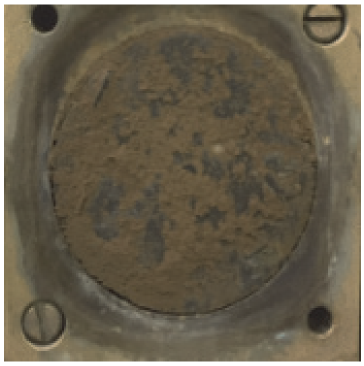
In geotechnical engineering, due to the great difference in mechanical deformation performance between saline soil and concrete block, shear failure such as relative slip or dislocation easily happens along the interface under load. During the process of loading, the soil-concrete system, as a medium to transfer stress and deformation, has a significant impact on the deformation and interaction between concrete and soil because of the particularity and complexity of the mechanical properties of the contact surface. The shear properties of saline soil-concrete interface affect the bearing capacity of the foundation and the stability of the superstructure to a large extent. The contact surface is composed of the concrete surface and the thin soil layer covered on the concrete block. And the thickness of the contact surface and the strength of the surrounding soil layer on concrete block directly affect the ultimate shear stress of the interface.

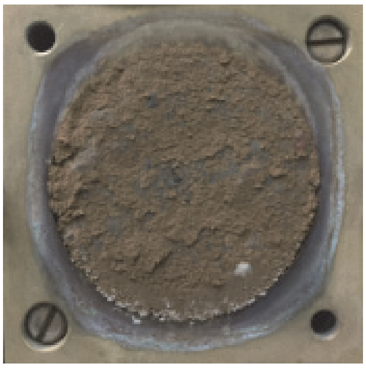
The shear failure surfaces of concrete-unsaturated chlorinated soil with 8% salt content under different freezing-thawing times (Fig. 6) and their shear stress-shear displacement curves (Fig. 7) are taken as examples. From Fig. 6, it is found that the shearing surface is composed of the concrete block surface and the saline soil layer with a certain thickness covered on concrete block, which indicates that the shear stress is transmitted between the chloride saline soil and the concrete block contact surface before shear failure, and makes the shear failure surface occur in the soil layer near the contact surface (Selvadurai *et al.* 1995). Therefore, the shear stress-displacement curve of the contact surface mainly depends on the interaction between the chlorinated soil and the concrete block surface, and is affected by multiple factors such as the magnitude of normal stress, stress path, loading type, stress state and others.

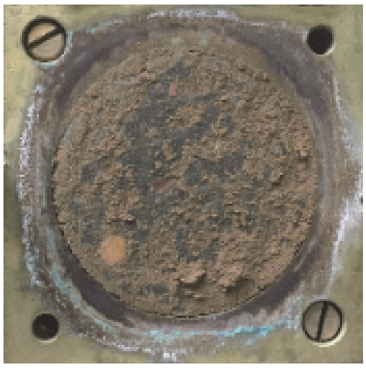
As can be seen from Fig. 7, under the same vertical load, first the shear stress on the contact surface gradually increases with the increase of shear displacement, and the increasing speed gradually slows down. Direct shear tests show that before peak strength, the shear stress-shear displacement curve has linear and nonlinear segments. Then the shear stress decreases gradually with the increase of shear displacement and finally tends to be stable. With the increase of freezing-thawing cycle, the maximum shear stress on the shear stress-shear displacement curve decreases and gets closer to or almost coincides with each other. The shear stress-displacement curve of the contact surface is divided into four stages: (1) linear elastic deformation stage: in the initial stage of shear, the relationship between shear stress and shear displacement is proportional; (2) strengthening stage: with the increase of shear displacement, the contact surface strength increases continuously, and the final

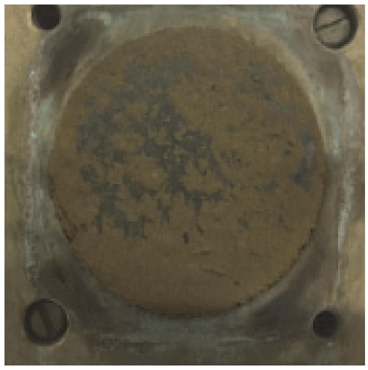

(a) Before F-T


(b) F-T once


(c) F-T 3 times

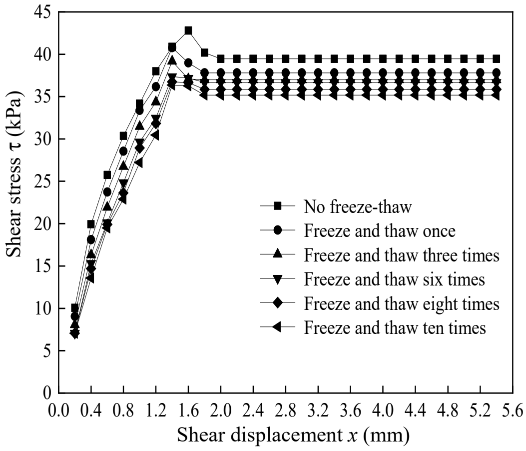

(d) F-T 6 times


(e) F-T 8 times

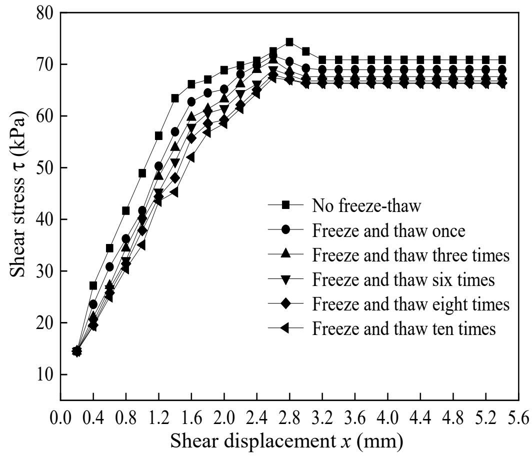

(f) F-T 10 times

Note: F-T means freezing-thawing cycles

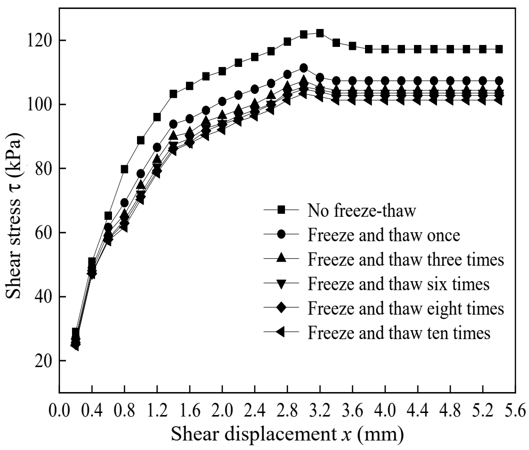
Fig. 6 The shear fracture plane samples with salt content of 8% under different freeze-thaw cycle



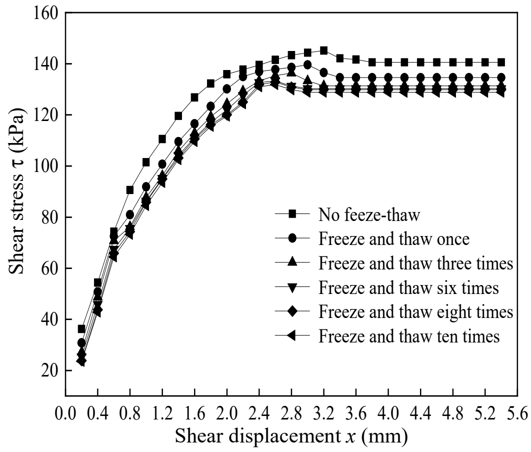
(a) 100 kPa



(b) 200 kPa



(c) 300 kPa



(d) 400 kPa

Fig. 7 Shear stress-displacement curves of samples with salt content of 8% under different normal pressures

shear strength reaches the maximum value; (3) softening stage: when the shear strength of the contact surface reaches the maximum value, as the shear displacement continues to increase, the shear strength of the contact surface will gradually decrease, and finally the shear strength of the contact surface will no longer change, thus reaching a stable state; and (4) flow stage: the value of the final shear stress is the residual stress of the contact surface. The shear stress on the contact surface will no longer change, and the shear displacement of the contact surface will continue to increase, eventually leading to shear failure of the contact surface.

4. APPLICABILITY OF CONSTITUTIVE MODELS TO SHEAR STRESS-DISPLACEMENT OF SOIL-CONCRETE INTERFACE

4.1 Applicability of Hyperbolic Model to Salty Soil-Concrete Interface

Clough *et al.* (1971) obtained the stress-strain relationship of the contact surface through direct shear tests of soil-concrete interface, and the equation is:

$$\tau = \frac{x}{a+bx} \tag{3}$$

where τ is the shear stress, x is the shear displacement, and a as well as b are both the test parameters, respectively. Since the shear stress-displacement curve of the unsaturated chloride saline soil-concrete interface is nonlinear and includes softening stage, and the parameters derived from the hyperbolic model have limitations, it should not be directly used as a criterion for evaluating the advantages and disadvantages of the fitting. Therefore, the correlation factor β has been introduced, and its expression form is shown as Eq. (4):

$$\beta = 1 - \frac{1}{n}\sum_{i=1}^{n}\frac{|x_{(i)} - x_i|}{x_i} \tag{4}$$

where $x_{(i)}$, and x_i are the shear displacement values of the predicted sample and the experimental sample, respectively; n is the capacity of the participating samples. According to the difference of the correlation factor β, the evaluation criteria were established to evaluate the fitting effect, as shown in Table 3. The experimental data are fitted by using MATLAB. However, herein there is no space to cover all the experimental data, so only the fitting parameter values of the chloride saline soil samples with 8% salt content under normal pressure of 400 kPa are taken, as shown in Table 4. It can be seen from the fitting values in Table 4 that the correlation coefficients β are all less than 0.85, which means none of the fitting values is unqualified. In other words, the hyperbolic model is not applicable to express the stress-strain relationship between the unsaturated chloride saline soil and concrete interface.

Table 3 Evaluation criteria for model fitting correlation factors

Evaluation factor	Evaluation standard			
	Excellent	Good	Qualified	Failed
β	≥ 0.95	≥ 0.90	≥ 0.85	< 0.85

Table 4 Applicability of hyperbolic model to salty soil-concrete interface at 400 kPa

Vertical load (kPa)	Number of freeze-thaw	Model parameter equation $\tau = \frac{x}{a+bx}$		Correlation factor β	Evaluation
		a	b		
400	0	– 2.559	59.576	0.127	Failed
	1	– 3.087	56.774	0.312	Failed
	3	– 2.704	54.855	0.358	Failed
	6	– 9.057	53.882	0.386	Failed
	8	– 3.496	53.477	0.425	Failed
	10	– 7.122	53.059	0.444	Failed

4.2 Applicability of Three-Parameter Model to Salty Soil-Concrete Interface

Wang (2006) studied the forward and reverse single shear test of soil-concrete interface, and proposed a three-parameter model based on the stress-strain relationship of the contact surface, as shown in Eq. (5).

$$\tau = \frac{ab\exp\left[(a-b)cx\right] - ab}{a\exp\left[(a-b)cx\right] - b} \tag{5}$$

where τ is the shear stress, x is the shear displacement, and a, b as well as c are the model parameters, respectively. The relevant factor β was introduced and the experimental data was fitted using MATLAB. Similarly, due to space limitations, only the fitting parameter values of the chloride saline soil samples with 8% salt content under normal pressure of 400 kPa are taken, as shown in Table 5. It can be seen from the fitting values in Table 5 that the correlation coefficients β are all less than 0.85, which indicates that the three-parameter model is not applicable to the unsaturated chloride saline soil-concrete interface.

Table 5 Applicability of three-parameter model to salty soil-concrete interface at 400 kPa

Vertical load (kPa)	Number of freeze-thaw	Model parameter equation $\tau = \frac{ab\exp[(a-b)cx]-ab}{a\exp[(a-b)cx]-b}$			Correlation factor β	Evaluation
		a	b	c		
400	0	9.919	8.929	0.246	0.759	Failed
	1	9.515	8.553	0.272	0.781	Failed
	3	9.317	8.371	0.282	0.777	Failed
	6	9.209	8.274	0.288	0.770	Failed
	8	9.126	8.197	0.295	0.771	Failed
	10	9.069	8.144	0.299	0.771	Failed

4.3 Applicability of the Exponential Curve Model to Salty Soil-Concrete Interface

Wang *et al.* (2005) started from the exponential function of the average consolidation degree of soil layer as time, and obtained the exponential curve model Eq. (6):

$$\tau = a\left[1 - \exp(-bx)\right] \tag{6}$$

where τ is the shear stress, x is the shear displacement, and a, b as well as c are the model parameters, respectively. The relevant factor β was introduced and the experimental data was fitted using MATLAB. Due to space limitations, only the fitting parameter values of the chloride saline soil samples with salt content of 8% at normal pressure of 400 kPa are taken, as shown in Table 6. It can be seen from the fitting values in Table 6 that the correlation coefficients β are all less than 0.85, which indicates that the hyperbolic model is not applicable to the unsaturated chloride saline soil-concrete interface.

Table 6 Applicability of the exponential curve model to salty soil-concrete interface at 400 kPa

Vertical load (kPa)	Number of freeze-thaw	Model parameter equation $\tau = a[1-\exp(-bx)]$		Correlation factor β	Eevaluation
		a	b		
400	0	139.836	3.683	0.597	Failed
	1	132.246	0.921	0.539	Failed
	3	129.195	5.060	0.506	Failed
	6	127.163	4.368	0.519	Failed
	8	126.516	3.357	0.568	Failed
	10	125.038	3.678	0.534	Failed

4.4 Applicability of Statistical Damage Model to Salty Soil-Concrete Interface

Based on the randomness of internal defect distribution, Yang *et al.* (2006) developed a damage constitutive model for soil-structure interface by using the continuous intension and statistical theory. The model can simulate the stress-strain behavior of soil-structure interface as Eq. (7):

$$\tau = ax\exp\left[-\left(\frac{x}{b}\right)^{c}\right] \tag{7}$$

where τ is the shear stress, x is the shear displacement, and a, b as well as c are the test parameters, respectively. The relevant factor β was introduced and the experimental data was fitted using MATLAB. Due to the large number of samples in the test, herein space is not enough to list them one by one. Therefore, the values of fitting parameters of chlorine saline soil samples with normal stress of 400 kPa are selected under different freezing-thawing times, as shown in Table 7.

It can be seen from the fitting factor β in Table 7 that the statistical damage model can better reflect the shear stress-shear displacement relationship under different freezing-thawing cycles, and the fitting effect meets the requirements. This shows that the statistical damage model is suitable for the relationship between shear stress and shear displacement at the interface of unsaturated chloride saline soil-concrete block.

Table 7 Applicability of statistical damage model to salty soil-concrete interface at 400 kPa

Vertical load (kPa)	Number of freeze-thaw	Model parameter equation $\tau = ax\exp\left[-\left(\frac{x}{b}\right)^{c}\right]$			Correlation factor β	Evaluation
		a	b	c		
400	0	248.176	1.230	0.559	0.945	Good
	1	198.340	1.617	0.618	0.931	Good
	3	182.692	1.739	0.633	0.940	Good
	6	173.216	1.838	0.644	0.882	Qualified
	8	164.803	1.959	0.662	0.993	Excellent
	10	158.720	2.048	0.677	0.872	Qualified

5. MECHANICAL MODEL OF SALINE SOIL-CONCRETE INTERFACE CONSIDERING FREEZING-THAWING PROCESS

In the above analysis, when the different constitutive models are used to analyze the applicability of the chloride saline-concrete interface, the freezing-thawing cycle is not taken into account. Although the experimental data confirm that the statistical damage model has a good fitting effect on the shear stress-displacement data of the contact surface between chloride saline soil and concrete, there are certain defects by using the statistical damage model to analyze the mechanical properties of the soil-structure contact surface considering the freezing-thawing cycle. Therefore, in order to study the mechanical properties of the contact surface under the action of freezing-thawing environment, it is of great significance to establish the interface model of chloride saline soil-concrete considering the freezing-thawing cycle.

On the shear stress-shear displacement curve of the contact surface between the chloride saline soil and the concrete block, the softening stage and the flow stage appear after the shear stress reaches the extreme value. During design of the foundation bearing capacity in actual engineering, it is of little significance to study the softening effect of saline soil interaction with structure. So, this section only considers the first two stages (including linear elastic stage and strengthening stage) of the shear stress-displacement curves of the interface between chloride saline soil and concrete, and establishes the mechanical model of the contact surface considering freezing-thawing cycle. The method of establishing the mechanical model: according to the relationship between multiple sets of test data and the number of freezing-thawing cycles, the number of freezing-thawing cycles is taken as the abscissa, as well as the shear stress is regarded as the ordinate. Based on the corresponding interface shear stress under the same shear displacement and different freezing-thawing cycles, a large number of direct shear test data can be used to deduce that the number n of freezing-thawing cycles and the interface shear stress τ are consistent with the Eq. (8).

$$\tau = s - \frac{t}{e^{n}} \tag{8}$$

where s and t are both the functions of shear displacement x, and s as well as t can be got from Eqs. (9) and (10), respectively.

$$s = k\,x\exp\left[-\left(\frac{x}{l}\right)^{v}\right] \tag{9}$$

$$t = m\,x^{2} + u\,x + f \tag{10}$$

where n, x and τ are experimentally measured values, respectively. All parameters, k, l, v, m, u, and f are related to the normal stress. The units of τ, s, and t are kPa, and n is the number of freezing-thawing cycles. All the parameters are obtained by the least square fitting method of MATLAB. The values of parameter under different salt contents and the same normal stress of 400 kPa are shown in Table 8, and the parameters under the same salt content of 8% and different normal stresses are shown in Table 9. The obtained parameter values are substituted into Eq. (8) to make the fitting curves at different freezing-thawing cycles with the salt content of 8% under different normal stresses (as shown in Fig. 8). The test data in Fig. 8 is the relationship between the interface shear stress and the shear displacement obtained from the test results. It can be seen from the fitting curves in Fig. 8 that the experimental results of different salt contents, different freezing-thawing cycles, different normal stresses, and different freezing-thawing cycles are in good agreement with the mechanical model. Due to the large experimental data, herein space is not enough to list all the data. In other cases, the experimental results are also in good agreement with this mechanical model. This indicates that the proposed mechanical model has good applicability to the shear stress-shear displacement of unsaturated chloride saline-concrete considering the effect of freezing-thawing cycles.

6. CONCLUSIONS

Based on the direct shear test, this paper investigated the mechanical behaviors of unsaturated chlorine saline soil-concrete interface considering freezing-thawing cycle. The following conclusions are drawn:

Table 8 Parameter values of different salt contents under 400 kPa vertical load

Salt content (%)	Parameter					
	k	*l*	*v*	*m*	*u*	*f*
2	210.362	1.738	0.603	2.370	– 13.320	– 5.215
6	163.291	2.079	0.717	3.105	– 11.641	– 1.870
8	170.801	1.908	0.576	5.062	– 12.891	– 8.301
10	149.196	2.531	0.885	1.154	– 4.413	– 13.103
12	193.779	1.790	0.627	1.999	– 10.041	– 8.206

Table 9 Parameter values under different vertical loads with salt content of 8%

Vertical load (kPa)	Parameter					
	k	*l*	*v*	*m*	*u*	*f*
100	61.316	2.812	0.746	6.680	– 10.894	– 1.896
200	90.653	0.893	0.505	3.502	– 8.234	– 4.880
300	140.361	0.457	0.427	4.299	– 13.707	– 6.256
400	170.801	1.908	0.576	5.062	– 12.891	– 8.301

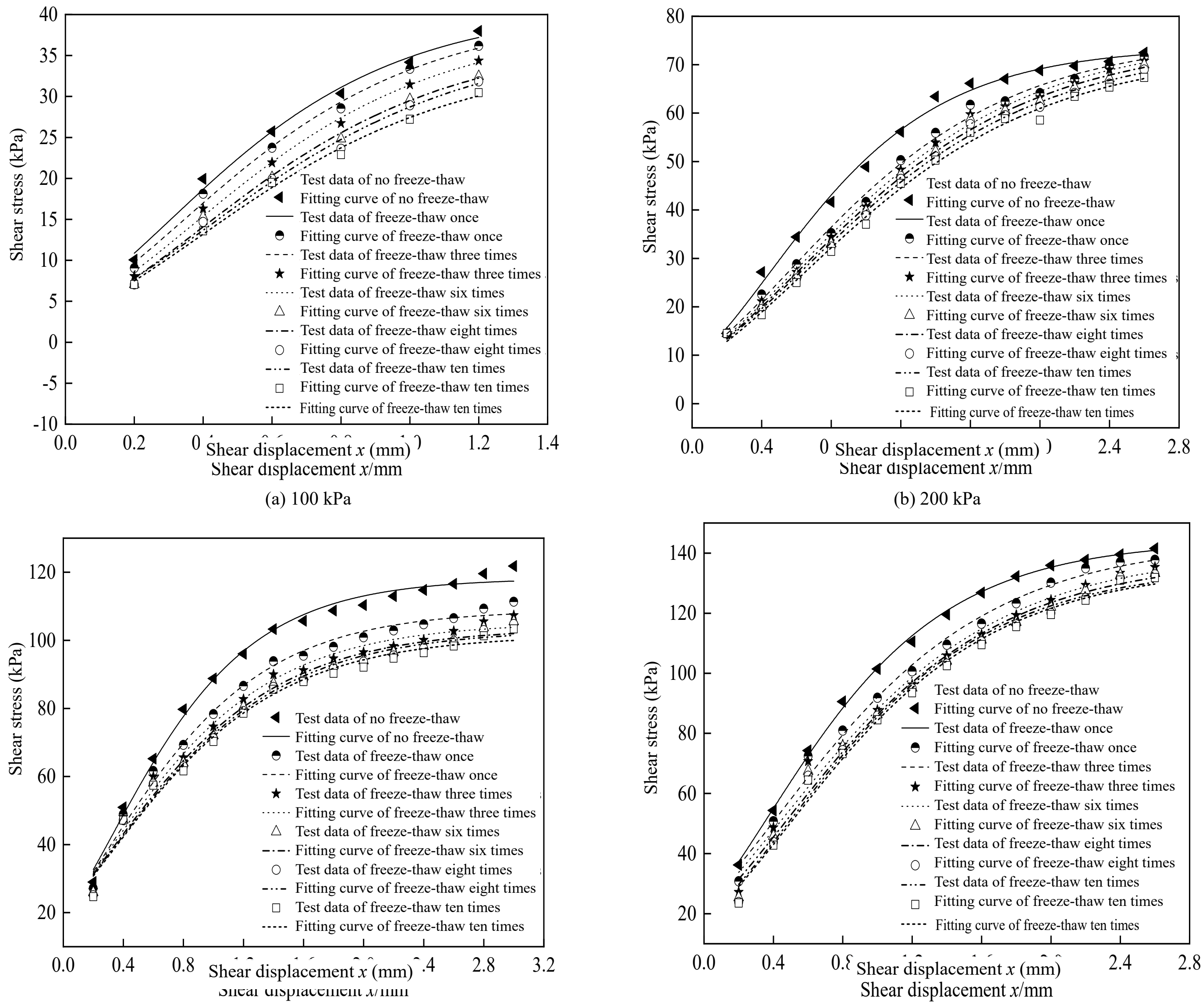


Fig. 8 Fitting curves of shear stress-displacement at different freezing-thawing cycles with the salt content of 8%

1. Before and after freezing-thawing, the mechanical parameters (including cohesion and angle of internal friction) of saline soil-concrete interface first decrease and then increase with the increase of salt content, which signifies there are threshold values of salt content. Moreover, before freezing-thawing, the threshold value of salt content is approximately equal to 6%, but it was approximated by 8% after freezing-thawing.
2. When there is no salt in soil, the mechanical parameters of the soil-concrete interface increase first and then decrease with the increase of freezing-thawing cycles. When the salt is contained in soil, the cohesive force of the saline soil-concrete interface decreases, but the internal friction angle has no significant change with the increase of freezing-thawing cycles. After six freezing-thawing cycles, the interface reaches a new dynamic equilibrium and the mechanical parameters of the interface tend to be stable.
3. The matric suction force is one of the main factors affecting the shear strength of unsaturated chlorine salinized soil-concrete interface, and it generally decreases with the increase of freezing-thawing cycle and eventually stabilizes. It decreases and then increases as the salt content increasing, and the threshold value of salt content is about 8%.
4. The shear stress-shear displacement curve of the saline soil-structure interface is divided into four stages, including linear elasticity, non-linear hardening, strain softening and flowing segment. In view of this, the applicability of the modes of the shear stress-shear displacement of the interface is evaluated and it is found that the statistical damage model can be well matched with the experimental results. Finally, the mechanical model of chlorine salinized soil-concrete interface considering freezing-thawing cycle is established and its reliability is verified by the experimental data.

FUNDING

This study was funded by the National Natural Science Foundation of China (grant number 51769013) and Basic Research Innovation Group of Gansu (20JR5RA478).

DATA AVAILABILITY

All data and/or computer codes used/generated in this study are included in this paper.

CONFLICT OF INTEREST STATEMENT

The authors declare that this paper has no conflict of interest.

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