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Effects of sodium sulfate content on mechanical behavior of frozen silty sand considering concentration of saline solution

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ABSTRACT

Triaxial compressive tests were conducted on a frozen silty sand with four sodium sulfate contents (0.0%, 0.5%, 1.5%, and 2.5%) at temperature of −6 °C. The test results revealed that it is important and necessary to firstly identify whether the concentration of sodium sulfate solution in the silty sand is saturated for studying effects of the salt content on the strength and deformation characteristics. We established a function which can interconvert the concentration of the sodium sulfate solution and the sodium sulfate content in the silty sand if either one of these two variables is a known quantity. Based on this function, the saturated or unsaturated state of the concentration of sodium sulfate solution corresponding to each given sodium sulfate content in the frozen silty sand can be conveniently identified. The influence of confining pressure and sodium sulfate content on the deformation characteristics, failure mode and strength of the frozen saline silty sand were then analyzed.

Introduction

Saline soil is wide spreading in China, and it is mainly distributed in the inland provinces including Xinjiang, Gansu, Qinghai, Ningxia, Inner Mongolia, Shan Xi, Heilongjiang, and Jilin etc., and coastal provinces such as Shandong, Hebei and Jiang Su. Most of those inland provinces are located at permafrost or seasonal frozen regions, where the cold climate provides a natural prerequisite for frozen saline soil formation [1]. The frozen saline soil in those coastal regions is created by artificial freezing during construction. Consequently, given the need of a rational design and construction in either inland or coastal regions covered by saline soil, a designer is always confronted with a careful exploration on the strength and deformation characteristics of frozen saline soil as well as an investigation on which factors are crucial to and how they affect the mechanical behavior of frozen saline soil.

The mechanical properties of frozen soils are strongly impacted by the existence of salt in it. The investigations by world-wide scholars arrived at the same conclusion that the presence of salt can reduce strength of frozen soil, and weaken its ability of resisting deformation. For instance, Nobuhide et al. [2] concluded that strength of frozen saline sandy soil is less than that of frozen sandy soil. Pharr and Merwin [3] performed a series of uniaxial tests that demonstrated the strength of frozen saline Ottawa sand decreases with the increase of salinity. For frozen saline silty clay, the similar uniaxial compressive strength characteristics were found by Yang et al. [4,5]. Chen et al. [6,7] experimentally studied the effects of salt contents on the uniaxial strength of frozen soils with two different types of salts, sodium chloride and sodium sulfate. From his tests results, he stated two findings: (1) the failure modes and the stress-strain properties of soil with sodium sulfate powder were totally different from that contained sodium chloride even the salt and water contents of two types of soil samples were the same; (2) the uniaxial compressive strength of frozen soils with sodium chloride exponentially decreased with the increase of salt content, however, the uniaxial strength of soil with sodium sulfate first decreased and then increased with the increase of salt content. Sun et al. [8] also confirmed that the uniaxial compressive strength of frozen saline soil reduced with the increase of salt content, and pointed out the cohesion and internal friction angle decreased with the increase of salt content. However, Cai et al. [9] raised a disagreement on above conclusions based on his uniaxial tests results, and he put forward the uniaxial strength of sand with low liquid limit sharply increased in the beginning and then dropped rapidly with the increase of water and salt content. This discrepancy suggests that the effect by salinity on the mechanical properties of fro-

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zen soil might be dominated by other factors, such as temperature and degree of saturation of salt solution.

Uniaxial compressive test was employed in the early investigations on mechanical properties of frozen salt soil. More recent contributions by Sun et al., [8], Hu and Lai [10] and Xu et al., [11] conducted triaxial compressive test on the frozen salt soil to discover the influence of the stress states on mechanical behavior of frozen saline soils. The previous research results provided a fundamental basis including accumulated valuable database and analysis methods to reveal mechanical behavior of frozen salt soil as well as its main affecting factors. However, a rational analysis of mechanical behavior of saline soils is arduous undertaking due to the complexity of affecting factors, not only thermal conditions, but also salt content and salt type. Consequently, it is more complicated to understand its mechanical behavior than that of normal soils. In spite of these challenges, some notable achievements have been made by the authors. Xu et al. [11] tested the frozen silty sand with 0.5% sodium sulfate content previously, and he analyzed influence of confining pressures on the strength and elastic modulus of frozen saline silty. For a further investigation on the deformation and failure characteristics of frozen saline soils together with its affecting factors, the silty sand, collected in Chaka town of Haixi city in Qinghai province, was used as our testing soil in this paper. A more comprehensive study presented herein advances the state of knowledge on frozen saline soil by considering the effects of different sodium content (0%, 1.5% and 2.5%) and confining pressure (0.3–5 MPa). After obtaining a series of tests at sodium sulfate content of 0%, 1.5% and 2.5% in this study together with the results at sodium sulfate content of 0.5% from Xu et al. [11], we brought up analyzing the effect of sodium sulfate content on the strength behavior of frozen silty sand should start first with a distinguish on whether the concentration of sodium sulfate solution is saturate or not. We also established a function for conversion relationship between the sodium sulfate content in silty sand and the concentration of sodium sulfate solution. Moreover, we evaluated the effect of sodium sulfate content on the internal friction angle and the cohesive force of frozen saline silty sand.

Sample preparation and test set

In order to have compatible results with the ones by Hu and Lai [10] and Xu et al. [11], the same type of silty sand was used to construct soil samples in this study. The ionic composition of this natural saline silty sand is listed in Table 1 (Hu and Lai [10]). Before reconstituting saline soil samples, the natural saline silty sand was screened by the sieve with 2 mm diameter, and then was desalted according to the method by Bing et al. [12]. We first injected distilled water into the sieved silty sand and stirred the mixture of sand and water thoroughly. Second, we let the mixture rest for 24 h and stratify into sand sediment and clear solution on top. Last, we pumped out the clear solution. This three-step desalting process mentioned above was repeated for a couple of times. After each desalting process, we primarily checked the desalting degree by measuring the electrical conductivity of the saturated soil sample. If it was closed to the electrical conductivity of distilled water, then the accurate desalting degree of saline silty sand was measured by ion chromate graph. If the measured total ion content in soil was less than 0.1%, we regarded the desalted silty sand met the criterion of clean silty sand and ready for sample preparation. The desalted silty sand was placed into oven to dry. After waiting for the dried sand cooled down, we performed a sieve analysis. The grain distribution of the desalted silty sand was listed in Table 2.

For the sake of the convenience to compare the testing result in this study to the previous experimental data, we kept the soil parameters consistent with Hu and Lai [10] and Xu et al. [11], that is, the water content of frozen samples is 13%, the dry density is 1.9 g/cm^3, and the sodium sulfate content is 0%, 1.5% and 2.5%, respectively. First, we measured the amount of distilled water which is 13% by weight of soil samples, and we mixed it with different amount of sodium sulfate to obtain different saline solution with different target salt content (0%, 1.5% and 2.5%). Then the saline solution was mixed with and fully stirred with the silty sand after desalting, sieving and drying process, and then kept for 24 h with no evaporation. Then this saline silty sand was poured into a mold with 125 mm in height and 61.8 mm in diameter to reconstitute specimen with target dry density of 1.9 g/cm^3. Next, the mold contained with sand were then put into a thermostat equipment with the temperature set up at −30 °C for quick freezing to prevent frost heave. After 48 h, the mold was removed from the specimen, a rubber membrane was wrapped around, and one epoxy resin platens was placed at the top and one at the bottom of sample. The frozen saline silty sand specimens were finally put into the thermostat equipment with temperature at −6 °C and kept at least 24 h to ensure homogeneous temperature distribution in the specimens.

The MTS low-temperature triaxial apparatus which has been used by many Chinese scholars to study the mechanical properties of frozen soil [13–17] was employed for compressive tests. The detailed description about the apparatus can be found in Xu et al., [18]. The temperature inside the triaxial loading chamber was set up at −6 °C. All tests were strain-controlled with a constant loading rate of 1.25 mm/min. The testing specimens were taken from the thermostat equipment and immediately transferred into the triaxial loading chamber. Then we waited for a couple minutes for the temperature reached back to −6 °C from temperature disturbance during sample transfer, and we slowly lowered down the loading piston until the platen of piton was perfectly in contact with the top of specimen. Next, we applied confining pressure at different preset targets (0.3 MPa, 0.5 MPa, 1 MPa, 2 MPa, 3 MPa, 4 MPa, and 5 MPa) for 5 min, and then started axial loading. The data acquisition system was capable to collect axial displacement, pressure piston displacement, confined pressure and axial load with frequency of 1 s. We stopped loading the sample when axial displacement reached at 30 mm.

Testing results and discussion

Deformation characteristics of frozen silty sand with sodium sulfate

Fig. 1 shows the stress-strain curves of frozen saline silty sand at 13% water content, but with different sodium sulfate contents (0%, 0.5%, 1.5% and 2.5%) and under different confining pressures (0.3 MPa, 0.5 MPa, 1 MPa, 2 MPa, 3 MPa, 4 MPa, and 5 MPa). From Fig. 1, it is obvious that the stress-strain behaviors and the failure modes of frozen saline silty sand strongly rely on confining pressure and salt content. At different salt contents, confining pressure shows different degree of impact on the deformation characteris-

Table 1
Ion contents of the nature saline silty sand (Hu and Lai, [10]).

Ion composition	F^-	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}
Mass content/%	0.004	0.514	0.001	0.011	0.121	0.553	0.012	0.005	0.029

Table 2
Grain size distribution of the desalted silty sand.

<0.005 mm	0.005–0.075 mm	0.075–0.1 mm	0.1–0.25 mm	0.25–0.5 mm	0.5-1 mm	>1 mm
3.17	26.54	10.29	44.89	13.24	1.84	0

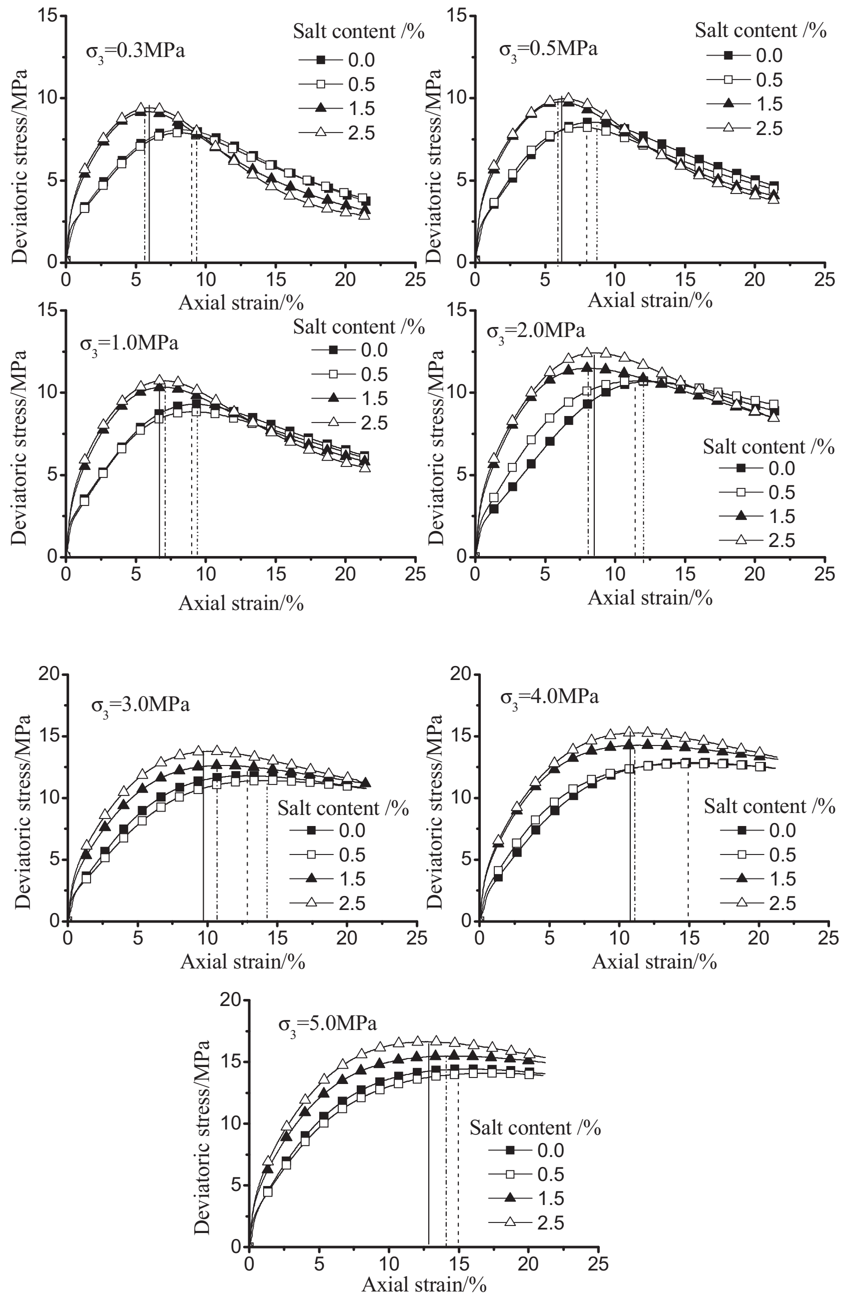

Fig. 1. Stress-strain curves of frozen saline silty sand under different confining pressures (the test results of salt content at 0.5% is from Xu et al. [11]).

tic. Particularly, when salt contents range from 0% to 0.5% and confining pressures are at or lower than 3 MPa, the stress-strain curves of frozen saline silty sand exhibit remarkable softening behavior and the degree of the softening reduces with the increase of confining pressure. The peak stress can be clearly picked out from the curves and the failure modes of frozen saline silty sand present brittle properties. When salt contents are between 0% and 0.5% together with confining pressure is more than 3 MPa, the stress-strain curves of frozen saline silty sand exhibit strain-hardening instead of strain-softening, and its failure mode alters from brittle to ductile failure. If the range of salt contents is 1.5–2.5%, the stress-strain curves of frozen saline silty sand represent strain-softening features and brittle failure under all different confining pressures; moreover, the degree of strain-softening decreases with the increase of confining pressure. The strain-softening behavior is always restrained by the increase of confining pressure no matter which salt content is. This restraining effect can be quantitatively described by establishing relationship between failure strain and confining pressure. The failure strain under different confining pressures and at different salt contents are summarized in Table3 and Fig. 2. As shown in Fig. 2, at the same salt content, the failure strain approximately linearly increases with the increase of confining pressure, especially when the salt content is at 2.5%. This observation instinctively demonstrates that the degree of strain-softening and brittleness decrease as confining pressure increases. The failure strain is also influenced by salt content. Under the same confining pressure, the failure strain of frozen saline silty sand with sodium sulfate content at 1.5% and 2.5% is less than those at sodium sulfate content at 0% and 0.5%.

From the above data analysis, it can be concluded that the higher the sodium sulfate content is, the higher the brittleness of frozen silty sand is; on the other hand, the higher the confining pressure is, the more restraining effect by confining pressure on the brittleness of soil represents. The conventional viewpoint thinks the increase of salt content results in a decrease of initial freezing temperature. Based on this, we can interpret that the unfrozen water content of frozen soil with lower salt content is less than that with higher salt content at same temperature, which directly cause that the brittleness of frozen soils with a higher salt content is lower than the one with a lower salt content. However, in this paper, the variations of stress-strain characteristics and failure modes with the salt contents are different from the above viewpoint and pre-existing experimental results in [6]. This discrepancy arises from that the unfrozen water content may not always increase even if a lower initial freezing temperature of frozen soil is accompanied with the increase of salt content. As a result, we encourage taking into account the degree of saturation of salt solution within soil. When salt solution is unsaturated, the increase of salt content causes the increase of unfrozen water content and the decrease of ice content in soil specimens which impairs the brittleness of frozen salt soils. However, if salt solution is saturated, the salt in the solution precipitates as solid state in the freezing process, which substantially leads to the decrease of the salt content and unfrozen water content, and strengthen the brittleness of frozen saline soil. For the frozen saline soil with sodium sulfate studied in this paper, each sodium sulfate molecule in the crystals needs to combine with ten water molecules during precipitation, which further decreases the actual water content and strengthens brittleness.

The strength characteristic of frozen silty sand with sodium sulfate

Influence of the sodium sulfate content on the strength

The strength of frozen saline silty sand is determined based on the National Standard (standard of soil test method) of the People's Republic of China [19]. In details, if the obvious peak point can be observed in the stress-strain curves, then the peak point is chosen as the strength; otherwise, the stress corresponding to axial strain of 15% is selected as the strength instead.

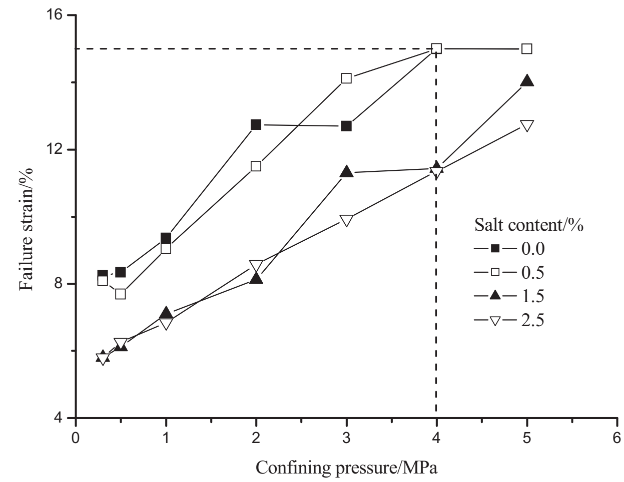

Fig. 2. Failure strain of frozen silty sand against confining pressure under various salt contents.

The strength of frozen silty sand with different salt contents is plotted against different confining pressures in Fig. 3. The strength of frozen silty sand with sodium sulfate linearly increases as the increase of confining pressure. Under low confining pressure, our results have a good agreement with the strength characteristics of other types of frozen soils [13,14,20]. This suggests that under lower confining pressure, there is no pressure melting and crushing occurred inside the frozen saline soil. The increase of confining pressure leads to the increase of the interlock force between soil particles and also the increase of the frictional force since the normal stress on the failure surface of the sample increases, which dominantly results in the increase of strength. Furthermore, the Mohr-Coulomb criterion is still suitable to describe the linear relationship between the strength of frozen saline silty sand at different salt contents and confining pressures (Eq. (1)).

$$q = A\sigma_3 + Bq_0 \quad (1)$$

where A and B are the material parameters related to sodium sulfate content, as listed in the Table 4, q_0 is the reference strength set as 1 MPa. The parameter A represents the rate of increase in the strength of frozen saline with confining pressure. As seen in Table 4, the parameter A is between 1.29 and 1.52 under four different salt contents. The lowest value of A is 1.29 with a sodium sulfate content of 0.5%, and the highest value of A is 1.52 with a sodium sulfate content of 2.5%. The parameter B represents the strength of frozen saline with zero confining pressure, and it is in the range between 7.64 and 9.17. The minimum value of B is 7.64 with a sodium sulfate content of 0.5%, and the maximum value of B is 9.17 with a sodium sulfate content of 2.5%.

Table 3
Failure strain of frozen silty sand under different salt contents and confining pressures.

Confining pressure/MPa	Salt content/%			
	0.00 Failure strain	0.50 Failure strain	1.50 Failure strain	2.50 Failure strain
0.30	8.24	8.08	5.81	5.80
0.50	8.34	7.69	6.12	6.27
1.00	9.36	9.04	7.11	6.84
2.00	12.74	11.50	8.13	8.58
3.00	12.69	14.11	11.31	9.93
4.00	15.00	15.00	11.43	11.35
5.00	15.00	15.00	14.01	12.75

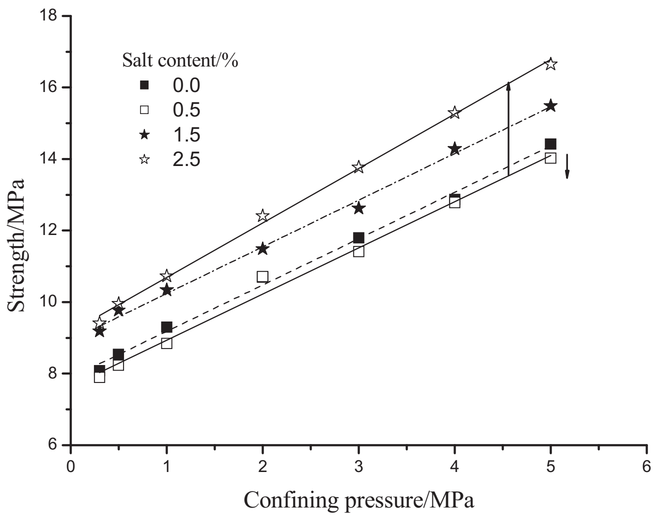

Fig. 3. Relationship between strength of frozen saline silty sand and confining pressure under different salt contents.

Table 4
Values of parameters *A* and *B* under different salt contents.

Salt content/%	*A*	*B*
0.0	1.30	7.89
0.5	1.29	7.64
1.5	1.30	8.94
2.5	1.52	9.17

As shown in Fig. 3, the strength of frozen silty sand first decreases then increases with the increase of sodium sulfate content. This result is opposite with the previous strength characteristics of frozen soils, which decreases with the increase of the sodium sulfate content [4,5]. The detailed discussion on this discrepancy as well as the corresponding mechanism can be found in the following paragraphs.

The strength of frozen silty sand with the sodium sulfate content at 0.5% is lower than that without sodium sulfate. This can be explained by that the salt solution in the silty sand is unsaturated, and the presence of salt reduces the initial freezing temperature of specimen. As a result, under the same temperature condition, the unfrozen water content of frozen saline soil is more than that of frozen soil itself, and the freezing force of frozen saline soil is less than that of frozen soil without salt. Moreover, the increase of unfrozen water content reduces the internal friction of frozen saline soil, and the decrease of freezing force weakens the cementation effect by ice. Those two factors directly lead to the decrease of the strength of the frozen silty sand with sodium sulfate.

When the sodium sulfate content is no less than 0.5%, the strength of frozen saline silty sand increases with higher sodium sulfate content. We suggest involving solubility of the sodium sulfate and crystallization phenomenon to illustrate the strength behavior in this sodium sulfate range. Solubility of a substance is defined as: under a given temperature, the mass of solute completely dissolved in 100 g of solvent to as a saturated state. The solubility of sodium sulfate in pure water at different temperatures is listed in Table 5 (Dean, [21]). The saturated concentration of the sodium sulfate can be obtained as following equation:

$$S_1 = \frac{m_{NS}}{100 + m_{NS}} \times 100\% \tag{2}$$

Where S_1 is the saturated concentration of sodium sulfate at a given temperature, and m_{NS} is the mass of sodium sulfate in the saturated solution with 100-gram pure water.

If the mass of the sodium sulfate in soil specimen is m_{NS}, the mass of water is m_{W}, the mass of dry soils is m_{S}, the moisture content is w, the concentration S of the sodium sulfate solution can be derived as follow:

$$S = \frac{m_{\mathrm{NS}}}{m_{\mathrm{W}} + m_{\mathrm{NS}}} \times 100\% = \frac{m_{\mathrm{NS}}/m_{\mathrm{S}}}{m_{\mathrm{W}}/m_{\mathrm{S}} + m_{\mathrm{NS}}/m_{\mathrm{S}}} \times 100\%$$
$$= \frac{C_{\mathrm{NS}}}{w + C_{\mathrm{NS}}} \times 100\% \tag{3}$$

where C_{NS} is the sodium sulfate content of soil specimen.

When the concentration of sodium sulfate S is more than the saturation concentration S_1 in the soil specimen (supersaturated state), a partial sodium sulfate in solution is crystallized as the temperature decreases during the freezing process. When the concentration of sodium sulfate S is less than the saturation concentration S_1 in soil specimen (unsaturated state), all sodium sulfate dissolves in solution, and the phenomenon of crystallizing precipitation does not occur as temperature decreases. When the concentration of the sodium sulfate S is equal to the saturation concentration S_1 in specimen (saturated state), all sodium sulfate should dissolve in solution. However, because of the decrease of temperature and soil disturbance to salt solution, sodium sulfate may precipitate from solution as crystal form under saturated state. The concentration of sodium sulfate S in frozen silty sand at different sodium sulfate content in this investigation can be calculated by Eq. (3), and the results are listed in Table 6.

According to Table 5 and Eq. (2), we can obtain the saturated concentration of sodium sulfate is 4.67% at 0 °C. On the other hand, the concentration of solution with sodium sulfate content at 0.5% does not reach the saturated state at 0 °C (listed in Table 6), which means the presence of salt reduces the initial freezing temperature of silty sand, and the unfrozen water content is higher than that in the soil specimen without salt. Therefore, the strength of frozen saline silty sand is less than that of frozen sand only at the same temperature. However, as shown in Table 6, when the salt content in silty sand exceeds 0.5%, the concentration of sodium sulfate does not reach saturated state at 25 °C which is the temperature when constructing soil samples, but it exceeds saturated concentration at 0 °C during the freezing process. Therefore, the sodium sulfate crystal separates out as temperature decreases during the freezing process and it fills the voids between soil particles, which improve the compactness of frozen silty sand. Meanwhile, the actual water content is lowered down by the formation of $Na_2SO_4{\cdot}10H_2O$ during crystallization process that one sodium sulfate molecule combines with ten water molecules. This decrease of water content makes the internal friction of frozen silty sand even smaller. In summary, the strength of frozen silty sand increases with the increase of salt content if the concentration of sodium sulfate is more than the saturated concentration at 0 °C.

Table 5
The solubility of sodium sulfate in different temperatures (Dean [21]).

Temperature/°C	0	10	20	30	40	50	60	70	80	90	100
Solubility/g/100 ml	4.9	9.1	19.5	40.8	48.8	45.3	45.3	43.7	43.7	42.7	42.5

Table 6
The concentration of sodium sulfate in the silty sand under different salt contents.

Salt content/%	0.0	0.5	1.5	2.5
Concentration/%	0.0	3.7	10.34	16.13

Influence of sodium sulfate content on the cohesive force and internal friction angle

It can be seen from Fig.3 that the strength of frozen silty sand linearly increases with the increase of confining pressure at different sodium sulfate contents, and the cohesive force and internal friction angle of frozen silty sand with different sodium sulfate contents can be availably obtained by the Mohr-coulomb strength criterion. To investigate the influence mechanism of the sodium sulfate content on the strength of frozen silty sand, the variations of the cohesion force and internal friction angle of frozen saline silty sand under different salt sodium sulfate contents are analyzed in this section.

Fig. 4 shows the failure envelopes of frozen silty sand with sets of Mohr circles under different confining pressures and at different salt contents. Based on the failure envelopes, we interpret the cohesive coefficient and the internal friction angle at different sodium sulfate as shown in Fig. 5.

Fig. 5(a) shows that when the concentration of sodium sulfate in frozen saline silty sand does not reach the saturate state (sodium sulfate content in soil below 0.5%) at 0 °C, the cohesive force decreases with the increase of sodium sulfate content. The main reason is that the cohesive force of frozen soil strongly depends on the cementation effect by ice. However, the presence of the sodium sulfate reduces the initial freezing temperature of soils and increases the unfrozen water content at the same negative temperature, which reduces the cementation effect by ice so the cohesive force is further decreased. When the concentration of sodium sulfate solution in silty sand corresponding to sodium sulfate content (sodium sulfate content in soil greater than 0.5%) is more than the saturate concentration at 0 °C, the cohesive force of frozen silty sand first increases then decreases with the increase of salt content since the effect of the sodium sulfate content within testing range on the initial freezing temperature is negligible [22]. At the sodium sulfate content of 1.5%, the sodium sulfate crystals separate out of the solution in soil and wraps around soil particles to provide the cementation effect when the temperature decreases. This results in the increase of cohesive force. However, the sodium sulfate crystalizes with the form of one sodium sulfate molecule combining with ten water molecules, the water content decreases as the process of crystallization. Thus, the cementation effect by ice reduces as the decrease of the actual water contents in specimens, although the cementation effect by sodium sulfate crystals can compensate the part of decreased cementation by ice. As a result, the cohesion force decreases.

As shown in Fig.5(b), the internal friction angle of frozen silty sand is barely influenced by salt content when the salt content is less than 2.5%. In this range of salt content, the concentration of sodium sulfate solution in soil transits from unsaturated state to saturated state. When salt content does not reach saturated state, the presence of salt makes the unfrozen water content increase. However, the existing unfrozen water acts as absorbed water layer which has a negligible influence on friction force. The sodium sulfate crystalizes out of the solution in soil during the freezing process if the solution is supersaturated. The amount of crystals separated out of the solution at low salt contents is not enough to fully fill the voids between soil particles so the effect on the increase of soil particle compactness and the internal friction angle is negligible. In contrast, once salt content reaches 2.5%, the internal friction angle of frozen soils increases sharply since more sodium sulfate crystalizes with the increase of sodium sulfate content. This increased amount of sodium sulfate crystals almost completely fills within the voids to strengthen soil particles compactness and sustain interlocking effect between soil particles; moreover, more water in frozen saline silty sand at this sodium sulfate content transforms to the solid states becomes part of $Na_2SO_4 \cdot 10H_2O$, which lowers down the actual water content and reduces the lubrication effect of water between soil particles. These two facts increase the internal friction angle of frozen saline silty sand with the sodium sulfate content of 2.5%.

From the above analysis, we can conclude that: (1) when the concentration of sodium sulfate solution corresponding to the salt content in soil is not at saturated state, the internal friction angle of frozen saline silty sand remains nearly constant, but the cohesion

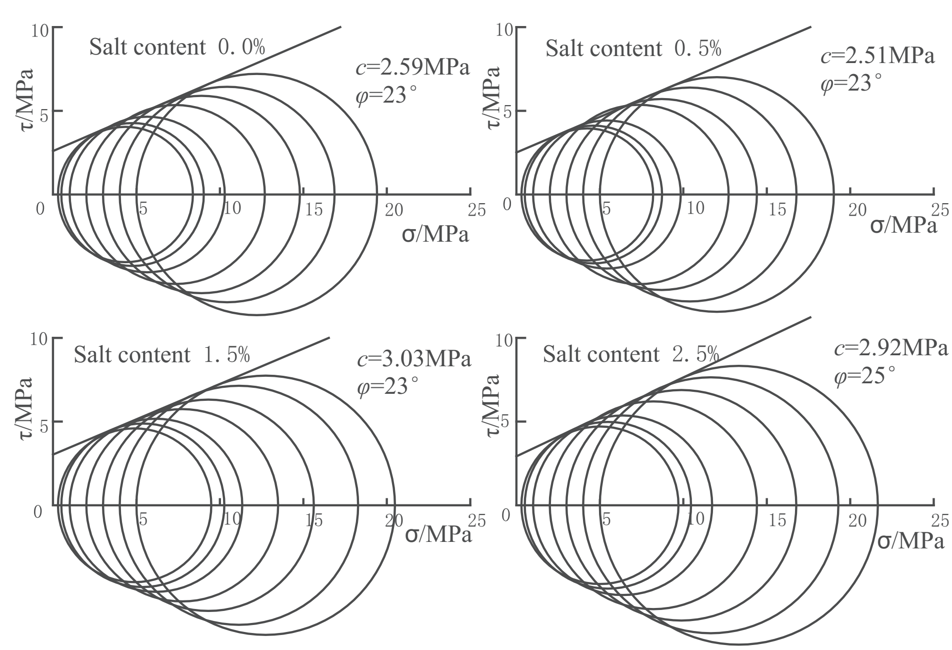

Fig. 4. The Mohr circles and failure envelopes of frozen silty sand with sodium sulfate under different salt contents.

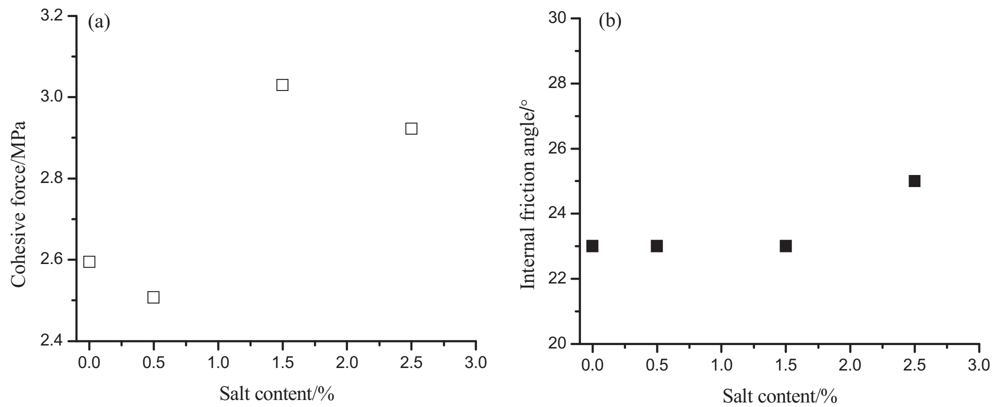

Fig. 5. Cohesion force and internal friction angle of frozen silty sand with sodium sulfate under different salt contents.

force decreases with salt content increasing, which causes the strength of frozen silty sand decreases with the increase of salt content; (2) when the concentration is at saturated state but the salt content is less than 2.5%, the internal friction angle of frozen silty sand remains almost at a constant with the increase of salt content, but the cohesive force increases as salt content increases, which leads to the strength of frozen silty sand increases with the increase of salt content in this stage;(3) when sodium sulfate content in soil is greater than 1.5%, the cohesive force of frozen silty sand decreases while the internal friction angle increases with the increase of salt content, but the increase of friction angle dominates the overall strength behavior, thus the strength of frozen saline silty sand increases with the increase of salt content.

Conclusion

To investigate the effect of confining pressure and sodium sulfate content on the characteristics of deformation and strength as well as the failure modes of frozen saline silty sand, triaxial compressive tests (confining pressures range of 0.3–5 MPa) are conducted on the frozen silty sand with the sodium sulfate content of 0.0%, 0.5%, 1.5% and 2.5% at the temperature of −6 °C. Main conclusions from experimental results are summarized as below:

(1) When the sodium sulfate content is 0–0.5%, the concentration of salt solution in frozen silty sand is not saturated at 0 °C, the softening degree of stress-strain curves gradually reduces with the increase of confining pressure. In this sodium sulfate content range, when confining pressure is more than 3 MPa, the deformation characteristic of frozen silty sand changes from strain softening to strain hardening and failure mode changes from brittle to plasticity. When the sodium sulfate content is 1.5–2.5%, the concentration of salt solution in frozen silty sand reaches or exceeds saturated value. The frozen saline silty sand exhibits the strain softening behavior under all testing confining pressure, which indicates that the existence of sodium sulfate enhances the brittle properties of frozen silty sand when the concentration of the sodium sulfate solution exceeds saturated value. The softening behavior of frozen silty sand with different salt contents is also restrained by the increase of confining pressure, and the failure strain has a linear increasing trend with the increase of confining pressure.

(2) The strength of frozen silty sand with different sodium sulfate contents perfectly linearly increases with the increase of confining pressure, and can be described by Mohr-coulomb strength criterion. The increasing rate of strength of frozen saline silty sand with the increase of confining pressure at different sodium sulfate contents are in the range from 1.29 to 1.52. When the concentration of salt solution is not saturated at temperature of 0 °C, the strength of frozen silty sand with sodium sulfate decreases with the increase of salt content. Oppositely, if the concentration of salt solution is saturated at temperature of 0 °C, the strength of frozen silty sand with sodium sulfate increases with the increase of salt content. A function has been established to interconvert the sodium sulfate content in silty sand and the concentration of sodium sulfate solution. Based on this equation, the phenomenon that the strength of frozen silty sand with sodium sulfate contents at 0.5–2.5% increases with the increase of salt content can be reasonably explained.

(3) When sodium sulfate solution is not saturated, the presence of salt causes the increase of unfrozen water content in frozen silty sand and further leads to the decrease of cohesive force as sodium sulfate content increases. However, the cohesive force first increases and then decreases with further increase of sodium sulfate content once the salt solution is saturated. When the sodium sulfate content is 0–1.5%, the value of internal friction angle is not affected by the sodium sulfate content. However, when the sodium sulfate content exceeds 1.5%, the internal friction angle of frozen silty sand increases with the increase of sodium sulfate content. This is because the sodium sulfate molecules separate out of solution with ten water molecules during crystallization in the freezing process. Those crystals lowered down the water content in soil and fill in the voids between soil particles which cause an increase of internal friction with the increase of sodium sulfate.

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References

[1] Zhao TY. Experimental Study on Salt Heaving Properties of Inland Sulphate Saline Soil in Cold and Arid Regions (Ph. D. Thesis). Lanzhou University; 2012. 16-17.
[2] Nobuhide O, Masayuki Y, Tetsuyuki K. Effects of salt concentration on strength and creep behavior of artificially frozen soils. Cold Reg. Sci. Technol. 1983;8:139–53.
[3] Pharr GM, Merwin JE. Effects of brine content on the strength of frozen Ottawa sand. Cold Reg. Sci. Technol. 1985;11:205–12.
[4] Yang CS, He P, Cheng GD, et al. Uniaxial compressive strength of frozen saline silty clay. Eng. Mech. 2006;23(1):144–8.
[5] Yang CS, He P, Cheng GD, et al. Study of stress-strain relationships and strength characteristics of saturated saline frozen silty clay. Rock Soil Mech. 2008;29(12):3282–6.
[6] Chen J, Li DQ, Bing H, et al. The experimental study on the uniaxial compressive strength of frozen salty silt with different salt content. Eng. Mech. 2013;30(12):18–23.
[7] Chen J, Li DQ, Bing H, et al. An experimental study of influence of water content on uniaxial compression strength of frozen salty silt. J. Glaciol. Geocryol. 2012;34(2):441–9.
[8] Sun QJ, Li DW, Wang SY. Test on triaxial shear of artificial frozen saline sand. Coal Technol. 2015;34(4):105–7.
[9] Cai ZY, Wu ZQ, Huang YH, et al. Influence of water and salt contents on strength of frozen soils. Chin. J. Geotech. Eng. 2014;36(9):1580–6.
[10] Hu K, Lai YM. Experimental study on the strength parameters and strength criteria of saline frozen silty sand. J. Glaciol. Geocryol. 2014;36(5):1199–204.
[11] Xu XT, Bai RQ, Lai YM, et al. Experimental study on mechanical properties of saline frozen silty sand. J. China Coal Soc. 2016;41(4):836–42.
[12] Bing H, Wu JJ, Deng J. Variations of physical and mechanical properties of saline loess before and after desalting. J. Glaciol. Geocryol. 2011;33(4):796–800.
[13] Lai YM, Xu XT, Yu WB, et al. An experimental investigation of the mechanical behavior and a hyperplastic constitutive model of frozen loess. Int. J. Eng. Sci. 2014;84:29–53.
[14] Zhou ZW, Ma W, Zhang SJ, Du HM, Mu YH, Li GY. Multiaxial creep of frozen loess. Mech. Mater. 2016;95:172–91.
[15] Li QL, Ling XZ, Sheng DC. Elasto-plastic behavior of frozen soil subjected to long-term low-level repeated loading, Part I: experimental investigation. Cold Reg. Sci. Technol. 2016;125:138–51.
[16] Li QL, Ling XZ, Sheng DC. Elasto-plastic behavior of frozen soil subjected to long-term low-level repeated loading, Part II: constitutive modelling. Cold Reg. Sci. Technol. 2016;122:58–70.
[17] Yang YG, Gao F, Lai YM, Cheng HM. Experimental and theoretical investigations on the mechanical behavior of frozen silt. Cold Reg. Sci. Technol. 2016;130:59–65.
[18] Xu XT, Lai YM, Dong YH, et al. Laboratory investigation on strength and deformation characteristics of ice-saturated frozen sandy soil. Cold Reg. Sci. Technol. 2011;69(1):98–104.
[19] People, s Republic of China National Standard, GB/T 20123-1999. Standard for Soil Test Method. Beijing: China Planning Press; 1999. p. 1–66.
[20] Ma W, Wu ZW, Sheng Y. Effect of confining pressure on strength behavior of frozen soil. Chin. J. Geotech. Eng. 1995;17(5):7–11.
[21] Dean JA. Lang's Handbook of Chemistry. 15th ed. McGraw-Hill Inc; 1999.
[22] Wan XS, Lai YM. Experimental study on freezing temperature and salt crystal precipitation of sodium sulphate solution and sodium sulphate saline soil. Chin. J. Geotech. Eng. 2013;35(11):2090–6.