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Volume changes and mechanical degradation of a compacted expansive soil under freeze-thaw cycles

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ABSTRACT

Expansive soils located in permafrost and seasonal frozen regions can easily suffer from the action of frost heaving and repeated freezing–thawing. When exposed to freeze–thaw (F–T) cycles, it may pose risk to civil engineering structures and thus causes heavy economic losses. In this study, a series of cylindrical expansive soil specimens were compacted at three different molding water contents (15%, 20% and 23%) and then subjected to a maximum of 12 closed–system F–T cycles. Besides, selected specimens compacted at the optimum water content were also tested under cyclic freezing–thawing with varying freezing temperatures (−5 °C, −10 °C and −20 °C). After each cycle of F–T, volume changes were measured and unconfined compression testing was also performed to estimate stress–strain behavior, resilient modulus and failure strength. Moreover, *meso*–structural analysis was conducted by using a simple optical test system to quantitatively extract the surface porosity and the pore orientation degree of expansive soil specimens after different F–T cycles. It is found that: 1) Volume changes for expansive soil specimens with higher and lower saturations present opposite directions and different magnitudes upon freezing, but show a similar trend of volume expansion after thawing. A moderate freezing temperature (i.e. –10 °C, in this study) has the greatest effect on volume changes. 2) Expansive soils tend to exhibit strain–softening behavior under unconfined compression conditions. The resilient modulus and failure strength decrease significantly at the first cycle of F–T and then reduce gradually to a stable value with increasing F–T cycles. The higher molding water content and a moderate freezing temperature will lead to a more pronounced degradation of mechanical behaviors with the F–T cycles. 3) It is suggested from the *meso*–structural analysis that the internal pores of expansive soils after a sequence of F–T cycles tend to become larger and more uniform, especially for the soil with higher water contents or experienced at a moderate freezing temperature.

1. Introduction

The areas of permafrost, seasonally frozen ground and temporal frozen ground in China are $206.8 \times 10^4\,km^2$, $513.7 \times 10^4\,km^2$ and $229.1 \times 10^4\,km^2$, respectively, accounting for the majority of China's land area (Zhao et al., 2004). With the accelerating construction of embankments, highways, high–speed railways, water conveyance canals, tunnels, and other constructions in permafrost and seasonal frozen regions (Cheng, 2005; Li et al., 2013; Ma et al., 2009; Niu et al., 2017; Sheng et al., 2014; Zhang et al., 2004), the prevention of frost heave and freeze–thaw damage has aroused widespread concern. Currently in China, large areas of expansive soils have been discovered in seasonal frozen regions during engineering construction. For instance, the middle route of South–to–North Water Transfer Project (SNWTP) in China is 1200 km long, of which about 180 km is open channel, located in seasonally frozen zones, has to pass through the expansive soil land (Liu et al., 2015; Ng et al., 2003); Some cutting slopes also cover a lot of expansive soils along the Jilin–Tumen–Hunchun high–speed railway in cold regions of Northeast China (Tang et al., 2018). Cracking and spalling are the most common results of freeze-thaw damage in clayey soils, which become more prominent in expansive soils because they contain active clay minerals like montmorillonite and illite (Andersland and Al-Moussawi, 1987; Lu et al., 2016). Thus, expansive soils in such areas, when exposed to freeze–thaw (F–T) cycles, can bring risks to the earth retaining system, as well as have potential negative effects on the long term stability of earthworks, thus causing heavy economic losses.

Expansive soil is a highly plastic soil that typically contains active clay minerals like montmorillonite and illite. It exhibits significant

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swell–shrink potential and are more prominent in volume change upon environmental factors, such as wet–dry cycles (Alonso et al., 1999; Shi et al., 2002). The volume change is typically characterized by expanding upon water absorption and contracting with water loss, which will cause extensive damage to the structures and infrastructure on top of them and cause natural disasters (Puppala et al., 2011; Zheng et al., 2009). Therefore, it was even been described as "calamitous soils" (Chen et al., 2007). Previous studies have mainly focused on the effect of wet–dry cycles on the cracking, mechanical, swell–shrink and hydro–mechanical behavior of expansive soils (Alonso et al., 2005; Cui et al., 2002; Cuisinier and Masrouri, 2005; Estabragh et al., 2015; Rosenbalm and Zapata, 2016), and the behavior of modified expansive soils has also been widely investigated (Abdullah and Al–Abadi, 2010; Al-Mukhtar et al., 2012; Cokca, 2001; Hotineanu et al., 2015; Khemissa and Mahamedi, 2014; Olgun, 2013; Soltani et al., 2018; Yazdandoust and Yasrobi, 2010). However, little attention has been paid to studies on expansive soils located in cold regions. Although some preliminary attempts have been made by the authors (Lu et al., 2016; Lu and Liu, 2017) to explore the cracking behavior of expansive soils under F–T cycles, the effects of F–T cycles on volume changes and mechanical behaviors of expansive soils is still limited. In particular, the effects of water content and freezing temperature, two vital factors concerned by practical construction, on deformation and strength characteristics of expansive soil is still unclear.

In this study, the volume changes and mechanical behavior of expansive soils at different molding water contents and freezing temperatures under F–T cycles were investigated, and a *meso*–structural analysis was performed to quantitatively evaluate the structural changes of the soils due to different numbers of F–T cycles.

2. Materials

The soil specimens tested in this study were prepared with a natural expansive soil, which was taken from a cutting channel slope on the middle route of South–to–North Water Transfer Project (SNWTP) in China. As shown in Fig. 1, the tested expansive soil is located in the seasonally frozen area, where the soil will commonly suffer from the potential damages of F–T cycles. The index properties of the prepared expansive soil are presented in Table 1. Based on the plasticity properties, the soil was classified as low plasticity clay (CL) in the Unified Soil Classification System (USCS). According to the free swell test following the Chinese code on Specification of soil test (SL237-, 1999), it can be classified as a medium expansive soil with a free swelling index of 67.0%.

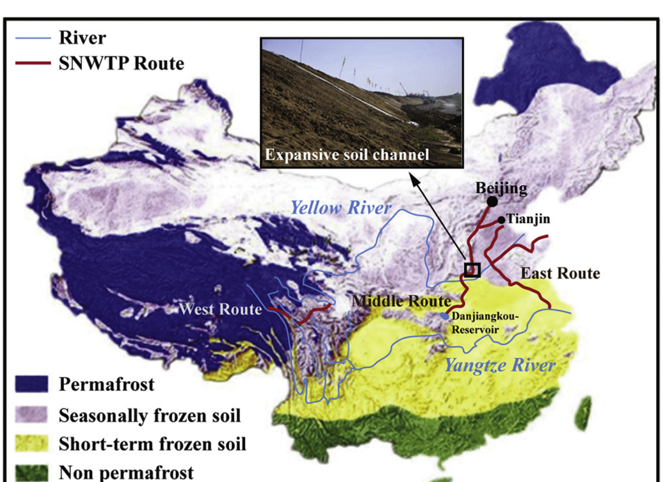

Fig. 1. Location of the tested expansive soil sampling area.

Table 1
Index properties of the tested expansive soil.

Soil property	Value
Specific gravity, Gs	2.72
Liquid limit, L_L (%)	42.6
Plastic limit, L_P (%)	22.5
Free swelling index, FSI (%)	67.0
Optimum moisture content (%)	20.0
Maximum dry density (g/cm^3)	1.78
Color	Brownish yellow

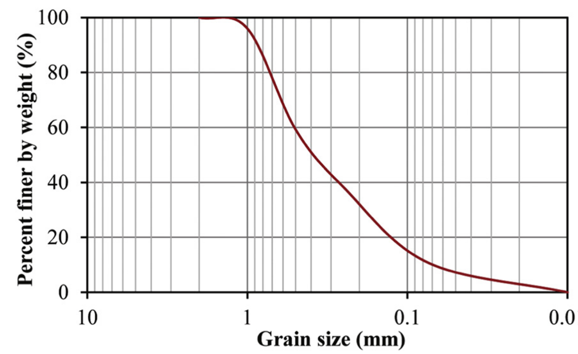

Fig. 2. Grain–size distribution of expansive soil.

3. Experimental procedures

3.1. Specimen preparation

The original expansive soil was firstly air–dried for about one week. It was then crushed with a hammer and sieved through a 2.0 mm sieve with the grain size distribution as shown in Fig. 2. The sieved soil was further added with water using spray bottle in measured quantities by weight and mixed thoroughly using spatulas until water contents reached 15%, 20% (optimum), and 23%, and then cured in plastic bags and sealed for about 24 h to make the soil moisture distributed as homogeneously as possible. Next, the soil mixtures were compacted inside a cylindrical stainless steel mold by using a stratified sample preparation device modified by Lu et al. (2017), as shown in Fig. 3. All the specimens were compacted to the same dry density of 1.65 g/cm^3, and the dimensions were 61.8 mm in diameter and 125 mm in height. After compaction, the soil samples were immediately extracted from the mold and coated with plastic wrap, which has been proved to be effective to avoid moisture loss during F-T cycles (Xu et al., 2015). The experimental conditions for each testing group are listed in Table 2. By comparison of test group No.1, 2, 3 and No.2, 4, 5, the effects of molding water contents and freezing temperatures on volume changes and mechanical behaviors under F–T cycles can be discussed,

Fig. 3. The device for compacting expansive soil specimen.

Table 2
Experimental conditions.

Test group no.	Molding water content (%)	Freezing temperature (°C)	Remarks
1	15	−20	Each Test group has 15 specimens, Four of which were used for volume measurement, eight for unconfined strength test, two for microstructure test and one for standby. 75 samples were prepared in total.
2	20	−20	
3	23	−20	
4	20	−5	
5	20	−10	

respectively.

3.2. Freeze–thaw testing

After the completion of compacted expansive soil specimens according to the designed experimental conditions (*See* Table 2), the freeze–thaw testing was further conducted in the cryogenic laboratory at Hohai University, as shown in Fig. 4. In this study, the cyclic freezing–thawing test was performed in a closed system and the expansive soil specimens were exposed to three-dimensional freezing conditions. Such conditions are typical of the expansive soils located on the shallow surface of the channel slope (*See* Fig. 1). During one freezing–thawing process, the soil specimen was firstly frozen for 12 h at a temperature of −20 °C and then thawed for another 12 h at the room temperature (about 20 °C). This timing was decided because 12 h is an adequate period after which the alteration of specimens' volumes would become constant. The cycles were continued up to 12 cycles, which was chosen since most soil strength reduction would occur in the primary cycles and after 5–10 cycles a new equilibrium condition would become predominant on specimens (Ghazavi and Roustaie, 2010). At the end of each F–T cycle, the tested specimens were weighed by using an electronic scale with a precision of 0.1 g and the corresponding water contents were thus calculated. The calculated results showed that there were almost no water losses in soil specimens during F–T cycles owing to the plastic wraps coated around.

3.3. Measurement of volume change

To investigate the volume changes of expansive soil specimens under F–T cycles, the diameters and heights of four specified specimens were measured by using a digital vernier calliper with a precision of 0.01 mm after each period of freezing and thawing. Then, the corresponding overall volumes can be calculated according to the measured values. Since all specimens were exposed to three–dimensional closed system freezing conditions, the deformation is basically homogenous along the sample height. It is noted that, after each F-T cycles, the average diameters and heights were derived from the measured dimensions of five cross-sections and two longitudinal sections of the specimens, respectively.

3.4. Unconfined compression testing

The strength of the specimens is measured using the unconfined compressive test by a universal compression loading machine (UTM4503S) with a maximum load capacity of 5kN (*see* Fig. 5(a)). The machine is able to measure accurately and reliably a huge number of data for drawing the stress–strain curves of the tested specimens. The loading was continued to an axial strain of approximately 25% for obtaining the complete stress–strain curves. Thus, the stress–strain behavior, resilient modulus and failure strength (i.e. unconfined compression strength, UCS) of the specimen could be determined simultaneously. The loading strain rate is kept constant at 1%/min through the testing procedure.

3.5. Extraction of meso–structural parameters

To acquire a more clear understanding of the meso–structural evolution of expansive soil under F–T cycles, a simple optical test system (Fig. 5(b)), developed by Hong and Liu (2010) in micro–meso structural laboratory at Hohai University, was used to extract the meso–structural parameters of the specimens subjected to different F–T cycles. Taking the specimen with a water content of 20% as an example, several meso–scopic images of the sample section after some typical numbers of F–T cycles were presented in Fig. 6. it was found that, after several F-T cycles, the expansive soil aggregates would be cracking or spalling (*See* regions a, b and c), which is also observed in cracking behaviour of an expansive soil from a macroscopic perspective, as reported by Lu et al. (2016). Then, a Geo–image software (Hong and Liu, 2010) was used to calculate the quantitative parameters, such as the surface porosity and the pore orientation (defined later). The test device and method were also applied in reported other researches (Cui et al., 2011; Liu et al., 2016). More details can be found in the reference book edited by Hong and Liu (2010).

4. Results and discussion

4.1. Effect of F–T cycles on volume change

As aforementioned in Section 3.3, four cylindrical soil specimens were used to measure the variations of diameters and heights during each F–T cycle and the average volume changes could thus be estimated. Herein, a dimensionless parameter (Volumetric strain, ε_v) is defined to reflect relative changes of the volumes during freezing–thawing process, and calculated as.

$$\varepsilon_v = 100\cdot(\Delta V/V_0) = 100\cdot(V_N - V_0)/V_0\,(\%) \tag{1}$$

Where V_0 and V_N are the initial volumes of expansive soil specimens prior to F–T cycles and current volumes after N cycles of F–T, respectively. When ε_v is positive, it refers to volume expansion; while

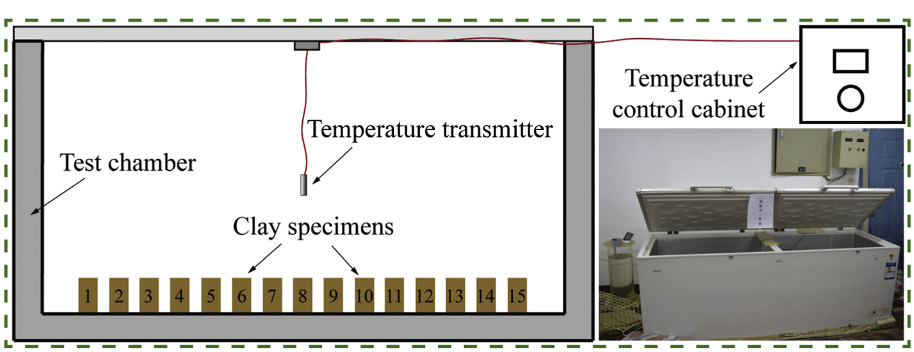

Fig. 4. Set–up for cyclic freezing–thawing.

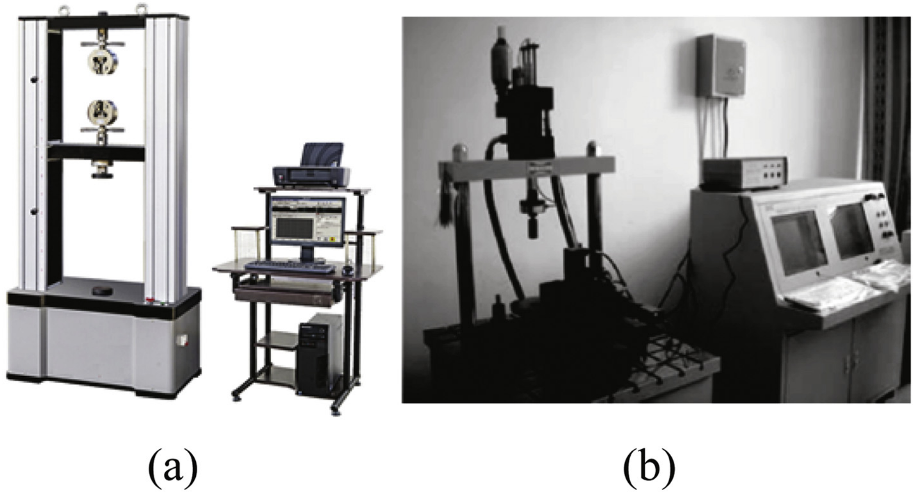

Fig. 5. Testing equipments: (a) unconfined compression, and (b) *meso*–structural analysis.

negative, it represents volume contraction. Fig. 7(a) and (b) show changes of ε_v with F–T cycles under different molding water contents and freezing temperatures, respectively. On the horizontal axis, 0 is the initial state, 0.5 is the completion of the first freezing and 1 is for the first thawing, and so on.

As shown is Fig. 7(a), it is observed that the directions and magnitudes of volume changes were significantly different for specimens with different molding water contents. For the soil specimens with a higher moisture content of 23% (the corresponding saturation is 96.5%), the overall volume increases upon freezing but decreases upon thawing. On the contrary, the specimen volumes of lower water contents of 15% and 20% (the corresponding saturations are 62.9% and 83.9%, respectively) decrease upon freezing but increase upon thawing. It indicates that freezing will induce either volume expansion or contraction for specimens with higher and lower water contents, respectively. The maximum freezing–induced expansion strain is 5.88%, occurring after the 6th freezing period. Whereas, the maximum freezing–induced contraction strains occurred after the 1st freezing period, which are 4.40% and 3.58% for specimens with water contents of 15% and 20%, respectively. Although volume changes present different directions upon freezing for lower and higher water contents, the volumes at each thawed period all present expansion and gradually tend to stable values with increasing F–T cycles. This is also observed in a high plastic clayey soil by Hamilton (1966) who found that, at the end of the first and second F–T cycles, the tested sample volumes were greater than the as-compacted volumes, regardless of whether the samples expanded or shrank upon freezing.

As motivated by Alonso et al. (1987), a schematic diagram of expansive soil structural variations upon freezing at different saturations is depicted in Fig. 8. Fig. 8 (a) and (b) illustrate the idealized types of particles and their arrangements for an unfrozen expansive clayey soil at higher and lower saturations, respectively. The clay grains form a series of aggregates controlling the packing and the macro–pore (or

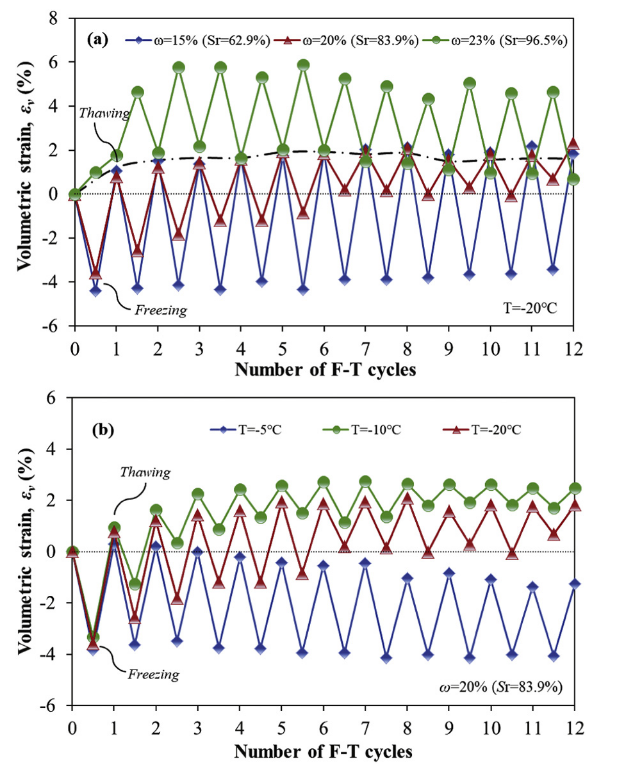

Fig. 7. Changes of volumetric strain with the F-T cycles. (a) At different moisture contents ($T = -20\,^{\circ}$C); (b) At different freezing temperatures ($\omega = 20\%$).

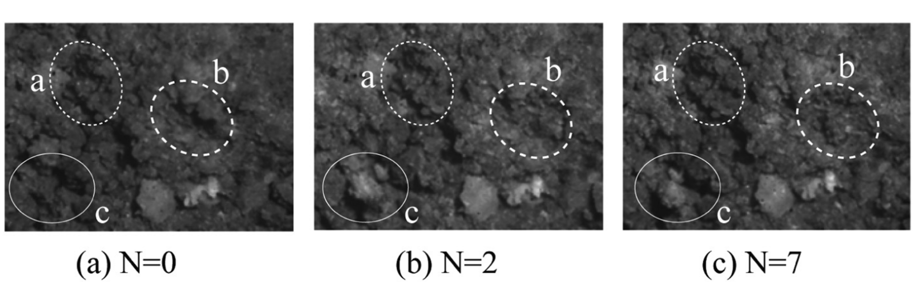

Fig. 6. Meso–scopic images of expansive soil ($\omega = 20\%$) after typical F–T cycles ($\times$150).

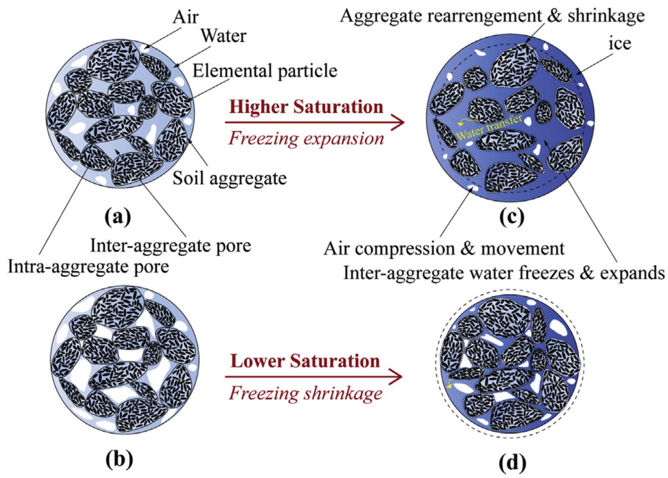

Fig. 8. Schematic diagram of freezing of expansive soils at lower and higher saturations.

inter–aggregate pores) space, while the elemental clay particles control the micro–pore (or intra–aggregate pores) distribution within the soil aggregate. As also stated by Sánchez et al. (2016), expansive clays typically exhibit a clear dual porosity with such two dominant pore sizes. When the soil at a higher saturation is under freezing, as shown in Fig. 8 (c), the inter–aggregate pore space is occupied fully by the growing ice lens, thus gradually making the inter–aggregates pores become larger because liquid water experiences a volumetric increase of 9% when it becomes frozen (ice). Also, soil aggregates may be compressed by ice crystals growing in inter–aggregate pores as growing ice crystals have been reported capable of generating surface pressures ranging from 100 kPa up to 460 kPa (Henry, 2000; Perfect et al., 1990). Therefore, some grain realignment is expected to accommodate the expansion of inter–aggregate pore water as it freezes (Czurda, 1983). Meanwhile, the intra–aggregate water driven by the cryogenic suction may migrate outwards towards centers of ice crystal growth in inter–aggregate pore spaces, resulting in the desiccation–induced shrinkage of the interior of aggregates (Dagesse, 2013; Hamilton, 1966). This is similar to the secondary compression of clays resulting from local transfer processes from the microstructural water, linked to clay aggregates and minerals, to the bulk water occupying the soil macro–pores (Navarro and Alonso, 2001). However, such shrinkage of aggregates is not enough to compensate the expansion contribution of the growing ice in inter-–aggregate pores. Under these circumstances, the bulk volume of the soil exhibits a tendency to become larger upon freezing.

Conversely, for the soil at a lower saturation as shown in Fig. 8(d), the volumetric expansion due to the phase change from inter–aggregate water to ice is being fully accommodated by the existing air in pores. Besides, freezing–induced desiccation and shrinkage of the soil aggregates is still being realized. In this case, volumetric shrinkage effects associated with such aggregate shrinkage would dominate over the expansion effects of inter–aggregate water phase change to ice as the initial empty pore volume is sufficient enough to accommodate the expansion.

Upon thawing, as soil surface temperature is usually higher than the internal temperature, the temperature gradient leads a water migration from inter–aggregate pores to intra–aggregate pores. Due to the hysteretic behavior, at a given value of suction, the soils retain more water in drying path than in wetting path (Lu and Likos, 2004). Thereby, the aggregates will no longer re–expand by water absorption to the original volumes. Besides, inter–aggregate pores will remain bigger than their original states owing to the irreversible plastic deformation induced by ice lenses. Therefore, the volume changes after thawing all present a tendency of expansion.

Fig. 7(b) shows the variation of volumetric strain with F–T cycles under different freezing temperatures for specimens with constant molding water contents of 20% (optimum). It is found that different freezing temperatures have little effect on the volume change during the 1st F–T cycle, whereas such effect gradually becomes prominent with increasing F–T cycles. For the specimen under a freezing temperature of −5 °C, the final volumetric strain reached −1.25% after 12 F–T cycles. Conversely, for the freezing temperatures of −10 °C and −20 °C, the final volumetric strains reached to 2.48% and 1.82%, respectively. It is suggested that, after adequate cycles of F–T, a higher freezing temperature (−5 °C) leads to a contraction trend of the soil volume, while relatively lower freezing temperatures (−10 °C and −20 °C) cause volume expansion. This phenomenon is similar to the concept of residual void ratio, e_{res} in terms of density (Viklander, 1998) or critical dry unit weight, γ_{dcr}, in terms of freeze–thaw (Qi et al., 2008). It is deduced that the freezing temperature might alter the residual void ratio or critical dry unit weight of soils in terms of F–T cycles.

4.2. Effect of F–T cycles on stress–strain behavior

As previously stated in Table 2, for each test group, unconfined strength tests were conducted on eight specimens subjected to different F–T cycles. In order to compare stress–strain characteristics, the corresponding complete stress–strain curves of expansive soil samples after different freeze–thaw cycles are plotted in Fig. 9.

All the stress–strain curves present strain softening for all the tested conditions. With increasing F–T cycles, the shapes of stress–strain curves are gradually flattened. Particularly, the initial slope of the curve and the strain at failure decrease sharply at the 1st F–T cycle. It is suggested that expansive soil is sensitive to freeze–thaw and loses its strength and stiffness, and this phenomenon is found to be the most pronounced after one F–T cycle. By comparison of Fig. 9(a), (b) and (c), it is observed that, prior to F–T cycles, the specimen with a higher water content has a lower initial peak strength and the corresponding curve

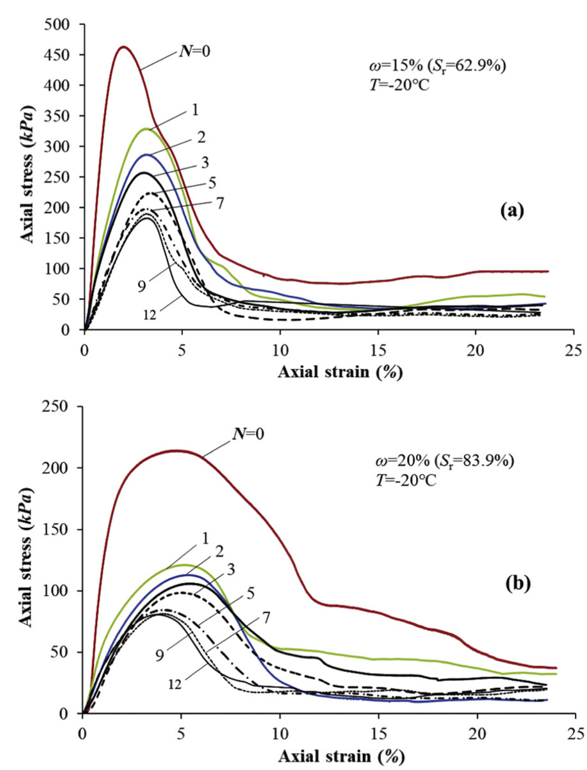

Fig. 9. Stress–strain curves of expansive soil samples under different numbers (N) of F-T cycles. (a) ω = 15%, T = −20 °C; (b) ω = 20%, T = −20 °C; (c) ω = 23%, T = −20 °C; (d) ω = 20%, T = −5 °C; (e) ω = 20%, T = −10 °C.

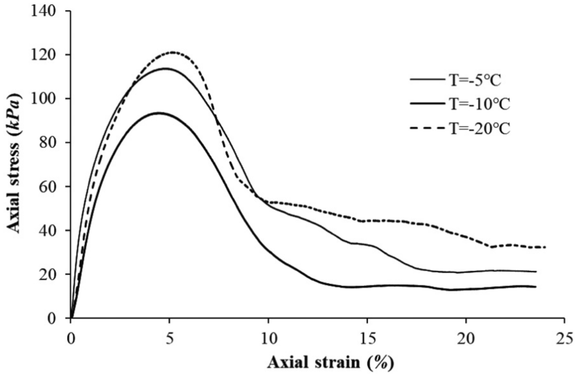

Fig. 10. Stress–strain curves of expansive soil samples under different freezing temperatures after one F–T cycle.

presents a flatter shape. After F-T cycles, the reduction of peak strength, strain at failure and stiffness becomes more significant with increasing water contents. For instance, after several cycles of freezing and thawing, peak strength of the sample with 23% water content decreased to less than 15% of the unfrozen strength. Fig. 7(a) indicates that the sample with 23% water content suffered the greatest structural damage because it almost experiences the maximum volume expansion measured during the whole F-T cycles. On the other hand, comparing Fig. 9(b), (d) and (e), it is found that the freezing temperature has little effect on the overall shape of stress–strain curves. To observe clearly the difference in quantity, the curves of three freezing temperatures after one F–T cycle are plotted in Fig. 10. As can be seen there is little difference in the stress–strain curves for −5 °C and − 20 °C. The stress-strain relationship for −10 °C indicates smaller peak strength, strain at failure and stiffness. It is suggested that the freezing temperature of −10 °C has a more significant effect on stress–strain behavior, which agrees well with the fact that, as shown in Fig. 7(b), the final volumetric strains for the specimen frozen at −10 °C after 12 F–T cycles reached a maximum value of 2.48% among the three freezing temperatures.

4.3. Effect of F–T cycles on resilient modulus

Resilient modulus (M_R) is a fundamental material property in pavement engineering used to quantitatively characterize material stiffness. It provides a mean to analyze stiffness of materials under different environments, such as moisture content, density, and stress level. It is also a required input parameter to mechanisic–empirical pavement design method (Ghazavi and Roustaei, 2013). The stress at 1% axial strain in the conventional unconfined compression test is a good indicator of the resilient modulus (Lee et al., 1995, 1997). In this study, the resilient modulus is defined as a ratio of the axial stress increment at 1% axial strain to the axial strain increment, which can be expressed by

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{1.0\%} - \sigma_0}{\varepsilon_{1.0\%} - \varepsilon_0} \tag{2}$$

Where $\Delta\sigma$ is the increment of axial stress, $\Delta\varepsilon$ is the increment of axial strain; $\sigma_{1.0\%}$ is the axial stress corresponding to the axial strain of 1.0% ($\varepsilon_{1.0\%}$); and σ_0 and ε_0 are the initial stress and strain, respectively (Wang et al., 2007). Herein, in order to estimate the attenuation degree of elastic modulus for specimens after N F–T cycles, the dimensionlessly normalized resilient modulus is defined as

$$M_{NR} = \frac{E_N}{E_0} \tag{3}$$

Where E_N is the resilient modulus after N F–T cycles, E_0 is the initial resilient modulus prior to freezing–thawing.

Fig. 11 shows the variations of resilient modulus and the corresponding normalized resilient modulus with increasing F–T cycles. As shown in Fig. 11(a), the specimens piror to freezing with the water

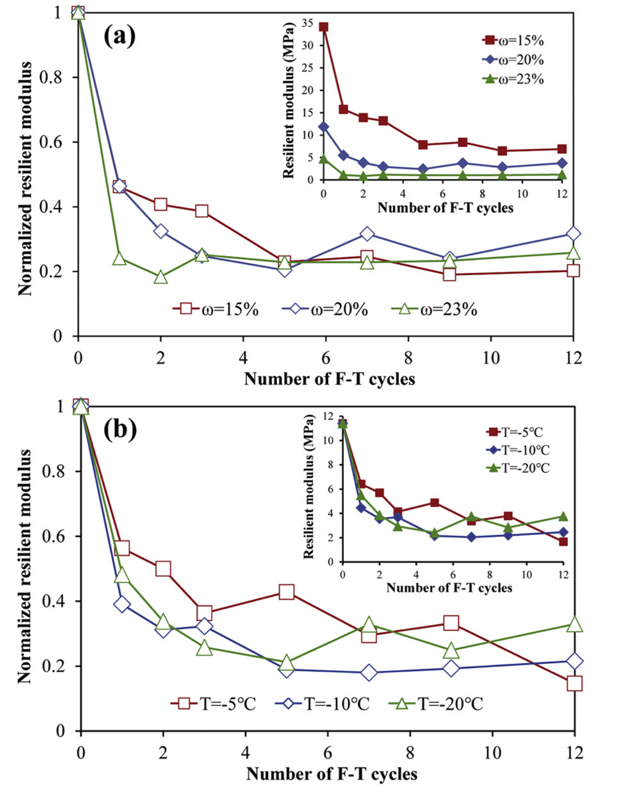

Fig. 11. Resilient modulus of expansive soil samples under different F-T cycles. (a) At different molding water contents ($T = -20$ °C); (b) At different freezing temperatures ($\omega = 20\%$).

contents of 15%, and 20% and 23% have initial resilient moduli of about 43.2 MPa, 11.9 MPa and 4.7 MPa, respectively. When subjected to a maximum of 5, 3 and 1 cycle of closed system freezing–thawing, the corresponding resilient moduli gurdually deceased to stable values of approximately 7.4 MPa, 3.1 MPa and 1.1 MPa, respectively. Fig. 11(b) describes the response of specimens with the same water content of 20% (optimum) when subjected to 12 F–T cycles at different freezing temperatures (−5 °C, −10 °C and − 20 °C). Although the corresponding resilient moduli reduced gradually from 11.4 MPa to 2-4 MPa, it is apparent that the specimen frozen at −10 °C has a faster reduction of resilient modulus after one F–T cycle than those at −5 °C and − 20 °C. It is concluded that the freezing temperature of −10 °C has a more significant influence on the stiffness softening of expansive soils under F–T cycles. This is owing to the volumetric change of the sample at freezing temperatures of −10 °C reached to the maximum expansion value of 2.48% among the three freezing temperatures, as shown in Fig. 7(b).

4.4. Effect of F–T cycles on failure strength

As previously described in Fig. 9, all the stress–strain curves present strain softening for all testing conditions. The unconfined compression strength (UCS) can thus be obtained from the peak values in the stress–strain curves.

Fig. 12(a) and (b) show the relationship between the UCS (as well as the dimensionlessly normalized UCS) of expansive soils subjected to F–T cycles versus different molding water contents and freezing temperatures, respectively. It is found that the 1st F-T cycle results in a remarkable reduction of UCS for the specimens at all conditions. The maximum strength reduction was measured for the highest water content (23%) since higher water content will generate more ice lenses altering the soil structure more significantly. This is also the reason why the degradation of resilient modulus for the sample with 23% water

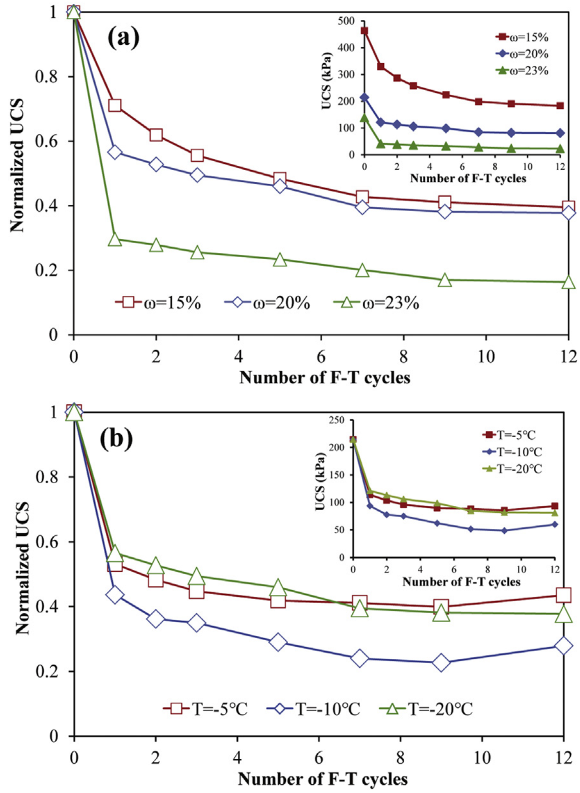

Fig. 12. Failure strength of expansive soil samples under different F-T cycles. (a) At different molding water contents ($T = -20$ °C); (b) At different freezing temperatures ($\omega = 20\%$).

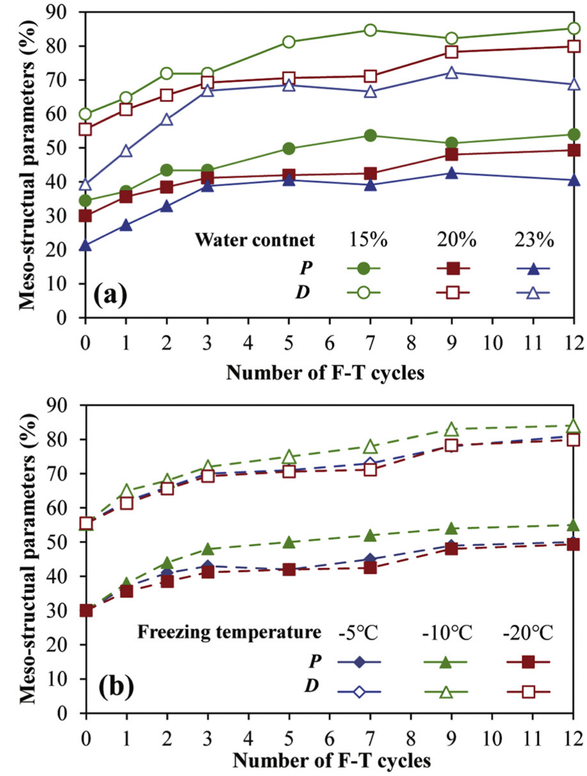

Fig. 13. Meso-structural parameters of expansive soil samples under different F-T cycles. (a) At different molding water contents ($T = -20$ °C); (b) At different freezing temperatures ($\omega = 20\%$).

content is the most prominent, as described in Fig. 11(a). Furthermore, it is worth noting that, similar to the behaviors of volume changes, stress–strain response and resilient modulus against F–T cycles, a moderate freezing temperature (−10 °C) also have more signifiant influence on the reduction of failure strength. This is similar to the findings reported by Steiner et al. (2017) that the largest change in shear strength of a illite clay occurred between −5 °C and −10 °C due to the formation of large ice lenses at such moderate temperature range, and these lenses acted as the primary failure plane in the thawed soil and caused a reduction in shear strength.

4.5. Effect of F–T cycles on meso–structural parameters

Freezing-thawing shows great influence on the micro–fabric features, usually described by particle orientation, pore volume and pore size distribution (Czurda et al., 1995). The extent of structural changes are dependent on the water content, freezing rate, thermal gradient, and applied surface temperature that result in ice lensing (Konrad, 1990). In this study, two quantified pore–scale meso-structual parameters (i.e. surface porosity and pore orientation degree) can be easliy estimated from soil section photographs captured by the method aforementioned in Section 3.5. The surface porosity (*P*), the ratio of the surface area of pores to the total area of the sample, is usually used to quantitatively describe the porosity on the sample surface (Rasa et al., 2012). Besides, the pore orientation degree (*D*) is used to characterize the ordering of the pore distribution (Cetin, 2004). The pore orientation degree can be calculated using the formulae reported by Tang et al. (2012). A larger value of *D* indicates a better orientation. Fig. 13 shows the surface porosity and the pore orientation degree of expansive soil specimens after different F–T cycles.

As can be seen from Fig. 13(a), at different molding water contents, both *meso*–structual parameters increase gradually and then tend to stable values with increasing F–T cycles. This indicates that freeze-thaw makes the internal pores of the soils increase in quantity and become more and more uniform in distribution. Besides, it is also observed that the meso–structual parameters increase more rapidly in the first few cycles of F–T, which is especially prominent for the specimen with a higher water content. This is aggrement with the afore-described phenomenon that volumes of specimens after thawing increase in comparison to unfrozen state. A higher water content results in a remarkable growth of ice crystal and thus has a significant expanding effect on the inter–aggregate pores, thereby causing the most significant degradation on resilient modulus and failure strength. Similar observation has also been verified by scanning electron microscopy (SEM) in a compacted unfrozen and frost-affected thawed Wiesloch clay (Czurda et al., 1995).

At different freezing temperatures, the meso–structual parameters were also evaluated, as demonstrated in Fig. 13(b). It is observed that the parameters were larger at the moderate freezing temperature of −10 °C. It suggests the specimens subjected to F–T cycles at the freezing temperature of −10 °C might generate more porosity and more homogeneous pores. As a result, it will alter the *meso*–structure of the soil aggregates and in turn leads to increasing macroscopic volume deformation and mechanical behavior degradation. It has been pointed out by Nmai (2006) that freezing temperature is an important factor controlling the rate of freezing (Newton's law of cooling) and the amount of freezable water within a material's structure. The rate of freezing will affect the formation of ice lenses, which in turn influence the soil structure (Andersland and Ladanyi, 2004). With slower freezing, larger ice lenses form, and pore water may end up on the surface before freezing completely (Liu and Peng, 2009; Rempel, 2007). Nevertheless, faster freezing rates result in a smaller change in grain structure, as the pore water will freeze in the available pore space before suction can have a significant influence. This consideration indicates that there may be a moderate freezing temperature causing the greatest impact on the volume changes and mechanical degradation of expansive soils. Actually, this has been verified experimentally in the previous discussion on volume change, stress-strain behavior, resilient modulus and failure strength. Such moderated freezing temperature in this study is −10 °C according to the experimental results.

5. Conclusion

Laboratory tests were performed to demonstrate the influence of F–T cycles on volume change, stress–strain behavior, resilient modulus, failure strength and meso–structural parameters of an expansive soil. The primary results are obtained as follows:

(1) The direction (expansion or shrinkage) and magnitude of volume changes of expansive soils under F–T cycles are significantly affected by initial molding water content (saturation). At higher saturations, the expansion effects due to the growing ice in inter–-aggregates dominate over desiccation–induced shrinkage of soil aggregates and thus the bulk volume increases upon freezing. Conversely, at lower saturations, the bulk volume decreases upon freezing. Besides, freezing temperature is an important factor controlling the freezing rate and freezable water content, closely related to the formation of ice lenses. A moderate low temperature environment, such as −10 °C in this study, can promote the full development of ice lenses, thereby inducing more a remarkable change in bulk volume.
(2) Expansive soil is sensitive to freeze–thaw and the stress–strain behavior under unconfined compression presents strain softening under F–T cycles. The reduction of failure strength, failure strain and stiffness is most pronounced after one F–T cycle and the degradation tendency increases significantly with increasing molding water content. The freezing temperature of −10 °C among the three tested freezing temperatures has the most evident effect on the mechanical degradation upon F–T cycles.
(3) The surface porosity and the pore orientation degree of the thawed expansive soils increase with increasing F–T cycles, which is prominent for the samples molded at higher molding water contents and frozen at a moderate freezing temperature. It is suggested that soil pores become larger and more homogeneous after repeated freezing-thawing. The volume changes and mechanical behavior of expansive soils are closely related to F–T cycles, presumably owing to the *meso*–structural changes of inter– and intra–aggregate pores.
(4) Engineering implication: The experimental study provides evidence that high water contents (especially close to saturated state) should be avoided to reduce frost heave of expansive soil foundation in cold regions. Besides, decreasing water content can effectively retard frost heave and mechanical degradation upon F-T weathering, but the potentially accompanying frost-shrinkage should receive more attention.

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