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Freeze-thaw performance of a cement-treated expansive soil

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ABSTRACT

This experimental study presents an attempt on the effect of cement addition to expansive soil on its deformation and strength behaviours when subjected to freezing–thawing (F–T) action. A series of laboratory tests on cemented-treated expansive clay samples after 28–d curing periods were conducted. The experimental program involved freezing–thawing test, volume measurement, and unconfined compression test. The effects were evaluated by focusing on the water loss, volume change, stress-strain response, unconfined compression strength, resilient modulus and strain at failure after a sequence of freeze–thaw cycles. Eight groups of expansive soil samples were prepared with four different cement contents (i.e. 0%, 3%, 5% and 7% by weight of soil) and subjected to 0, 1, 2, 3, 5, 7, 9, and 12 F–T cycles, respectively. The analysis of experimental results indicated that: 1) Cement additive makes expansive soil become less sensitive to moisture and cement–induced hydration reaction will reduce swelling–shrinkage characteristics triggered by F–T cycles; 2) The inclusion of cement within expansive soil causes an increase in unconfined compressive strength, resilient modulus, but a decrease in strain at failure. However, such effect induced by cement will be diluted by F–T cycles; 3) Cement can retard the degradation of resilient modulus but increase a faster strength reduction against F–T weathering. 4) Upon F–T cycles, un–cemented expansive soil will become more brittle, while cement-treated soils more ductile before 1st F-T cycle. A power function, independent of F–T cycles and cement contents, exists between the strain at failure and UCS. The results obtained from the study are fairly promising to employ cement additive against freeze–thaw resistance of expansive soils.

1. Introduction

Expansive soil, extensively distributed worldwide, is a highly plastic soil typically containing active clay minerals, such as montmorillonite and illite. It exhibits prominent swelling–shrinkage potentials and thereby creates numerous cracking upon desiccation, wet-dry and freeze–thaw cycles (Shi et al., 2002; Alonso et al., 2005; Lu et al., 2016; Chaduvula et al., 2017). Some scholars even refer expansive soils as "calamitous soils" (Chen et al., 2007). This is because the great volume change of expansive soils upon water content variation will cause massive damage to the infrastructure and buildings built on the foundations (Ferber et al., 2009). Therefore, extensive efforts have been paid to the treatment of expansive soils and the treatment methods may be mainly classified into two types: mechanical and chemical stabilization. The mechanical stabilization may include the deep soil mixing method, the cationic–electrokinetic method and the synthetic reinforcement method (Madhyannapu et al., 2009; Viswanadham et al., 2009; Abdullah and Al-Abadi, 2010). For the chemical treatment method, lime is the most effective and economical added materials. Besides, calcium chloride, fly ash and cement are also commonly used (Murty and Krishna, 2006; Sharma and Sivapullaiah, 2016; Jamsawang et al., 2017; Xu et al., 2018). Considering the long–term safety and some other demands of projects, cement is usually adopted in many large projects despite its higher cost. For instance, in the middle route of world's largest water diversion project, the South–to–North Water Transfer Project (SNWTP) in China, a 180 km open channel has passed through the expansive soil land where cement was adapted to stabilize the canal slope (Liu et al., 2015; Gong et al., 2016). Also, in the Erbil–Haj Omran highway, cement grouting method was applied to stabilizing the expansive soil slope and the results indicated that soil swelling decreases for > 90% by injecting 6% of cement grout (Daraei et al., 2018).

In seasonally frozen regions, expansive soils are subjected to not only seasonally repeated drying–wetting but also frequent

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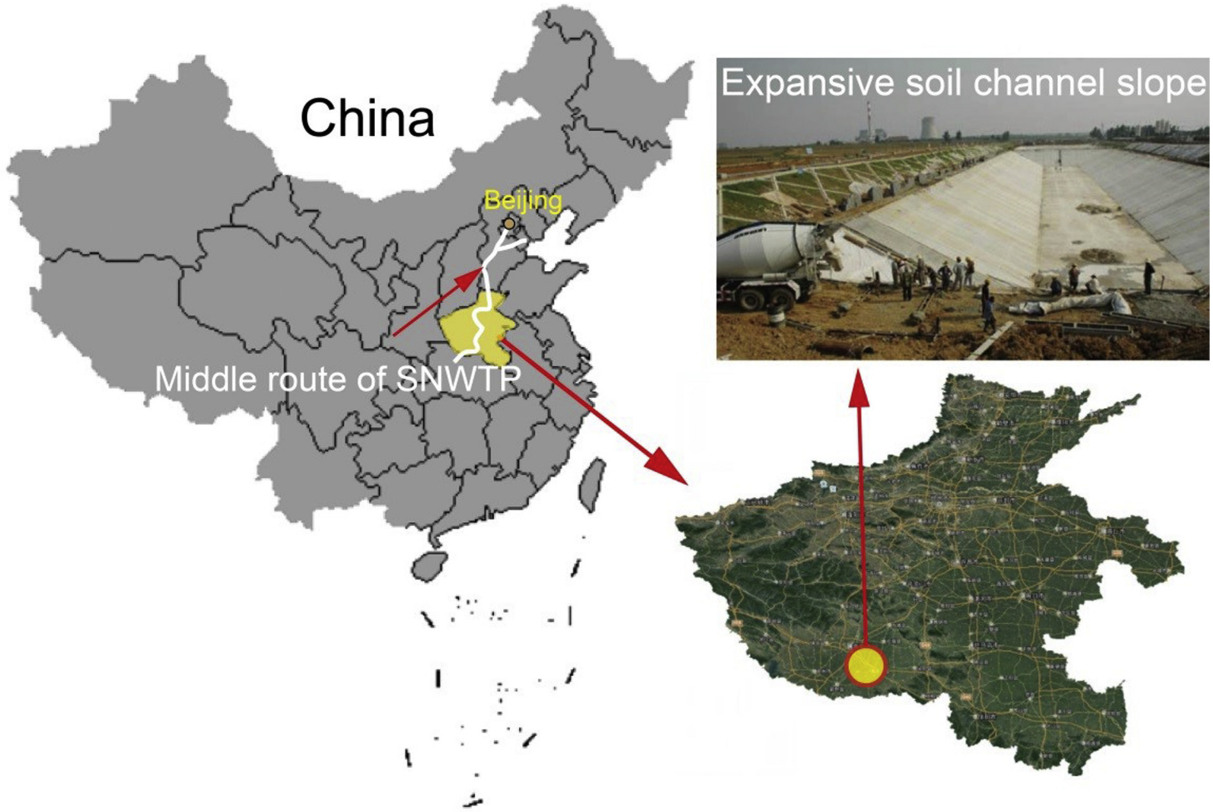


Fig. 1. Geographical location where the expansive soil sample originated.

Table 1
Physical indexes and mineral components of the expansive soil.

Properties	Index	Value
Physical index	Specific gravity, G_s	2.72
	Liquid limit, L_L (%)	42.6
	Plastic limit, L_P (%)	22.5
	Plasticity index, P_I	20.1
	Free swelling index, I_{FS} (%)	67.0
	Optimum moisture content (%)	20.2
	Maximum dry density (g/cm^3)	1.78
	Color	Brownish yellow
Mineral components	Quartz (%)	35
	Albite (%)	6
	Calcite (%)	1
	Montmorillonite (%)	36
	Illite (%)	10
	Kaolinite (%)	8
	Chlorite (%)	4

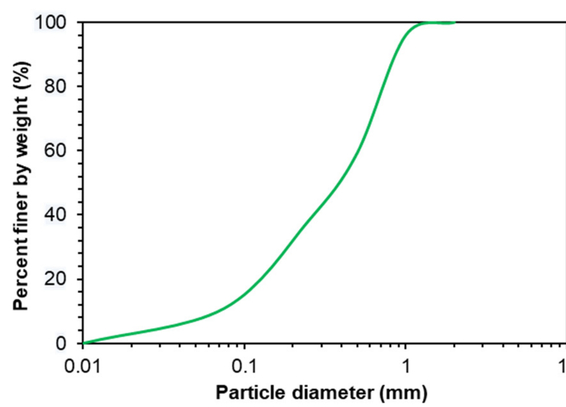


Fig. 2. Grain distribution of the tested expansive soil.

Table 2
Chemical properties of the added Portland cement.

Chemical composition	Content (%)
SiO_2	29.36
Al_2O_3	10.52
Fe_2O_3	3.48
CaO	44.22
MgO	3.17
SO_3	4.26
K_2O	0.96
Na_2O	0.37
L.O.I.	3.16

freezing–thawing. Cracking behaviour and mechanical degradation of expansive soils due to freeze–thaw weathering has been paid academic and practical attention (Lu et al., 2016, 2019). In recent years, with the accelerate project construction on additive-treated expansive soil foundations in cold or seasonally frozen regions, some researchers have used modification additives to treat expensive soils subjected freeze–thaw cycles. For instance, Jafari and Esna-ashari (2012) conducted several unconfined compression tests to study the effects of stabilization by lime and reinforcing with waste tire cord on freeze–thaw subjected kaolinite. Olgun (2013) used the response surface methodology method to examine changes in the properties of an expansive clay soil, which was stabilized by lime, rice husk ash and fiber additives and subjected to F–T cycles. Hotineanu et al. (2015) explored the influence of lime content and curing time on swelling pressure and frost heaving resistance of two expansive soils with bentonite and kaolinite. However, for cement–treated expansive soils, despite some attempts have been

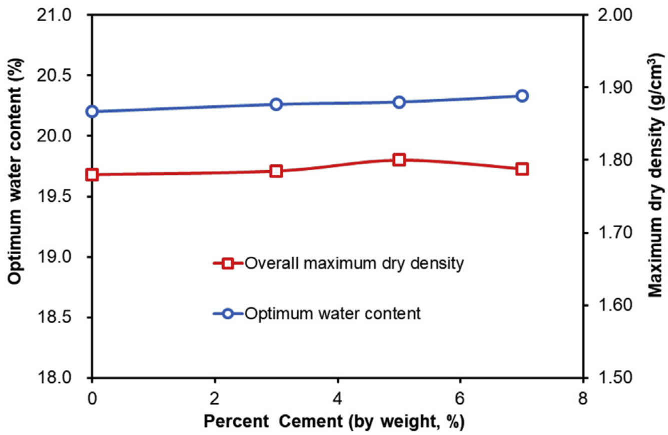


Fig. 3. Changes of maximum dry density and optimum water content with cement contents.

made on the effects of wet–dry cycles (Por et al., 2017; Chittoori et al., 2017), the effect of freezing–thawing on mechanical degradation is still unclear and little attempts have been performed on this topic. In view of frequent extreme weather events and global climate change, the action of cyclic freezing–thawing has been faced with occurrence as common as the wetting–drying events. Further knowledge as well as urgent attention is required to the potentially detrimental effects of F–T cycles on earthworks built on cement–treated expansive soils.

In this study, an expansive clayey soil taken from the middle route of SNWTP was firstly stabilized by use of cement. Then, a series of laboratory repeated freezing–thawing tests were performed on the cement–modified soils. Thus, water loss, deformation and strength performances upon cement contents and F–T cycles were evaluated and discussed.

2. Materials

2.1. Expansive soil

In this study, we extracted the sample of expansive clayey soils from a cutting canal slope on the middle route of SNWTP in the vicinity of Nanyang City, Henan Province in China (*see* Fig. 1). The sample site is situated in seasonally frozen regions where the expansive soil canal could endure freeze-thaw weathering action. The main physical indexes and mineral components of the tested expansive soil are listed in Table 1. The physical properties testing were conducted following procedures described by the Chinese standard for soil test method (GB/T 50123-1999, 1999). The mineral components were measured using an X–ray diffractometer, and then a quantitative analysis was performed via the K–value method (Chung, 1974). It can be found that the three main mineral components of the tested soils are montmorillonite, quartz and illite.

2.2. Additives

The middle route of SNWTP delivers water from water–sufficient southern China to water–deficient northern China to alleviate the water shortage in northern China (Li et al., 2016). Due to the high demand for water quality, it is not appropriate to adopt the improvement method that has a negative impact on the water quality. In practical construction, cement modification method was used to treat the expansive soil canal slope rather than lime additives. In this study, a commercial Chinese ordinary Portland cement (Grade 32.5, Hailuo Industry Co., Ltd) according to the Chinese standard GB 175–2007 (SAC, 2007) was used and the main chemical properties of the additive are listed in Table 2.

3. Experimental program

3.1. Sample preparation

The unprocessed expansive soils were air–dried and then crushed and sieved through a 2 mm sieve. The soil grain size distribution is shown in Fig. 2. Besides, according to the results obtained from the standard Proctor compaction test (ASTM D698-12e2, 2012), as shown in Fig. 3, it is obvious that the maximum dry density changes slightly with increasing cement content from 0% to 7%, and the optimum water content almost maintains a stable value of 20.20–20.33%. This is because the cement content is relatively small compared with the total amount of soil matrix. For the cement-modified expansive soil samples, considering the quick hydration of cement, the sieved soil was firstly prepared at the target water content and then sealed in plastic bags for approximately 24 h to ensure the soil moisture as uniform as possible (Sreedeep et al., 2017; Han et al., 2018). Next, the wetted expansive soil was mixed with cement thoroughly at three different cement contents (i.e. 3%, 5% and 7% by weight of soil) using spatulas. Thereafter, by using a modified device patented by Hohai University (Lu et al., 2017), the cement–treated soil mixtures were compacted layer by layer. All the samples were compacted at the same water content of 20.2% and dry density of 1.60 g/cm^3 (about 90% degree of compaction), respectively, reaching a dimension of 61.8 mm in diameter and 125 mm in height. It should be noted that the time for compacting samples should not exceed the initial setting time of Portland cement. After compaction, the soil samples were removed from the mold and wrapped with plastic wrap for a curing time of 28 days. This is because many studies have reported that the reaction degree basically reaches a stable state after 28 days of curing (Kim et al., 1998; Parreira et al., 2003; Skibsted and Snellings, 2019).

3.2. Freezing-thawing tests

After the completion of molding the cement–treated expansive soil samples, the freezing–thawing tests were then conducted in a closed system in the cryogenic laboratory at Hohai University (*see* Fig. 4).

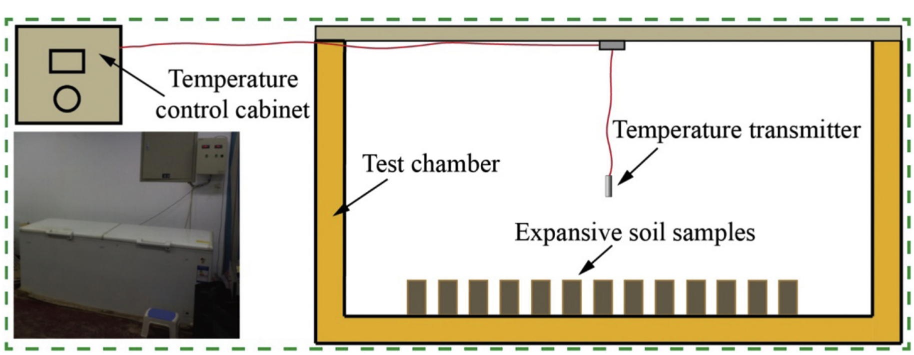


Fig. 4. Set–up for laboratory freezing–thawing tests.

Table 3
Experimental conditions of freezing–thawing tests.

Test group no.	Cement content (%)	Remarks
1	0	Each Test group has 13 samples, Four of which were used for volume measurement, eight for unconfined strength test, and one for standby. 52 samples were prepared in total.
2	3	
3	5	
4	7	

Before testing, the samples were coated with plastic wrap to avoid the atmosphere interaction during F-T cycles. During one freeze–thaw cycle, the soil sample was firstly frozen at a temperature of −20 °C for 12 h and then thawed at the room temperature (about 20 °C) for another 12 h. Considering most soil will show a stable tendency in deformation and strength characteristics after adequate F–T cycles (Ghazavi and Roustaie, 2010), the F-T tests in this study continued up to 12 cycles. At the end of each F–T cycle, the samples were weighed via an electronic balance with a precision of 0.1 g. Thus, the changes of water content for each sample could be determined. The experimental conditions of each F–T test group are listed in Table 3.

3.3. Volume change measurement and unconfined compression tests

To monitor the volume changes of soil samples subjected to F–T cycles, the dimensions (height, H and diameter, D) of four preordained samples (*see* Table 3) after each freeze–thaw period were measured using an electronic vernier calliper with a precision of 0.01 mm. It is noted in Fig. 5 (a) that the measured values of H and D were derived from two values in longitudinal section and five values in cross section, respectively. Accordingly, the average volumes of samples can be calculated based on the above measured dimensions upon each F–T cycle.

Unconfined compression test was conducted by a universal unconfined compression loading device, as shown in Fig. 5 (b). The machine is able to measure accurately a huge number of data for depicting the relationships between axial load and axial displacement. The compression loading was adopted at a strain rate of 1%/min (1.25 mm/min) and continued to an axial strain of approximately 25% in order to acquire the complete stress–strain curves. Therefore, the stress–strain response, unconfined compression strength (UCS), resilient modulus as well as strain at failure could be determined. Fig. 6 shows the typical photos of the samples with cement content of 0%, 3%, 5% and 7% before and after the experiment.

4. Results and discussion

4.1. Effect of F-T cycles on water loss and volume change

Freeze–thaw cycle is a multi–physical process during which thermal gradient causes the movement of pore water in the direction of lower temperatures under uniform pressure fields (Konrad, 1989). Although the samples are coated with plastic wrap, as described previously, to prevent exposed directly to the atmosphere during F–T cycles, water loss is still inevitable as shown in Fig. 7 (a). Consider now in the horizontal axis, 0 refers to the initial unfrozen state, 0.5 refers to 1st freezing time and 1 is the ending of 1st thawing, and so on. It is apparent that with increasing F–T cycles, the water loss increases gradually, that is, the water content of soil samples all decreases gradually. It is well acknowledged that water loss is mainly owing to two multi–-physical processes: liquid moisture evaporation and solid ice sublimation (Jong and Kachanoski, 1988). Actually, the phenomenon of water evaporation takes place throughout the whole process of freezing–thawing, but ice sublimation only occurs upon the freezing period. This finding has also been verified by the authors in a cracking experiment of expansive soil layers (Lu et al., 2016). It is also found that during each freezing period, the water loss presents a significant increase, however, it exhibits a sudden decrease in moisture loss upon thawing. This is because the inside water will migrate outside under the action of cryogenic suction induced by thermal gradient, and further form ice crystals attached on the sample surface (Thomas et al., 2009). When thawed, the surface ice gradually becomes liquid, but only part of the surface water will be sucked back into samples under an opposite temperature gradient. Furthermore, it is observed that water loss will be reduced remarkably when the samples were treated with cement. The higher the cement content is, the less the water loss could be. It is thus concluded that cement–treated expansive soil is a moisture insensitive material compared with the pure expansive soil. Meanwhile, it is interesting to find that water loss has a sharp increase after 4 F-T cycles for the cemented clay samples. This might be because the hydration products of cement will coat the samples surface (Sujata and Jennings, 1992), retarding the process of water evaporation and ice sublimation. However, with the increasing numbers of freeze-thaw cycles, the coated protective cover would be gradually broken, leading to a significant increase in the rate of water loss.

Volume change (expansion or shrinkage) is usually accompanied in expansive soils subjected to F–T cycles, which is a coupled thermo-hydro-mechanical process and might be attributed to many factors,

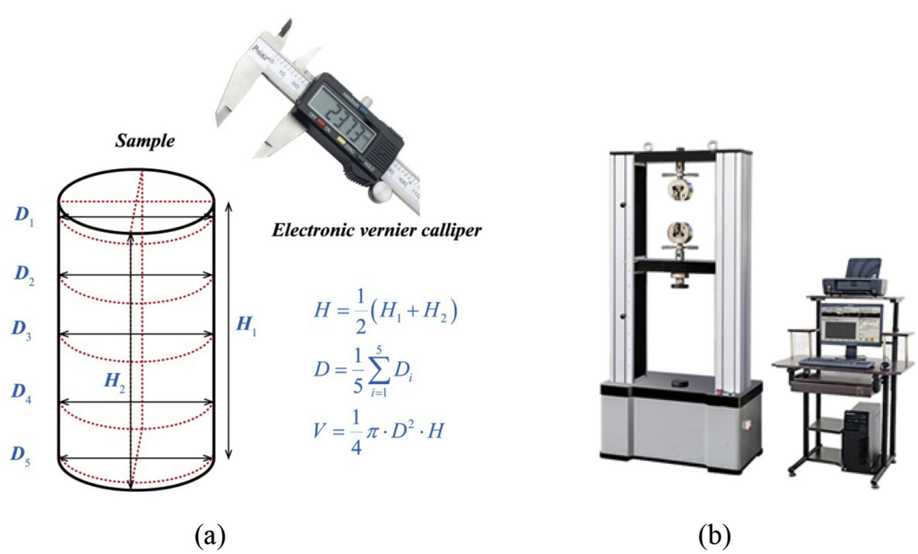
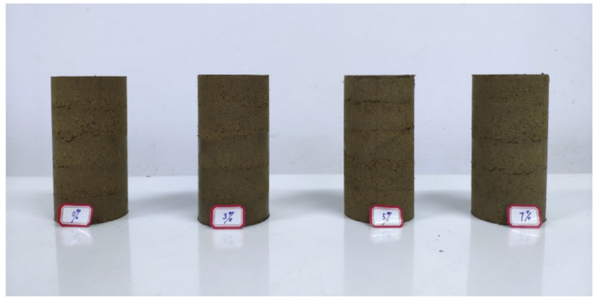
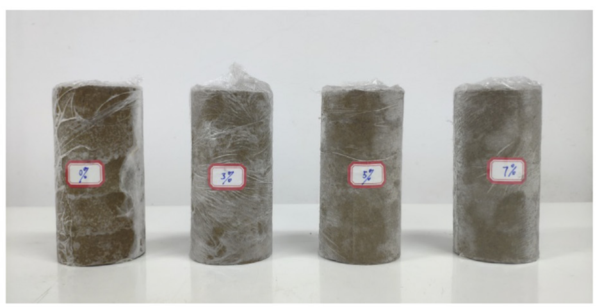


Fig. 5. (a) Schematic diagram of volume change measurement, and (b) testing equipment for unconfined compression.



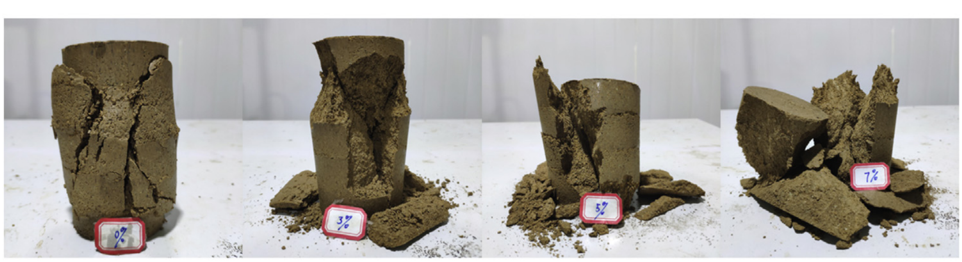
(a) After molding

(b) Under curing



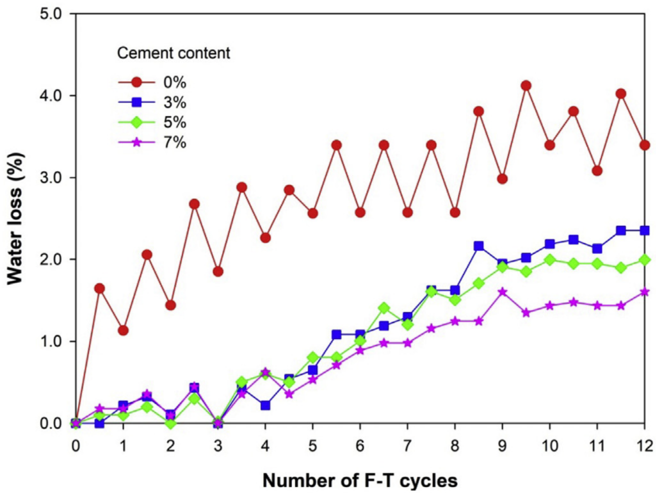
(c) After one time of freezing

(d) After one freeze-thaw cycle

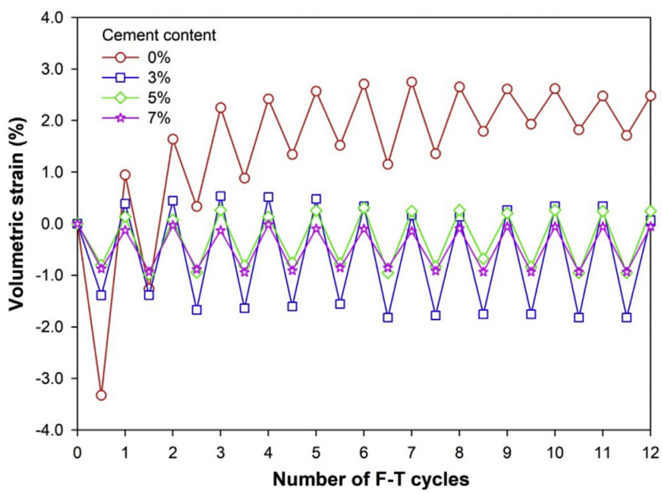


(e) After the unconfined compression test

Fig. 6. Typical photos of the samples (cement content = 0%, 3%, 5% and 7%) before and after the experiment.



(a)



(b)

Fig. 7. (a) Water loss and (b) volume change versus the number of F–T cycles.

such as ice-water phase change, water loss, freezing temperatures and initial molding saturation (Lu et al., 2019). As aforementioned in Chapter 3.3, the changes of *D* and *H* were measured after each F–T cycle to estimate the average volume changes. Herein, a dimensionless volumetric strain, ε_v is defined to describe such volume change, as.

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

where V_0 is the initial volumes of unfrozen samples; V_N is the volumes after *N* F–T cycles. The positive value of ε_v reflects expansion, while the negative one refers to contraction. Consider now in Fig. 7 (b) a plot of volumetric strains against number of F–T cycles. The whole volume decreases upon freezing but increases upon thawing. For the pure expansive soil (cement content = 0%), freezing will induce volume contraction of a maximum value of 3.45% after the 1st freezing period, and volume change tends to a stable expansion value of 2.6% after six F–T cycles. It indicated that the volume changes of pure expansive soil after several F–T cycles will present a tendency of expansion. Conversely, for the cement-treated expansive soil, the final volume after F–T cycles remains basically unchanged, although samples will exhibit volume contraction upon freezing and expansion upon thawing. Besides, the amplitude of volumetric strain of each F–T cycle also presents a lower value for the expansive soil samples stabilized by cement. It suggests that the volume of cement–modified expansive soil is less affected by freeze–thaw cycles. This is owing to the fact that the mixed cement will result in hydration reaction, and the hydration product will further react with expansive soil particles (Chai et al., 2017), leading to the reduction of swelling-shrinkage characteristics. It was also observed that the larger the cement content, the smaller the volume change. However, in this study, the effect of adding 5% additive on volume changes is almost the same as that of 7% additive. That is, the contribution of further increase of cement content (7%) to volume change mitigation was insignificant. Therefore, for practical application, adding appropriate amount of cement additives would be more efficient and economical than excessive additives.

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

As previously mentioned, unconfined strength tests were carried out on all samples subjected to different F–T cycles. For the purpose of comparing stress–strain responses at different F–T cycles, complete stress–strain curves of samples after 0, 1, 2, 3, 5, 7, 9, and 12 F–T cycles are plotted in Fig. 8. The pattern of stress–strain relationships all presents strain–softening characteristic. With the increase of F–T cycles, the stress–strain curve shapes for pure expansive soil seem to gradually become “shorter” and “fatter” (*see* Fig. 8(a)), while the shapes of cement–treated expansive soil gradually get “shorter” and “thinner” (*see* Figs. 8 (b), (c) and (d)). In particular, it can be seen that the initial slope of the stress–strain curve decreases sharply at 1st F–T cycle. It suggests that not only the pure expansive soil but also the cement–treated expansive soil is sensitive to freeze–thaw weathering and loses its strength and stiffness. Such degradation phenomenon is found to be the most pronounced at 1st F–T cycle. Moreover, it is also obvious that the cement content has significant influence on the overall shape of the tested stress–strain curves. In order to capture clearly the differences, the curves of samples with four cement contents under non-frozen and one F–T cycle are plotted in Fig. 9. It is apparent that the cemented expansive soil exhibits more brittle behavior and higher peak strength than the un–cemented one. In addition, it shows that the initial stiffness of soil appears to be evidently affected by the addition of cement and the cemented soil exhibits a marked stiffness and brittleness, which is also observed from the failure patterns of the samples with different cement contents (*see* Fig. 6 (e)). Its failure strain seems to be much smaller than that of the un–cemented soil. Undoubtedly, one of the main advantages of cement reinforcement when applied to soil is the improvement in material strength, but the drawback is the loss of ductility.

It is also interesting to observe that, for the pure expansive soil samples, the ductility reduces as *N* keeps increasing. However, for all the cemented clay samples, the stress-strain behavior is more ductile at $N = 1$ than at $N = 0$. The ductility then gradually reduces as *N* keeps increasing above 1. This seems that the behaviour of cemented clay after one F-T cycle is very similar to that of the pure expansive clay upon F-T cycles. It is easy to understand that the addition of cement will make the samples more brittle due to the formation of hydration products. The reason why the cemented clay becomes more ductile at $N = 1$ than at $N = 0$ is that the hydrate structure of cemented samples would be basically destroyed during the 1st cycle of F-T. In the following cycles of freeze-thaw action, the damaged cemented samples get more and more brittle due to the water loss upon F-T cycles. For the pure expansive soil samples, however, the samples will just become more and more brittle because of the continuous water loss upon F-T cycles.

4.3. Effect of F-T cycles on unconfined compression strength

The unconfined compression strength (UCS) can be estimated based on the peak values of the stress–strain curves (*see* Fig. 8). Fig. 10 (a) shows the changes of unconfined compression strength with cement contents and the number of F–T cycles in a three–dimensional coordinate space. It can be seen that the UCS increases significantly with

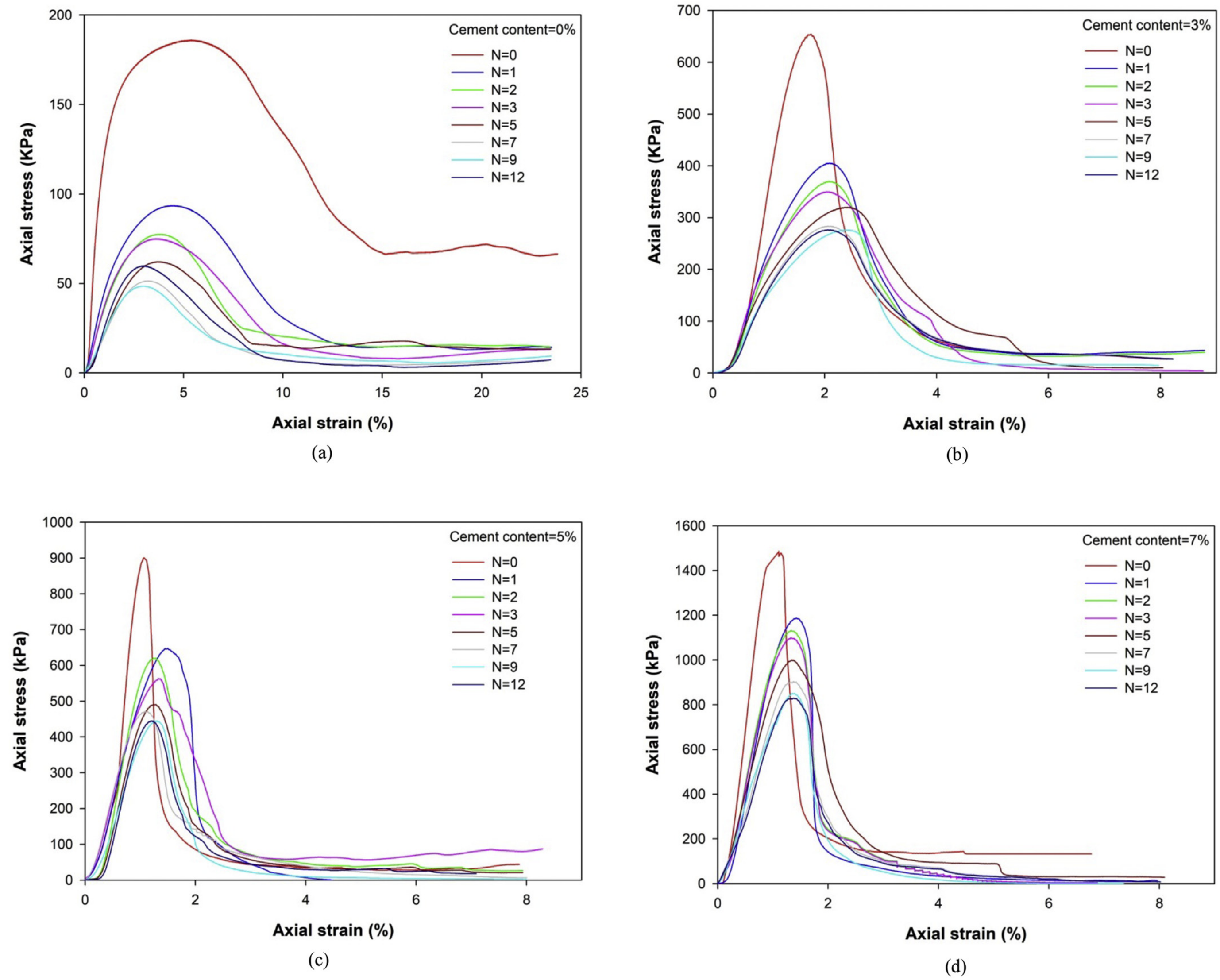


Fig. 8. Stress-strain relations for samples under different F–T cycles. (a) Cement content = 0%; (b) Cement content = 3%; (c) Cement content = 5%; (d) Cement content = 7%.

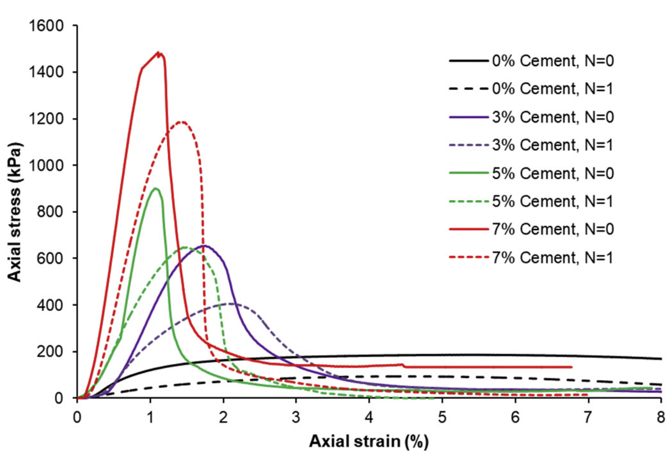


Fig. 9. Stress-strain relations for samples under different cement contents under non-frozen and one F–T cycle.

the increase of cement content, but decreases with increasing F–T cycles. This observation indicates that the addition of cement can highly improve the unconfined compression strength of pure expansive soil. This is attributed to the process that the hydration products of cement, such as $CaO{\cdot}2SiO_2{\cdot}3H_2O$ (C–S–H) and $CaO{\cdot}Al_2O_3{\cdot}3H_2O$ (C–A–H), will not only fill the soil pores but also be distributed surrounding soil particles to form a relatively stable spatial network structure. This effect will lead to a great increase in strength and stiffness (Peethamparan et al., 2009). However, freezing–thawing action will weaken such effect of filling and bonding. On another hand, it is found in Fig. 7 (b) that freezing will induce volume shrinkage (ε_v is negative), while thawing causes volume expansion (ε_v is positive). That is to say, the sample volume always expands at the end of each freeze-thaw cycle. Thus, the sample density will decrease upon F-T cycles. Accordingly, these effects will together cause a sustained reduction in strength. In order to quantify the magnitude of such F–T weakening effects on degradation of UCS, the UCSs were normalized considering the maximum UCS at each cement content (i.e. test point *a*, *b*, *c*, and *d*), as shown in Fig. 10 (b). Herein, the normalized UCS ($\bar{q}_u$) is defined as

$$\bar{q}_u^i = q_u^i / q_u^{\max},\ i = 0, 1, 2, 3, 5, 7, 9, 12 \tag{2}$$

where i is the number of F–T cycles, q_u^i the UCS after i F–T cycle and $q_u^{\max}$ the maximum UCS at the unfrozen state. It is observed that the normalized UCSs decrease upon F-T cycles, depending on the cement contents. All the three curves present a maximum decrease at the first F-

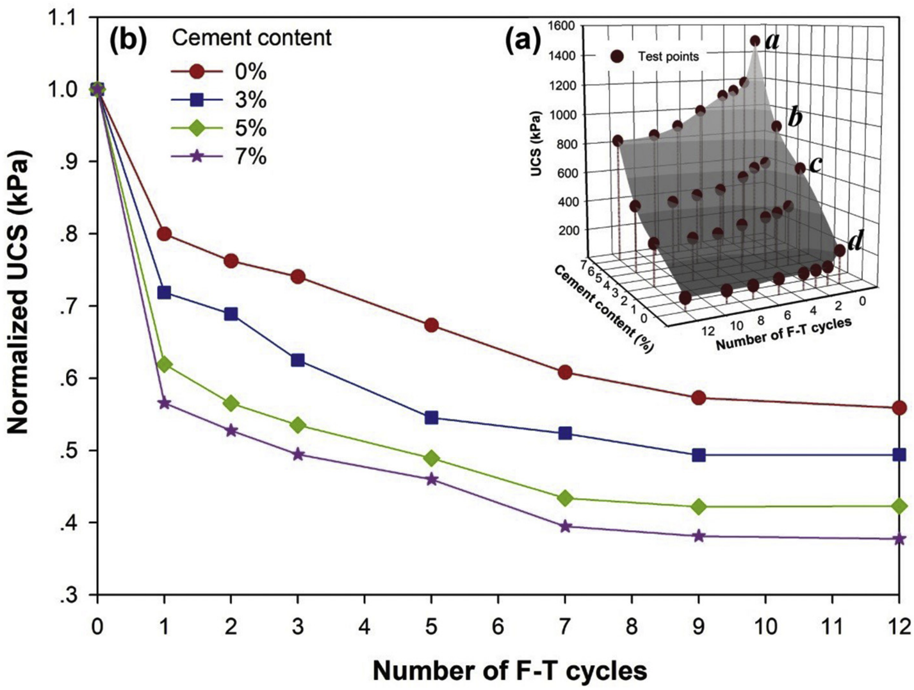


Fig. 10. (a) Changes of UCS with cement content and the number of F–T cycles in a three–dimensional coordinate space; (b) Changes of normalized UCS with F–T cycles.

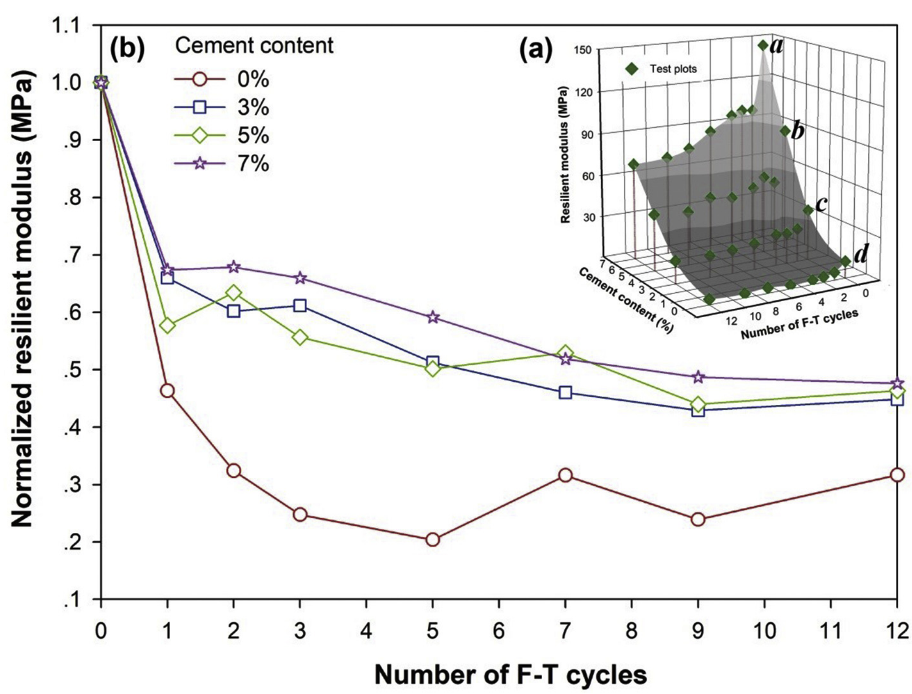


Fig. 11. (a) Changes of M_R with cement content and the number of F–T cycles in a three–dimensional coordinate space; (b) Changes of normalized M_R with F–T cycles.

T cycle, and the highest decreasing rate is measured at 7% cement content. On the contrary, the residual normalized UCS increases with the decreasing of cement content. It is indicated that cement additive, despite of increasing the curing UCS, might aggravate the deterioration of strength upon F-T weathering.

4.4. Effect of F-T cycles on resilient modulus

Resilient modulus (M_R) is a important material property for quantitatively characterizing the stiffness of material. Herein, it is estimated from the stress at 1% axial strain, which is a good indicator of the resilient modulus (Lee et al., 1995; Lu et al., 2019). Fig. 11 (a) gives the changes of resilient modulus (M_R) with cement contents and the number of F–T cycles in a three-dimensional coordinate space. It is apparent that the cement will sharply increase the resilient modulus of expansive soil. This indicates a great cementation effect occurred between soil particles, resulting from the hydrate product of cement. Nevertheless, the resilient modulus shows a pronounced decrease upon

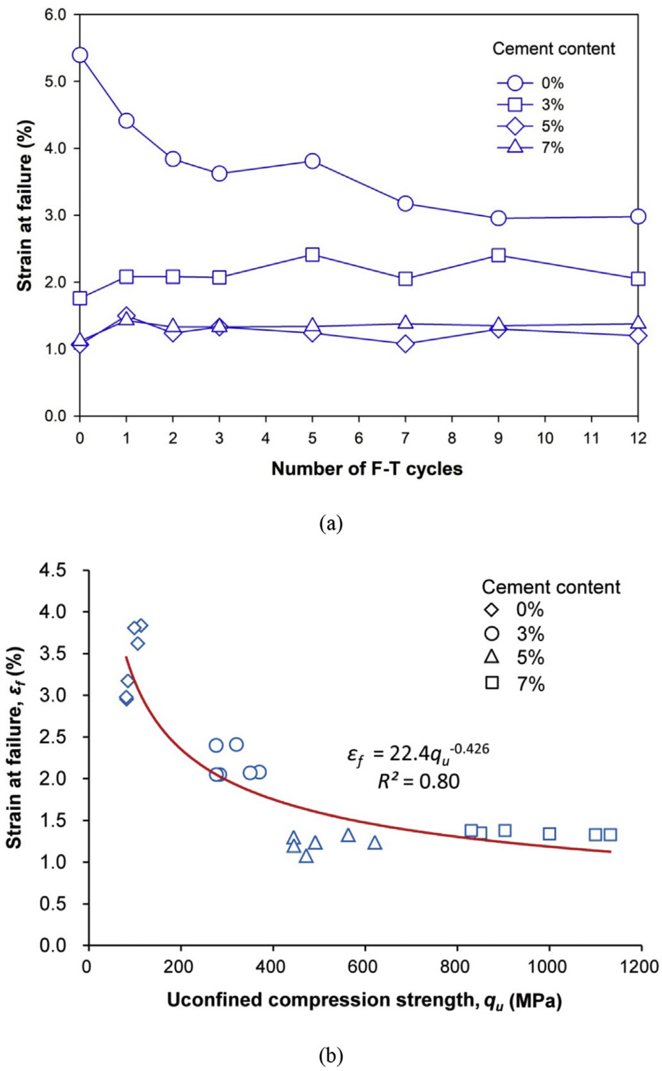


Fig. 12. Changes of strain at failure (ε_f) with (a) the number of F-T cycles and (b) unconfined compression strength (q_u).

F–T cycles duo to degradation induced by freeze–thaw weathering. Further, in order to quantify the magnitude of such F–T weakening effects, the M_R was also normalized considering the maximum resilient modulus at each cement content (i.e. test point *a*, *b*, *c*, and *d*), as shown in Fig. 11 (b). It is found that the normalized resilient modulus ($\overline{M_R}$) decreased with F–T cycles, and the expansive soil sample with a higher cement content has a lower decreasing trend. It suggests that the cement can retard the degradation of resilient modulus against F–T weathering.

4.5. Effect of F-T cycles on strain at failure

For the stress–strain relations with strain–softening patterns, the failure state can be regard as the peak strength state. The axial strain at peak strength can thus be defined as "strain at failure". Strain at failure (ε_f) is an important index to reflect the ductile or brittle characteristics of soil. The larger the failure strain is, the better the ductility of soil will be. That is, the smaller the failure strain is, the greater the brittleness will be (Tang et al., 2007; Du et al., 2013). Consider in Fig. 12 (a) a plot of strain at failure in terms of F-T cycles for different cement contents. For the pure expansive soil, strains at failure decreases with increasing numbers of freeze–thaw until reaching a stable value. For the cement–treated expansive soil, however, the strains at failure are mainly affected by the 1st F–T cycle, and almost maintain stable values with increasing F–T cycles. Interestingly, with increasing cement contents, the strain at failure becomes smaller. Besides, the effect of adding 5% additive on brittleness is almost the same as that of 7% additive. Considering the UCS, stiffness performances, as aforementioned, together with cost–benefit advantages, the effective content of cement stabilizer was thus found as 5% in this study.

Fig. 12 (b) presents the relations between unconfined compressive strength, UCS (q_u) and strain at failure (ε_f) of expansive soils with cement content of 0%, 3%, 5% and 7%. It can be seen that ε_f decreases with the increase of q_u. Based on a regression analysis by the Least–Squares–Fitting method, the relationship between ε_f and q_u can be well expressed using a power function as:

$$\varepsilon_f = 22.4\, q_u^{-0.426} \quad (3)$$

The fair correlation coefficient, R, ($R^2 = 0.80$) indicates that the proposed power function might be a potentially useful engineering tool to present the relation between ε_f and q_u of the cement–treated expansive soil. Such unique relationship could be attributed to the similar influence of increasing F–T cycles and cement contents on strain at failure and unconfined compression strength of the tested expansive soils. Similarly, this phenomenon is also observed in cement–treated zinc–contaminated clay and sedimentary clay, as reported by CDIT (2002) and Du et al. (2013), which show that the $\varepsilon_f - q_u$ relationship is not sensitive to the zinc concentration, cement content or curing time. It suggests that, for cement–treated expansive soil, there exists a unique power relation between ε_f and q_u, independent of F–T cycles and cement contents.

5. Conclusions and summary

This study experimentally investigates the effect of cement addition to expansive soil on its deformation and strength behaviours under freeze–thaw cycles. Water loss, volume change, stress–strain response, unconfined compression strength, resilient modulus and strain at failure were evaluated. Based on the findings, the following conclusions can be obtained:

1) The tested expansive clayey soil is a kind of moisture sensitive soil. In seasonally frozen regions, the swelling–shrinkage behaviour triggered by freezing–thawing is also very significant. Cement additive makes expansive soil become less sensitive to moisture and the accompanied hydration reaction will reduce swelling–shrinkage characteristics of expansive soil. The larger the cement content is, the smaller the volume change becomes. In this study, the effect of adding 5% additive on volume changes is almost the same as that of 7% additive.
2) The pattern of stress–strain curves of cemented–treated expansive soil under F–T cycles all presents strain softening. With increasing F–T cycles, the shapes of stress–strain curves for pure expansive soil gradually become "shorter" and "fatter", while the shapes of cement–treated expansive soil are gradually "shorter" and "thinner". Addition of cement makes expansive soil exhibit higher peak strength and stiffness.
3) UCS of expansive soils increases significantly with the increase of cement content, but decreases with increasing F–T cycles. Freezing–thawing action will weaken the effect of cement hydration products on filling in soil pores and bonding soil particles, which occurs more notably in expansive soils treated with higher cement content. It is indicated that cement treatment might aggravate the deterioration of strength despite of increasing the curing UCS.
4) Cement will contribute to increasing the resilient modulus of expansive soil. But it will be degraded by cyclic freeze–thaw weathering. Expansive soil samples with higher cement contents have a lower decreasing trend of resilient modulus. It suggests that the cement can retard the degradation of resilient modulus against F–T

weathering.

5) With increasing cement contents, the strain at failure becomes smaller. Increasing cement content will increase soil brittleness. In terms of increasing F–T cycles, the un-cemented expansive soil will become more brittle, while the cement–treated soils present more ductile at 1^{st} F-T cycle. Besides, a power function, independent of F–T cycles and cement contents, exists between the strain at failure and unconfined compression strength.
6) Engineering implication: It is promising to employ cement additive against freeze–thaw resistance of expansive soils. Considering the UCS, stiffness performances and brittleness together with cost–benefit advantages, the effective content of cement stabilizer was found as 5% in this experimental study.

Declaration of Competing Interest

None.

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