Laboratory investigation of mechanical behaviour of cement-treated Edmonton clay subjected to freeze/thaw cycles

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ABSTRACT
Since the 1930s, cement has been used as a binder to enhance the mechanical properties of soft soils, and research on mixtures of cement and soft soils has been documented for many kinds of earthwork. However, the literature is limited to clays with high moisture content, low binder contents, ambient conditions, and short-term stability. The present research investigates the development of strength in soils cemented with a high content of cement (i.e. soilcrete) served as a deep mixing foundation for heavy load and subjected to severe weather conditions in the long-term point of view. The soil is Edmonton clay with low plasticity and 21.8% moisture content. As the seasonal temperature change is vast, it is critical to inspect the mechanical properties of the soilcrete subjected to freeze/thaw (F/T) cycles in the cold regions. A temperature control system was built to conduct the F/T cycles with cylinder samples. To simulate the heat transform in situ, dry sand was selected as the medium to transfer the heat instead of the commonly-used air. Unconfined compressive strength (UCS) tests were carried out at different curing ages, after exposure to different F/T cycles, and under various freezing temperatures. Changes in the strength, the weight of specimens, stress-train behaviour, and the modulus were monitored after exposure to different F/T cycles with different temperatures. Results show that the strength increases with the curing age and decreases with the F/T cycles. The weight loss of the specimen gradually increased with the F/T cycles. The soilcrete behaves similarly to an overconsolidated clay and reaches peak strength at strains lower than 3%.

RÉSUMÉ
Depuis les années 1930, le ciment a été utilisé comme liant pour améliorer les propriétés mécaniques des sols mous, et la recherche sur les mélanges de ciment et de sols mous a été documentée pour de nombreux types de terrassements. Cependant, la littérature se limite aux argiles à forte teneur en eau, à faible teneur en liant, aux conditions ambiantes et à la stabilité à court terme. La présente recherche étudie le développement de la résistance dans les sols cimentés avec une teneur élevée en ciment (c'est-à-dire du béton de sol) servant de fondation de mélange en profondeur pour des charges lourdes et soumis à des conditions météorologiques sévères à long terme. Le sol est de l'argile d'Edmonton avec une faible plasticité et une teneur en eau de 21,8%. Comme le changement de température saisonnier est considérable, il est essentiel d'inspecter les propriétés mécaniques du béton du sol soumis à des cycles de gel / dégel (F / T) dans les régions froides. Un système de contrôle de la température a été construit pour effectuer les cycles F / T avec des échantillons de cylindres. Pour simuler la transformation de la chaleur in situ, le sable sec a été choisi comme milieu pour transférer la chaleur au lieu de l'air couramment utilisé. Des tests de résistance à la compression non confinée (UCS) ont été effectués à différents âges de durcissement, après exposition à différents cycles F / T et sous différentes températures de congélation. Les changements dans la résistance, le poids des spécimens, le comportement du train de contraintes et le module ont été surveillés après exposition à différents cycles F / T avec différentes températures. Les résultats montrent que la résistance augmente avec l'âge de durcissement et diminue avec les cycles F / T. La perte de poids de l'échantillon a progressivement augmenté avec les cycles F / T. Le béton du sol se comporte de manière similaire à une argile surconsolidée et atteint une résistance maximale à des déformations inférieures à 3%.

1 INTRODUCTION

Edmonton clay is the glaciolacustrine deposit of Great Edmonton Lake that existed after the last glacial period in Holocene (Godfrey 1993), which is an interlayered combination of cohesive soils with silt or sand. Despite the soil's high strength, it was still insufficient to support the heavy load caused by some superstructures such as oil storage tanks to be built in eastern Edmonton. To ensure the bearing capacities and limit the settlement of the foundations supporting oil storage tanks, deep mixing (DM) with cement was adopted. DM is a common method to modify soils so that the soft or problematic natural soil would gain sufficient improvement both in strength and modulus. Cement has been used as a cementitious material to enhance the mechanical properties of soft soils since the 1930s. After that, many researchers have studied the physical, chemical, and mechanical behaviors of the treated soil with cementitious materials, such as cement, lime, fly ash, and so on (Pakbaz and Alipour 2012; Eskisar 2015; Luis and Deng 2018).

However, most of the studies targeted the factors that influence the behaviour of the treated soil in moderate temperatures. With the rapid municipal expansion and industrial facilities construction in the cold regions, the need for soil improvement increased rapidly. However, studies on the impact of cold weather on the treated soil by DM method is limited. Several studies investigated the changes in mechanical and physical behavior after various cycles of freezing/thawing (F/T) in the context of road construction or contaminant containment (Jamshidi and Lake 2015). As the temperature of different zones ranged from as low as -40 °C to marginal subzero, it is important to study the impact of different freezing temperatures on the modified soil, particularly when the modified soils are anticipated to be subjected to a significant bearing load from the superstructure.

In the past research where F/T cycles to cemented soils were executed, researchers selected air as the medium to conduct the F/T process as it was relatively easy to handle (Jamshidi and Lake 2015). But, the thermal conductivity at room temperature of unfrozen dry sandy soil (about 0.2 W/mK) was much higher than air (0.026 W/mK). In this paper, coarse sand (0.25 W/mK) was used as the medium to transfer the heat during the F/T cycles to accelerate the process. This temperature control system would be more like the in situ freezing process.

In this paper, Edmonton clay was mixed with cement in the laboratory to simulate the in situ DM construction. Cylindrical molds with a diameter of 75 mm and a height of 150 mm were chosen to make specimens after mixing. Then the specimens were conducted to the consequential tests after exposure to several F/T cycles under different freezing temperatures. Jamshidi (2016) found that the variation between 3D and 1D freezing was insignificant, so it was reliable to adopt the 3D freezing. Thus 3D freezing using coarse sand around specimens were chosen to implement the F/T cycles. After each cycle, damage to specimens was quantified by measuring the mass lass. Specimens subjected to F/T cycles were under the uniaxial compression tests. The stress-strain behaviour was captured and the failure pattern was also illustrated.

2 MATERIALS AND METHODS

2.1 Soil Properties

The oil storage tanks located in eastern Edmonton were supported by deep mixing columns that combined the local soil with cement. The columns were about 20 m deep. The natural soil was obtained from a layer of 5 to 9 m deep, which is mostly glaciolacustrine deposit. Luis and Deng (2018) characterized the natural soil and Table 1 showed the results.

Table 1. Natural soil characteristics

Property	Value
Sand	33%
Silt	43%
Clay	24%
USCS classification	Sandy CL
Liquid limit	40.9%
Plastic limit	12.5%
Plasticity index	28.4%
Undisturbed soil strength	63-72 kPa (vane shear), 50 kPa (UCS)
Specific gravity	2.54

The composition of natural soil was determined by XRF and the mineral components by XRD. To make sure the soil stable after being kept in the moist room for more than 2 years, the reserved soil was tested by XRD and XRF again. The results implied that the difference in chemical composition between the old soil and the fresh soil was very marginal so that the soil kept in the moist room was good to conduct the subsequent processes.

2.2 Cement Properties

The binder used in this research was normal Portland cement, i.e. GU1. The composition of the cement from the manufacture was shown in the before-mentioned paper (Luis and Deng 2018) as well as results by XRF.

2.3 Sample Preparation

In this research, the samples were made by the laboratory mixing method and the parameters were shown in Table 2. All samples would be named by C representing cement. The number after C indicated the cement content, such as C1 represented a sample with a cement content of 175 kg/m^3 (175 kg cement per 1 m^3 soil) or 17.2% (ratio of the mass of cement to that of dry soil).

Table 2. Parameters of different samples

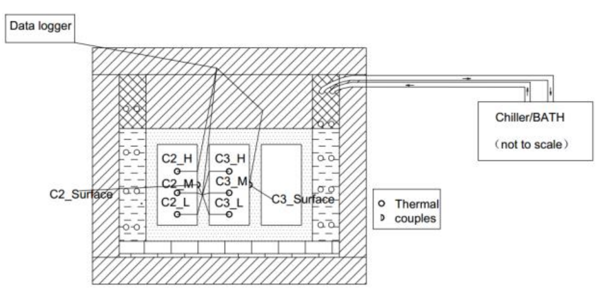
Property	C1	C2	C3
W_c [%]	55.57	53.84	52.14
C_c [%]	17.50	22.39	27.47
W_c/C_c	3.18	2.40	1.90
Binder content [kg/m^3]	175	225	275

Note: W_c = water content; C_c = cement content.

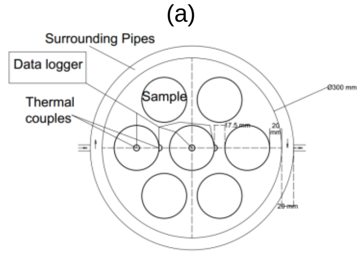
The cement and tap water were mixed by an electrical mixer (Waring Commercial WSB60) to get the slurry. The natural soil was crushed into small lumps by hand and poured into the big container. The slurry was sprinkled to the lumped soil. After about 5 min, the slurry and natural soil were mixed with a dough mixer (Hobart Legacy HL200 18.9 L volume) by a dough blender hook for 2 minutes. Then the paste was filled into the plastic mold layer by layer. The bottom of each mold was drilled a small hole for extruding. Before filling, the hole was sealed by waterproof tape. For each layer of filling, the mold was tapped against the hard surface of the test bench to remove the trapped air. After three layers of filling, the surface of the completed sample was leveled. The samples were covered with plastic film and sealed by the lid. Then they were stored in a rubber container filled with about 20 cm tap water. The container was covered by a plastic lid to keep the moisture. The samples were kept in room temperature (20 ± 1°C) and left to cure for the required period ranging from 14 to 300 days.

2.4 Freezing and Thawing Method

To simulate seasonal weather in Edmonton, a temperature control system was designed. A steel cell circulated by spiral pipes was used as the main container, and a temperature Bath/Chiller was connected to the cell by two cyclic pipes. The glycol was used to circulate the heat between the cell and the Bath/Chiller (Figures 1 to 2). Sand has a higher thermal conductivity and it is more like the in situ natural soil that enclosed the DM columns. Thus coarse sand was chosen to encircle the soilcrete samples and to freeze them in three dimensions. If the wet freezing is needed in the future, coarse sand is easy to manipulate. To investigate the efficiency of the F/T process, two samples (Figure 2) were mounted with thermal couples to record the temperature change during the F/T cycle.



(a)



(b)

Figure 1. A temperature control system with instrumented dummy samples: (a) cross-section view, and (b) plan view of the freezing cylinder

The system located in a cold room that has a constant temperature of about -2 °C. There were 7 samples in the container spread uniformly to make the symmetric transition heat flows (Figure 1-b). In this research, -10, -6, and -2 °C were used to freeze the samples. After 24 h of freezing, the Bath/Chiller was set to 20 °C to warm the sample for another 24 h, which makes a full cycle of F/T.

Figure 2. Temperature control system and instrumented dummy sample in a mold

2.5 Mass Loss

Before the F/T process, the weight of each sample was measured. After each F/T cycle, the sample was taken out of the cell and the loose particles on the surface were removed by a brush. Then the weight of the sample was measured again. The decrease in the weight of a specimen after F/T cycles was defined as the mass loss.

2.6 Unconfined compressive strength (UCS) tests

The cylindrical samples were taken out of the mold through pressurized air injected to the bottom hole. Before the uniaxial test, the specimen was capped on both ends by gypsum (ASTM 2015) to get even surfaces for loading. The uniaxial test was conducted on two duplicated specimens at a strain rate of 0.5 mm/min. The timely load and displacement were recorded until failure or 10% strain. The shear plane and failure pattern of each specimen were observed.

3 RESULTS AND DISCUSSION

3.1 Freezing and Thawing

One F/T cycle was conducted on the dummy samples to get the temperature change diagram.

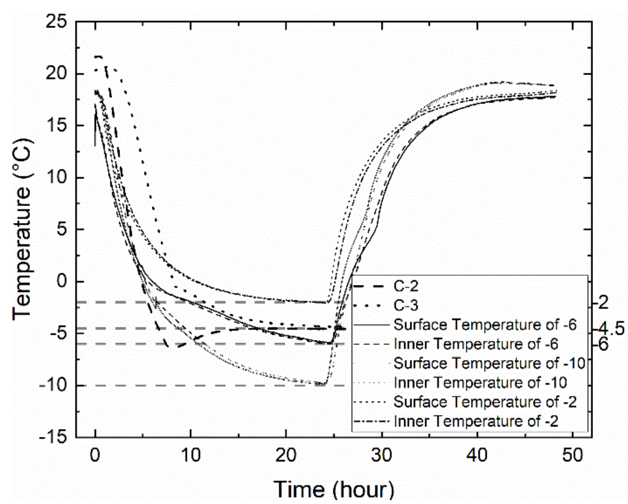


Figure 3. Temperature changes of the samples in the F/T cycles under various freezing conditions

The thermal-couples instrumented in dummy samples showed that the target temperatures, i.e. -2, -6, and -10 °C, were gained by setting the Bath/Chiller to -4, -10, and -15 °C, respectively (Figure 3). The warming temperature of 20 °C made the samples about 18 °C at the end of the thawing process. C2 and C3 dummy samples were frozen by the same temperature of -9 °C. The result (Figure 3) indicated that the C2 sample would get the target temperature almost at the same rate as C3 though it approached a lower temperature first.

It was noticeably fast for the samples to get to zero degrees from room temperature. However, it took a longer time than the first stage for the sample to freeze to the target degree after it reached the negative temperature. For the thawing process, the temperature increased fast until it attained about 15 °C.

Soilcrete samples showed a similar temperature change curve for F/T cycles under differing freezing temperatures. The thermal couples attached to the surface of the samples confronted the cold front firstly so the temperature of the surface would change a bit more quickly than the inner core. When the freezing process was completed, i.e. reaching the target temperature, the final state of the outer surface and inner samples would be the same. Though soilcrete had three cement contents, the temperature change curves shared a similar trend. So the cement content and the freezing temperature did not significantly impact the thermal conductivity of the soilcrete.

3.2 Mass Loss

Currently, some industry method of percent mass loss was assumed as a possible indicator to estimate the resistance of cement-treated soils subjected to F/T cycles (Jamshidi and Lake 2015). It was difficult to build samples that have the same weight as the mixing was not ideally uniform. But the weight after curing ranged from 1206.8 to 1270.7 g, so the difference in weight of most samples was quite marginal (<5%) and could be neglected. Assume that all samples were in the same shape, so they had the same volume of 664.5 mm^3. The calculated density of the sample ranged from 1.82 to 1.91 g/cm^3.

The difference in weight caused by the hydration and cement content was small, but that caused by the F/T processes could not be ignored. To make the data comparable, the normalized mass loss (Δm) was defined as follows:

$$\Delta \mathrm{m} = \frac{m_0 - m_n}{m_0} \times 100\% \qquad [1]$$

where m_0 is the mass of the sample before being exposed to any F/T cycles and m_n is the mass of the sample after n times of F/T cycles.

C2 samples were exposed to 1, 2, 4, 8 F/T cycles and the mass loss of each sample was recorded. The average loss of samples under the same exposure was calculated. As the samples were exposed to more F/T cycles, the loss of mass increased from 1.19% to 2.17% (Table 3). For the same dosage of cement but cured for a longer time, the samples had some resistance to lose weight during the F/T process. Table 3 shows a minor decrease in the mass loss as the curing time increased to 110 and 300 days.

Table 3. Mass loss due to F/T cycles

F/T cycles	C2-56D	C2-110D	C2-300D
1	1.19	0.56	0.33
2	1.26	N/A	0.37
4	1.61	N/A	N/A
8	2.17	N/A	N/A

The mass loss of soilcrete exposed to F/T cycles, which was close to the values found by Jamshidi and Lake (2015), was not very significant although noticeable. As the F/T cycles increased, the cracks caused by temperature change would penetrate the inner part of the samples which would cause more clusters to burst into small debris. Thus the surface particles of the specimen became loose and easy to remove. When the freezing temperature got lower, the penetration of the cold front moved fast into the sample so that the water was unable to escape but to freeze. This would make a bigger volume increase in the pores of the soilcrete sample and the cracks would evolve fast. It caused more loss of the surface particles as well. As the hydration continued, water in the sample reacted with cement and there was less water to make ice. The mass loss decreased as less volume change due to more curing time.

3.3 Unconfined compression strength (UCS) tests

3.3.1 Axial Stress-strain Behaviour

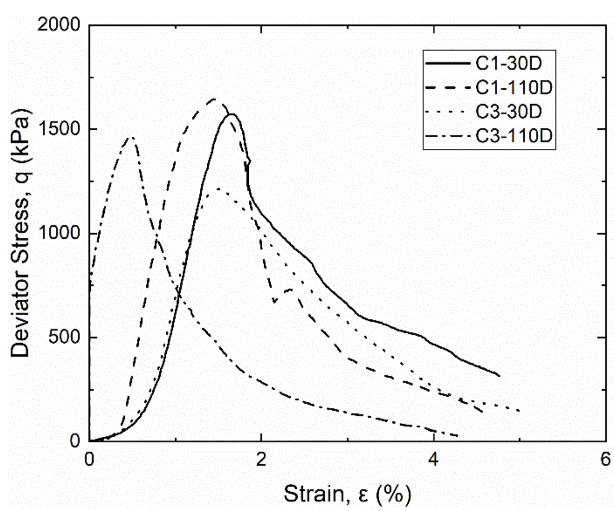


Figure 4. Typical axial deviator stress vs. axial strain curves for soilcrete at several curing ages

Figures 4 to 6 show some typical deviator stress (q) versus axial strain (ε) behaviour of soilcrete produced by various cement content with or without exposure to F/T cycles under differing curing age. Natural soil has a ductile behaviour (Luis and Deng 2018), while the soilcrete mostly showed strain-softening behaviour, which is similar to a heavily consolidated clay.

The peak strength increased with curing ages (from 14 days to 300 days) and decreased with the F/T cycles and cement content. Soilcrete samples had the maximum strength at the cement content of 17.50% (C1) in this study (Figures 4 to 5). The curves exhibited an obvious shifting of the axial strain at peak strength owing to that the soilcrete became more brittle with curing age and with cement content due to the changing degree of hydration. The post-peak curves varied markedly indicating that the residual strength (q_r, defined as the stress at the axial strain of 3.5%) scattered as the residual strength of the natural soil was deteriorated after being exposed to F/T cycles. It also showed that the residual strength of soilcrete without F/T cycles approached the residual strength of the natural soil which was inconsistent with Luis' findings (Luis and Deng 2018). The curves did not shift much under different freezing temperatures.

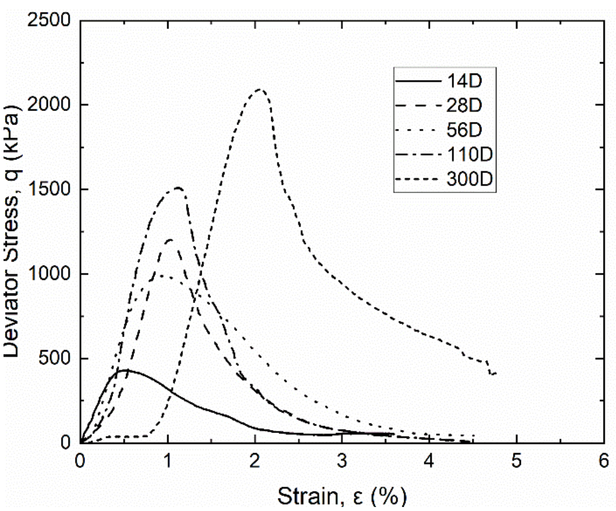


Figure 5. Typical axial deviator stress vs. axial strain curves for C2 soilcrete at several curing ages

After reaching the peak strength, the specimens tended to collapse at an axial strain of less than 5% (Figures 4 to 6) as the bounds among clusters were broken, which showed a typical brittle behaviour. However, as the cement content increased dramatically from 17.50% to 27.47%, some specimens with higher cement content had a trend to behave more ductile than those with lower cement content.

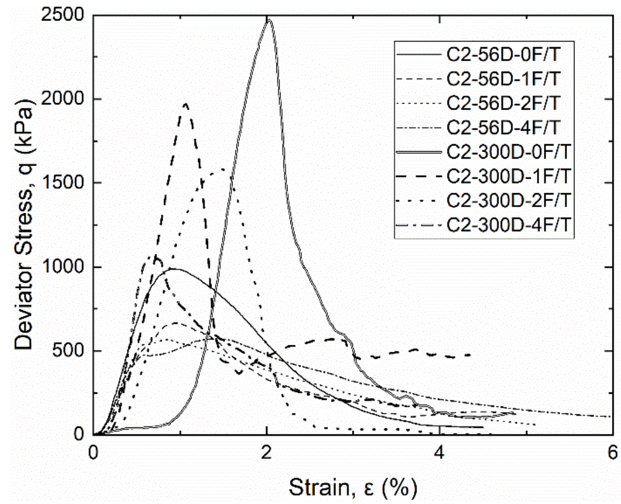


Figure 6. Typical axial deviator stress vs. axial strain curves for soilcrete under various F/T cycles

3.3.2 Peak Strength

Duplicated soilcrete samples for 3 kinds of binder ID were tested at varying curing ages under different F/T cycles. The results of peak strength were compiled. Figure 7 shows the development of q_{peak} versus w_c/C at curing ages of 28 and 110 days. It indicated that q_{peak} increased with w_c/C. Figure 8 illustrates the q_{peak} versus curing ages curves for C2 specimens. Though some of the specimens were exposed to 1 F/T cycle, it was obvious that the q_{peak} rose with curing ages dramatically, which was consistent with many other findings by Porbaha (2000), Eskişar et al. (2015), and so on. It also indicated that the loss of strength due to the first F/T cycle was as large as 30 percent of the sample's normal value without F/T cycles. As long as 300 days, the hydration of cement in these samples continued while it became very marginal after 56 days.

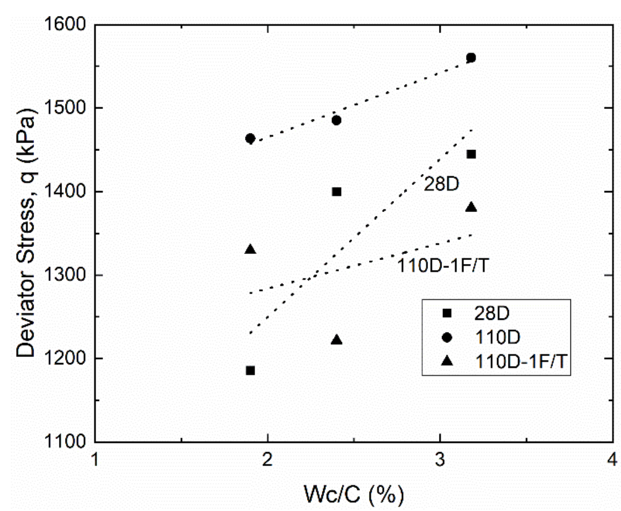


Figure 7. Average peak strength development vs. clay-water/cement ratio for all tested binders

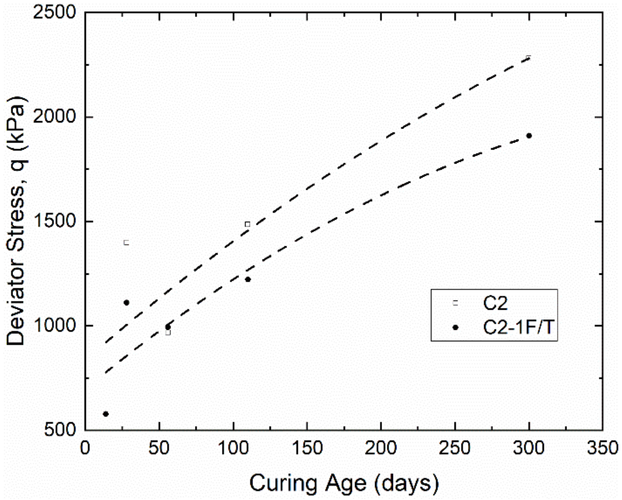


Figure 8. Average peak strength development vs. curing ages for C2 samples

As the exposure to F/T cycles increased, the strength of soilcrete sharply decreased (Figure 9). It exhibited a different trend to Jamshidi's work (2015), which concluded that the first 1 and 2 cycles would damage the soilcrete most. Figure 9 shows that the damage kept happening after 2 F/T cycles and it was still noticeable.

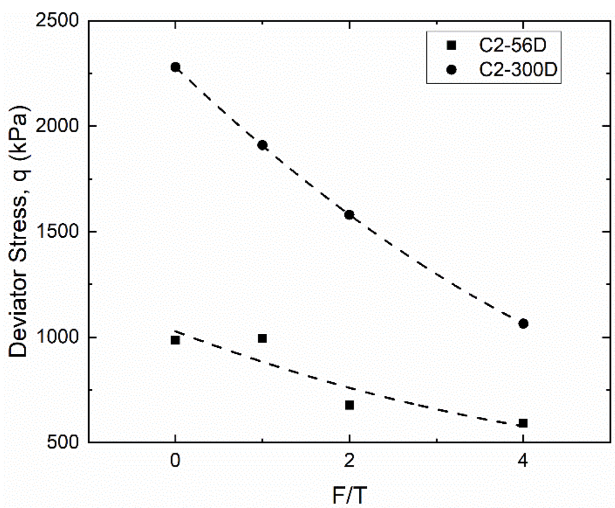


Figure 9. Average peak strength development vs. F/T cycles for C2 samples under -5 °C freezing temperature

Figure 10 shows the strength loss of exposed samples under different freezing temperatures. The strength loss increased significantly as the temperature lowered from -2 to -10 °C. And the decrease from -6 to -10 °C was much larger.

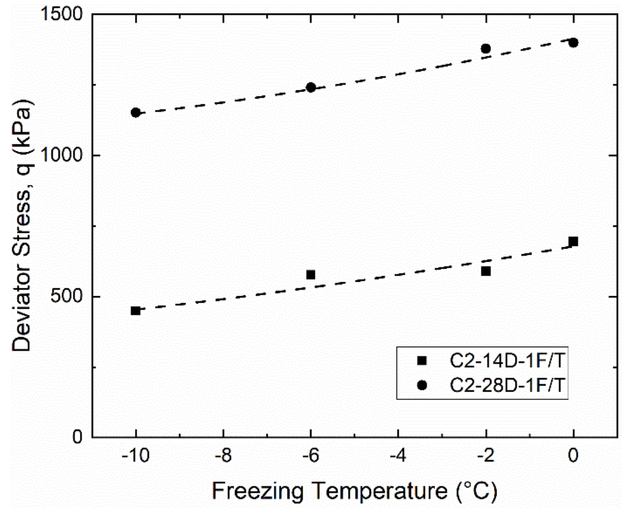


Figure 10. Average peak strength development vs. freezing temperature for C2 samples

Figure 11 exhibits a typical failure pattern of soilcrete specimens. The images were taken for C2 specimens at curing ages of 56 and 110 days. The failure plane developed after the shear failure has an angle of 70° – 80° relative to the horizontal plane in all specimens.


Figure 11. Failure plane in C2 soilcrete specimens: the left is a specimen cured for 56 days exposed to 2 F/T cycles failed on loading frame; the middle is a specimen failed at 56 days of curing with exposure of 4 F/T cycles; the right is a specimen failed at 110 days of curing

3.3.3 Young's Modulus E_0 and Secant Modulus E_{50}

The Young's modulus (E_0) and secant modulus (E_{50}) were calculated with all the specimens under differing conditions. In this paper, E_0 was defined as the slope of the initial linear part of the stress-strain curve. E_{50} was the ratio of 50% of the maximum strength to the corresponding strain.

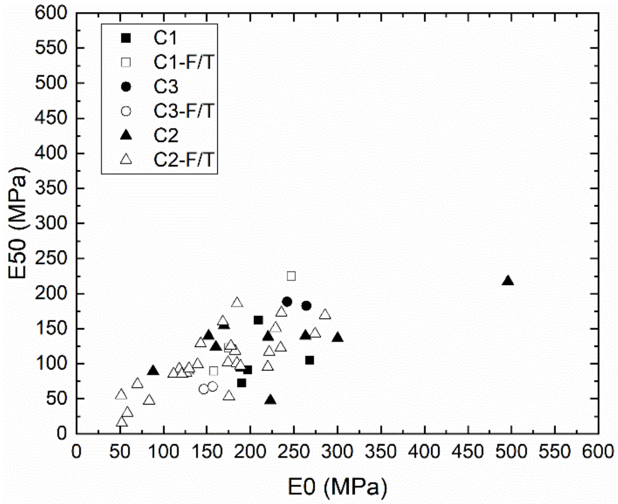


Figure 12. Young's modulus E_0 vs. secant modulus E_{50} for all soilcrete specimens

A summary of the measured moduli is plotted in Figure 12. The parameter had a large range from about 50 MPa to 300 MPa. It also showed that E_0 was bigger than E_{50} for most samples. For some specimens, the difference could be as large as 50%.

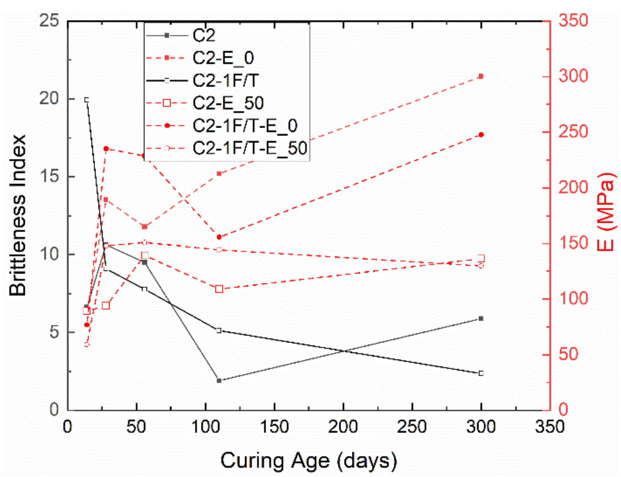


Figure 13. Average moduli and I_B vs. curing ages for C2 samples

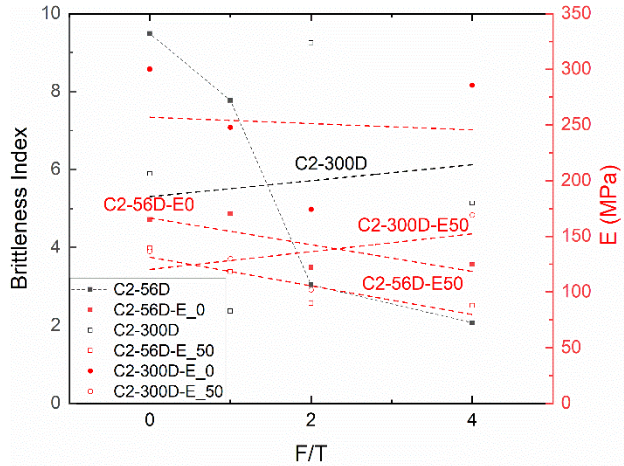


Figure 14. Average moduli and I_B vs. F/T cycles for C2 samples

The modulus showed similar trends under various conditions as the maximum strength. As curing ages increased, the value of both moduli showed an obvious rise (Figure 13). For F/T exposure, samples would generate cracks after F/T cycles, which made them more vulnerable, and hence the moduli went down dramatically (Figure 14). As for different freezing temperature, the change of moduli from the initial drop of -2 to -6 °C was negligible while it was a vast change when the temperature plummeted to -10 °C (Figure 15).

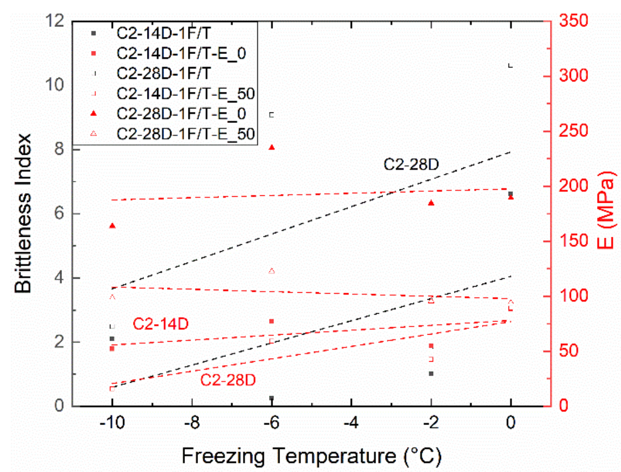


Figure 15. Average moduli and I_B vs. freezing temperature for C2 samples

The brittle behaviour could be defined by a parameter called brittleness index (I_B) used by Eskişar (2015) as below:

$$I_B = \frac{q_{peak}}{q_{residual}} - 1 \quad [2]$$

where q_{peak} is the maximum strength and $q_{residual}$ is the before-mentioned residual strength. According to Eskişar (2015), the soilcrete behavior in this study is classified as follows: very ductile (0<I_B≤ 1), ductile (1<I_B≤ 2), semi brittle (2<I_B≤ 3), brittle (3<I_B≤ 5) and very brittle (I_B>5). The calculated values of I_B were summarized in the Figures 13 to 15.

It showed that the brittleness index of soilcrete increased with the cement content and F/T cycles generally.

5 CONCLUSIONS

Soilcrete with three kinds of cement content was studied in this paper. The cement slurry was mixed with natural soil to mimic the in situ deep mixing procedure. The cylinder samples after specific curing ages with or without exposure to F/T cycles were conducted with UCS tests. Also, the loss of mass after each F/T cycle was recorded. In this study, the following conclusions may be drawn:

1) A temperature control system composed of 3D freezing and thawing and using coarse sand as the medium was a good way to change the temperature of the cylindrical soilcrete homogeneously. The temperature changes on the surface and in the samples were almost simultaneously.

2) The weight of each sample was measured after each F/T cycle and was compared with the initial weight after curing. It suggested that the loss of mass was as small as less than 5%, but the loss increased with the increasing F/T cycles. So the loss of mass was a tenable method to reflect the impact of F/T cycles.

3) The stress-strain curves of soilcrete showed an obvious strain-softening behaviour, and it indicated that the soilcrete was like overconsolidated clay while the natural soil was normally consolidated clay. Brittleness index was a possible parameter to quantify the change of brittleness in soilcrete samples.

4) The maximum strength of soilcrete samples increased with curing age (from 14 days to 300 days) and decreased dramatically with F/T cycles. The strength loss in the range of -6 to -10 °C freezing was much bigger than that in -2 to -6 °C range. Thus the lower freezing temperature would make more severe damage to the soilcrete samples.

5) Young's modulus (E_0) was bigger than the secant modulus (E_{50}) in most samples. The moduli showed a similar trend as the temperature dropped and curing ages and F/T cycles increased. It was the same for the brittleness index.

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