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Laboratory investigation of unconfined compression behavior of ice and frozen soil mixtures

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Abstract. Unconfined compression test (UCT) is widely conducted in laboratories to evaluate the mechanical behavior of frozen soils. However, its results are sensitive to the initial conditions of sample creation by freezing as well as the end-surface conditions during loading of the specimen into the apparatus for testing. This work compared ice samples prepared by three-dimensional and one-dimensional freezing. The latter created more-homogenous ice samples containing fewer entrapped air bubbles or air nuclei, leading to relatively stable UCT results. Three end-surface conditions were compared for UCT on ice specimens made by one-dimensional freezing. Steel disc cap with embedded rubber was found most appropriate for UCT. Three frozen materials (ice, frozen sand, and frozen silt) showed different failure patterns, which were classified as brittle failure and ductile failure. Ice and frozen sand showed strain-softening, while frozen silt showed strain-hardening. Subsequent investigation considered the influence of fines content on the unconfined compression behavior of frozen soil mixtures with fines contents of 0-100%. The mixtures showed a brittle-to-ductile transition of failure patterns at 10%-20% fines content.

Keywords: unconfined compression test; one-dimensional freezing; ice; frozen soil mixture; stress-strain behavior; fines content

1. Introduction

Frozen soil is widely distributed in cold regions. Its stress-strain behavior for geotechnical engineering design is frequently evaluated in the laboratory via unconfined compression test (UCT), a relatively simple procedure (Arasan and Nasirpur 2015, Güllü and Fedakar 2017, Yilmaz and Fidan 2018, Zhang *et al.* 2019). However, experimental measurements of a given frozen soil can vary greatly because of the influence of such as specimen size, its end-surface condition, temperature, and strain rate. Haynes and Mellor (1977) thoroughly reviewed the effects of ice specimen size and end-surface condition, concluding that the stress–strain behavior under unconfined compression varied by 13% as the specimen height-diameter ratio ranged from 0.74 to 2.5 when aluminum cylinders with rubber-like urethane were placed at each end of the specimen. Mellor and Cole (1982) bonded fabric-based phenolic (synthane) end caps (19 mm thick) to ice samples during freezing, which solved the contact problem and prevented end-plane failure at large strain during unconfined compression at -5°C. Ideally, any effect that a frozen soil sample end surface may have on its measured properties should be minimized, i.e., friction between the specimen and test platen should be minimized. Experimental studies (Bishop and Henkel 1962, Baker 1978, Ladanyi and Arteau 1979) have shown that frozen soil specimens with a height:diameter ratio ranged from 2 to 3 give consistent strength results under unconfined compression regardless of the condition of their end surfaces. However, ASTM International (2018a, b) recommends that the unconfined compression of frozen soils should involve lubricated platens consisting of circular membrane sheets of 0.8 mm-thick latex with a 0.5 mm-thick layer of high-vacuum silicone grease. While it is established that specimen end-surface conditions should be carefully arranged, the influence exerted by these conditions has not been analyzed in detail.

The mechanical behavior of frozen soils is significantly affected by temperature and strain rate. The brittleness of frozen soils has been reported to increase with decreasing temperature (Sayles and Haines 1974, Haynes and Karalius 1977, Haynes 1978), and the unconfined compressive strength (UCS) of ice and frozen sand has been found to increase as the strain rate increases (Hawkes and Mellor 1972, Haynes *et al.* 1975). At relatively low strain rate, the stress–strain behavior under unconfined compression can be classified as ductile yielding; brittle behavior emerges as the strain rate increases (Bragg and Andersland 1981, Mellor and Cole 1982). Sayles (1987) recommended applying strain at constant rates of $0.1\%\cdot min^{-1}$ and $1.0\%\cdot min^{-1}$, while Andersland and Ladanyi (2004) recommended $1.0\%\cdot min^{-1}$.

Previous findings have revealed the UCS of frozen soils to be significantly affected by many factors. This paper focuses on establishing end-surface conditions for frozen specimens. Laboratory tests under unconfined compression compared different end-surface conditions. Additional

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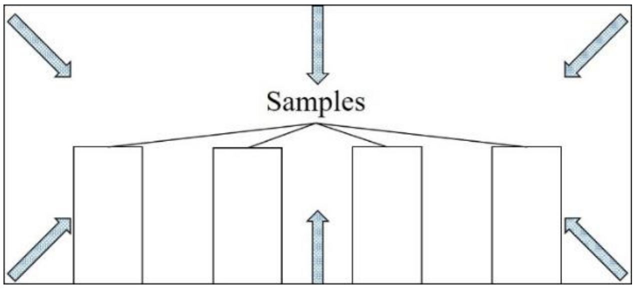
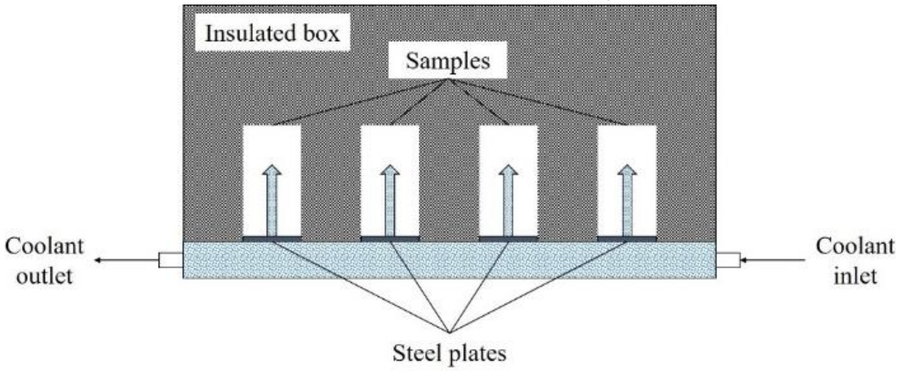


(a) Three-dimensional freezing



(b) One-dimensional freezing

Fig. 1 Schematic diagram of frozen sample maker

laboratory tests of frozen soil mixtures with various weight fractions of sand and silt assessed the effect of fines content under unconfined compression with a constant strain rate of $1\%\cdot\text{min}^{-1}$.

2. Sample preparation for laboratory test

Reconstituted or remolded frozen soil samples are often used for laboratory tests due to the difficulty of obtaining and handling undisturbed frozen samples (Jin *et al.* 2019b). Two freezing methods reported by Ladanyi and Arteau (1979) are conventionally used for the preparation of ice and frozen soil samples: three-dimensional (3D) freezing (where a soil sample is frozen from all of its surfaces simultaneously) and one-dimensional (1D), or unidirectional, freezing (where freezing applied at one end propagates to the other). When reconstituted or remolded frozen soil samples are used, their unfrozen water content is affected by the freezing method (Alnouri 1969). Since the unfrozen water content has a significant impact on stress-strain behavior of frozen soils, establishing a standardized freezing method is important.

To obtain reliable experimental data, it is important to make a representative reconstituted frozen specimen using an optimized freezing method. This study compares two methods of making frozen samples (Fig. 1) to establish an optimized method. The samples were formed using cylindrical paper molds (100 mm high and 50 mm in diameter). Three-dimensional freezing uses what is essentially a refrigerator to freeze each sample from all of its surfaces. The 1D freezer, on the other hand, was newly developed for this study. Coolant is circulated through a stainless steel bottom plate with high thermal conductivity, and a steel plate is placed between the bottom plate and the cylindrical paper molds to facilitate 1D freezing. Water in the mold can only be frozen from the bottom upward. Insulators are installed between the molds to minimize interference by the ambient temperature.

(a) Samples created by a flexible cylindrical paper mold

(b) Samples created by a rigid cubic steel mold

Fig. 2 Ice samples made by 3D (left) and 1D (right) freezing

Distilled water was used to make ice samples to avoid any influence of minerals and to reduce air bubbles during freezing. Fig. 2 shows the different ice samples obtained at

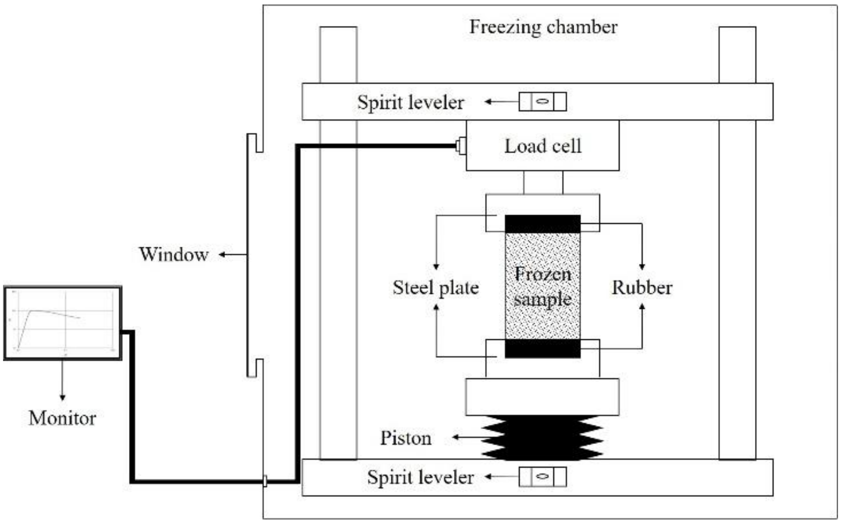
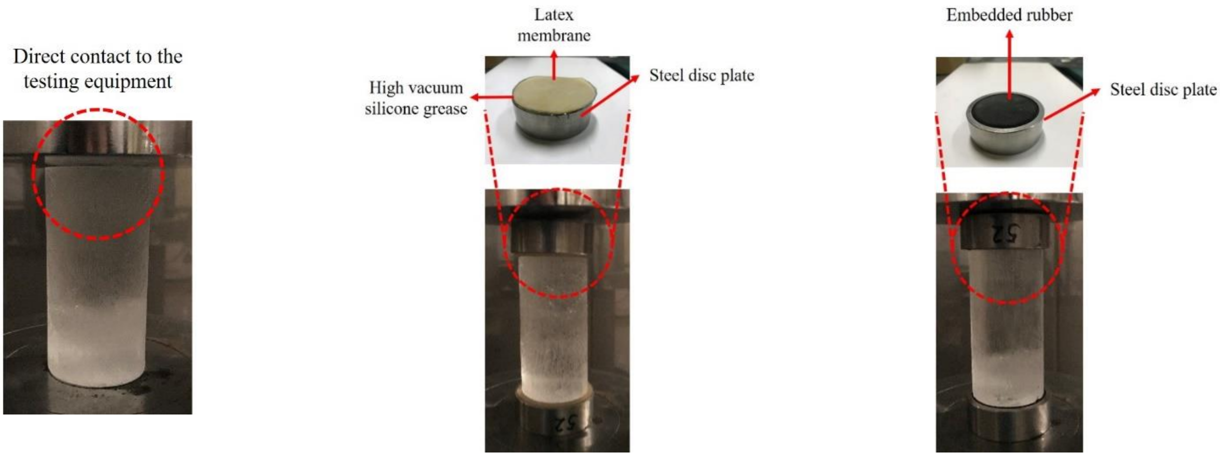


Fig. 3 Schematic diagram of equipment for unconfined compression test



(a) Direct contact with loading plate (b) Steel disc cap with latex membrane applied high vacuum silicone grease (c) Steel disc cap with embedded rubber

Fig. 4 Comparison of three types of end-surface condition

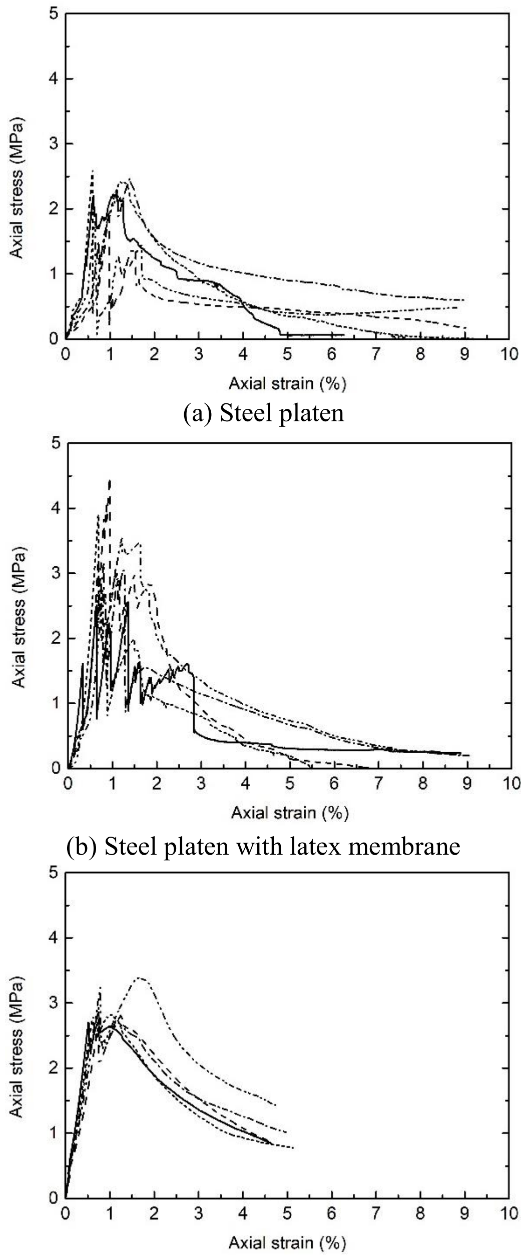
-10°C by the two freezing methods. Three-dimensional freezing trapped air bubbles, and the central part of the specimen showed volume expansion. Air nuclei seem to have formed as the air in the water gathered at the sample center. In contrast, 1D freezing of distilled water led to few visible cracks or entrapped air bubbles (or even ice nuclei) inside the ice sample (Fig. 2(a)). For further confirmation of the difference between the ice samples created by the two methods, the same distilled water was used in a steel box rather the cylindrical paper mold. Three-dimensional freezing cracked the constrained ice sample, which was completely broken due to a 9% volume expansion upon its phase change (Jin *et al.* 2019a). In contrast, clear ice was formed by 1D freezing (Fig. 2(b)). Overall, 1D freezing can prepare suitable ice samples regardless of whether a flexible or rigid mold is used. It therefore appears applicable to the preparation of frozen soil samples.

3. Effect of end-surface condition on unconfined compression test

Fig. 3 shows the equipment used for laboratory mechanical testing. It could apply unconfined compression within the freezing chamber to minimize thermal disturbances caused by temperature fluctuations. The freezing chamber was set to the same temperature as the frozen sample maker and curing room. A constant displacement rate of 1 mm·min^{-1} (approximately equivalent to a strain rate of 1%·min^{-1}) was applied. The electronic load cell limit was 100 kN. Specimen displacement was monitored automatically using embeded displacement control system.

The investigation of the effect of the sample end-surface condition during unconfined compression tests was performed with only ice samples, because ice comprises approximately a single component and the differences between individual ice samples are likely to be smaller than those between frozen soil samples. For specimen preparation, both ends of the specimen were trimmed by an electric trimming machine to achieve planeness. Unconfined compression was loaded after 1 day curing at the temperature to be used during testing (-10°C).

Three different end-surface conditions were applied to both the top and bottom end surfaces of the specimen: (1)



(a) Steel platen

(b) Steel platen with latex membrane

(c) Steel cap with embedded rubber

Fig. 5 Stress-strain relationships recorded at -10°C under three different end-surface conditions

direct contact of the sample with the steel plates of the testing equipment (Fig. 4(a)); (2) as specified by ASTM International (2018a, b), a 0.8 mm-thick latex membrane was placed between the sample and an additional steel platen disc (52 mm in diameter, about 2 mm greater than the specimen diameter) with a 0.5 mm-thick layer of high-vacuum silicone grease (Fig. 4(b)); (3) the specimen was in contact with an additional 52 mm-diameter steel disc cap with embedded rubber (Fig. 4(c)).

Unconfined compression tests on ice specimens were conducted at an ambient temperature of -10°C, and repeated 10 times for each condition. Fig. 5 shows the resulting stress-strain curves for each case. Unstable results (e.g., axial stress fluctuations) significantly changed the slope (corresponding to the modulus) of the beginning section of each curve when either a steel platen or a steel disc cap with 0.8 mm-thick latex membrane was used. Specimens with steel caps with embedded rubber, on the other hand, showed more consistent curves among the individual cases. The test results are highly likely affected by the planeness of end-surface conditions of the specimens. It is difficult to achieve high planeness of frozen specimens without grinding and polishing. Therefore, a customized capping is considered to reduce influence of difference in planeness of individual specimen. The steel caps with embedded rubber was the optimized end-surface condition among the three cases in Fig. 4 for the subsequent UCT of frozen soils.

4. Unconfined compression behavior of frozen materials

4.1 Materials

After analyzing the specimen preparation method and the end-surface condition, a series of laboratory tests assessed frozen sand and frozen silt to investigate their unconfined compression behavior. Joomunjin standard sand with an average grain size of 0.47 mm was used here. Grain-size distributions of the selected sand and silt are shown in Fig. 6. The sand and silt are classified as SP and ML, respectively, by the unified soil classification system. The silt comprised soil particles passing through a #200

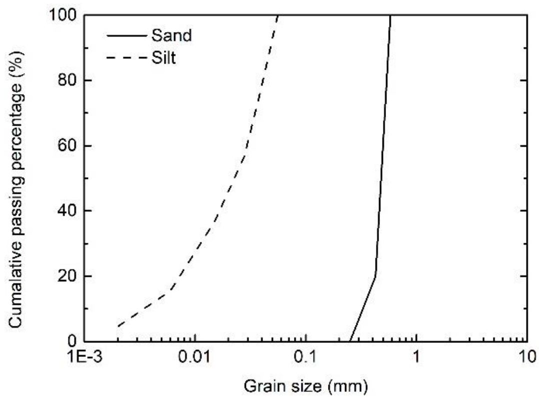


Fig. 6 Grain size distributions of sand and silt

Table 1 Initial conditions of the sand and silt mixtures specimen

No.	Weight fraction (%)		Dry unit weight ($kN{\cdot}m^{-3}$)	Water content (%)
	Sand	Silt		
1	0	100	15.5	26.8
2	30	70	16.7	18.8
3	50	50	16.8	17.9
4	70	30	16.8	17.7
5	80	20	16.6	18.1
6	90	10	15.6	21.4
7	95	5	15.1	22.5
8	100	0	14.9	25.5

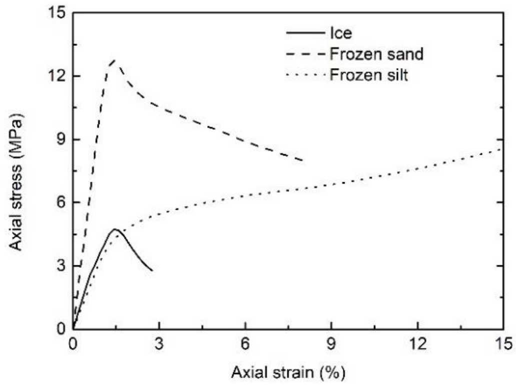


Fig. 7 Representative stress-strain curves of ice, sand, and silt frozen at -10°C

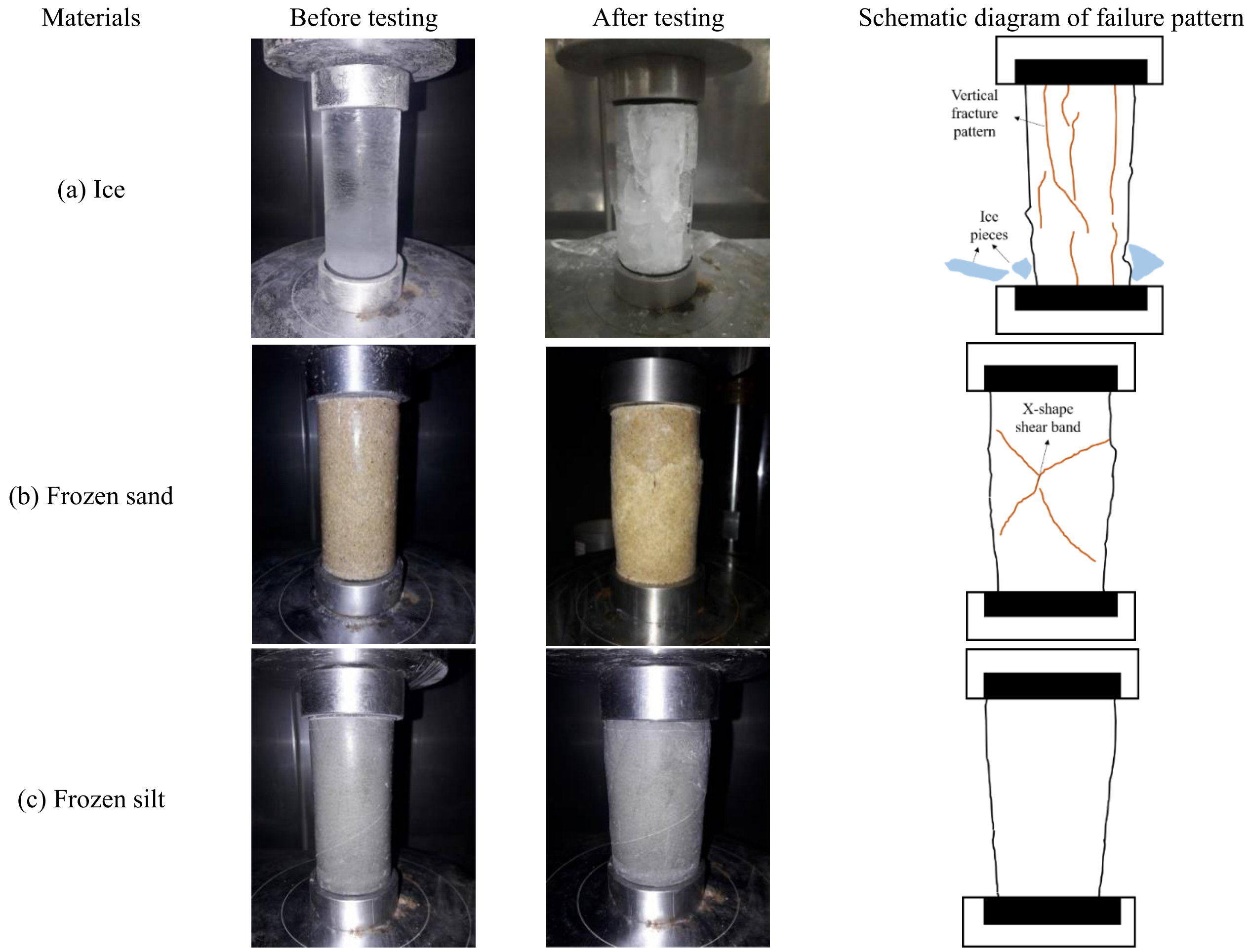


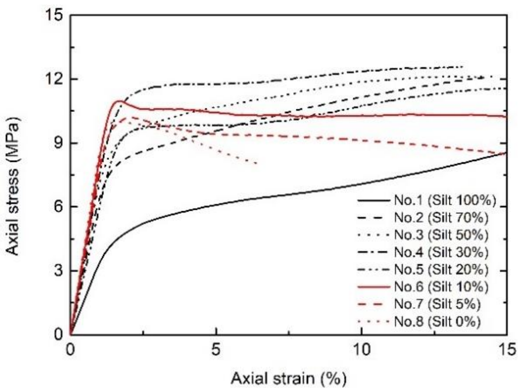
Fig. 8 Schematic diagram of failure patterns of frozen materials under unconfined compression

sieve. Fully saturated soil samples were prepared by vibroflotation. No further water supply was allowed to prevent ice lens formation in the silt. Specimens were frozen one-dimensionally. The average dry unit weights of fully saturated sand and silt were 15.5 and 14.9 kN·m^{-3}, respectively. The average water contents were 25.5% and 26.8%, respectively.

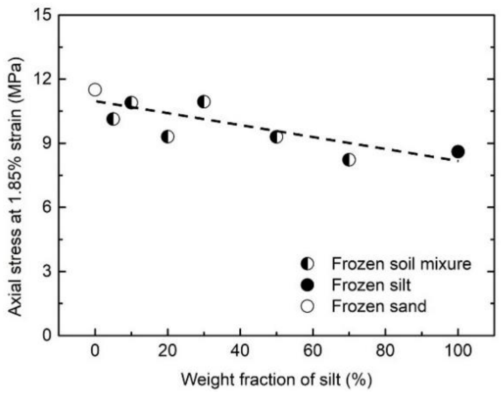
Table 1 gives details of the tested materials, including six mixtures of the sand and silt prepared with weight fractions of sand of 30%-95%. Each mixture's dry unit weight and water content averaged for 10 saturated specimens are also listed. All the samples were frozen at -10°C, the temperature at which all tests were performed.

4.2 Stress-strain behavior of frozen materials

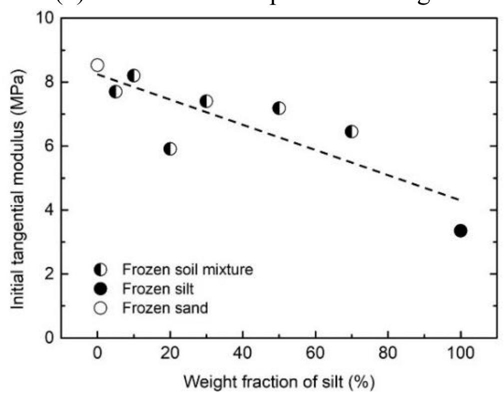
Fig. 7 plots representative stress-strain curves for ice, sand, and silt frozen at -10°C. The ice and frozen sand showed axial stress increasing almost linearly up to a peak at about 1.85% axial strain; stress then decreased to about 80% of the peak value at about 2.0% and 3.5% axial strain, respectively, indicating the complete failure of the



(a) Representative stress-strain curves



(b) Unconfined compression strength



(c) Initial tangent modulus

Fig. 9 Results for frozen soil mixtures at -10°C

specimen. The frozen silt behaved differently from the other materials: its axial stress increased monotonically, and did not show a peak up to 15% axial strain. The change in axial stress with increasing axial strain can be divided generally into two stages: an initial linear section and a subsequent nonlinear section.

Fig. 8 compares the failure patterns of the three frozen materials under unconfined compression. Ice showed multiple vertical fracture planes, with pieces of ice peeling off, indicating splitting failure. Frozen sand showed approximately X-shaped shear bands in the middle of the sample, which formed due to shear dilation. Frozen silt showed totally different fracture patterns in comparison to the other materials: it was compressed and dilated in the horizontal direction, with no fracture observable at its surface, and it finally deformed into a drum shape.

4.3 Effect of fines content

Frozen sand and silt behaved differently under unconfined compression due to the influence of the grain-size distribution. Further UCT on frozen soil mixtures at the same testing conditions investigated the transition between the two types of unconfined compression behavior.

Fig. 9(a) compares representative stress-strain behaviors of the eight types of specimens listed in Table 1. Specimens 1-5 showed strain-hardening, while specimens 6-8 showed strain-softening: the transition occurred at 10%-20% silt by weight. Fig. 9(b) shows a decreasing trend of specimen average axial stress at 1.85% axial strain, where ice and sand specimen show the peak strength (Fig. 7), as the silt content increased. The initial tangent modulus also decreased with increasing silt content (Fig. 9(c)).

5. Discussion

The stress-strain behavior of an unfrozen soil mixture is significantly affected by its fines content (Cabalar 2011). Undrained triaxial compression test results have shown that silty sand behaves as a silt when its fines content exceeds 30% (Thevanayagam 1998). Consistency tests have observed a threshold fines content of approximately 20% for sand-fine particle (silt and clay) mixtures (Kim *et al.* 2016, 2017). Kim *et al.* (2018) also conducted oedometer and direct shear tests using dry sand-clay mixtures, finding their behavior to be governed by coarse particles when the clay content was < 23.5%.

Previous research on frozen sand mixtures has focused on the influence of factors such as temperature, strain rate, water content, and dry unit weight (Yuanlin and Carbee 1984, Joshi and Wiieweera 1990, Li *et al.* 2003, Christ and Kim 2009), while the effect of fines content was rarely reported. The current study shows that a brittle-to-ductile transition of the failure pattern for frozen soil mixtures occurs at 10%-20% weight fraction of fines content. Interestingly, the frozen soil mixtures showed similar behavior to unfrozen soil mixtures in terms of both the effect of fines and the threshold fines content.

Providing previously unknown information on the stress-strain behavior of frozen soils has a special significance in frozen ground engineering, as it allows geotechnical engineers to understand the mechanical behavior of frozen soils. It is not appropriate to classify frozen ground simply as either frozen sand or frozen silt, because the stress-strain behavior depends on the fines content.

6. Conclusions

Unconfined compression behavior of ice and frozen sand-silt mixtures is investigated and the following conclusions are drawn.

• One-dimensional freezing is better than 3D freezing, as it forms ice specimen with relatively uniform dilation and less entrapped air bubbles or air nuclei.

• The specimen end-surface condition significantly affects UCT results. A steel disc cap with an embedded rubber provides relatively consistent and stable results compared with those given by steel platen and steel disc cap with a greased membrane.

• Ice, frozen sand, and frozen silt showed different failure patterns. Ice and frozen sand were strain-softening, while frozen silt was strain-hardening.

• Frozen soil mixtures showed increasing trends of axial stress at 1.85% axial strain and initial tangent modulus as the weight fraction of silt decreased (from 100% to 0%). A brittle-to-ductile transition of the failure pattern occurred at 10%-20% weight fraction of silt, which is consistent with previous results for unfrozen soil.

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