

# POST PEAK AXIAL COMPRESSIVE STRENGTH AND DEFORMATION BEHAVIOR OF FINE-GRAINED FROZEN SOILS

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## Abstract

Constant strain rate uniaxial compressive strength tests were conducted on saturated samples of six fine-grained frozen soils. The post peak compressive strength behavior of the frozen soils with respect to the variation in total water content, dry unit weight and the temperature conditions are studied.

Test results indicated a ductile type of deformation for the frozen soils with generally low total water contents and at temperature conditions close to freezing. A brittle type of failure was observed for the frozen soils with high total water contents. The residual compressive strength of the frozen soils are found to be independent of the dry unit weight. However, for all the frozen soils the ratio of peak compressive strength to residual strength is found to decrease with increasing dry unit weight. An empirical relationship has been developed to express this behavior, which is also relatively temperature independent.

## Résumé

Des essais de résistance à la compression uniaxiale à taux de déformation constant ont été menés sur des échantillons saturés de six sols gelés à grain fin. La résistance des sols gelés après compression maximale a été étudiée en fonction de la variation du contenu total en eau, de la masse unitaire sèche et de la température. Les résultats indiquent que la déformation est de type ductile pour les sols ayant en général une faible teneur totale en eau, au voisinage du point de congélation. Une rupture de type cassante fut observée pour les sols gelés ayant un contenu en eau totale élevée. La résistance résiduelle à la compression des sols gelés est indépendante de la masse unitaire sèche. Toutefois, pour tous les sols gelés, le rapport de la résistance à la compression maximale à la résistance résiduelle diminue en fonction de la masse unitaire sèche. Une relation empirique a été établie pour exprimer ce comportement, lequel est relativement indépendant de la température.

## Introduction

The strength and deformation behavior of frozen soils under short term loading conditions is of importance specially for design and excavation of shafts and pits by the method of artificial ground freezing. In excavations in the artificially frozen ground the frozen soil wall, which supports the unfrozen soils, may undergo large strains, sometimes approaching the post peak region in its stress strain behavior. A clear understanding of the post peak behavior and residual compressive strength of frozen soils is therefore required.

Both ductile and brittle types of deformation behavior are observed in frozen soils subjected to compressive strength tests under different conditions. The brittle type of failure is characterized by the formation of failure planes after the soil has reached its peak strength. In the case of ductile type of failure the soil remains intact without rupture even at large strains well beyond its peak strength.

The post peak strength and deformation behavior of six frozen clays and silty soils are investigated with respect to temperature, total water content and dry unit weight conditions. Such information on frozen clayey soils is still sketchy and scarce.

## Literature Review

The results from constant axial deformation rate tests conducted on frozen clayey silt and Sault-Ste-Marie clay samples at temperatures between -1°C and -22°C by Akili (1971) showed a brittle type of stress strain behavior associated with low plastic clayey silt. A ductile type of behavior was observed for the high plastic frozen clay soil. It was also reported that the deformation behavior was more of a ductile type when the temperature was increased and more of a brittle type at lower temperatures. Ladanyi and Sayles (1978) reported the peak strength to residual strength ratio as

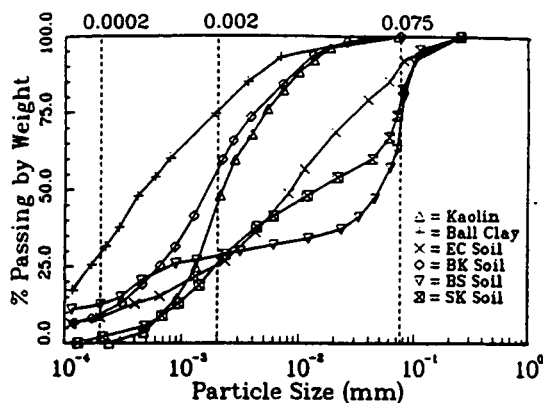


Figure 1. Gradation curves for the soils.

a measure of the ductile or brittle type of behavior in a frozen soil subjected to compressive strength tests. They indicated that lower the strength ratio more ductile is the type of deformation behavior for a frozen soil.

Sayles and Carbee (1981) observed frozen silt specimens subjected to constant compressive strain rate at  $-1.67^{\circ}\text{C}$  failed in a plastic or ductile manner. The total water content of the test samples ranged between 28 % to 54 % and for the samples with low total water contents the peak stress was found not to have occurred even at large strains close to 0.3. This type of plastic behavior may be mainly due to the large amount of unfrozen water present at this high temperature in the frozen silt. It was also reported that the compressive strength of the specimens at 20 % strain is nearly independent of the dry unit weight and the ice content of the soil.

Zhu and Carbee (1987) presented compressive strength test results on frozen Fairbanks silt at temperatures between  $-0.5^{\circ}\text{C}$  to  $-10^{\circ}\text{C}$  with different constant strain rates ranging from  $1.1 \times 10^{-6}$  to  $6.2 \times 10^{-2}\text{s}^{-1}$  and at various dry unit weights between  $10.6 \text{ kN/m}^3$  and  $13.7 \text{ kN/m}^3$ . It is reported that all the specimens tested in general failed in a ductile manner with fracture not occurring until strains approached more than 25 %. At very high constant strain rate and low temperature conditions a moderate brittle type of failure was observed. At lower dry unit weights of the soil the deformation behavior was found to be more of a brittle type.

Table I  
Soil Properties

| Soil      | Atterberg Limits  |       |       | $S^2$<br>( $\text{m}^2/\text{g}$ ) |
|-----------|-------------------|-------|-------|------------------------------------|
|           | Type <sup>1</sup> | $w_L$ | $w_P$ |                                    |
| Kaolin    | CL                | 43.0  | 25.0  | 18.0                               |
| Ball Clay | CH                | 56.9  | 24.7  | 32.2                               |
| EC Soil   | CL                | 27.8  | 11.9  | 15.9                               |
| BK Soil   | CH                | 75.9  | 27.0  | 48.9                               |
| BS Soil   | CH                | 112.0 | 21.1  | 90.9                               |
| SK Soil   | CL                | 24.9  | 16.0  | 8.9                                |

<sup>1</sup> Soil Classification

<sup>2</sup> Specific surface area

Evidence from compressive strength test results of frozen soils indicates that the strength and deformation behavior depends not only on the material properties but also, to a certain degree, on the test conditions such as the specimen size and shape and the way the load is transferred at the specimen ends (Baker, 1978 and Ladanyi and Arteau, 1979).

## SPECIMEN PREPARATION

### Material

Six fine-grained soils were used in the present investigation with their liquid limits varying from 25 to 112 (Table I) and different gradation (Fig. 1).

### Consolidation

In the present study, the saturated soil was initially prepared using slurry consolidation technique in a specially fabricated 200 mm internal diameter consolidation cell. Saturated bulk samples of the soils with different water contents were prepared by consolidating the initially deaired slurry under various pressures ranging from 70 kPa to 2450 kPa.

### Sample extraction and freezing

Using a core cutting tube about 15, 38 mm diameter test specimens were extracted from the 200 mm diameter consolidated sample, with very little disturbance to them. The length of the samples obtained varied between 90 to 110 mm in most cases for the soils subjected to various consolidation pressures. The water contents obtained from the bulk samples indicated that generally the degree of saturation of the consolidated soil was greater than 96 %.

The test specimens were frozen unidirectionally from top to bottom in an open system in a freezing cabinet to a temperature of  $-73^{\circ}\text{C}$ . This process of freezing eliminated formation of ice lenses in the samples as they were frozen quickly without any access to water at the bottom. Examination of frozen specimen sections of the different soils revealed a massive texture in most of the cases. These quick frozen specimens were then stored in a walk-in type cold room until they were subsequently tested. The details of the sample preparation procedure are discussed by Wijeweera and Joshi (1989) in a research report.

### Uniaxial compressive strength tests

The constant strain rate uniaxial compression tests were conducted on a closed loop control MTS (Material Test System) machine using trimmed frozen specimens (nominal length of 80 mm). Aluminum loading platens with diameters larger than the specimen were used at both ends of the sample. A thin aluminum foil coated with a very thin layer of silicone grease was also used as a friction reducer on either end of the specimen. This way the specimen ends were allowed to deform laterally without much restraint when under compression.

All the specimens were subjected to an average constant axial strain rate of  $10^{-2} \text{ s}^{-1}$  in compression, until an axial strain

**Table II**  
**Properties<sup>1</sup> of the Frozen Soil Test Specimens**

| Soil Type   | Total w.c. | Rel. <sup>2</sup> w.c. | $\gamma$ (kN/m <sup>3</sup> ) | -5°C | $\sigma_m^3$ (MPa) | -10°C | -17°C |
|-------------|------------|------------------------|-------------------------------|------|--------------------|-------|-------|
| Kaolin Clay | 45.00      | 1.05                   | 11.12                         | 3.57 | 5.05               | 6.63  |       |
|             | 42.00      | 0.98                   | 11.75                         | 3.70 | 4.68               | 7.10  |       |
|             | 36.50      | 0.85                   | 12.46                         | 3.47 | 4.66               | 6.48  |       |
|             | 35.83      | 0.83                   | 12.64                         | 3.49 | 5.12               | 6.53  |       |
|             | 31.70      | 0.74                   | 13.49                         | 3.01 | 4.64               | 6.00  |       |
| Ball Clay   | 56.78      | 1.00                   | 9.81                          | 3.15 | 4.62               | 5.80  |       |
|             | 51.81      | 0.91                   | 10.39                         | 2.63 | 3.63               | 5.34  |       |
|             | 47.84      | 0.84                   | 10.85                         | 2.21 | 3.23               | 5.09  |       |
|             | 42.11      | 0.74                   | 11.65                         | 2.13 | 3.13               | 4.80  |       |
|             | 38.51      | 0.68                   | 12.08                         | 2.06 | 3.11               | 4.52  |       |
|             | 33.31      | 0.58                   | 13.14                         | 1.84 | 3.10               | 4.81  |       |
|             | 27.20      | 0.48                   | 14.31                         | 1.99 | 2.87               | 4.42  |       |
|             | 25.77      | 0.93                   | 15.45                         | 2.84 | 4.24               | 7.27  |       |
| EC Soil     | 23.80      | 0.86                   | 15.60                         | 2.71 | 4.29               | 7.12  |       |
|             | 21.35      | 0.77                   | 16.30                         | 2.24 | 4.36               | 7.00  |       |
|             | 18.47      | 0.66                   | 17.29                         | 2.75 | 4.83               | 7.61  |       |
|             | 14.94      | 0.54                   | 18.44                         | 3.99 | 5.28               | 8.72  |       |
| BK Soil     | 84.50      | 1.11                   | 7.43                          | 3.22 | 4.14               | 6.70  |       |
|             | 61.40      | 0.81                   | 9.25                          | 2.37 | 3.60               | 5.88  |       |
|             | 52.53      | 0.69                   | 10.28                         | 1.70 | 2.78               | 4.46  |       |
| BS Soil     | 104.66     | 0.93                   | 6.49                          | 5.98 | 8.32               | 11.77 |       |
|             | 80.15      | 0.72                   | 7.86                          | -    | -                  | 10.23 |       |
|             | 75.90      | 0.68                   | 8.14                          | 4.37 | 6.25               | 10.19 |       |
| SK Soil     | 21.44      | 0.86                   | 16.13                         | 3.47 | 5.61               | 8.18  |       |

<sup>1</sup> average values

<sup>2</sup> relative w.c. is the ratio of total w.c. to w.c. at liquid limit

<sup>3</sup>  $\sigma_m$  = peak strength

of 0.20 was reached. The axial load deformation curve for each specimen was recorded by a x-y plotter connected to the MTS machine during the test.

The strength tests were conducted at temperatures between -5°C and -17°C. The average total water contents of the specimens used in the tests varied between 15% to 105% with their average dry unit weights ranging from 6.5 to 18.5 kN/m<sup>3</sup>, see Table II. The degree of saturation of the frozen specimens were generally 95% and above. Except in a very few cases all the compressive strength tests were repeated a number of times under the same testing conditions using different samples.

## Test Results and Discussion

### STRESS STRAIN CURVES

The axial stress strain curves derived, from the constant strain rate tests, for the soils at their minimum and maximum total water contents and at various temperature conditions are given in Figs. 2 to 6. For SK soil, the compressive strength tests were conducted corresponding to only one total water content (Fig. 7). In a typical stress-strain curve the yield

point is considered as the point at which the initial slope of the curve starts to decrease noticeably, Y in Fig. 2a. The yield strains for the different frozen soils were around 1%. Mellor and Cole (1982) observed the peak compressive strength of polycrystalline ice tested at -5°C and between constant strain rates of 10<sup>-7</sup> to 10<sup>-3</sup>s<sup>-1</sup> to be close to 1% strain with a brittle type of failure. This indicates that the yield point of a frozen soil may correspond to the failure or fracture of the ice matrix in the soil.

Following the yield point, with increasing strain, a strain hardening region can be observed, YM in Fig. 2a, where mobilization of the interparticle friction takes place. The peak axial compressive strength,  $\sigma_m$ , is considered as the maximum axial stress attained by the sample during the compressive strength test, M in Fig. 2a. If the stress is continuously increasing with the strain, the peak strength is taken as the stress at 20% axial strain. The average peak strength values for the different frozen soils at various dry unit weights and temperatures are given in Table II.

For saturated frozen soils with high dry unit weights or low total water contents the strain hardening region becomes very noticeable (Fig. 4b) for EC soil. The data in the figure indicates that the frictional resistance mobilized may mainly

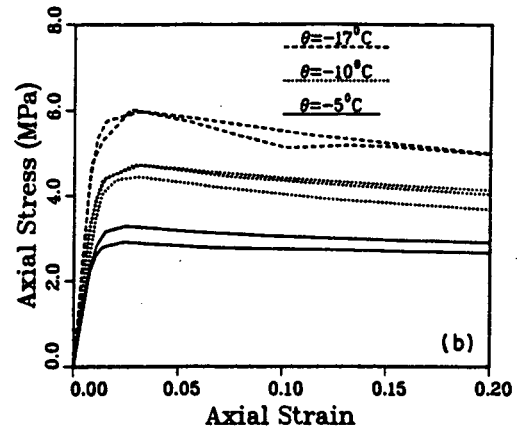
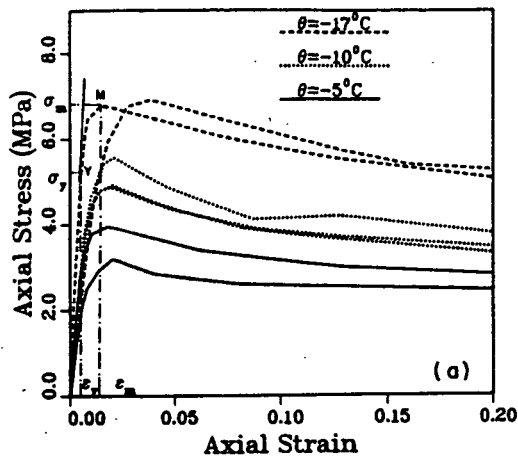


Figure 2. Stress strain curves of Kaolin Clay; total w.c. (a) 45.00 and (b) 31.70.

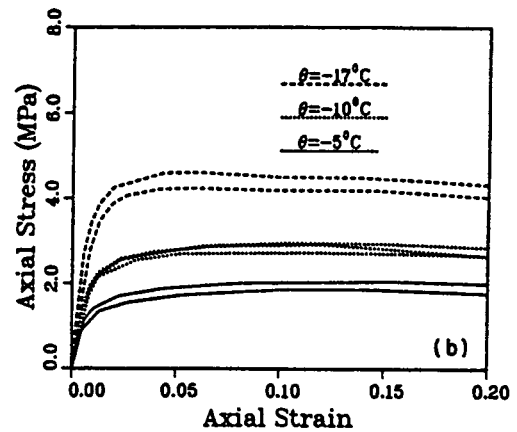
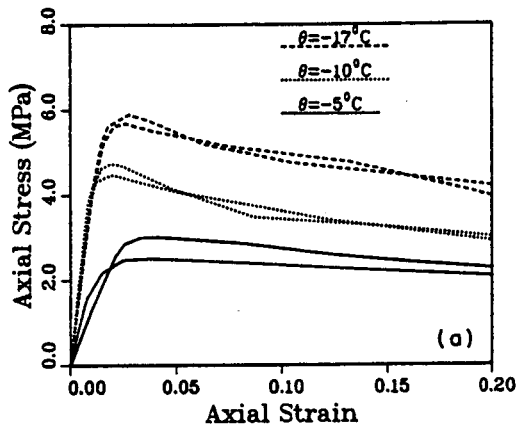


Figure 3. Stress strain curves of Ball Clay; total w.c. (a) 56.78 and (b) 27.20.

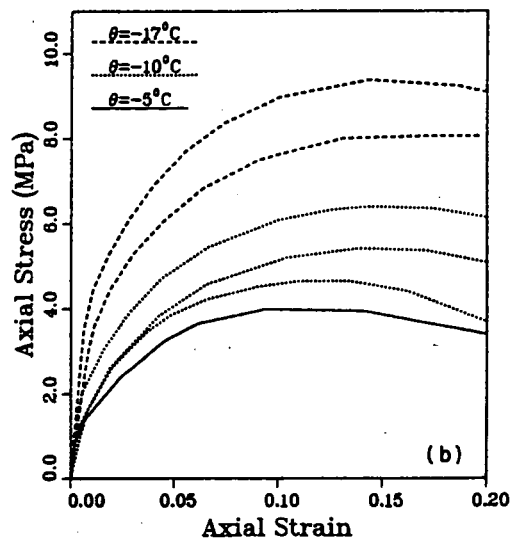
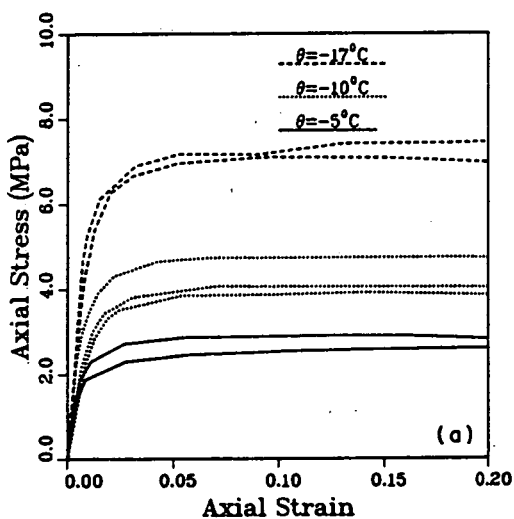


Figure 4. Stress strain curves of EC Soil; total w.c. (a) 25.77 and (b) 14.94

contribute to the overall strength of the frozen soil at very high dry unit weights. On the other hand for frozen soils with very high total water contents the overall strength may be mainly due to the ice matrix strength (Figs. 5a, 6a and 6b) where the strain hardening region is barely noticeable.

From the Figs. 2 to 7 it can be seen that, except in the case of EC soil, the post peak stress strain behavior of all the other soils at low relative water contents is such, that the slope of the curves in this region are close to being horizontal. This indicates a more ductile type of deformation behavior. The relative water content is the ratio of total water content to the water content at liquid limit of the soil (see Table II). At high total water contents a prominent peak is observed in the stress strain curves of the above soils, particularly at low temperatures. This is very clearly noticeable in the case of BK and BS soils at high total water contents (Figs. 5a, 6a and 6b). This indicates a more brittle type of deformation. In EC soil the compressive strength

increases with increasing axial strain even at strain values as high as 0.10, Table II. A high strain value at peak strength indicate a more ductile type of behavior for the soil. This soil has the lowest total water contents studied, Table II.

Figs. 8a to b show the relationship between axial strain at peak compressive strength,  $\epsilon_m$ , versus relative water content behavior for EC soil and Ball Clay. The  $\epsilon_m$  values for the other frozen soils are found to be around 2% to 3%. The strain values at peak strength for EC soil are around 10% and greater (Fig. 8a). For Ball Clay the strain at peak strength, increases with decreasing relative water content (Fig. 8b). At low relative water contents of this soil the strain at peak strength is greater at higher temperatures. The above results therefore suggest a ductile type of behavior for specimens of EC soil and also for Ball Clay samples with very low relative for (a) EC Soil and (b) Ball Clay. Mean data points are plotted water contents and at high temperatures. The total water contents of these two soils

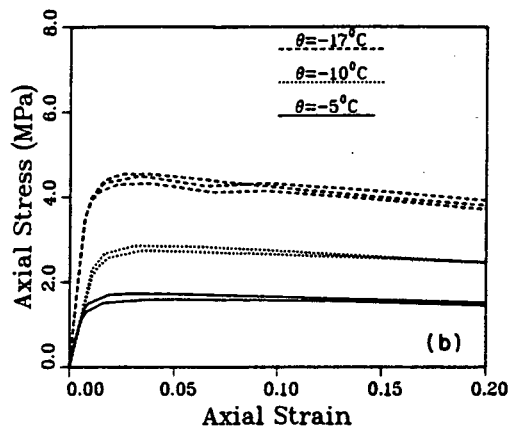
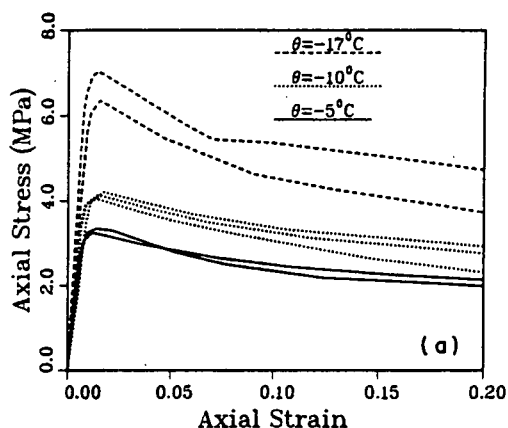


Figure 5. Stress strain curves of BK Soil; total w.c. 84.50 and (b) 52.53.

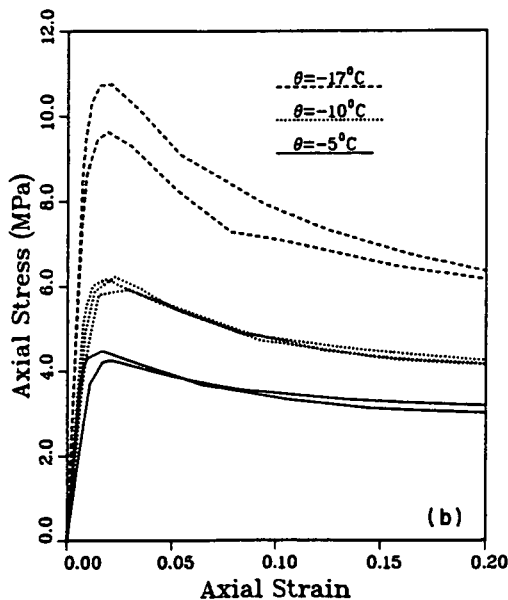
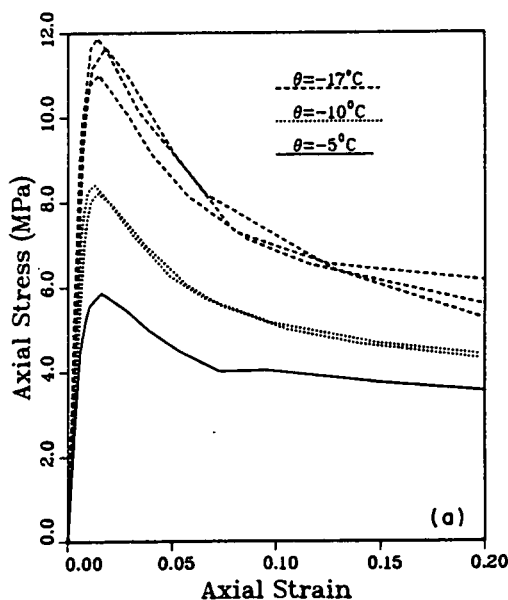


Figure 6. Stress strain curves of BS Soil; total w.c. (a) 104.66 and (b) 75.90.

includes the lowest relative water contents studied in this investigation.

From the behavior of the stress-strain relationship and the strain values at peak strength for the different fine-grained frozen soils the following may be suggested. In fine-grained frozen soils with low relative water content and high temperature conditions the deformation behavior is generally of a ductile type. This type of deformation also occurs in the frozen soils with low total water contents. However, in fine-grained frozen soils with high relative water contents and at low temperatures a brittle type of deformation may occur.

#### FAILURE MODES OF THE SAMPLES

Typical failure modes observed in the samples after the uniaxial compressive strength tests are shown in Figs. 9a to

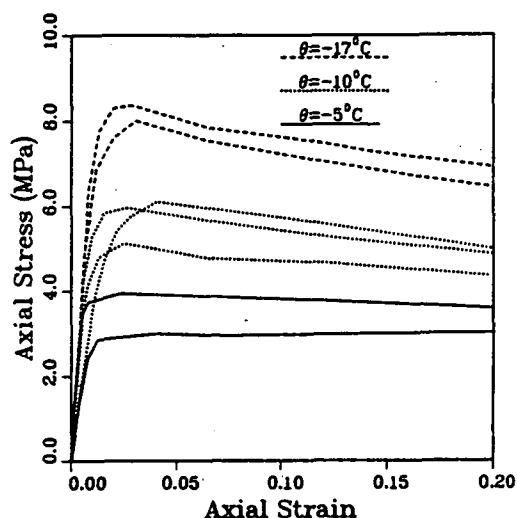
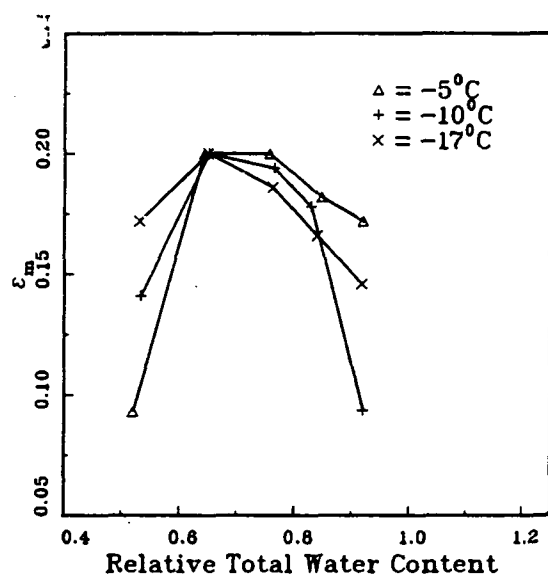


Figure 7. Stress strain curves of SK Soil; total w.c. = 21.44.



(j) for the various frozen soils. The frozen Kaolin clay specimens with a high total water content of 45%, i.e. at a water content above the liquid limit of the soil, tested at temperatures  $-10^{\circ}\text{C}$  and  $-17^{\circ}\text{C}$  exhibit distinct shear failure planes, indicating a brittle type of failure, (fig. 9a). However, the samples of the soil having lower total water contents deformed in a ductile manner (Fig. 9b), with no indication of failure cracks. The Ball Clay specimens subjected to compressive strength tests showed a brittle type of failure at all temperatures particularly at high to medium total water contents of the soil (Fig. 9c). However, in some of the specimens of this soil having a low total water content, i.e. about 27%, a more ductile type of deformation behavior was observed (Fig. 9d).

A ductile type of failure was observed in general for the frozen specimens of EC soil (Fig. 9e). Nonetheless, the specimens having the lowest total water content of about 15% exhibited distinct failure planes (Fig. 9f). This type of brittle failure in the soil at very low water contents is the reason for the decrease in the strain values at peak strength observed (Fig. 8a). A brittle type of failure was observed at all temperature conditions for BK soil specimens having a total water content of 84.5%, i.e. above its liquid limit, (Fig. 9g). A ductile type of deformation was observed for specimens of this soil with total water contents below the liquid limit (Fig. 9h). BS soil specimens also exhibited a brittle type of failure at high total water contents of 104.6%, i.e. close to their liquid limit (Fig. 9i). Failure planes were however, not apparent for the specimens with lower total water contents for this soil (Fig. 9j). The failure mode for the SK soil specimens was mainly of a ductile type.

The above failure modes suggest that ductile type of behavior is common for fine-grained soils at low relative water contents and at high temperatures. At high relative water contents of the soil and at low temperatures a more brittle type of failure occurs. In the cases of EC soil with very low total water contents and BS soil at very high total water contents, splitting of the samples vertically were

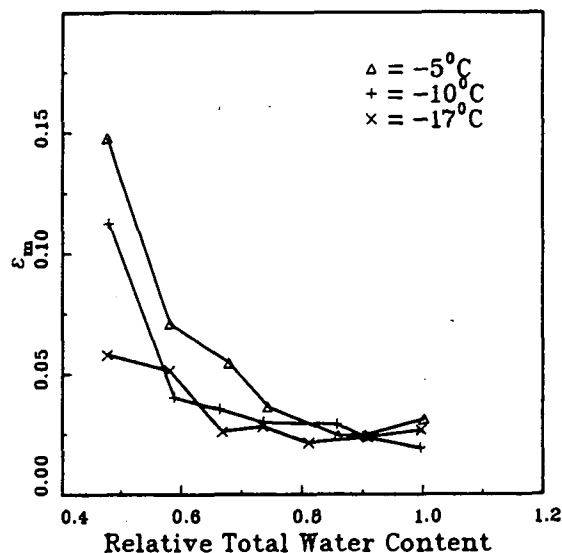
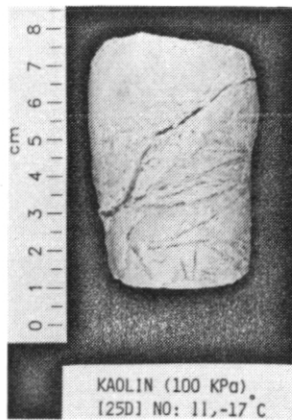
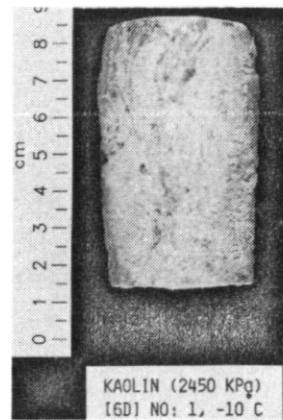


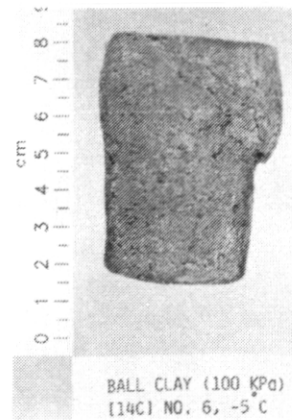
Figure 8. The behavior of axial strain at peak strength vs relative total water content



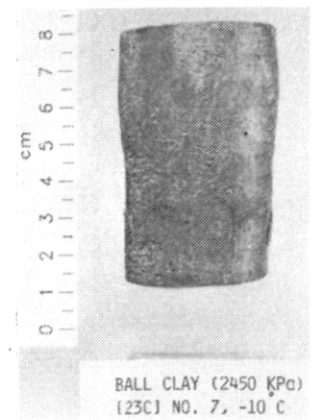
(a)



(b)



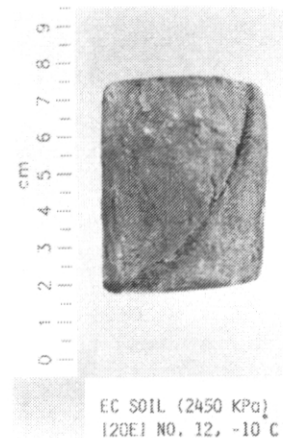
(c)



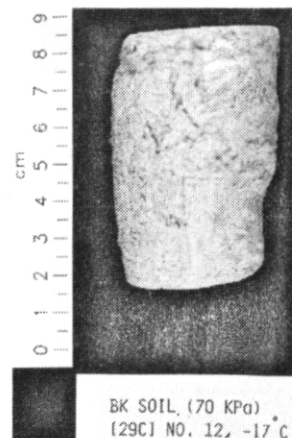
(d)



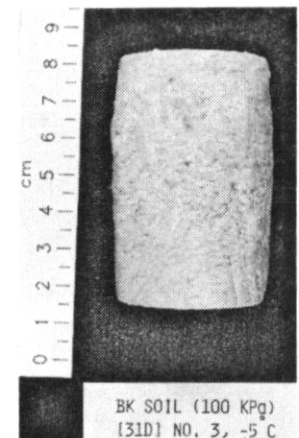
(e)



(f)



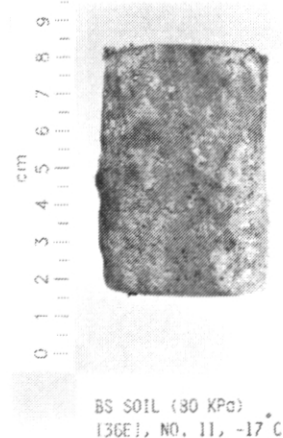
(g)



(h)



(i)



(j)

Figure 9. Failure modes of the various frozen soil specimens subjected to axial compressive strength tests. The maximum pressure under which the soil was consolidated in specimen preparation and the test temperature are as indicated. Kaolin Clay (a) brittle failure, w.c. = 45.00 (b) ductile failure, w.c. = 31.70; Ball Clay (c) brittle failure, w.c. = 51.81 (d) ductile failure, w.c. = 27.20; EC Soil (e) ductile failure, w.c. = 25.77 (f) brittle failure, w.c. = 14.94; BK Soil (g) brittle failure, w.c. = 84.50 (h) ductile failure, w.c. = 61.40; BS Soil (i) brittle failure, w.c. = 104.66 (j) ductile failure, w.c. = 80.15.

observed (Figs. 9f and 9i). The peak compressive strength of these two soils, Table II, are among the highest peak strengths of the frozen soils tested. These results may suggest that the vertical splitting of the samples observed above may be due to excessive transverse tensile stresses developed under very high axial compressive stresses causing the failure.

Frozen soils may be expected to exhibit a brittle type of failure at low temperatures when their total water content is high, due to the high ice content in the soil. However, in the cases of frozen BK soil and BS soil which are high plastic clays having high specific surface area values (Table I) a ductile type of behavior is observed even at large total water contents. Anderson and Tice (1972) have predicted higher unfrozen water contents for frozen soils with high specific surface area values. This suggests that in the case of BK and BS soils the ductile type of behavior observed at high total water contents may be due to the large amounts of unfrozen water content present in them. Ductile or plastic type of failure is also prominent in the fine-grained frozen soils with low relative water contents, due to the low ice content in them.

#### RESIDUAL COMPRESSIVE STRENGTH

The data (Fig. 10) indicates that the axial compressive strength at 0.20 strain ( $\sigma_{0.2}$ ), is generally independent of the dry unit weight of the soils except in the case of EC soil with very high dry unit weights. From Figs. 2 to 7 it can be noticed that except for EC soil, the stress strain curves approach a constant stress value or a residual stress at 0.20 axial strain. In EC soil due to the greater mobilization of frictional resistance the residual stress occurs at strains higher than 0.20. The axial compressive strength at 0.20 axial strain is considered, hereafter, as the residual strength for the frozen soils. The data (Fig. 10) suggests that generally the residual compressive strength of a fine-grained frozen soil is independent of its dry unit weight. The residual strength however, is seen to increase with decreasing temperature for all the soils as evidenced in this figure.

The logarithm of the strength ratio of peak compressive strength to residual strength when plotted against the logarithm of  $\gamma_d w_L^{1/3}$  for the various frozen soils, corresponding to a temperature of  $-5^\circ\text{C}$ , shows a linear relationship (Fig. 11). Here  $\gamma_d$  is the dry unit weight of the sample and  $w_L$  is the liquid limit. This relationship is relatively independent of the soil type. Similar behavior was found at other investigated temperatures  $-10^\circ\text{C}$  and  $-17^\circ\text{C}$  (Fig. 12). It can be seen from this figure that the data points are only slightly influenced by the temperature condition. The above results suggest that the strength ratio for a particular soil decreases with increasing dry density. The relationship between strength ratio vs  $\gamma_d w_L^{1/3}$  can be expressed by Eq. (1).

$$\log \frac{\sigma_m}{\sigma_{0.2}} = a \log(\gamma_d w_L^{1/3}) + b \quad (1)$$

The parameters  $a$  and  $b$  are found using a linear regression analysis and the best fits are shown in Figs. 11 and 12. The values of  $a$  and  $b$  corresponding to the temperature of  $-10^\circ\text{C}$  may be taken to approximate the

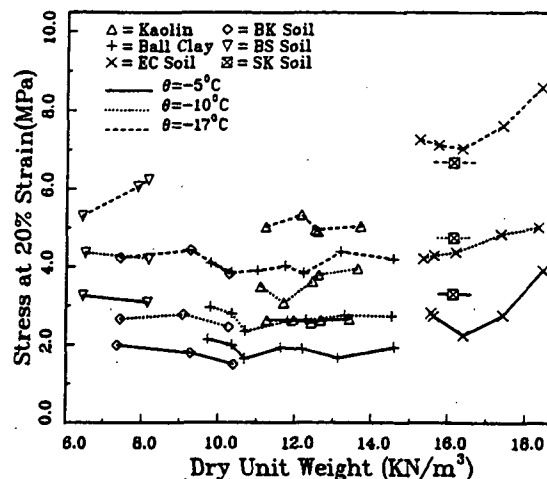


Figure 10. The behavior of axial compressive strength at 20% axial strain vs dry unit weight for the frozen soils at various temperatures. Mean data points are plotted.

strength ratio vs  $\gamma_d w_L^{1/3}$  behavior at temperatures between  $-5^\circ\text{C}$  and  $-17^\circ\text{C}$  with little loss of accuracy for practical applications (Fig. 12). The eq. (1) can now be rewritten using the values of  $a$  and  $b$  at  $10^\circ\text{C}$  as in Eq. (2).

$$\frac{\sigma_m}{\sigma_{0.2}} = 65.4 (\gamma_d w_L^{1/3})^{-1.052} \quad (2)$$

where  $\sigma_m$  = peak axial compressive strength in MPa  
 $\sigma_{0.2}$  = axial compressive strength at 20% axial strain in MPa  
 $\gamma_d$  = dry unit weight of the soil in  $\text{kN/m}^3$   
 and  $w_L$  = liquid limit of the soil expressed as a percentage.

Therefore, by knowing the peak axial compressive strength behavior of a fine-grained frozen soil its residual strength at a temperature between  $-5^\circ\text{C}$  to  $-17^\circ\text{C}$  can be found from Eq. [2].

The results of this study suggest a method from which the axial compressive strength corresponding to a 20% axial strain or the residual strength may be determined. The study also indicates the type of deformation that can be expected in a wide variety of frozen soils with a wide range of properties under the action of rapid compressive loads. However, more detailed studies are necessary before implementing these results with a high degree of accuracy for a wider range of fine-grained soils at different temperature conditions.

#### Conclusions

The following conclusions may be drawn from the present study and would be true only for the soils tested unless verified for other soils. These findings are consistent with those of Sayles and Carbee (1981) for a non-plastic silt tested at  $-1.67^\circ\text{C}$ .



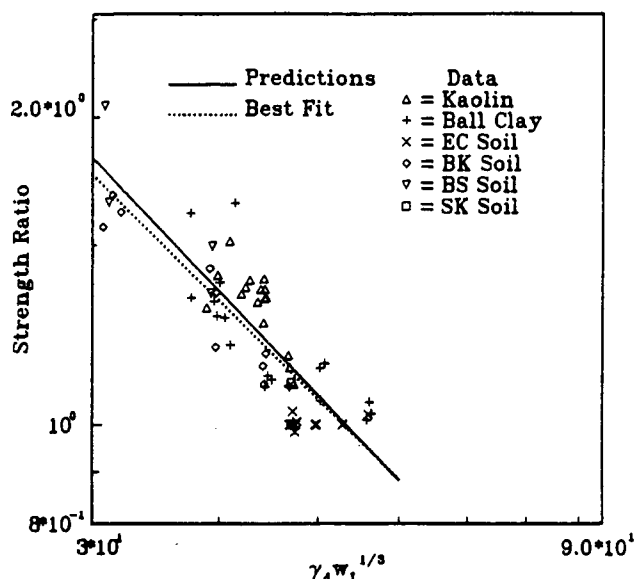


Figure 11. The strength ratio vs  $\gamma_d w_L^{1/3}$  behavior for the frozen soils at  $-5^\circ\text{C}$ .

Saturated fine-grained frozen soils having low total water contents generally exhibit a ductile type of deformation when subjected to compressive strength tests. At high relative water contents of the soil and at low temperature conditions the deformation behavior becomes more brittle. Saturated fine-grained soils having high total water contents generally behave in a brittle manner. At low relative water contents of the soil and at high temperatures a more ductile type of behavior can be expected. However, frozen soils with high specific surface area values may exhibit ductile type of deformation even at large total water contents.

The axial compressive strength of the frozen soils with medium to low dry unit weights approaches a constant

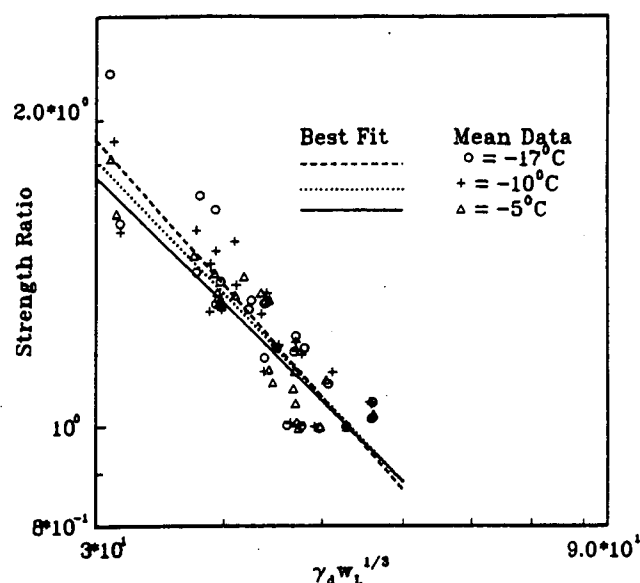


Figure 12. The strength ratio vs  $\gamma_d w_L^{1/3}$  behavior for the frozen soils at various temperatures.

residual value at 20% axial strain. The residual compressive strength of the frozen soils is found to be independent of their dry unit weight at a particular temperature. The residual strength, however, increases with decreasing temperature.

A linear relationship is found to exist between the logarithm of the ratio of peak axial compressive strength to residual axial compressive strength and the logarithm of the function  $\gamma_d w_L^{1/3}$  for the frozen soils studied. This relationship is found to be only slightly influenced by the temperature condition and it can be generally expressed in the form given in Eq. (2) within the investigated temperature range of  $5^\circ\text{C}$  to  $-17^\circ\text{C}$ .

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