STRESS-STRAIN BEHAVIOR OF FROZEN FINE-GRAINED SOILS

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The objective of this experimental study was to investigate the effect of below-freezing temperature, constant axial deformation rates, and soil type on the stress-strain behavior and strength of frozen fine-grained soils. Two soils were selected for this investigation: a highly plastic clay and a clayey silt. Samples were cored out of statically compacted soil cakes and were quickly frozen. Average molding densities and average molding water contents of test samples fell on the wet side of optimum conditions determined by standard Proctor curves of compaction. Constant axial deformation rate tests were carried out on frozen samples at -1, -5, -9, and -22 C, and at different constant axial deformation rates. Two types of stress-strain behavior were exhibited; the brittle type was associated with the clayey silt, and the plastic type was associated with the clay. Results also show a strong dependency of ultimate strength (peak strength) derived from stress-strain curves on temperature for both soils tested. Ultimate strength is also shown to depend on deformation rate. The inference may be drawn that the amount of liquid water present as a thin film between solid and ice surfaces and the ratio of liquid water to ice in a frozen soil are responsible for ice cementation bonds. These bonds in turn control the stress-strain behavior and the ultimate strength of frozen soils.

•IT HAS BEEN SHOWN that engineering properties, such as creep behavior, strength, and thermal properties, of frozen soils are temperature dependent (1, 2, 3, 4, 5). When temperature dips below freezing, the phase composition of water in fine-grained soils changes accordingly. Part of the available water turns into ice, whereas the rest remains as supercooled water.

The amount of unfrozen water in a frozen soil, its nature, and its equilibrium side by side with ice depend primarily on temperature, mineralogy and particle gradation, water content, and molding conditions of the wet soil. Different soils have different phase compositions at a given subzero temperature, and this composition changes appreciably with the lowering of temperature (6). The ratio of frozen to unfrozen water appears to depend on temperature history, salt concentration in the water (2), and lowest temperature reached during freezing (6).

Many theories have been formulated regarding the mechanisms responsible for the presence of unfrozen water in frozen soils. Williams (7, 8) states that capillarity and suction properties of the soil are the cause of the unfrozen water. Others (9) explain it in terms of the oriented water structure. The least structured water freezes first. Additional cooling freezes lesser amounts of water. A film of water, although very thin, exists at the ice-particle interface at very low temperatures. This film, in particular, and the unfrozen water, in general, seem to have significant effect on stress-strain behavior and strain-time behavior of frozen soils. Vialov (5) postulates that strength and deformation of frozen soils are controlled by cohesive bonds resulting from cementation by ice. Such cementing is the result of the bonds between the ice crystals and the mineral particles that are separated by a film of unfrozen water. This type of bond is very unstable because it changes with any variation in the temperature field. Under the

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influence of a load, the ice cementation bonds break up, and partial melting of ice occurs. The water film, which increases because of phase change of ice, moves from zones of high stress to zones of smaller stress where it refreezes in time.

To provide information on the stress-strain behavior of frozen fine-grained soils required that constant axial deformation rate tests be carried out on identically molded samples of a plastic clay soil and a clayey silt soil at several subzero temperatures and at different deformation rates. The test results indicate that stress-strain curves of the frozen samples differ in shape depending on soil type, test temperature, and axial deformation rate. The data show convincingly that ultimate strength derived from strain curves depends strongly on temperature and moderately on axial deformation rate.

TABLE 1
CHARACTERISTICS OF 2 SOILS

Characteristic	Sault Ste. Marie Clay	Lafayette Clayey Silt
Liquid limit	60	24
Plastic limit	25	17
Plasticity index	35	7
Specific gravity	2.79	2.69
Gradation, percentage finer		
2 mm	100	100
0.06 mm	90	92
0.002 mm	60	8

EXPERIMENTAL PROGRAM

Soils Studied

The 2 soils selected for this investigation were a red plastic clay obtained from Sault Ste. Marie, Michigan, and a tan glacial clayey silt obtained from a location near Lafayette, Indiana. The Sault Ste. Marie clay was used previously by the author (1). The characteristics of both soils are given in Table 1. The mineral contents of the clay are illite, vermiculite, and chlorite. Illite and quartz are predominant in the clayey silt. The compaction moisture-density relations obtained by using the standard Proctor test are shown in Figure 1.

The major difference between the soils selected is the degree of plasticity and particle gradation. When mixed with sufficient water, the clay soil behaves like putty, whereas the clayey silt has no apparent plasticity when worked by hand.

Molding of Test Samples

The clay and the clayey silt were allowed to air-dry. Then they were processed by crushing and sieving until they passed the No. 40 sieve. Distilled water was added to the air-dried soil in predetermined quantities according to the desired molding conditions. Vigorous periodic hand mixing of the moistened soil ensured even water content distribution prior to molding. The prepared soil was statically compacted in a 12-in. diameter mold specially made for this investigation.

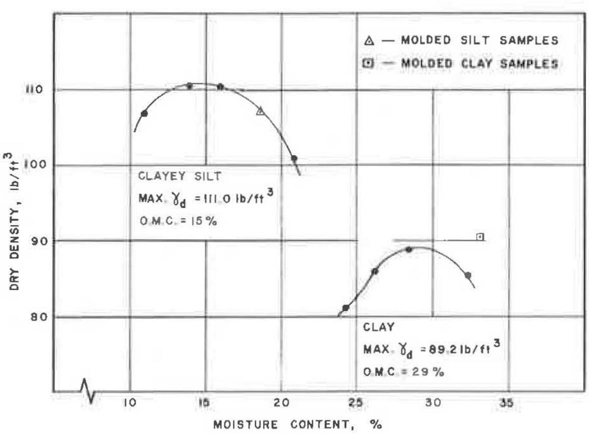

Figure 1. Moisture-density relations determined by using the standard Proctor compaction test.

In the molding process, a predetermined weight of the soil-water mix was placed evenly in the large cylindrical mold (12 in. in diameter and 6 in. high) and was subjected to static load by using a Tinus-Olsen loading machine. The desirable axial load was applied to the wet soil in the mold through a plunger and was maintained constant for a period of about 10 min until desirable density was reached. The compacted soil cake was taken out of the mold, sliced into 21 pieces, wrapped individually in aluminum foil, and covered with wax pending later use. Cylindrical test samples were prepared as needed from the waxed pieces by punching a cylindrical mold through covered pieces with a hand press (Fig. 2). The cylindrical soil cores were taken out of the split mold (1.3 in. in diameter) and trimmed to the desired height. This coring process was selected over trimming with a soil lathe because of its ease in producing samples with identical cross sections, which are difficult to obtain when the trimming method is used.

Figure 2. Compacted soil piece in wax (left), cylindrical split mold with soil core in it (center), and trimmed sample in a rubber membrane with Lucite disks on top and bottom (right).

The method described in the foregoing permitted preparation of good cylindrical samples with no surface cracks or cavities. It is believed that the structure of the molded samples is the flocculated type associated with an edge-to-face particle arrangement as a result of the static method of compaction applied. Molded samples fell on the wet side of the standard Proctor curve of compaction (Fig. 1) for both soils. Dry densities and water contents of individual samples were within 2 percent of the average density and average water content of all samples used in this investigation.

Sample Preparation and Freezing

The molded soil samples were weighed and measured. Their initial water content was determined. Lucite disks were placed on each end of the cylindrical samples with specially prepared friction reducers to minimize end friction during deformation of samples. The friction reducers consisted of a perforated sheet of aluminum foil coated with a thin layer of silicone grease and covered with a polyethelene sheet on the top and bottom. Rubber membranes were placed over samples with tightly fitting rubber bands placed around the Lucite disks, thereby preventing any loss in moisture prior to or during testing. Samples were then placed in a pan filled with water and were stored at ambient temperature for a period of about 2 weeks before freezing to minimize thixotropic effects.

Test samples were mounted in a triaxial cell, secured in place on the pedestal of the cell, and quickly frozen by filling the cell with a coolant. The coolant, a mixture of ethylene glycol and water, circulated around the cell at a constant temperature by pumping the coolant through a low-temperature bath. All test samples were cooled 3 C below test temperature, then warmed up to test temperature, and left to reach equilibrium for at least 12 hours before they were tested. Freezing of cylindrical samples begins on the surface and progresses inward. Water in large spaces freezes first, and the ice-water interface will extend into smaller spaces and channels until faced with too small a space to allow ice to grow. There the water in the space will remain supercooled as long as the temperature of the sample is constant.

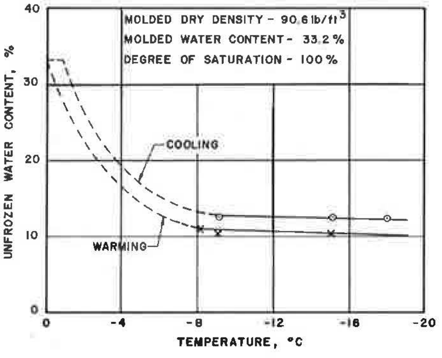

Figure 3. Unfrozen water content versus temperature for Sault Ste. Marie clay.

A sample warmed from a colder temperature to a test temperature will have more moisture frozen than a duplicate sample that is cooled to test temperature. Figure 3 shows the variation of unfrozen water content with temperature for a typical molded sample of Sault Ste. Marie clay. This was determined by the calorimetric method similar to the procedure used by Lovell (6). Reproducibility of calorimetric results for the clayey silt, used in this investigation, was poor and therefore is not reported here.

Equipment and Testing

The triaxial cell, with the sample mounted in it, was immersed in a circular tank filled with a mixture of ethylene glycol and water (Fig. 4), which was maintained at a constant temperature by circulating it through an adjacent cold temperature bath. Temperature fluctuations near sample were less than ±0.05 C because of delayed temperature response in the triaxial cell as compared to larger variations in the cold temperature bath. Constant axial deformation rates were applied to the loading ram of the triaxial cell by using a variable speed mechanical loading system. Axial loads were measured with a load cell mounted on top of the loading ram and connected to an automatic recorder. Loads were recorded with an accuracy close to ± 2 lb. Uniaxial deformations were determined by means of a linear variable differential transformer connected to a strip chart recorder. LVDT readings were checked occasionally with a 0.0001 in. per division dial gage mounted on the triaxial cell and were substituted for chart readings whenever power fluctuations in line affected the accuracy of such readings. The recorder used a 10-in. wide strip of paper that permitted accurate measurement of sample deformation and served as a permanent record of the test.

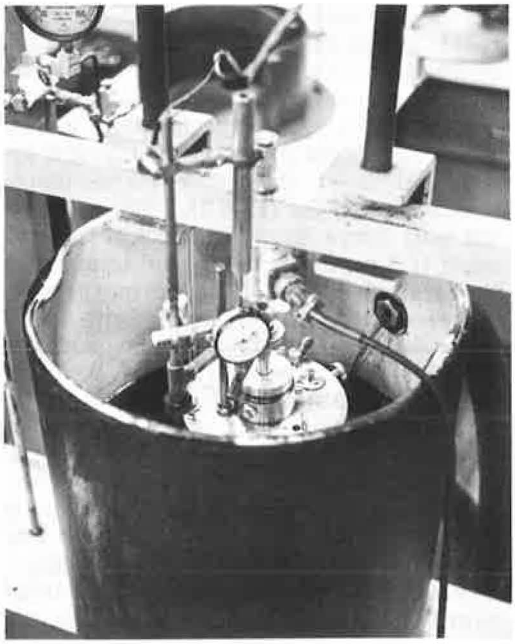

Figure 4. Triaxial cell in tank with coolant circulating.

EXPERIMENTAL RESULTS

Constant axial deformation rate tests were carried out on frozen cylindrical soil samples of clay and clayey silt at several temperatures below freezing. Deformation rates were maintained constant by means of a variable speed mechanical loading system. A summary of the characteristics of the 2 soils used is given in Table 1. Results of the constant axial deformation rate tests are presented in 2 groups according to the soil type.

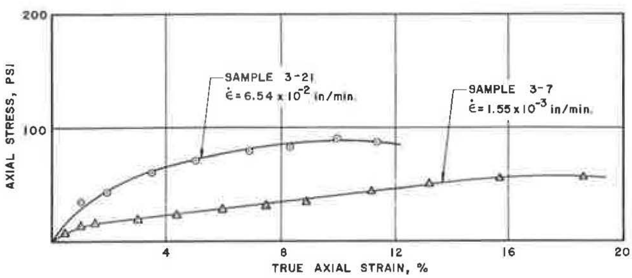

Figure 5. Typical stress-strain curves at −1 C for Sault Ste. Marie clay.

Clay Samples

Typical stress-strain curves for identically prepared and frozen Sault Ste. Marie clay samples deformed at constant deformation rates are shown in Figures 5, 6, 7, and 8. The average molded dry density and average molding water content were 90.6 lb/ft^3 and 33.2 percent respectively. Test temperatures were -1 C (Fig. 5), -5 C (Fig. 6), -9 C (Fig. 7), and -22 C (Fig. 8). At each temperature 2 tests are shown, one for deformation at a

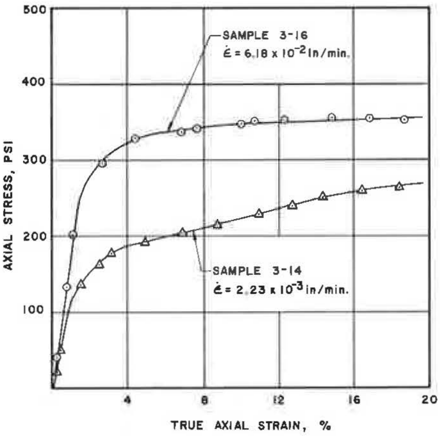

Figure 6. Typical stress-strain curves at −5 C for Sault Ste. Marie clay.

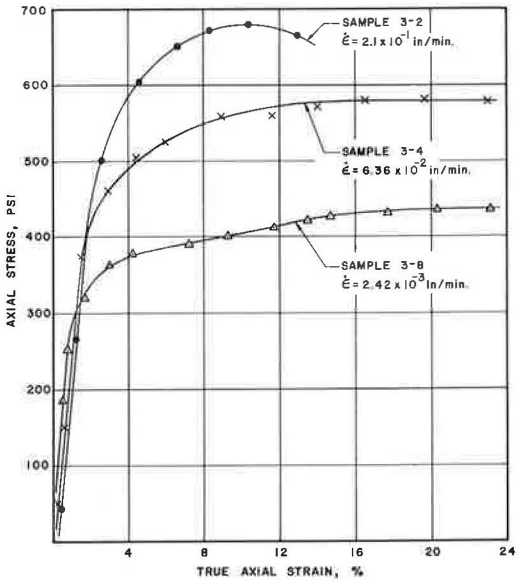

Figure 7. Typical stress-strain curves at −9 C for Sault Ste. Marie clay.

fast rate and one for deformation at a relatively slow rate, except that for temperature -9 C (Fig. 7) 3 different rates of deformation are shown. Tests shown in Figure 9 were conducted at approximately the same rate of deformation. Thus, different stress-strain curves (Fig. 9) reflect the effect of temperature alone on the stress-strain behavior.

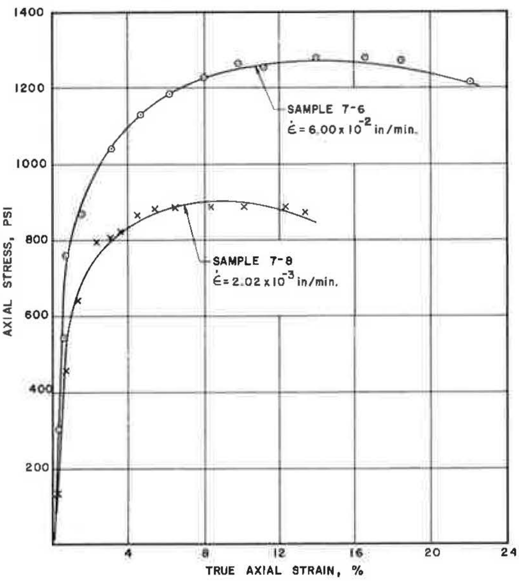

Figure 8. Typical stress-strain curves at −22 C for Sault Ste. Marie clay.

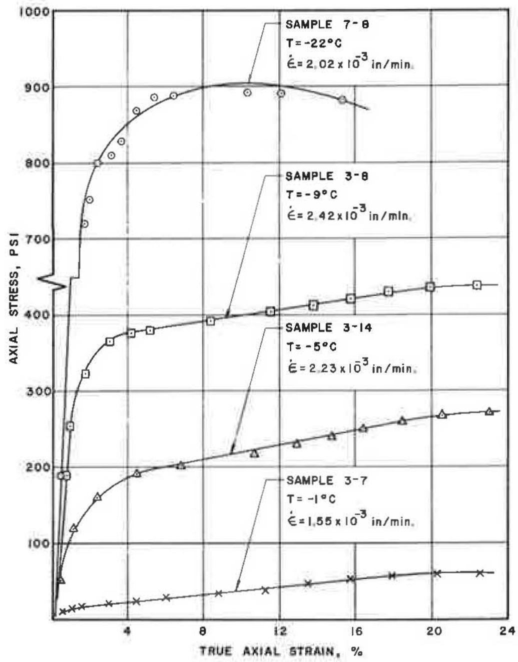

Figure 9. Stress-strain curves at different subzero temperatures and approximately constant axial deformation rate for Sault Ste. Marie clay.

Data shown in Figures 5, 6, 7, 8, and 9 reveal the following:

1. The stress-strain behavior differs depending on the deformation rate. The initial part of these curves at a particular temperature does not seem to be affected by deformation rates. This is the so-called elastic part of the stress-strain diagram that would correspond to expulsion of air present in the sample and to elastic changes in the crystal lattice of the ice and mineral particles. The major portion of this strain is recoverable when load is lifted.

2. The effect of deformation rate becomes well pronounced when samples begin to deform plastically. This is observed in all samples at all temperatures. It is apparent that the faster the deformation rate is, the higher the ultimate strength reached by the sample will be.

3. At relatively slow rates, samples appear to gain resistance to deformation (such as sample 3-14 in Fig. 6 and sample 3-8 in Fig. 7) while deforming plastically. This is a strain-hardening phenomenon that was not observed at -22 C. Samples that deformed slowly at -1, -5, and -9 C kept flowing under load, and ultimate strength, once reached, was almost constant the remainder of the test duration. No fracture or sudden failure resulted in the preceding samples in comparison with samples deformed at -22 C where sudden failure took place on all samples strained at this temperature. It appears that samples deformed at -9 C and higher exhibit considerable viscous flow especially close to the melting point of ice (-1 C), whereas samples deformed at -22 C were less viscous and more brittle.

Clayey Silt Samples

Typical stress-strain curves for identically prepared and frozen clayey silt samples deformed at constant deformation rates are shown in Figures 10 and 11. The average molded dry density and average molding water content were 107 lb/ft^3 and 18.6 percent respectively. Samples 5-10, 5-5, and 5-13 shown in Figure 10 were deformed at constant temperature (-5 C) but at varying deformation rates, indicating that the faster the rate of deformation was, the higher the ultimate strength was. Samples 5-13 and 5-17 reflect the effect of different temperatures (-5 and -1 C) at identical deformation rates. The following observations can be made for the clayey silt soil:

1. The elastic portion of the stress-strain curves appears to be smaller than that of the highly plastic clay at comparable

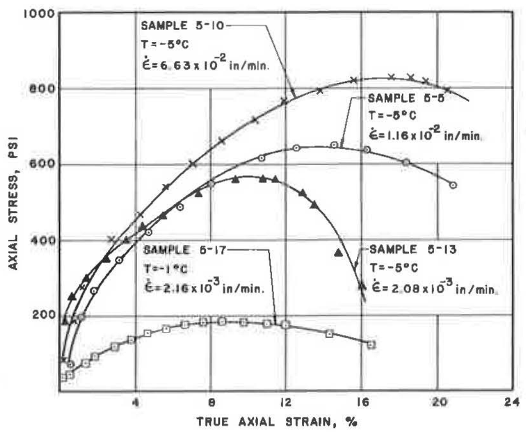

Figure 10. Stress-strain curves at −1 C, −5 C, and different axial deformation rates for Lafayette clayey silt.

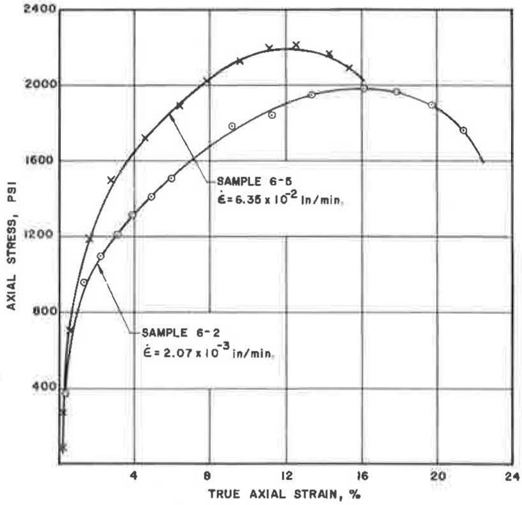

Figure 11. Typical stress-strain curves at −22 C for Lafayette clayey silt.

temperatures and deformation rates. Deformed samples exhibit well-pronounced stress-strain curves with well-defined peaks.

2. Samples deformed at rates and temperatures comparable with those of the clay soil samples reach peak strength at smaller strains. All samples fail by sudden rupture shortly after peak strength has been reached, except at -1 C where some viscous flow has been exhibited.

3. Most of the samples tested in this category demonstrated definite failure surfaces with an approximate angle of 60 deg in the major principal plane.

DISCUSSION OF RESULTS

Based on the experimental data presented, it seems possible to distinguish between the behavior of those samples that deformed and failed shortly after deformation in a brittle fashion and those samples that deformed rather excessively with no visible fracture or sudden failure, which is referred to here as plastic failure. The first type of deformation and failure was exhibited by the clayey silt, except at a high temperature (-1 C), and the latter type was exhibited by the plastic clay, except when the temperature was too low (-22 C) or the deformation rate was too large (2.1×10^{-1} in./min).

When a sample fails in a brittle fashion, the inference may be drawn that the ice cementation bonds between ice crystals and mineral particles have been overcome and destroyed completely. On the other hand, in a plastic type of failure these bonds seem to stretch permitting mineral particles to slide past one another and to rotate from their initial positions so that bonds are preserved and the material remains intact. The extent to which particles can rotate or slide past one another is dependent on the amount of liquid water and on the ratio of liquid water to ice present in a sample. The liquid water exists as a film of variable thickness between solid and ice surfaces. The thickness of this film depends strongly on temperature and soil type.

Ultimate strength values derived from stress-strain curves shown in Figures 5 through 11 as a function of test temperature at constant rates of deformation are shown in Figure 12. The linear variations shown are meant to be used in a relative sense. Both soils exhibit strong dependency of ultimate strength on temperature. For example, the approximate ratio of ultimate strength at -22 C to that at -5 C was 3.6 to 1 for the clayey silt and 3.3 to 1 for the clay soil at the same deformation rate of 2.1×10^{-3} in./min.

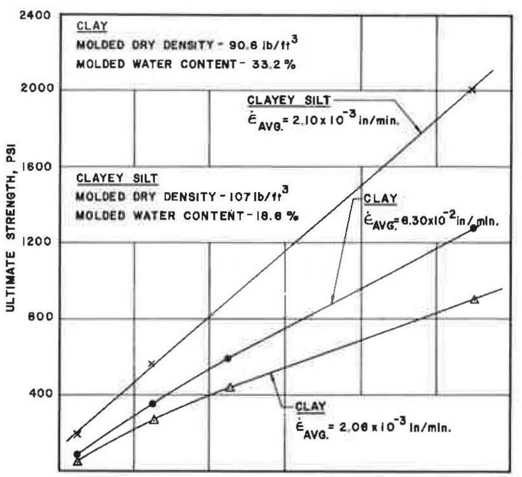

Figure 12. Ultimate strength derived from stress-strain curves versus subzero temperature for Sault Ste. Marie clay and Lafayette clayey silt.

Both soils have shown moderate deformation rate effect (Fig. 12); that is, the strength increases with increasing deformation rates. For example, the ultimate strength of the clay soil increases approximately 30 percent as the axial deformation rate increases from 2.06×10^{-3} in./min to 6.30×10^{-2} in./min. This is a rate increase of the order of 33 times.

CONCLUSIONS

In this investigation, constant axial deformation rate tests were carried out on identically molded and frozen cylindrical soil samples in an attempt to gain information concerning the effects of soil type, subzero temperature, and axial deformation rates on the stress-strain behavior of frozen fine-grained soils. From the results of the testing, the following conclusions have been drawn:

1. Two types of stress-strain behavior have emerged—a brittle type associated

with low plasticity soils (clayey silt) and a plastic type of failure associated with high plasticity soils (clay);

2. Low plasticity soils exhibit plastic behavior when temperature is relatively high (-1 C), and high plasticity soils exhibit brittle behavior when temperature is relatively low (-22 C) or when axial deformation rates are rather fast (0.21 in./min) or when both occur;

3. Ultimate strength derived from stress-strain curves depends strongly on temperature, and, based on molding conditions and soils used here, seems to increase about 3-1/2 times as the temperature decreases from -5 C to -22 C;

4. Ultimate strength depends moderately on deformation rate and increases by 30 percent when deformation rate increases from about 0.002 to 0.063 in./min; and

5. Data in this investigation suggest that it is primarily the amount of liquid water and the ratio of liquid water to ice present in a frozen soil matrix that control its stress-strain behavior and its ultimate strength.

ACKNOWLEDGMENTS

The author acknowledges and is grateful for the support provided by the National Science Foundation for this investigation. This paper is a portion of the research work on creep and strength of frozen soils carried out at Drexel University, Philadelphia, Pennsylvania. Further appreciation is extended to the College of Petroleum and Minerals, Dhahran, Saudi Arabia, for its support and encouragement.

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