Mechanical Properties of Frozen Soil

O. B. ANDERSLAND

A review of the following data on frozen soils was presented by Dr. O. B. Andersland at the Research Seminar on Construction Problems in Permafrost held at the University of Saskatchewan on March 11-12, 1971.

Interest in the mechanical properties of frozen soil has increased with the demand for more basic design criteria for structures built in or on permafrost. Some of the questions raised include what effect do temperature, deformation rates, and relative amounts of ice and soil have on peak compressive strength? When segregated ice formations are present in the frozen soil does the overall response to loads depend primarily on ice behavior? For long term or sustained loads how can time-dependent behavior of the frozen soil be introduced into realistic design criteria? The following experimental data raise some interesting possibilities as to field design applications.

Peak Strength

Peak strength data (Goughnour and Andersland, 1968) based on constant axial strain rate tests on ice and frozen saturated sand are summarized in Figure 1. The Ottawa sand, sized between the No. 20 and No. 30 U.S. standard sieves, was formed into samples at low sand volume concentrations by uniformly mixing natural snow with a selected proportion of precooled sand, placing this mixture into a mold, and pouring precooled water into the mixture. Little snow melted during this process and sand particles remained in dispersed positions during freezing.

The relative amounts of ice and soil have a large effect on both peak strength and creep behavior. The data show a bilinear relationship with interaction between sand particles drastically increasing the peak strength at close to 42 percent sand by volume. At low sand volume concentrations the increase in strength appears to be related to faster deformation rates required in the remaining ice matrix to accommodate the overall sample deformation. At high sand-volume concentrations interparticle friction and dilatancy of sand particles come into prominence. Dilatancy must act against the cohesion of the ice matrix and the adhesion between sand grains and ice creating an effect analogous to higher effective stresses.

Superimposed on the effect of relative amounts of ice and soil are strain-rate effects. The upper two curves in Figure 1 show the influence of strain-rate differences at the same temperature. The strain-rates shown differ only by a factor of two. This effect carries through for both the ice and the full range of sand volume concentrations. The upper and lower curves in Figure 1 show the influence of temperature on peak strength on ice over the full range of sand volume concentrations. Changes in unfrozen water content are not a factor in these tests since essentially all the water is frozen at both temperatures.

Creep Strength

Creep strength may be defined in terms of the stress level corresponding to an allowable secondary creep rate. This creep rate might be determined by the allowable total deformation less primary creep and the required service life for a frozen soil element or structure constructed in or on permafrost. To provide new information on this creep strength, a series of step-stress creep tests were conducted on samples containing 64 percent by volume Ottawa sand. Sample deformation versus time is shown in Figure 2. The axial stress was held constant by a hanger type dead load. Zero cell pressure was maintained until deformation had progressed into the secondary creep region. An increment of confining pressure was then applied and the ram load increased to keep a constant stress difference. This loading process was repeated at 30 minute intervals until the cell pressure reached 150 psi. The jump in

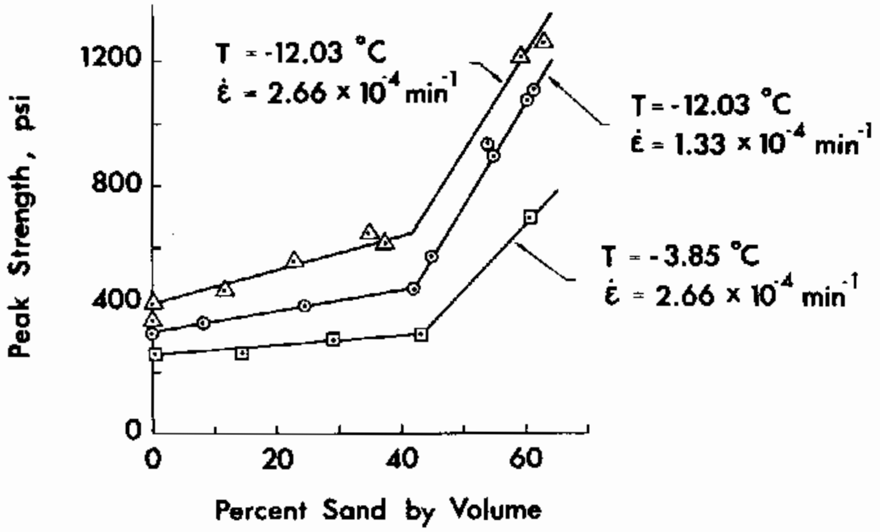

Figure 1. Peak strength versus percent Ottawa sand by volume.

strain at each change in confining pressure corresponds to elastic expansion in the triaxial cell tie rods. Test results (Andersland and AlNouri, 1970) are summarized in Figures 3 and 4.

For any given value of stress difference D and temperature T it was found that the axial creep rate $\dot{\epsilon}_1$ decreased exponentially with increase in the mean stress,

$$\sigma_m = {}^1/_3 (\sigma_1 + 2\sigma_3),$$

as shown by each of the straight lines of identical slope m in Figure 3. A stress parameter, $\Sigma = D - \sigma_m$, was selected for convenience in curve fitting the trixial type test data. The only difference in the three tests illustrated in Figure 3 is the magnitude of the stress difference D. The equation of these lines is of the type

$$\dot{\epsilon}_1 = b \exp (m\Sigma)$$

where b is the intercept of the line on the $\Sigma = 0$ axis. The data confirm that $b = C \exp (n\ D)$ where C and n are constants. Hence for tests at a given temperature,

$$\dot{\epsilon}_1 = C \exp (N\ D) \exp (-m\sigma_m) \quad (1)$$

where $N = n + m$.

Tests on four duplicate sand-ice samples all subjected to the same stress difference D with each at a different temperature T are shown in Figure 4. Again each line can be represented by an equation

$$\dot{\epsilon}_1 = b \exp (m\ \Sigma)$$

but now the data show that $b = C' \exp (-L/T)$ so that for a given stress difference D

$$\dot{\epsilon}_1 = C' \exp (-L/T) \exp (m\ \Sigma) \quad ((2)$$

where C′ and L are constants. Equations (1) and (2) suggest that, more generally,

$$\dot{\epsilon}_1 = A \exp (-L/T) \exp (N\ D - m\sigma_m) \quad (3)$$

where A, L, N, and m are constants determined by experiment. Data (Andersland and AlNouri, 1970) show a similar relationship for frozen Sault Ste. Marie clay.

At any stage of these creep tests the major and minor principal stresses are

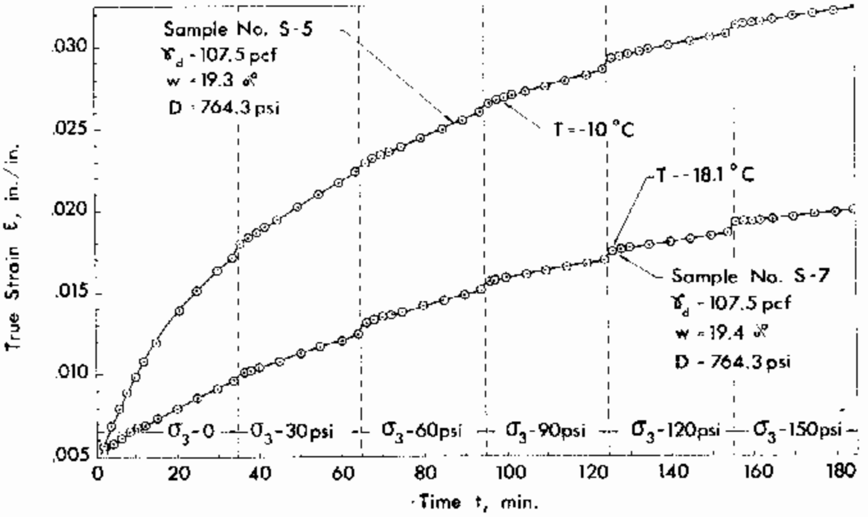

Figure 2. Step-stress creep tests on sand-ice at temperatures of -10°C and -18.1°C

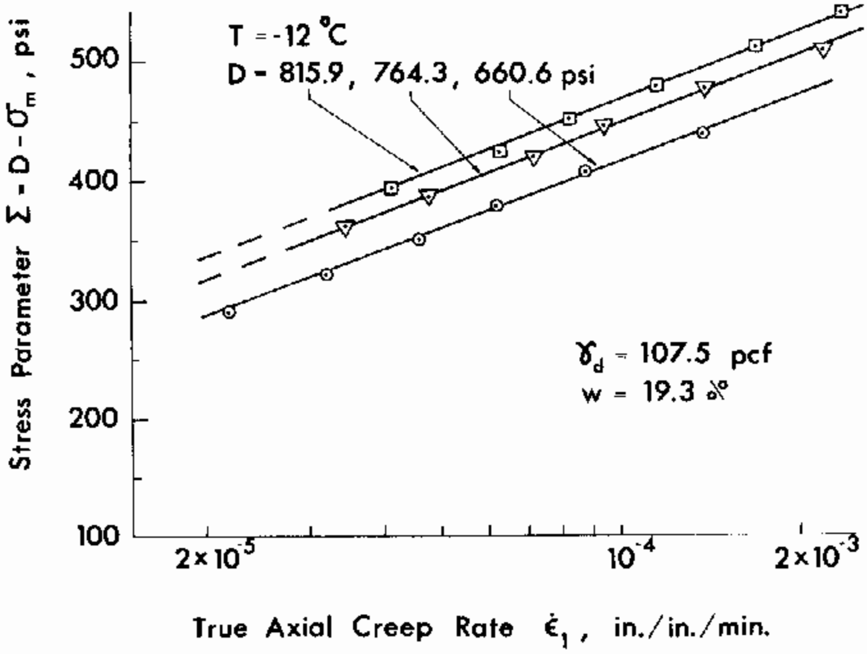

Figure 3. Effect of $D = \sigma_1 - \sigma_3$ on creep rate versus stress for sand-ice samples.

$$p = \frac{\sigma_1 + \sigma_3}{2} \qquad q = \frac{\sigma_1 - \sigma_3}{2}$$

plot. From the data for all creep tests on the sand-ice material it was possible, for any specified creep rate and temperature, to plot several such stress circles; these were found to have a straight line envelope as illustrated for several creep rates and one temperature in Figure 5. The intercepts on the q axis and the slopes of these lines showed that for the saturated frozen Ottawa sand: (1) the angle of internal friction was constant (equals 37 degrees) and independent of creep rate, and (2) the cohesion is smaller at slower creep rates and is some function of temperature. In contrast to the step-stress creep test results, constant axial, strain-rate tests (Andersland and AlNouri, 1970) showed a much smaller effect on confining pressure on the peak strength of the frozen saturated sand.

These experimental results show that the peak strength of frozen soil will be influence by deformation rates, temperature, and relative ice and soil contents. Unfrozen water content will influence strength indirectly by reducing the ice content. Creep strength is improtant for long term or sustained loads. Either lengthy creep tests or special test techniques are needed to evaluate creep strength. The step-stress creep test discussed above appears to have merit for obtaining design parameters. More laboratory and field research is needed to expand our knowledge on the strength behavior of frozen soils.

References

Andersland, O.B. and I. AlNouri (1970) "Time-dependent strength behavior of frozen soils," **Soil Mechanics and Foundation Div.** ASCE, Vol. 96, No. SM 4, pp. 1249-1265.

Goughnour, R. R. and O. B. Andersland (1968) "Mechanical properties of a sand-ice system," **Soil Mechanics and Foundation Div.,** ASCE, Vol. 94, No. SM 4, pp. 923-950.

O.B. ANDERSLAND, Prof. of Civil
Engineering, Michigan State Univ.,
East Lansing, Michigan 48823

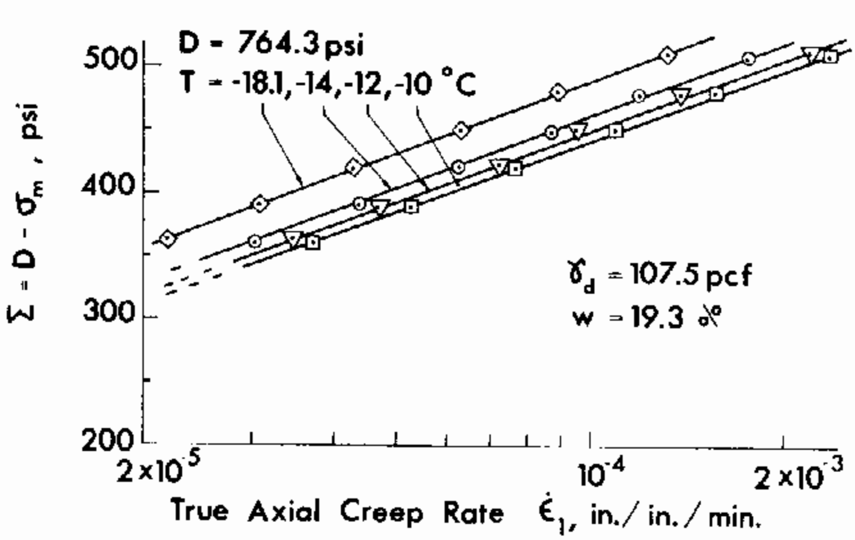

Figure 4. Temperature effect on creep rate of sand-ice samples at D = 764.3 psi.

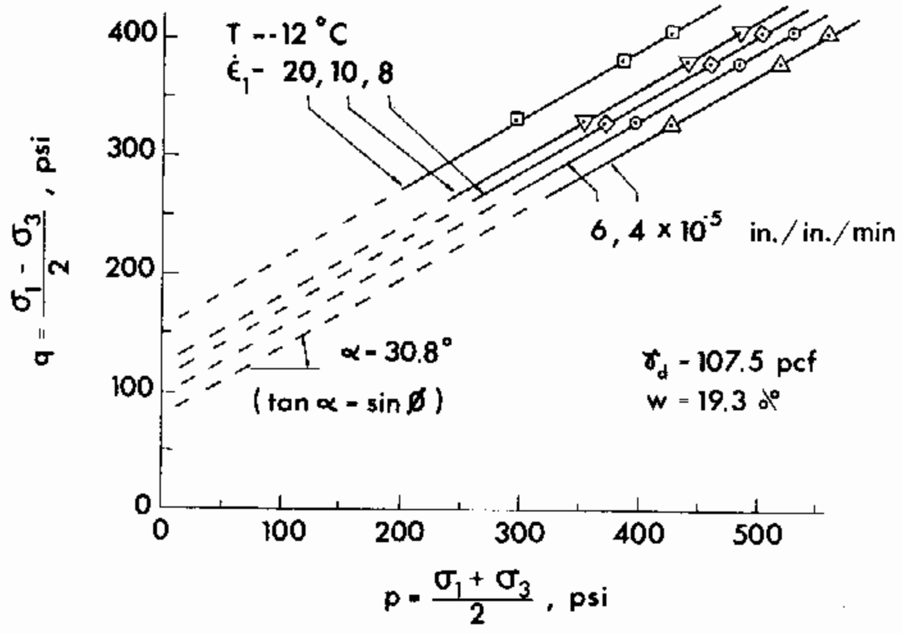

Figure 5. Creep rate effect on strength of frozen saturated Ottawa sand samples at -12° C.