

Confined and unconfined compression tests on frozen sands

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The design of foundations in permafrost, excavation of frozen ground, and artificial freezing of ground to provide temporary support during construction of tunnels and other underground structures require understanding of the mechanical properties of frozen soils. This paper describes the equipment and procedures developed by the authors to determine the compressive strength of artificially frozen sands under confined and unconfined conditions at different temperatures and strain rates. A comparison of the results obtained under various conditions is made to assess the effects of testing conditions on the strength, strain at failure, and deformation behaviour of frozen sand. This comparison should assist in the standardization of laboratory testing procedures for the determination of the mechanical properties of frozen soils.

La conception des fondations dans le pergélisol, l'excavation dans le sol gelé et la congélation artificielle du sol pour fournir un appui temporaire pendant la construction de tunnels et autres structures souterraines nécessitent une connaissance des propriétés mécaniques des sols gelés. Cette communication décrit l'équipement et les méthodes développés par les auteurs pour déterminer la résistance à la compression des sols gelés artificiellement tant dans des conditions confinées que sans confinement latéral, à des températures et vitesses de déformation différentes. On compare les résultats obtenus dans diverses conditions afin de pouvoir évaluer les effets des conditions d'essai sur la résistance, la déformation à la rupture et le comportement de déformation du sable gelé. Cette comparaison devrait aider à normaliser les méthodes d'essai en laboratoire servant à déterminer les propriétés mécaniques des sols gelés.

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Specimens and Testing Machines

Mechanical behaviour of frozen soils is greatly affected by such factors as specimen homogeneity, grain-size, total moisture content, ice content, dry density, strain rate, and the state of stress. In order to evaluate testing procedures and techniques, it was necessary to produce a large number of identical frozen specimens. Frozen saturated sand was chosen as the standard material in this present test series because the technique for controlling the aforementioned factors was well established. Ottawa sand of specification ASTM C-109 was compacted, saturated, and frozen unidirectionally following a procedure described by Baker (1976). The average moisture content of the frozen specimens at the time of testing was about 19 to 20 per cent by dry weight and their dry density was about 1,670 kg/m³. All tests were carried out on floor model screw-driven universal testing machines of 250 kN capacity.

Unconfined Compression Tests ($\sigma_3 = 0$ MPa)

Unconfined compression tests were carried out on test specimens 50 and 75 mm in diameter having

length/diameter ratios greater than 2. Strain rates were varied between 10^{-7} and 10^{-2} /s. Some tests were performed with the specimens exposed to the ambient temperature in a cold room maintained at -6°C . For these specimens sublimation was prevented by a cellophane wrapper. The test set-up is shown in Figure 1. An extensometer consisting of three displacement transducers located on the specimens 120° apart around the circumference, measured the axial deformation and tilting of the specimen.

Figure 2 shows the low-temperature bath arrangement for unconfined compression tests at temperatures between -2 and -15°C . Specimens were immersed in kerosene during the tests to control the temperature to $\pm 0.1^\circ\text{C}$ and to prevent sublimation of ice. No membrane was used to isolate the specimen from the kerosene. The bath temperature was maintained with an immersed heat-exchange coil through which methanol was circulated from a Tenney low-temperature bath.

Results from unconfined compression tests at various temperatures, discussed in detail by Parameswaran (1980), are summarized in Figure 3. The peak stress (compressive strength) increases with increasing

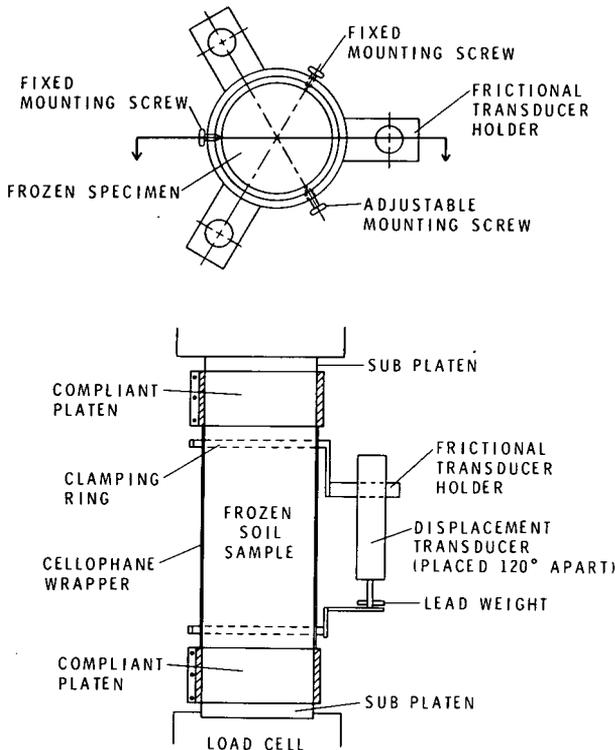


FIGURE 1. Schematic diagram of unconfined compression testing apparatus showing extensometer mounted on the specimen.

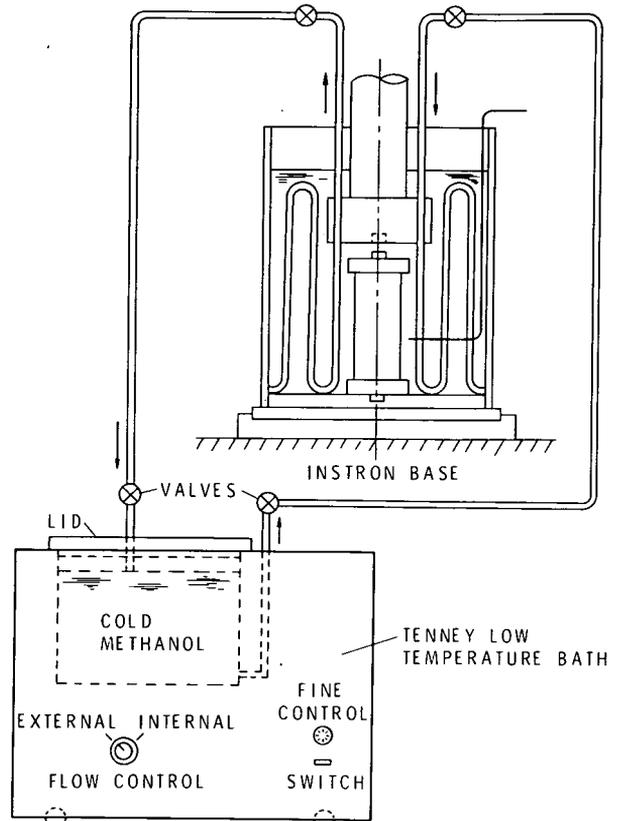


FIGURE 2. Low-temperature bath for unconfined compression testing.

strain rate and decreasing temperature. At -2°C , for rates above $10^{-5}/\text{s}$, the strength was independent of strain rate, but decreased rapidly for strain rates below $10^{-5}/\text{s}$. This may be due to an increase in the amount of unfrozen water at -2°C in the samples under stress, and the increased mobility of this unfrozen water at low strain rates.

Tests with various types and configurations of platens showed that neither the unconfined compressive strength nor the axial strain at the peak stress were significantly affected by the type of platen (Baker 1979). Figure 4 shows the variation of unconfined

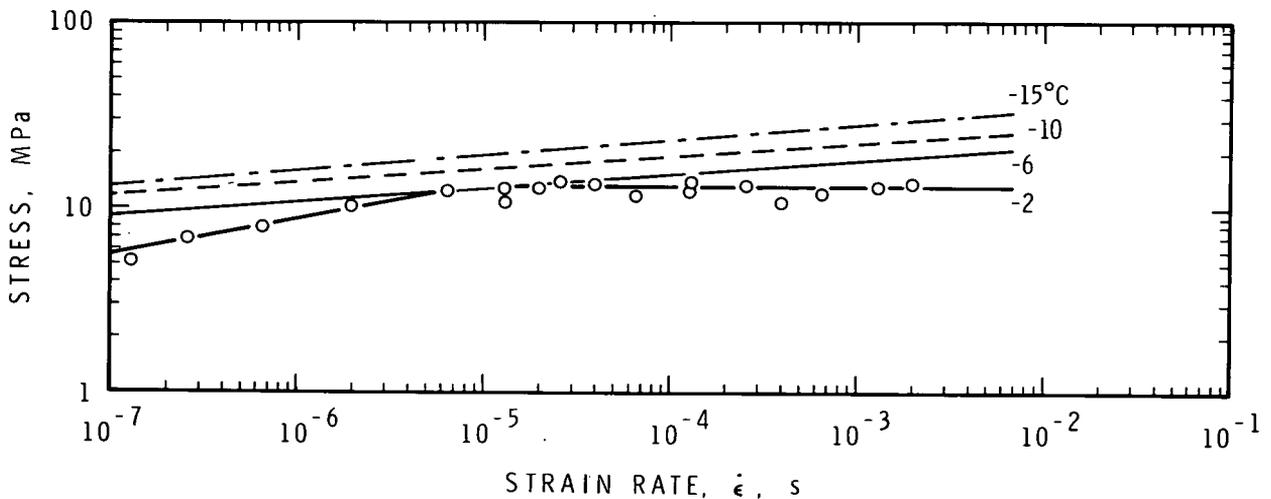


FIGURE 3. Variation of compressive strength with strain rate and temperature.

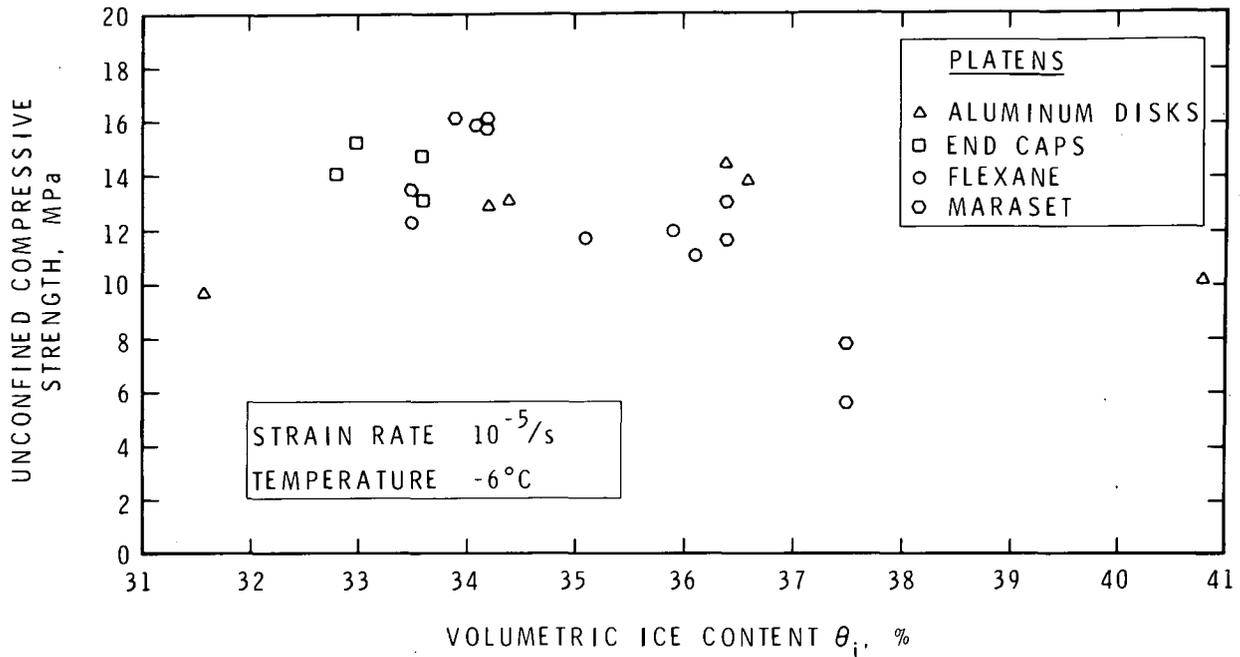


FIGURE 4. Effect of ice content on unconfined compressive strength.

compressive strength with volumetric ice content, θ_i . The volumetric ice content of the frozen sand specimens was found to vary between 31.5 to 41.0 per cent with 83 per cent of the specimens in the 34.5 ± 2 per cent range. The compressive strengths of these specimens varied between 5.6 and 16.2 MPa with 83 per cent of the specimen in the range 10.5 and 16 MPa. The compressive strengths obtained by different end conditions were within the same range. For this reason, one cannot separate the effect of end conditions on the compressive strength from the effect of ice content. A similar situation was found for the axial strain at the peak stress (Baker 1979). It was determined that the type and configuration of the end condition affected the slope of the stress-strain curve and the axial strain at the peak stress when testing at low strain rates.

Confined Compression Tests

Low Confining Pressures ($\sigma_3 = 0$ to 0.35 MPa)

A specially designed double-walled triaxial cell was constructed to carry out tests under low confining pressures. A volume measurement device developed by Mitchell and Burn (1971) was modified to measure automatically the volume displacement of the triaxial cell fluid at low temperatures. This allowed measurement of the total volumetric deformation of the test specimen under load. The axial deformation was measured using a displacement transducer mounted

between the piston and the cell. The apparatus used in these low-pressure tests is shown in Figure 5.

Tests were carried out at strain rates between 10^{-6} and $10^{-4}/s$, at a temperature of $-6^{\circ}C$. Figure 6 shows typical stress-strain and volumetric strain versus axial strain curves for specimens tested at a confining pressure of 0.28 MPa.

Figure 7 shows the variation of maximum deviatoric stress $(\sigma_1 - \sigma_3)_{max}$ with axial strain rate at $-6^{\circ}C$. Figure 8 shows the variation of the strain at peak stress with time to failure. Both figures, also show the results from unconfined compression tests. Figure 8 shows that specimens that attained peak stress in less than 10^2 s show an average strain of one per cent at peak stress and specimens that took longer than 10^2 s have average strains of about four per cent at peak stress. This would seem to indicate that there are two different modes of deformation associated with the unconfined compression tests in the range of strain rates used. The transition between these two modes of deformation occurred at approximately 10^2 s corresponding to a strain rate of $3 \times 10^{-4}/s$.

These results show that confining pressures in the 0 to 0.35 MPa range had very little effect on the stress or axial strain at peak stress for these frozen sands. Effects of confining pressure are well within the scatter of the data. This range of hydrostatic pressure is within the approximate limit of most engineering considerations. Triaxial tests on unfrozen sands of the same density (Lau 1975) have shown that the stress

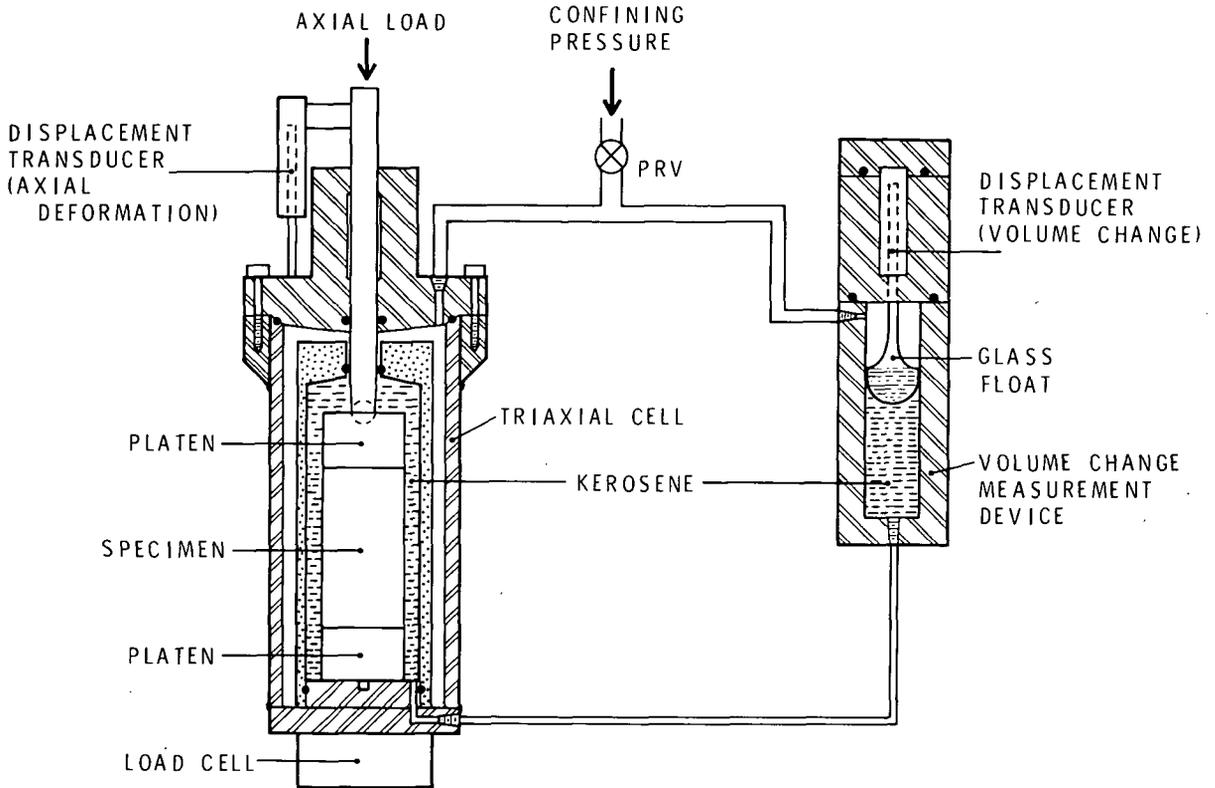


FIGURE 5. Schematic diagram of triaxial apparatus for low-pressure tests.

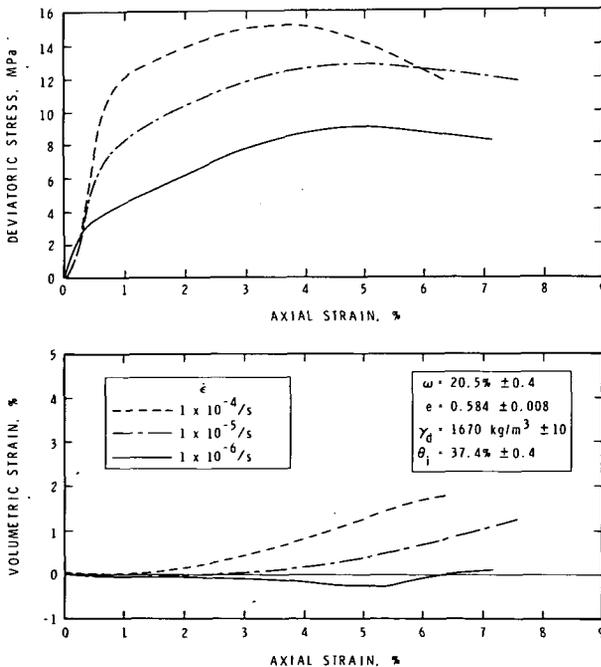


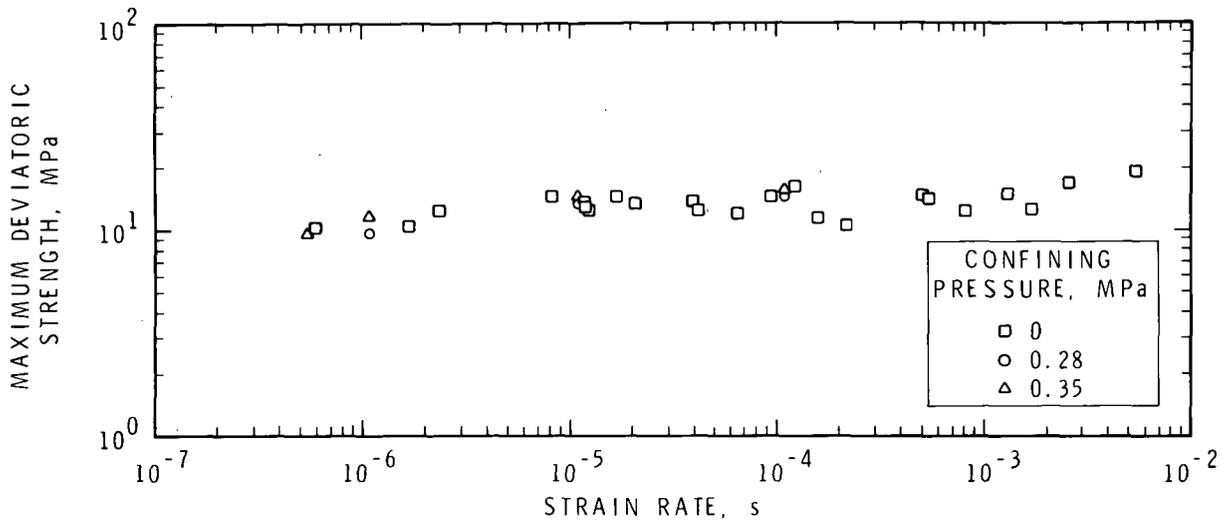
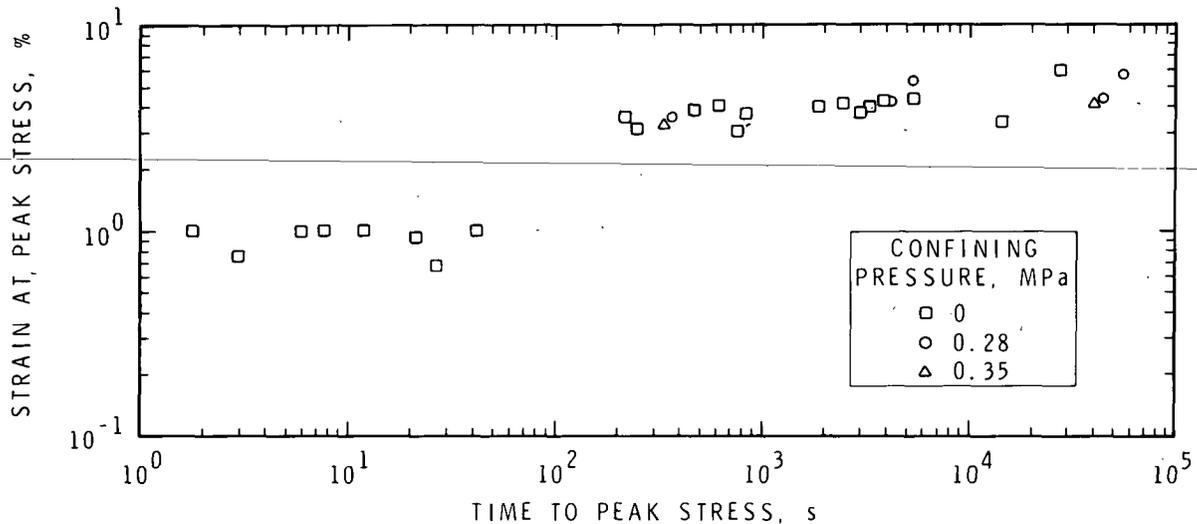
FIGURE 6. Stress-strain-volume curves at a confining pressure of 0.28 MPa at -6°C .

and axial strain at peak stress are significantly affected by confining pressures within this same range.

High Confining Pressures ($\sigma_3 = 0$ to 76 MPa)

Triaxial tests at high confining pressures were carried out in a high-pressure cell having a wall thickness of 100 mm and internal dimensions of 100 mm diameter and 250 mm height. A schematic diagram of the cell is shown in Figure 9. The pressure vessel was surrounded by an environmental chamber maintained at $-10^\circ \pm 1^\circ\text{C}$. Most of the tests were carried out at a strain rate of about $7.7 \times 10^{-5}/s$. Dow Corning silicone fluid 200 was used as the pressurizing medium. Tests were carried out in a closed system. An initial hydrostatic pressure was applied to the specimen and as the piston was forced into the cell the hydrostatic pressure, σ_3 , was increased. No volume change measurements were made. Details of the testing procedure are to be published (Parameswaran and Jones 1981).

The stress-strain curves showed that for strains less than one per cent the stress increased linearly with strain. At low hydrostatic pressures a sharp yield point and a yield drop were observed at the end of

FIGURE 7. Strain rate vs. maximum deviatoric strength at -6°C .FIGURE 8. Time vs. strain at peak stress at -6°C .

this linear region. As confining pressure increased, the yield drop was suppressed and for high confining pressures (> 20 MPa), the transition from the linear to the nonlinear region was smooth. Figure 10 shows some typical stress-strain curves obtained at various confining pressures. Yield and peak stresses are also indicated.

Figure 11 shows the relationship between the hydrostatic confining pressure and the deviatoric stress at yield and at peak stress. The yield and peak stresses increased with increasing hydrostatic pressure up to about 40 MPa, beyond which these stresses dropped. The initial increase in strength with confining pressure is probably due to the closure of voids and microcracks in the sample. Beyond 40 MPa,

pressure melting presumably increased the amount of unfrozen water in the sample and decreased the shear strength. Chamberlain (1973) observed a similar behaviour in high pressure tests, at 51.5 MPa, on frozen Ottawa sand and attributed it to the complete suppression of dilatancy and a resultant increase in pore pressure stimulating pressure melting of the ice phase.

As pointed out by Parameswaran and Jones (1981), tests over a wide range of confining pressures are required to determine the relationship between the maximum deviatoric stress $(\sigma_1 - \sigma_3)_{\max}$, and confining pressure σ_3 , and to determine the Mohr Coulomb strength parameters C (cohesion) and ϕ (angle of internal friction).

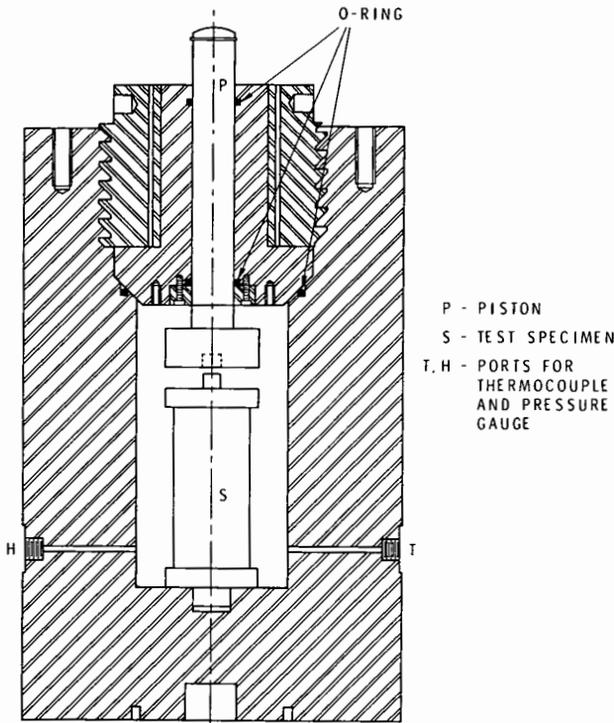


FIGURE 9. Schematic diagram of the high-pressure cell.

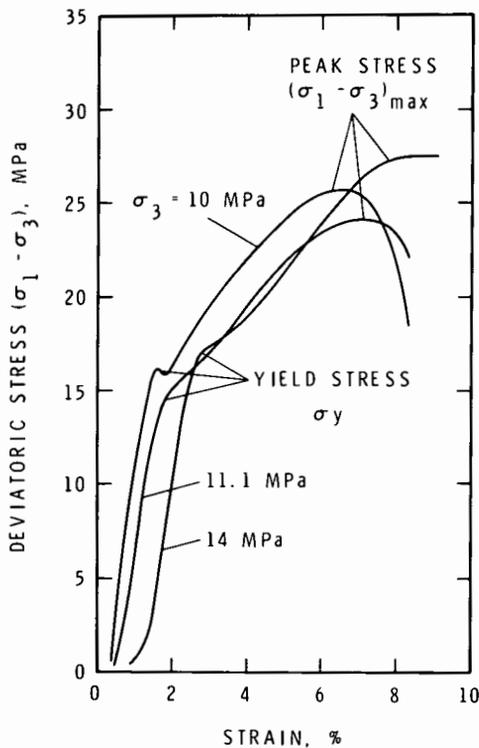


FIGURE 10. Stress-strain curves of frozen sand under high confining pressures, σ_3 .

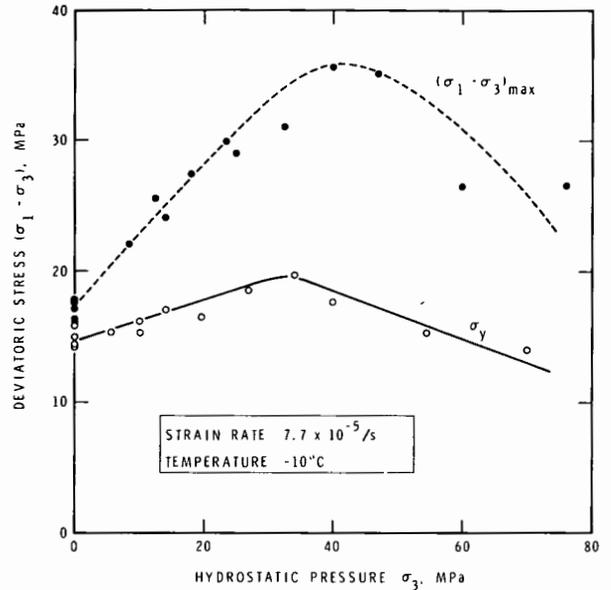


FIGURE 11. Variation of yield stress σ_y , and peak stress, $\sigma_{max} = (\sigma_1 - \sigma_3)_{max}$, with hydrostatic confining pressure σ_3 .

Conclusions

Unconfined compressive strength of frozen sand at -2°C dropped at a much faster rate with decreasing strain rate below $10^{-5}/\text{s}$, than that observed at higher strain rates. At lower temperatures, such a change in slope of the stress versus strain rate curve was not observed. The behaviour at -2°C could be attributed to the mobility of unfrozen water.

Volumetric ice content had as much an effect on the compressive strength and axial strain at peak stress as platen configurations. The deformation mode at low strain rates did depend on the type of platen.

Low confining pressures (0 to 0.35 MPa), in the range of most engineering considerations, had very little effect on the compressive strength or axial strain at failure. Dilational (expansion) volumetric strains were observed at high strain rates, but were negligible at low strain rates.

A transition in the mode of deformation was observed at a strain rate of about $3 \times 10^{-4}/\text{s}$. Specimens that required less than 10^2 s for peak stress showed a strain of about one per cent at the peak stress, and those that required times longer than 10^2 s had an axial strain of about four per cent.

Tests at high confining pressures (up to 76 MPa) showed an increase in yield and peak stresses up to about 40 MPa beyond which these stresses dropped. Below 40 MPa, the increasing strength was attributed

to the closure of voids and microcracks. Beyond 40 MPa, the decreasing strength can be attributed to an increase in unfrozen water due to pressure melting.

Comments and Suggestions

Standardization of test methods for the laboratory testing of frozen soils has been suggested by Jessberger (1980) and Bragg and Andersland (1980). The International Association of Hydraulic Research (IAHR 1975, 1978) has a task committee that has recommended several standards for testing the mechanical properties of ice. Based on the present results, the authors offer the following comments with respect to compression testing of frozen soils.

(1) Compliant platens offer the possibility of applying uniform normal pressure to the ends of a conventional cylindrical test specimen without imposing significant radial stresses at the specimen-platen interface, either positive or negative.

Other practical advantages are:

(a) It is not necessary to make the specimen end planes perfectly flat since the soft platen material can conform to the minor irregularities without creating adverse effects.

(b) It is possible to test relatively short cylinders as test specimens which is a useful economy when samples are obtained in the field by core drilling.

Some practical disadvantages are:

(a) Use of compliant platens reduces the stiffness of the test system making it more difficult to control the strain rate, or displacement rate of the specimen in simple loading devices.

(b) Soft loading permits uncontrolled displacements (bursting) when the specimen yields and strain energy is released. This is only a problem at very fast loading rates.

(2) It would be preferable to measure strain by using an extensometer mounted on the specimen.

(3) A method of measuring volume displacement of the cell fluid has been described in this paper. Volumetric strain measurements are required for a more complete understanding of the stress-strain behaviour and mode of failure of frozen soil specimens.

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