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FIELD TESTS ON RATE SENSITIVITY OF VERTICAL STRENGTH AND DEFORMATION OF FIRST–YEAR COLUMNAR–GRAINED SEA ICE

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RÉSUMÉ

Dans cette note on présente les résultats d'essais de déformation et de résistance à la compression uniaxiale d'échantillons de glace de mer columnaire de première année. Les charges ont été appliquées parallèlement à l'axe des colonnes-échantillons avec plusieurs vitesses de déplacement à l'aide d'une machine d'essai portative d'un laboratoire situé à Mould Bay dans l'Ouest de l'Arctique canadien. Les résultats sont analysés en fonction du taux mesuré de contrainte et de déformation jusqu'aux contraintes maximales. On a obtenu des résistances allant jusqu'à 16 $MN\cdot^{-2}$ à -10°C, avec des déformations de rupture de l'ordre de 0,1 à 0,3 p. cent.

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FIELD TESTS ON RATE SENSITIVITY OF VERTICAL STRENGTH AND DEFORMATION OF FIRST-YEAR COLUMNAR-GRAINED SEA ICE

Abstract

Observations on rate sensitivity of uniaxial, unconfined compressive strength and deformation of freshly recovered columnar-grained first-year sea ice are described. Loads were applied parallel to the axis of the columns over a wide range of displacement rates, using a portable test machine in a field laboratory at Mould Bay in the western High Arctic of Canada. Results are analysed in terms of measured stress and strain rate to peak stress. Strengths up to 16 $MN \cdot m^{-2}$ at -10°C were obtained, with failure strains in the range of 0.1 to 0.3 per cent.

1 INTRODUCTION

Tests carried out in the Canadian Eastern Arctic on the strength of vertical and horizontal samples of columnar-grained sea ice have been discussed /1/ in terms of measured strain and stress rates. Although vertical samples proved to be considerably stronger than horizontal samples, no significant differences were established for failure strain. Analysis revealed that there were anomalies linked to the performance characteristics of the test machine, which was rather small and could not develop a load of more than about 10 kN, and that problems with this test system could be common to field test equipment generally. The present paper discusses results obtained for vertical strength with a test system of much larger capacity. This study was carried out in June-July 1982 as part of a comprehensive Canada-U.S.A. program, the RADARSAT/FIREX Project, at the High Arctic Weather Station at Mould Bay to determine the microwave properties of first-year and multi-year sea ice under natural conditions. Tests were carried out on samples of first-year ice oriented vertically and horizontally with respect to the ice cover in Mould Bay.

2 TEST PROCEDURES

Experiments were conducted in a field laboratory at Mould Bay, using a commercial test machine (Soiltest CT-405) with a design load capacity of 50 kN. A screw-driven machine, it is capable of delivering an actuator rate, $\dot{x}$, of 3×10^{-3} to 7×10^{-2} mm s^{-1} or a nominal strain rate, $\dot{\varepsilon}_n = \dot{x}/\ell$, of about 1.2×10^{-5} to 2.8×10^{-4} s^{-1} for a specimen length, ℓ, of 250 mm. Tests were made at -10°C (to be consistent with the previous study /1/) on cylindrical samples of 76 mm diameter (cross-sectional area of 4500 mm^2) and length of 250 mm prepared from vertical cores taken from an ice cover more than 2 m thick. Specimens were tested between a pair of polished steel platens. Load was measured with a calibrated load cell. Specimen deformation was measured using a pair of specially designed gauges (gauge lengths of 150 mm) mounted directly on the specimen /2/. The outputs from the load cell and the two displacement gauges were recorded separately, using strip chart recorders kept warm in heated and well-insulated boxes that also housed the load cell electronics and the 6 V dry cells for the displacement gauges. The displacement gauges were calibrated from time to time to ensure the accuracy of the strain measurements.

On 13 June 1982, at night when the air temperature was -2°C (the minimum for the day), eight vertical cores of 76 mm and more than 2 m in length were recovered from the ice cover in Mould Bay.

Recovery time was about one hour, from a flat area of about 1 m^2 at Station 3, in the channel and about 1.5 km from the shore. The samples were transported to base camp within the next 30 min. Six cores were immediately stored in a freezer maintained at about -25°C. One core was sectioned immediately with a bandsaw in the cold room (-10°C) for salinity measurements, the other was cut for microstructural examination. The top 100 mm of the core, used for salinity measurements, was cut into 10 mm thick discs; the remainder was sectioned into 20 mm thick segments. These were melted in sealed plastic containers in a microwave oven and stored in a warm room for more than 10 h so that they were at equilibrium temperature before their salinities were measured by means of a calibrated refractometer.

After storage in the freezer for about 36 h at -25°C the six cores were brought, one at a time, into the cold room (-10°C) for processing and testing. Each was cut to make a 250 mm long cylindrical sample. Five or six specimens could be made from each core. The average depth of each specimen from the top of the ice cover was noted. The cylinders were then carefully finished with sandpaper to remove the cut marks and end surfaces of each specimen were given a final polish with fine sandpaper to make certain that they were flat and at right angles to the axis of the cylinders. Finished specimens were weighed and their dimensions measured. All procedures were carried out while the ice was still below about -15°C, and samples were turned over periodically during subsequent storage until tested in order to reduce brine drainage or migration.

Six different actuator speed settings were selected, including the slowest and the fastest, for the six cores. All samples from any one core were tested at the same speed at a temperature of -10°C ± 0.5°C. Surface temperature of the specimens was measured before and after testing, using a commercial thermistor system. In addition, the inside temperature of one specimen from each batch was monitored by inserting a mercury thermometer into a deep hole drilled along its longitudinal axis. This specimen was not, of course, used for strength testing. Half of each specimen was melted for salinity measurements after testing.

3 RESULTS AND ANALYSIS

The ice was columnar-grained along its entire depth, with a density of about 0.90 ± 0.02 $mg.mm^{-3}$, except for the top 50 mm. The salinity distribution in the ice on the day of sampling is shown in Fig. 1, which also presents the salinities measured in a number of samples (albeit from different cores) after testing and plotted according to their average depth. The adopted sample preparation technique did not seem to affect the brine content of the specimens.

A set of results is given in Fig. 2, including those for tests showing the minimum and maximum strengths obtained during this

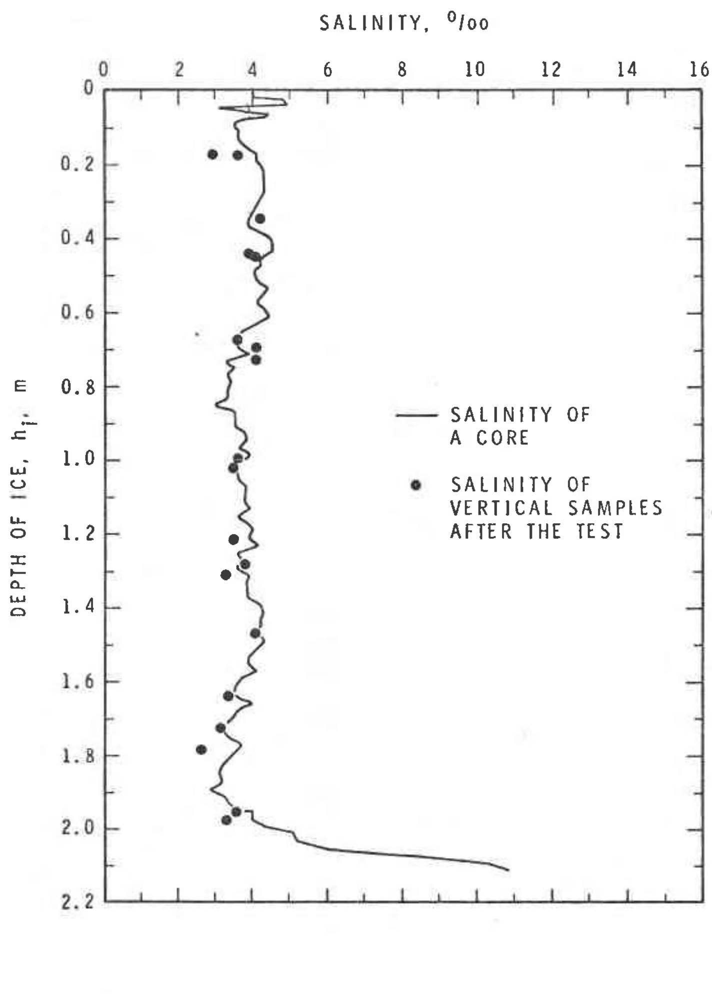

Fig. 1

Vertical salinity profile Station 3, Mould Bay, 13 June 1982, plus salinity of a few samples taken after the strength tests series. Examples of stress-strain diagrams are given in Fig. 3. Figure 2 is of particular interest because it demonstrates the scatter in the results and the variation in the mode of failure. A distinct upper yield type of failure, with stress decreasing rapidly from the maximum value, occurred at lower rates of loading. At higher rates some specimens fractured after experiencing upper yield type of failure; others fractured prematurely, the higher the rate the earlier the fracture. These observations are consistent with previous observations on horizontally-oriented, fresh-water, columnar-grained S-2 ice under truly constant cross-head /2/ and strain rates /3/.

Figure 2 shows that the design load capacity of the machine was exceeded during many of the tests. Stress-time and strain-time observations for two of them are shown in Figs. 4 and 5. Both exhibited upper yield type of failure, the total load at failure in the slower test (Fig. 4) being about 60% of the design load capacity of the machine. The measured specimen strain rate was not constant, but increased gradually as the test progressed. This is consistent with earlier observations for tests at truly constant cross-head rate /2/. The strain rate in the faster test (Fig. 5) also increased gradually, but after about 45 s (Point A) when the total load (Point A') was about 70% of the load capacity of the machine there was a distinct deceleration. Independent measurements of cross-head rate indicated that this could be due to failure of the machine to maintain a constant rate of displacement during the latter part of the test. The test conditions were therefore not strictly comparable, demonstrating the importance of measuring actual loading conditions. The loading path given by the average stress rate $\dot{\sigma}_{af} = \sigma_f / t_f$, where σ_f is the maximum stress and t_f the time corresponding to this point, describes well the actual load history obtained in Fig. 4. On the other hand, the deformation path given by the average strain rate $\dot{\varepsilon}_{af} = \varepsilon_f / t_f$, where ε_f is the strain at failure, could be more appropriate than $\dot{\sigma}_{af}$ for the case shown in Fig. 5. It is, perhaps, appropriate to mention that recent measurements at the Division of Building Research, National Research Council Canada, during closed-loop, constant strain-rate

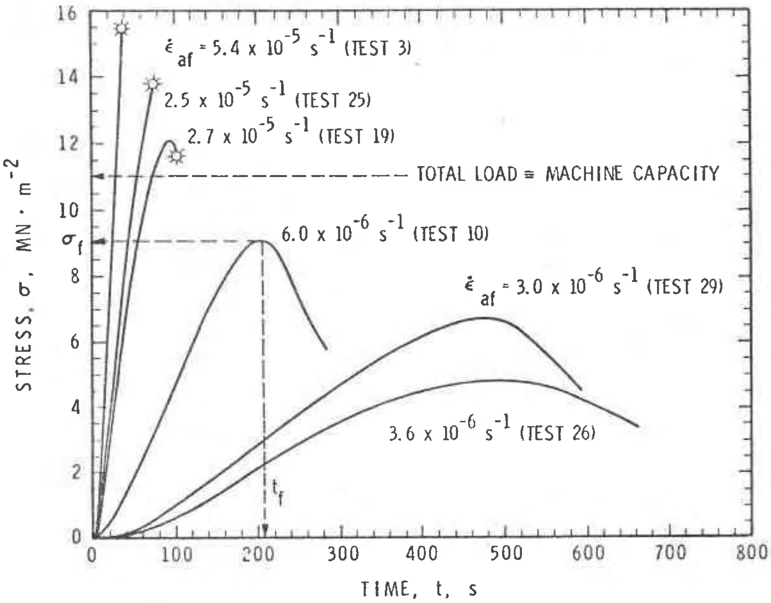

Fig. 2

Stress-time curves for several strain rates at -10°C for vertical samples of first-year sea ice

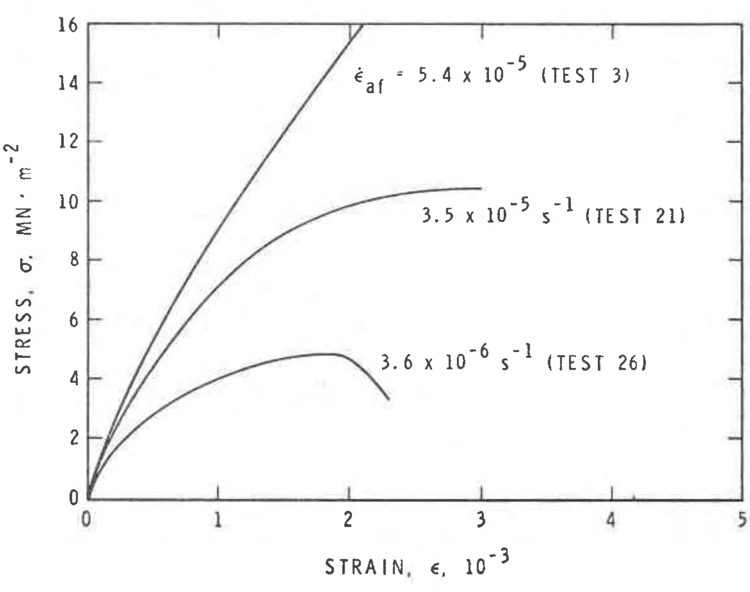

Fig. 3

Stress-strain diagrams at -10°C for vertical samples of first-year sea ice experiments indicated that the cross-head rate should indeed decrease during the pre-upper-yield period to maintain a constant deformation rate in the specimen. Decrease in the cross-head displacement rate during the field test with increase in load (involving high loads) was therefore beneficial from the point of view of maintaining a favourable strain path. As most of the tests in this series were carried out at high loads, the analysis of results, on the basis of measured strain history, is thought to be appropriate.

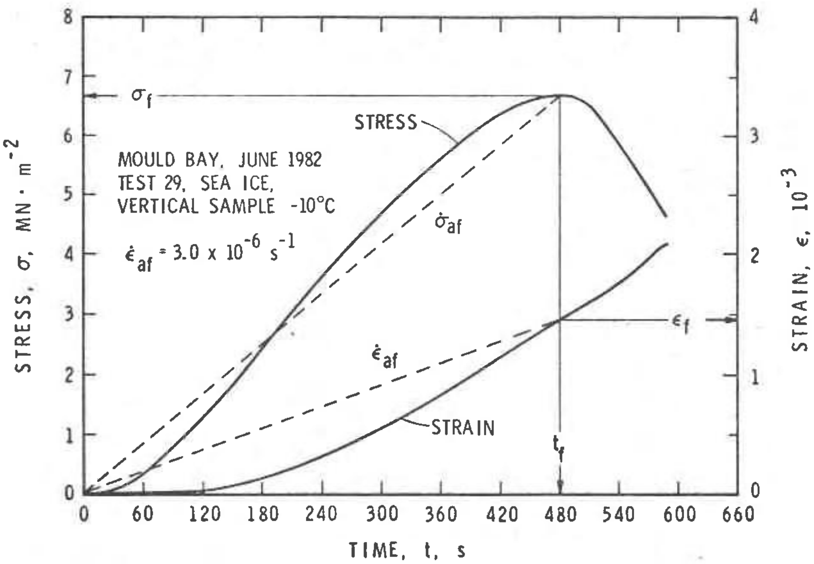

Fig. 4

Stress and strain history at low rate of loading

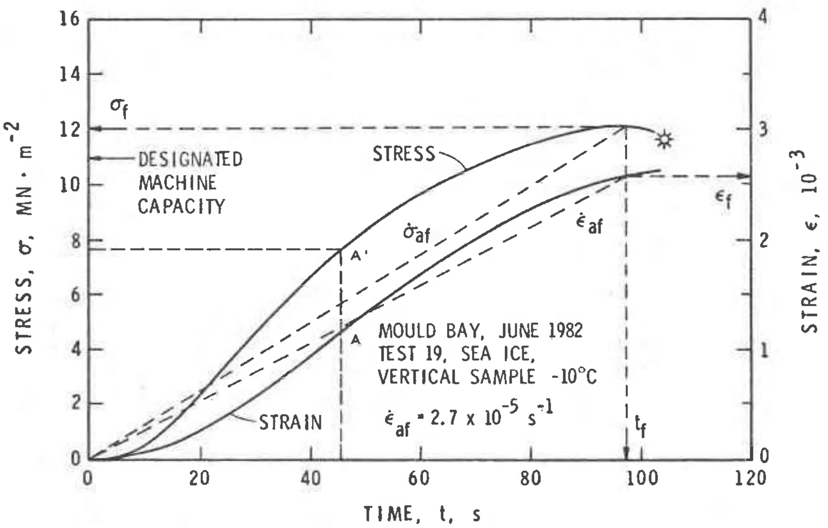

Fig. 5

Stress and strain history at intermediate rate of loading

The dependence of upper yield or fracture stress and corresponding strain on $\dot{\varepsilon}_{af}$ is shown in Fig. 6. The results indicate variations, but no dependence of strength or deformation on depth of specimen (shown in cm in Fig. 6) with respect to the top surface of the ice cover. The presence of brine channels (very irregular in shape and size) and differences in the loading conditions partly induced by these defects were thought to be responsible for the large variations. In general, both stress and strain at failure increased with strain rate, corroborating observations on fresh-water ice /2, 3/. Strain, however, showed less rate sensitivity than strength and this also corroborates previous observations /2, 3/. The lower ductility for the premature fracture failures, in comparison with those undergoing upper yield type failure, was also similar to the behaviour of fresh-water ice /2, 3/. The dependence of strength on strain rate may be represented by

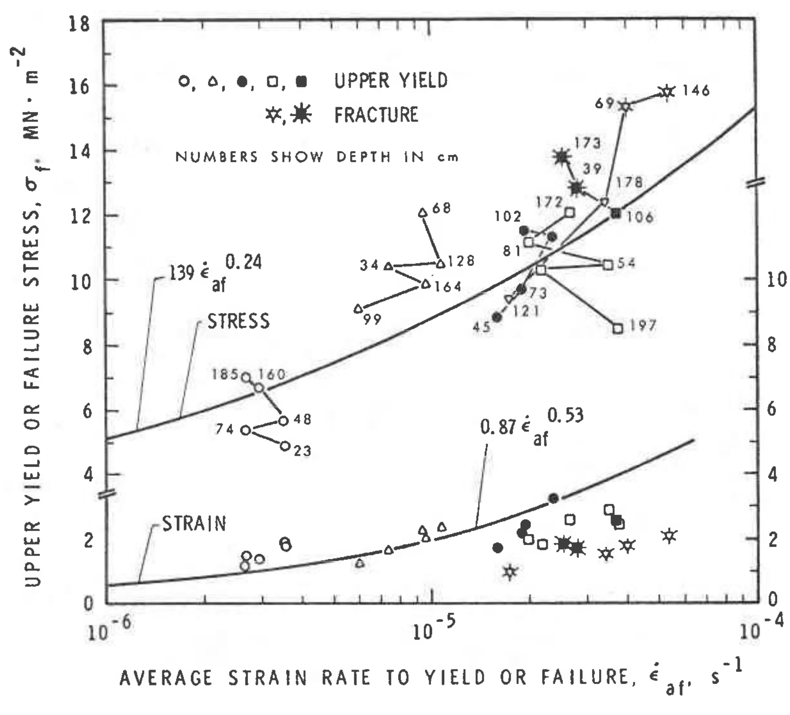

Fig. 6

Dependence of upper yield or fracture stress and strain on average strain rate to peak stress for vertical samples of columnar-grained first-year sea ice at −10°C

$$\frac{\sigma_f}{\sigma_1} = P\left(\frac{\dot{\varepsilon}_{af}}{\dot{\varepsilon}_1}\right)^p \quad (1)$$

where σ_1 is the unit or reference stress (= 1 $MN \cdot m^{-2}$) and $\dot{\varepsilon}_1$ is the unit or reference strain rate (= 1 s^{-1}). Regressional analysis of the results for only upper yield type failure gave P = 139 ± 75 and p = 0.24 ± 0.04, with a correlation coefficient of 0.78. The strain rate sensitivity, p, is close to the values obtained for fresh-water ice /2, 3/ and for horizontal samples of the same sea ice as that used for the present tests /4/ it differs greatly, however, from that obtained in a previous study on horizontal strength of sea ice /5/.

The relation between failure time and stress is shown in Fig. 7. Increase in t_f with increase in σ_f can be seen for some loading speeds, due almost certainly to the differences in the degree of slowing of the cross-head displacement rate discussed earlier; the general trend can be expressed as

$$\frac{t_f}{t_1} = C\left(\frac{\sigma_f}{\sigma_1}\right)^{-\theta} \quad (2)$$

where t_1 is the unit or reference time (= 1 s). Regression analysis of the results exhibiting only upper yield behaviour gave $C = 1.32 \times 10^4 \pm 1.32 \times 10^4$ and $\theta = 1.95 \pm 0.39$ with a correlation coefficient of 0.76. By definition,

$$\frac{\dot{\sigma}_{af}}{\dot{\sigma}_1} = \frac{\sigma_f}{\sigma_1} \Big/ \frac{t_f}{t_1} \quad (3)$$

Substitution of t_f / t_1 from equation (2) in equation (3) and rearrangement gives

$$\frac{\sigma_f}{\sigma_1} = C^{\frac{1}{1+\theta}}\left(\frac{\dot{\sigma}_{af}}{\dot{\sigma}_1}\right)^{\frac{1}{1+\theta}} \quad (4)$$

On substitution of the values C and θ, determined earlier, this gives

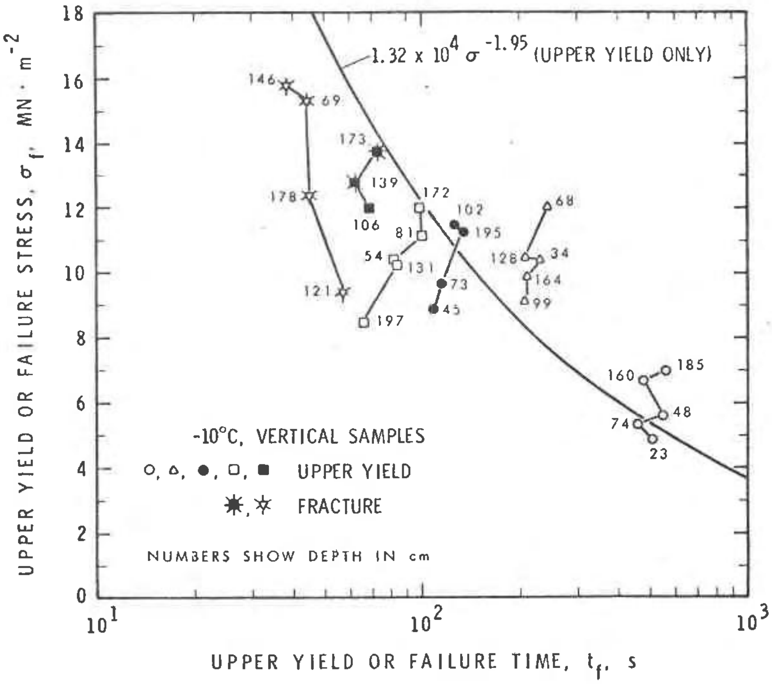

Fig. 7

Dependence of upper yield or fracture stress on failure time

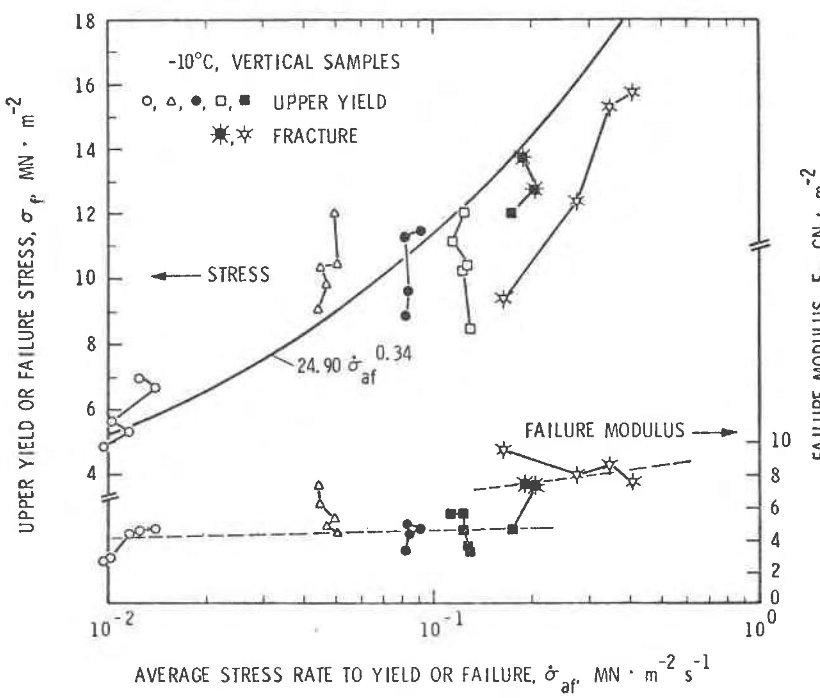

Fig. 8

Dependence of upper yield or fracture stress and failure modulus on average stress rate

$$\sigma_f = 24.9 \left(\dot{\sigma}_{af} \right)^{0.34} \quad (5)$$

Experimental results are compared with equation (5) in Fig. 8. The stress rate exponent in equation (5) is comparable to that obtained for horizontally-oriented sea ice /1, 4, 6/ and fresh-water ice /2, 3/ and indicates rate sensitivity similar to that observed previously. The numerical value of the coefficient in equation (5) is, however, more than five times greater than that obtained for horizontal samples of sea ice /1, 4/.

It is common engineering practice to determine effective modulus from the slope of the stress-strain diagrams. In agreement with theoretical predictions /7/, Fig. 3 shows that even the slope of the early part of these curves depends on rate of loading owing to the contribution of delayed elastic strain to total strain. It was decided, therefore, to present the failure modulus, $E_f = \sigma_f / \varepsilon_f$, in Figure 8 in accordance with previous analysis /2, 3/. The high moduli obtained for the fracture failures show that the initial loading conditions approach quasi-elastic conditions at high rates.

4 CONCLUSIONS

Compressive strengths of 5 to 16 $MN \cdot m^{-2}$ at -10°C for stress applied parallel to columnar grains were obtained for first-year sea ice with a salinity of 4‰. The strain rates actually measured in the specimens were in the range of 2.5×10^{-6} to 5.5×10^{-5} s^{-1}; corresponding stress rates were in the range of 0.01 to 0.4 $MN \cdot m^{-2}$ s^{-1}. Failure strains of 0.1 to 0.3% and failure moduli of 3 to 9 $GN \cdot m^{-2}$ were observed. Vertical samples were found to be about five times stronger than horizontally-oriented samples (measured earlier and confirmed by recent measurements). The rate sensitivity of sea-ice strength was similar to that of fresh-water ice. The study showed that consistent results can also be obtained under field conditions. That the test machine was incapable of maintaining a constant cross-head displacement rate during loading was actually beneficial in obtaining a favourable strain path.

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