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by N.K. Sinha

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Uniaxial compressive strength of first-year and multi-year sea ice[1]

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Strain-rate and stress-rate sensitivity of the compressive strength of first-year columnar-grained ice, first-year congealed frazil ice, and columnar-grained ice from an old floe have been investigated with load applied in the horizontal plane. In spite of similar salinity and density, the frazil ice proved to be considerably stronger than the columnar-grained ice. The strength of porous old floe ice with columnar-grained structure was very much the same as that of first-year ice of similar structure, but the clear bulk ice of the old floe was strongest. Rate sensitivity of strength for the three types of saline ice was similar to that of fresh-water ice. Ductility of the old clear ice (as measured by the strain at upper yield) was the same as that of fresh-water ice; ductility of porous old ice was comparable to that of new frazil ice. New columnar-grained ice proved to be the most ductile material.

Keywords: columnar-grained, compressive strength, ductility, first-year, frazil, multi-year, rate sensitivity, sea ice.

Nous avons étudié la sensibilité de la résistance en compression aux taux de déformation et de contrainte de la glace colonnaire de première année, du frasil congelé de première année et de la glace colonnaire d'une vieille banquise. L'étude a été faite sous charge appliquée dans le plan horizontal. En dépit d'une salinité et d'une densité semblables, le frasil s'est montré beaucoup plus résistant que la glace colonnaire. Bien que la résistance de la glace poreuse à structure colonnaire d'une vieille banquise ait été la même que celle de la glace de première année ayant la même structure, la glace claire massive d'une vieille banquise s'est avérée la plus forte. La sensibilité de la résistance en compression aux taux de déformation et de contrainte des trois types de glace saline était semblable à celle de la glace d'eau douce. La ductilité de la vieille glace (déterminée par la déformation à la limite supérieure de la résistance) était la même que celle de la glace d'eau douce; la ductilité de la vieille glace poreuse était comparable à celle du frasil. La nouvelle glace colonnaire s'est avérée le matériau le plus ductile.

Mots-clés: glace colonnaire, résistance à la compression, ductilité, première année, frasil, vieille banquise, glace de mer.

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Introduction

Interest in the strength and deformation properties of sea ice is growing as a result of increasing exploration in the ice-affected waters off the coast of Newfoundland and Labrador and in the Arctic. Participation in the Canada–U.S.A. Radarsat/Firex Project to determine the microwave properties of first-year and multi-year sea ice under natural conditions offered an opportunity to make observations at the High Arctic Weather Station at Mould Bay, Prince Patrick Island (76°14′N, 119°20′W). Tests were carried out in October 1981 to determine loading rate sensitivity of uniaxial, unconfined, compressive strength of freshly recovered, first-year columnar-grained and congealed frazil slush ice from Mould Bay and of old sea ice from a large floe about 10 km in diameter in Crozier Channel. In all cases the major axis of the samples and the applied load were in the horizontal plane.

Site, weather, and ice characteristics

With the exception of a few grounded pieces of multi-year ice near the shore, all of Mould Bay (Fig. 1) was covered with a uniform flat sheet of new ice under a snow cover of 1–2 cm. A variety of old floes surrounded by new ice covered most of Crozier Channel, although open leads kept occurring in many places since the floes were mobile. Figure 2 shows the SLAR (Side Looking Airborne Radar) imagery of the ice conditions in Mould Bay and the surrounding regions obtained by AES Electra (NDZ-734) during a flight on October 11, 1981. A detailed report on this phase of the work is in preparation (B. E. Troy, Jr., J. P. Hollinger, R. O. Ramseier, K. W. Asmus, M. F. Hartman, and C. A. Luther. Microwave emission from sea ice at Mould Bay, Canada, October 1981. Private communication).

Freeze-up for complete ice cover in Mould Bay was September 24 under calm conditions that prevailed for almost another 10 days. During this time the ice grew to a thickness of about 25 cm. A record of air temperatures for this period of September–October is shown in Fig. 3. The warm spell made it very difficult to work on the ice in the Bay, but it provided an excellent opportunity to gather microwave data on new ice with a thin water-saturated snow cover. This warm period was also used for surveying the area by helicopter and for examining the surface conditions of a large (about 8 × 10 km) floe in Crozier Channel (Fig. 2) that

[1]This paper was presented at the 1983 Annual Conference of the Canadian Society for Civil Engineering, Ottawa, Ontario, June 1–3.

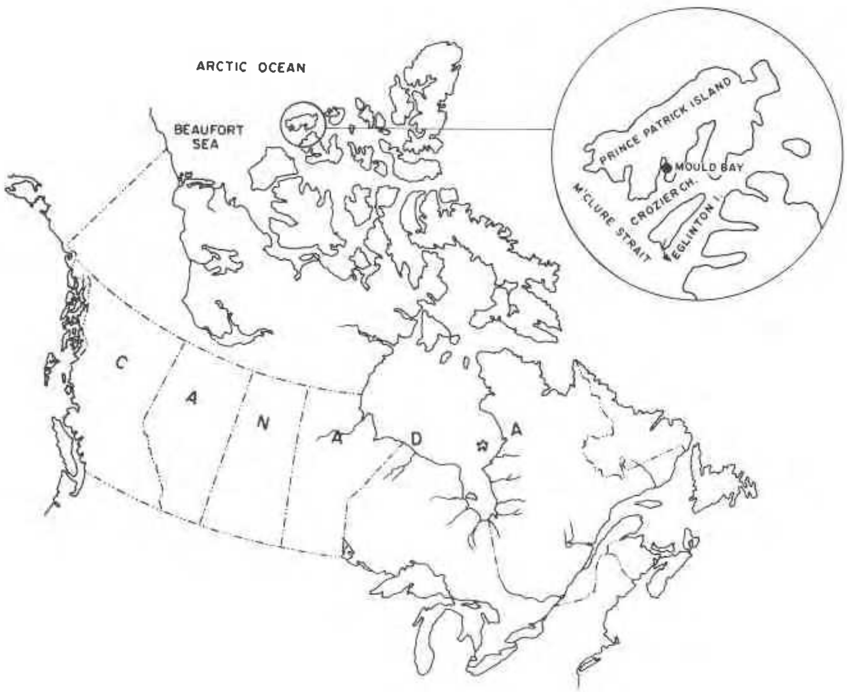

FIG. 1. Map showing site location.

was uniformly covered with hummocks and melt ponds. All the melt ponds were covered with a thin layer of new ice; in some cases it covered sea water and in other cases, brackish water. Large blocks of samples of hummock ice were obtained on October 7 with a chain saw and brought to the base camp for storage at about −10°C and for subsequent detailed microstructural analysis and mechanical tests. It is possible that this was a second-year floe (R. O. Ramseier, private communication), but since its life history was unknown it will be referred to as old or multi-year floe ice in this paper.

An east−west experimental line across Mould Bay was established for microwave studies and 11 stations were marked along it. Examination of the ice at the various stations showed predominantly columnar-grained structure, except for the ice cover around Station 2 that consisted almost entirely of congealed, frazil slush type ice (see the classification of fresh-water ice by Michel and Ramseier 1971).

Experimental procedures

The High Arctic Weather Station at Mould Bay was used as the base camp (Figs. 1 and 2). A small, portable, unheated structure served as a cold laboratory and part of the sleeping quarters as the warm laboratory. Mechanical tests were performed during the second half of October when air temperatures dropped below about −15°C (see Fig. 3) so that the desired temperature of the laboratory could be controlled by heating. Large blocks of first-year sea ice were cut with a chain saw when the air temperature was below about −15°C. A commercial test machine (Soiltest CT-405) with a design load capacity of 50 kN was used. This is a conventional screw-driven machine capable of delivering an actuator displacement rate, $\dot{x}$, of 3×10^{-3} to 7×10^{-2} mm·s^{-1}, or a nominal strain rate, $\dot{\epsilon}_n = \dot{x}/l$, of 1.2×10^{-5} to 2.8×10^{-4} s^{-1} for a specimen length, l, of 250 mm.

Tests were made on large prismoidal samples with final dimensions of 50 × 100 × 250 mm, their long dimensions parallel to the surface of the ice cover or floe. A portable band saw was used to prepare samples from large blocks cut by chain saw. The specimen surfaces were finished by hand with sandpaper to remove all cut marks and the end surfaces (50 × 100 mm) of each specimen were given a final polish to make certain that they were flat and at right angles to the long axis of the cylinders. Finished specimens were weighed and their dimensions measured. These procedures were carried out at a room temperature of about −15°C. The samples were turned periodically during subsequent storage until tested in order to reduce adverse effects due to brine drainage or migration.

The tests were conducted at −10 ± 0.5°C and at −18 ± 0.5°C, dictated primarily by air temperatures outside the laboratory (Fig. 3). Surface temperatures of the specimens were measured both before and after testing,

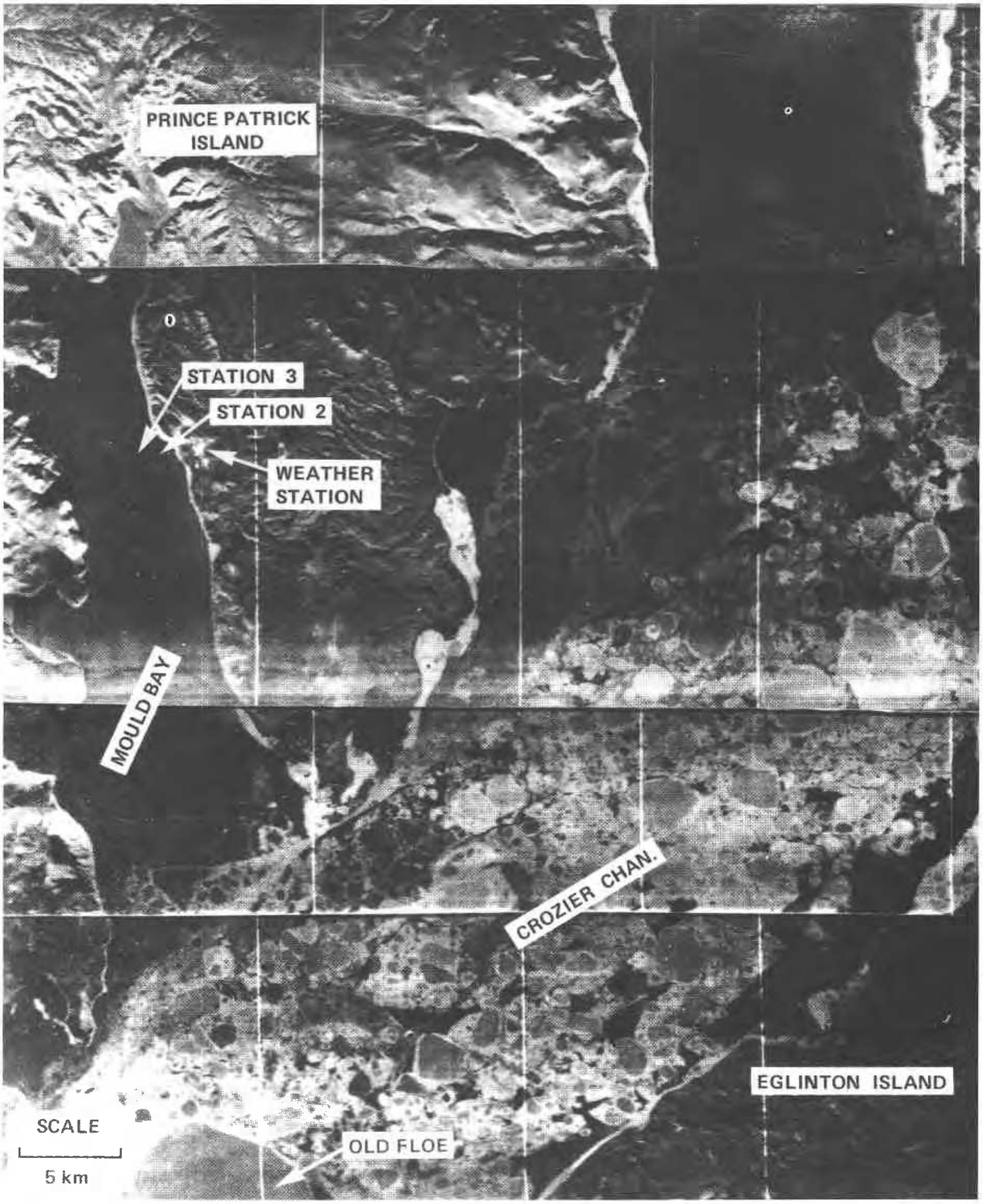

FIG. 2. SLAR image October 21, 1981 recorded by AES Electra.

using a thermistor system. As well, a deep hole was drilled along the longitudinal axis of one specimen from each batch and a mercury thermometer inserted to monitor temperature during the test. This specimen was not

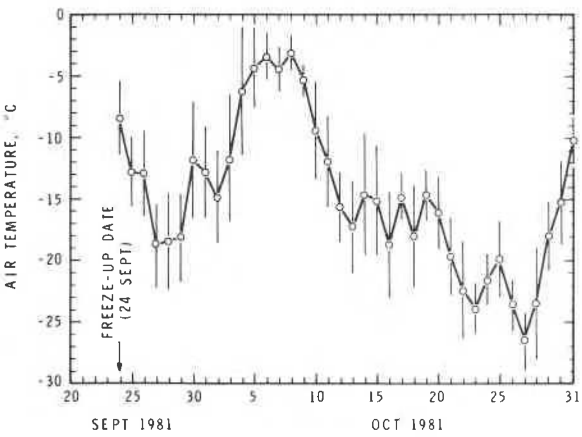

FIG. 3. Daily minimum, maximum, and mean air temperatures in Mould Bay during September–October 1981.

used for strength testing. For most of the specimens, an examination of the microstructure of the ice was also carried out after testing.

Each specimen was tested between a pair of polished steel platens and load was measured with a calibrated load cell. Deformation was measured by means of a pair of specially designed gauges (gauge lengths of 150 mm) mounted directly on the two 100 × 250 mm faces of the specimen (Sinha 1981*a*). Output from the load cell and from the two displacement gauges was recorded separately using strip chart recorders warmed in heated and well-insulated boxes that also housed the load cell electronics and the 6 V dry cells for the displacement gauges. Calibration of these gauges was checked after every few tests to ensure the accuracy of the strain measurements.

When the ice blocks were brought to the base camp a vertical slice was removed and sectioned in 10 mm thick sections for salinity profile determination. These sections were melted in sealed plastic containers in a microwave oven and stored overnight in a warm room before their salinities were measured by means of a calibrated refractometer.

Results and analysis

The ice sheet at all the stations across the Bay (7 km) was uniform. Variations were not more than about 0.05 m. All first-year columnar-grained ice used for strength testing was taken from station 3, situated about 1.5 km from the eastern shore of Mould Bay. Here, the ice was columnar-grained through its entire depth (about 0.4 m), the *c* axis of the grains tending to be in the horizontal plane except for about 50 mm at the top (Fig. 4). The *c* axis of the grains in the horizontal plane tended to be parallel to the axis of the channel and the tidal current and therefore similar to the ice observed by Weeks and Gow (1978, 1980) in the western Arctic and by Sinha (1983*a*) in the eastern Arctic. Because of this anisotropy in the horizontal plane, samples were prepared with their major axes parallel, perpendicular, or 45° to the direction of the channel axis, designated ‖c, ⊥c, and ∠c, respectively. Vertical salinity and density profiles of this ice are given in Fig. 5. Density was calculated from the mass and the volume estimated from the dimensions of the samples. As these were large and each contained at least two brine channels, the densities are a good representation of the bulk characteristics of the ice. The lowest salinity and the corresponding highest density at a depth of about 0.25 m correlated well with the lowest growth rate occurring during the warm spell in October. Similar field observations had also been made earlier in the eastern Arctic (Nakawo and Sinha 1981; Nakawo 1983).

Ice at station 2 about 1 km from the eastern shore was congealed frazil slush (Fig. 4). No anisotropy was observed in the horizontal plane. The vertical salinity and density profile are shown in Fig. 6; it is significant that both the density and salinity were comparable to those of columnar-grained ice.

The upper layer of the hummock ice from the old floe was very bubbly and white, but the number of large bubbles decreased rapidly with depth until, at about 0.2 m, the ice was almost transparent, with uniform distribution of very small bubbles. It was, however, columnar-grained (Fig. 4) from the top surface (including the white top ice) to the bottom of the blocks (about 0.7 m in depth). The shape of the grains, at right angles to the length of the columns, was ill defined and the ice could best be described as bottom ice. This indicated that a considerable amount of the top ice of the original ice cover from which the floe came had melted away. The vertical salinity and density profiles of this ice are shown in Fig. 7. Density was determined not only from the large samples of ice (50 mm thick) prepared for strength testing but also from smaller prismoidal samples (30 mm thick) prepared from a neighbouring block. Both measurements showed that density increased rapidly with depth down to about 0.2 m.

All tests, irrespective of type of ice or rate of loading, showed upper yield type of failure. An example of a stress and strain history, including recovery, and the stress–strain diagram for the entire loading and recovery period for a moderate rate of loading are shown in Fig. 8. Note the differences in the slope of the stress–strain diagram during the initial loading period and beginning of recovery, and the high contribution of elastic and delayed-elastic (delayed recovery) strain to total strain. Figure 9 shows the response of different types of ice subjected to the highest crosshead displacement rate that could be delivered by the test machine. In spite of a constant crosshead displacement rate dur-

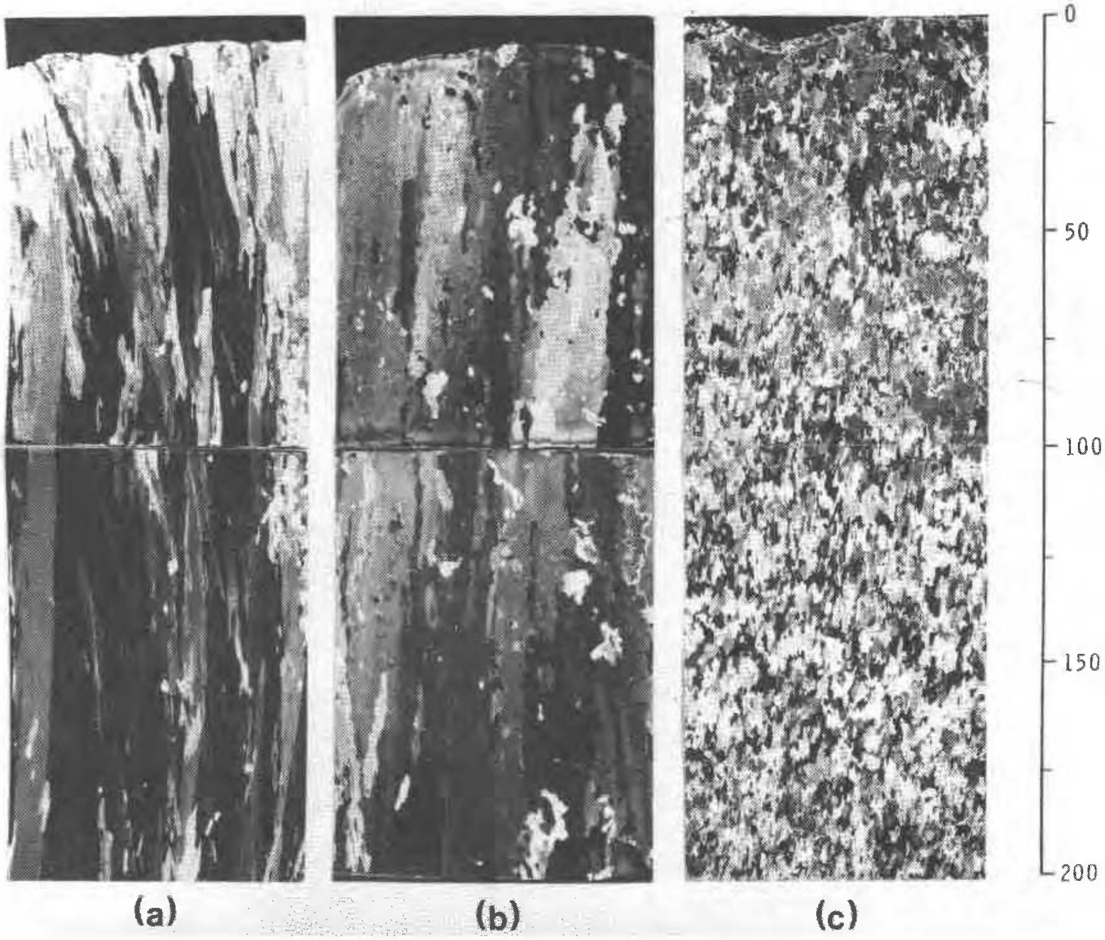

FIG. 4. Vertical thin sections showing columnar-grained structure for (*a*) first-year ice from station 3, (*b*) hummock ice from old floe, and (*c*) frazil ice from station 2. (Scale in mm.)

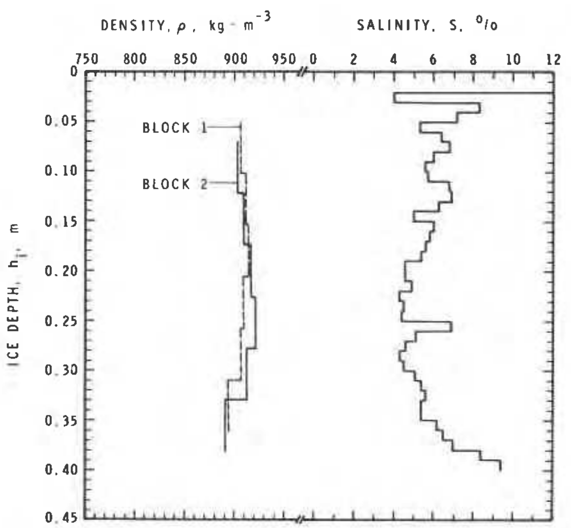

FIG. 5. Vertical density and salinity profile of first-year sea ice from station 3, October 18, 1981.

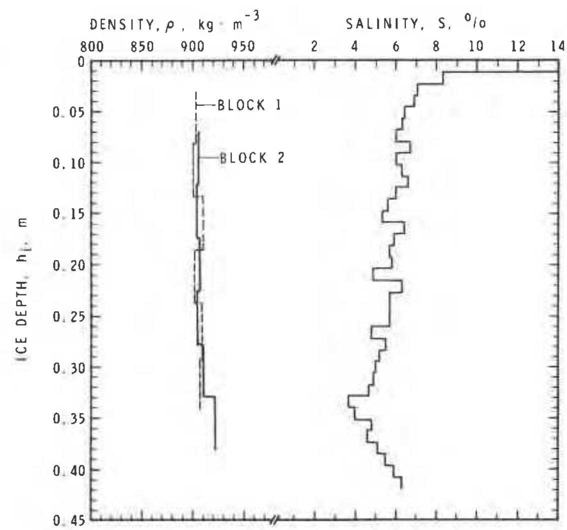

FIG. 6. Vertical density and salinity profile in frazil ice from station 2, October 18, 1981.

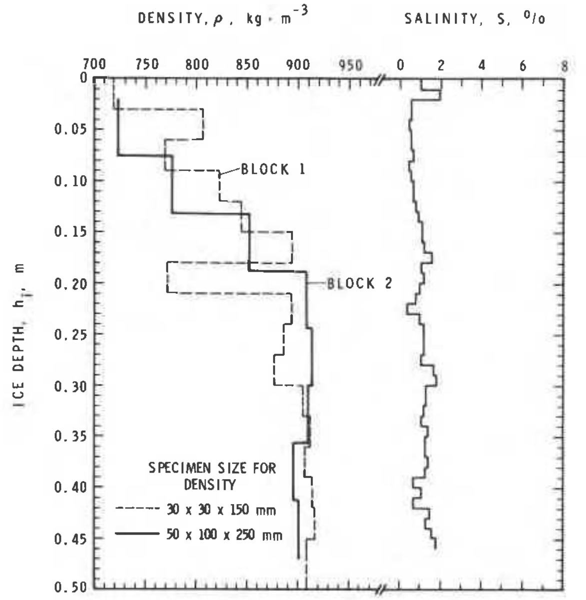

FIG. 7. Density and salinity profile of the hummock ice in an old floe.

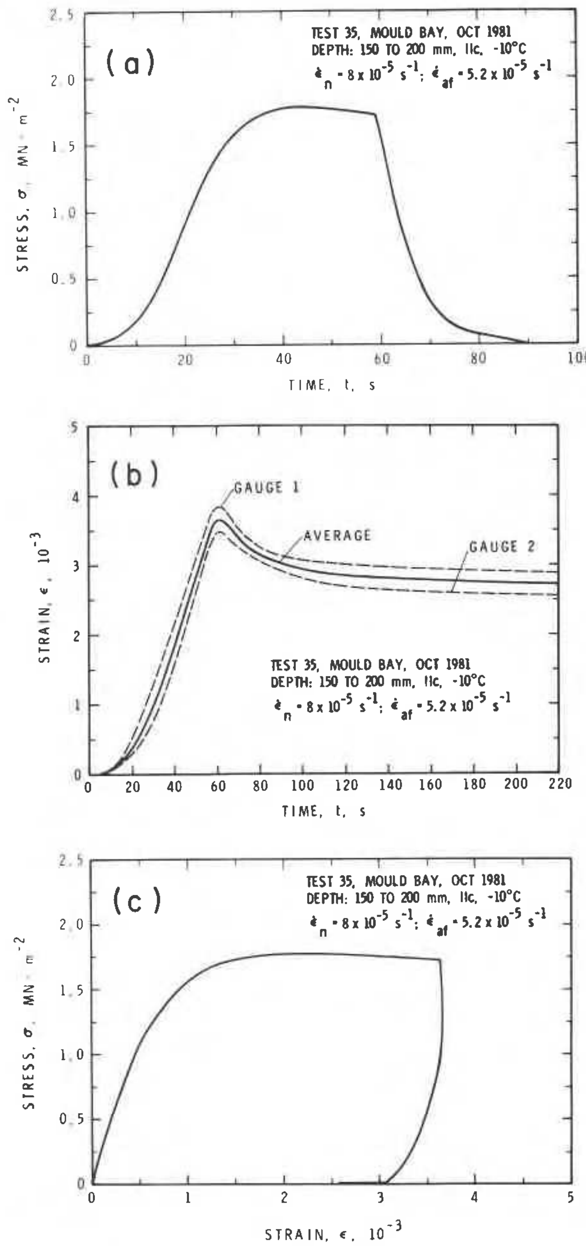

FIG. 8. (a) Stress−time record for a horizontal sample of first-year sea ice during loading and unloading; (b) deformation history during loading and recovery on unloading for the test in Fig. 8a; (c) stress−strain diagram for the test in Fig. 8a, b.

ing a test, the true strain rate of the specimen was not constant. There were differences in the strain paths if strain rates were constant at nominal rates, $\dot{\epsilon}_n$, and in the actual paths recorded by the strain gauges in Figs. 8b and 9$a-c$. The peak strain rate after the upper yield stress, σ_f (to be referred to as failure stress), in all these figures approached the nominal strain rate, $\dot{\epsilon}_n$, as indicated by the slope of the strain−time records. The average strain rate, $\dot{\epsilon}_{af} = \epsilon_f/t_f$, where ϵ_f and t_f are failure strain and failure time, respectively, was observed, however, to be considerably lower than $\dot{\epsilon}_n$ (see Sinha 1981a). The strain rate in the specimen and its variation with time during testing depend on the relative stiffness of the specimen with respect to that of the test machine and load train (Sinha 1981b).

An example of special interest is given in Fig. 10 for the test series on multi-year ice from different depths. All these samples were loaded on the same crosshead displacement rate. Particularly noticeable is the dependence of loading history on the quality of the specimen. The denser samples were stiffer than the porous ice, so that the loading rate imposed by the test system depended on the stiffness of the samples. The increase in strength with depth correlates well, in general, with the corresponding variation in density (Fig. 11).

A knowledge of failure times is required if one intends to use strength data for any application for which loading times or rate of loading are important. Load (hence stress for small strain) and time for failure are simple to ascertain accurately, even under adverse field conditions. Figure 12 illustrates the relation between σ_f and t_f for all the tests carried out at -10°C. Although there are only a few experimental results at various rates for multi-year ice, clear ice from depths greater than about 0.2 m appeared to be significantly stronger than the white top ice. Figure 12 also shows that the frazil ice samples were significantly stronger than the young

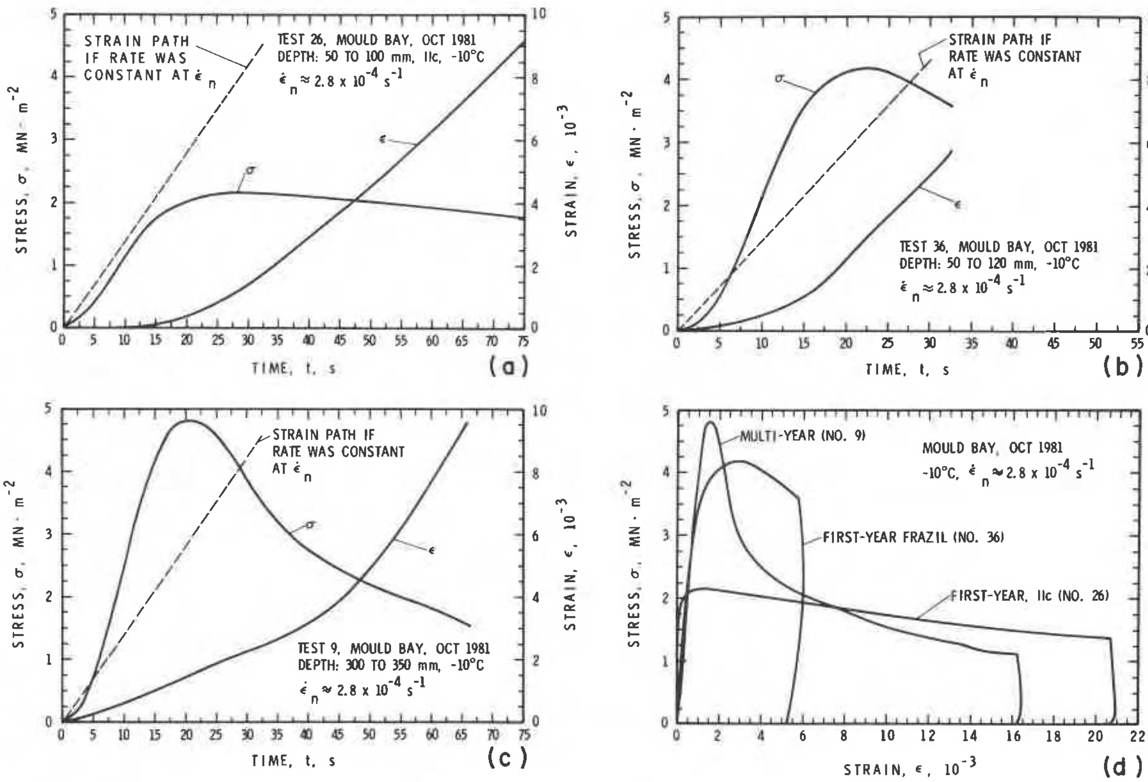

FIG. 9. (*a*) Stress and strain history for horizontal samples of first-year columnar-grained ice; (*b*) stress and strain history for horizontal samples of first-year congealed frazil ice; (*c*) stress and strain history for horizontal samples of columnar-grained hummock ice of an old floe; (*d*) stress–strain diagrams during loading and recovery on unloading for the tests in Fig. 9*a*, *b*, *c*.

columnar-grained ice samples of type ‖c, the strongest orientation in the horizontal plane. Only ‖c samples were tested at −10°C, but both ‖c and ∠c types, exhibiting highest strength for ‖c, were tested at −18°C. Previous tests at −10°C (Sinha 1983*a*) indicated that ‖c and ⊥c samples have similar strengths at the same rate of loading. This has now be confirmed by the field tests at −10°C at Mould Bay (June–July 1982). This author's field experience has shown that ‖c ≈ ⊥c > ∠c. Laboratory tests by Wang (1979) at −10°C under closed-loop controlled, constant strain rates, however, indicated ‖c > ⊥c > ∠c. The rate sensitivity determined by Wang (to be discussed later) also showed significant differences.

Longer failure times for slower loading rates and hence lower strengths were observed, irrespective of the type of ice. The relation between t_f and σ_f for any ice can be presented as

$$[1] \quad \frac{t_f}{t_1} = C\left(\frac{\sigma_f}{\sigma_1}\right)^{-\theta}$$

where t_1 is the unit or reference time (= 1 s) and σ_1 is the unit or reference stress (= 1 MN·m^{-2}).

Regression analysis of the results of first-year ‖c gave $C = 208 \pm 29$ and $\theta = 2.48 \pm 0.27$, with a correlation coefficient of 0.95. Despite the large scatter, the numerical values of both coefficient C with stress exponent θ are in good agreement with values of 210 and 2.57, respectively, obtained earlier (Sinha 1983*a*) in the eastern Arctic with a smaller test machine and smaller specimens. The shape of the $\sigma_f - t_f$ curves, determined by the value of θ, is also similar to curves obtained for fresh-water ice. The value of θ for conditions of constant crosshead displacement rate at −10°C for horizontally oriented, fresh-water S-2 ice samples was found to be 2.30 (Sinha 1981*a*) and the corresponding value under closed-loop controlled, constant strain rate was 2.37 (Sinha 1982).

Regression analysis of the results for frazil ice yielded $C = 636 \pm 190$ and $\theta = 2.32 \pm 0.25$, with a correlation coefficient of 0.97. Again there was a similarity in the value of θ with previous results. Old floe ice, whether clear ice from the bulk or porous material from the top, also exhibited a $\sigma_f - t_f$ response similar to other types of ice (Fig. 12).

The simplest evaluation of the rate sensitivity of

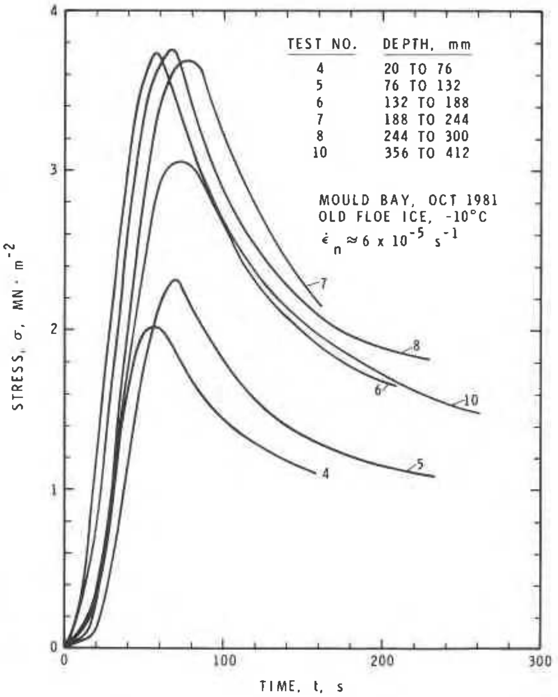

FIG. 10. Stress history for horizontal samples of columnar-grained ice from different depths, in a hummock of an old floe, subjected to the same crosshead displacement rate.

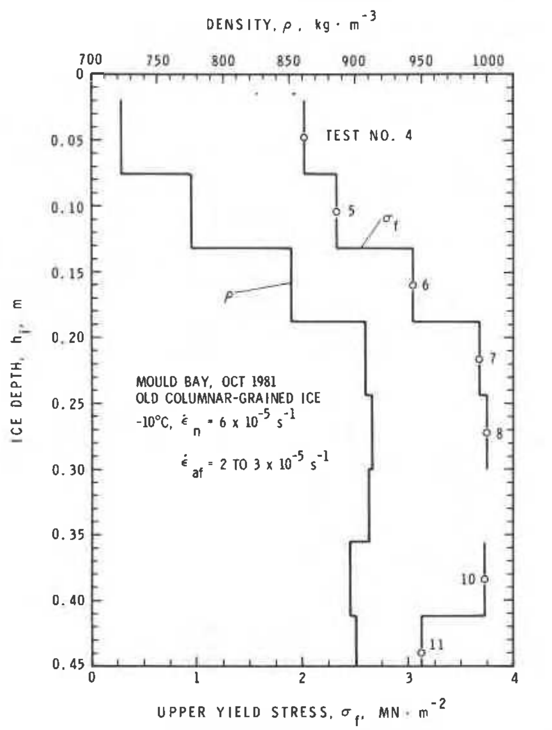

FIG. 11. Depth dependence of density and upper yield stress for horizontal hummock ice from an old floe at −10°C subjected to the same crosshead rate.

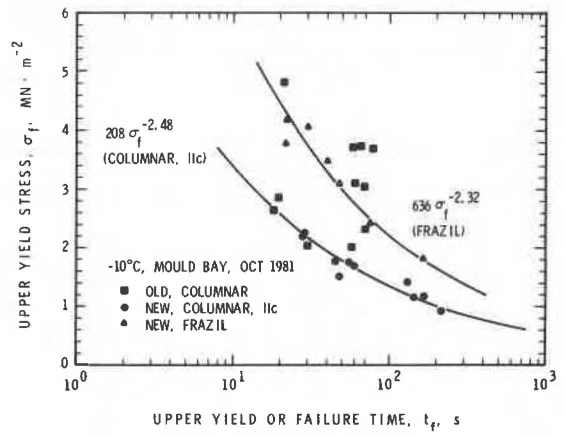

FIG. 12. Dependence of upper yield or failure stress on failure time for sea ice in the horizontal plane.

strength (see Sinha 1982 for detailed discussion) may be obtained by using the average stress rate, defined as

$$[2] \qquad \frac{\dot{\sigma}_{af}}{\dot{\sigma}_1} = \frac{\sigma_f/t_f}{\sigma_1/t_1} \text{ or } = \frac{\sigma_f/\sigma_1}{t_f/t_1}$$

where $\dot{\sigma}_1$ is unit stress rate (= 1 MN·m^{-2}·s^{-1}).

Substitution of t_f/t_1 from [1] in [2] and rearrangement gives

$$[3] \qquad \frac{\sigma_f}{\sigma_1} = C^{1/(1+\theta)}\left(\frac{\dot{\sigma}_{af}}{\dot{\sigma}_1}\right)^{1/(1+\theta)}$$

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

$$[4a] \qquad \sigma_f = 4.64(\dot{\sigma}_{af})^{0.29} \qquad \text{for } \| \text{c ice}$$

and

$$[4b] \qquad \sigma_f = 6.99(\dot{\sigma}_{af})^{0.30} \qquad \text{for frazil ice}$$

Experimental results are compared with [4*a*, *b*] in Fig. 13. The stress rate exponents in [4], describing the stress rate sensitivity of strength, are comparable to 0.28 obtained for horizontally oriented sea ice (Sinha 1983*a*) and to 0.30 for similarly oriented fresh-water ice (Sinha 1981*a*). Vertically oriented, first-year, columnar-grained ice from Mould Bay also had a comparable stress rate sensitivity of 0.34, according to the field tests performed during the summer of 1982 (Sinha 1983*b*). Later field tests on first-year Beaufort Sea ice were analysed following the method developed by Sinha (1981*a*) and showed similar stress rate sensitivity (Frederking and Timco 1983) for columnar-grained ice but significant differences for granular ice.

Deformation in ice is difficult to measure even under the controlled conditions of a well-equipped laboratory. Techniques reported by Sinha (1981*a*) and subsequently corroborated in the field (Sinha 1983*a*)

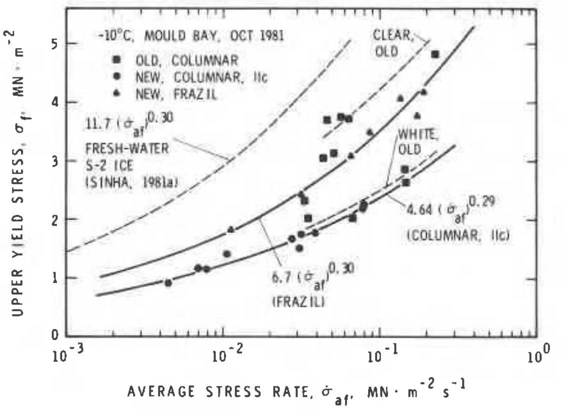

FIG. 13. Dependence of upper yield stress on average stress rate for sea ice with load applied in the horizontal plane.

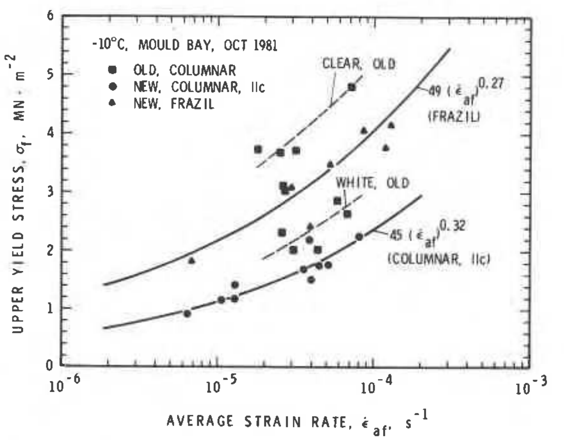

FIG. 14. Dependence of upper yield stress on average strain rate for sea ice subjected to loading in the horizontal plane.

bolstered confidence in the reliability of the strain measuring system. Results shown in Figs. 8 and 9 (discussed earlier) also confirm that highly accurate strain measurements can be made in the field. Such reliability of strain measurements makes it possible to apply strain rate analysis to strength results. The dependence of σ_f on $\dot\epsilon_{af}$ for all the tests in Fig. 12 is shown in Fig. 14. The strain rate sensitivity of strength can be represented (Sinha 1981*a*) by

$$[5] \quad \frac{\sigma_f}{\sigma_1} = P\left(\frac{\dot\epsilon_{af}}{\dot\epsilon_1}\right)^p$$

where $\dot\epsilon_1$ is the unit or reference strain rate ($= 1\ s^{-1}$). Regression analysis of the results for first-year ||c ice gave $P = 45 \pm 23$ and $p = 0.32 \pm 0.05$, with a correlation coefficient of 0.92. The results for frazil ice gave $P = 49 \pm 26$ and $p = 0.27 \pm 0.05$, with a correlation coefficient of 0.93. The numerical value of the strain rate sensitivity, p, for first-year columnar-grained ||c ice shows excellent agreement with the value of 0.33 obtained for fresh-water columnar-grained ice for constant crosshead rate tests (Sinha 1981*a*) and of 0.35 obtained for the same fresh-water ice tested under closed-loop controlled, constant strain rate loading conditions (Sinha 1982). These values differ significantly, however, from the value p obtained by Wang (1979), that is 0.54, for the same type of sea ice subjected to closed-loop controlled, constant strain rates at the same temperature.

Failure strain, ϵ_f, is, by definition,

$$[6] \quad \epsilon_f = \frac{\dot\epsilon_{af}}{\dot\epsilon_1}\frac{t_f}{t_1}$$

Substitution of $\dot\epsilon_{af}/\dot\epsilon_1$ from [5] and t_f/t_1 from [2] in [6] gives

$$[7] \quad \epsilon_f = CP^{-1/p}\left(\frac{\sigma_f}{\sigma_1}\right)^{(1-\theta p)/p}$$

Thus, on substitution of the values of C, P, p, and θ, obtained earlier,

$$[8a] \quad \epsilon_f = 1.42 \times 10^{-3}\sigma_f^{0.65} \quad \text{for columnar-grained ||c}$$

and

$$[8b] \quad \epsilon_f = 3.50 \times 10^{-4}\sigma_f^{1.38} \quad \text{for frazil ice}$$

The relation between σ_f and ϵ_f and the calculations based on [8*a*, *b*] are shown in Fig. 15. The increase in failure strain with increase in strength observed here for two types of first-year ice is characteristically similar to the earlier behaviour of fresh-water ice (Sinha 1981*a*, 1982). An increase in ϵ_f with increase in σ_f was also noticed for vertical samples of columnar-grained sea ice (Sinha 1983*b*). An apparent tendency for decreasing ductility with increasing strength, noticed for first-year ice by Sinha (1983*a*), is now thought to be questionable. The data were highly scattered and varied in the range of 4×10^{-3} to 10×10^{-3}. These values are significantly larger than those obtained during the present study. The errors could have been introduced in the measurements by end effects; the strain gauge was mounted not on the sample but between the top and bottom platens since the investigator was forced to use a small specimen size because of the low capacity (less than 10 kN) of the test machine. The softer nature of that machine in comparison with the present equipment could also have introduced errors (Sinha 1981*b*).

Conclusion

This study has confirmed that strength testing of sea ice can be readily carried out in the field using relatively simple equipment, provided care is taken to control the factors that affect strength and deformation properties.

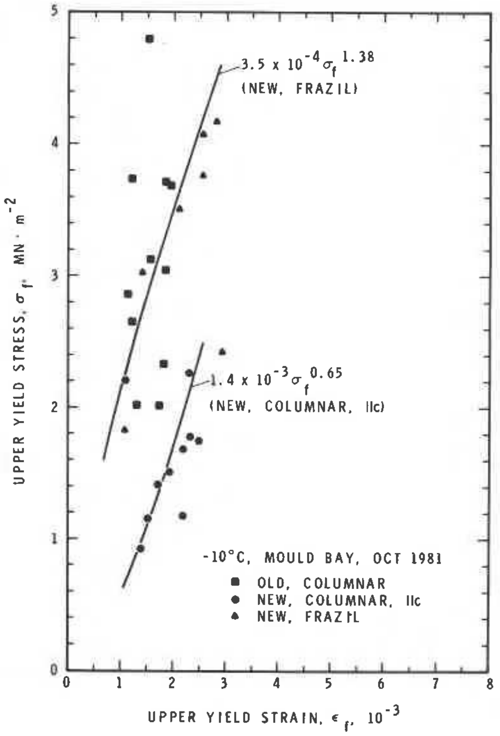

FIG. 15. Relations between stress and strain at upper yield.

Rate sensitivity of strength, that is, increase in strength with increase in rate of loading, was similar for the three types of ice studied, namely, first-year columnar-grained and frazil ice, and multi-year columnar-grained ice. This rate sensitivity has also been shown to be similar to that previously measured in fresh-water ice. Strength and ductility at a given rate of loading, however, depend on the type of ice, that is, on texture, fabric, impurity, and air bubble inclusions. Consequently, large variations in strength and deformation can be expected if strength tests are performed without strict attention to the structural differences in the types of ice.

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