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Is it a Useful Arctic Tool?

by N.K. Sinha

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RÉSUMÉ

Les températures de service de la glace étant très proches de son point de fonte, la glace se comporte de façon visco-élastique et présente ce qu'on appelle communément une fragilité aux températures élevées. Ses propriétés mécaniques sont sensibles à la vitesse et à la température, et l'analyse doit prendre en compte les données concernant les charges et les déplacements. On peut améliorer les essais au vérin de forage en utilisant une pompe électro-hydraulique tout en enregistrant simultanément la pression et le déplacement diamétral en fonction du temps. Ces légères mais importantes modifications du mode opératoire permettent d'analyser la réponse d'un système d'essais au vérin de forage sur des glaces de mer de l'année ou pluriannuelles dans des conditions hivernales opérationnelles, dans l'Extrême Arctique.

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THE BOREHOLE JACK
IS IT A USEFUL ARCTIC TOOL?

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ABSTRACT

As the working temperatures in ice are very close to its melting point, it behaves visco-elastically and experiences what is commonly known as high temperature embrittlement. Its mechanical properties are rate and temperature sensitive and analysis must include load and displacement history. Borehole jack tests can be improved by the use of an electrohydraulic pump in conjunction with simultaneous recording of pressure and diametral displacement as a function of time. These small but significant modifications in the test procedures permit analysis of the response of a borehole jack test system under operational winter conditions in the High Arctic in first-year and multi-year sea ice.

INTRODUCTION

A number of testing devices that can be inserted into boreholes to measure in situ load deformation properties have been constructed in the last 30 years. Such a device is the "borehole jack," which applies unidirectional pressure to two small, diametrically opposed areas of the borehole wall and measures the corresponding diametral displacement (Goodman et al., 1968). The equipment is reasonably light so that tests are easy to perform. Moreover, relatively higher pressures can be applied with the borehole jack than with, for example, a borehole dilatometer. These features led to its development as a hydraulic borehole jack for in situ determination of mechanical properties of ice (Kivisild, 1975). The adaptation has proved to be a rugged, portable, and relatively trouble-free tool that has been used extensively in the Arctic over the last 12 years. Interpretation of the readings it provides, however, has been uncertain (Masterson, 1983). Consequently, it has been used only to give a qualitative picture of ice to be tested.

The work now described examined the response and usefulness of borehole jack test system under operational conditions in the High Arctic on first-year and multi-year sea ice. When, as a first step, the operation of the instrument and the established test procedures were examined, it became clear that the difficulty in interpreting past readings rested primarily in shortcomings of the established test procedure itself. This paper proposes new procedures for testing, showing that small but significant modifications will permit systematic comparison of field results with those obtained in a laboratory for small samples under uniaxial and confined conditions.

BOREHOLE JACK

The borehole jack used in the present case was developed by FENCO (Kivisild, 1975) to operate in a 150-mm diam (D) borehole in ice (Fig. 1). Load is applied hydraulically to an internal piston that pushes plates on opposite ends of the jack against the sides of the borehole. The 91-mm diam plates (R_o) are curved in one plane to match the curvature of the wall. During a test the plate pressure is registered on a dial gauge attached to the supply line and the maximum noted. There is provision also for recording the pressure against diametral displacement, using an X-Y recorder. A transducer in the hydraulic line is calibrated to give the average applied pressure, σ, on the plates, and an internal potentiometer provides data on their relative displacement, u_D, into the ice.

Although this jack has been widely known in the ice engineering community for more than a decade, no data have been published in the open literature. Private communications indicate that users, and there are many, are not certain how to interpret the results. No study had been carried out to compare the borehole jack measurements with those obtained on the same ice using established and readily interpreted compression tests. It was felt that there was a need to undertake such a comparison if borehole jack test results were to be made quantitatively useful.

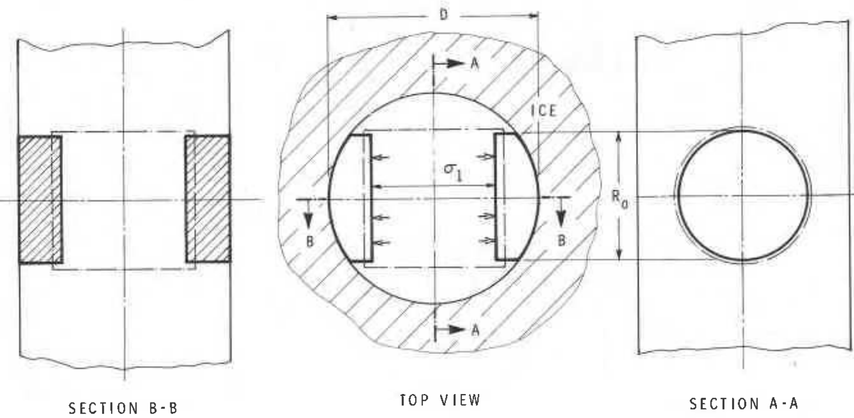

Fig. 1 Schematics of borehole jack in hole

GENERAL CONSIDERATIONS

Although the working temperatures in ice are low in terms of human comfort, they are very high in terms of materials. The temperature of ice in nature rarely goes below -40°C for any extended period. Its working temperatures are therefore greater than the homologous temperature of 0.85 T_m, where T_m is melting point in Kelvin. In metals and alloys, working temperatures higher than about 0.4 T_m are considered to be elevated temperatures. At these levels polycrystalline materials, ice no exception, exhibit pronounced creep and grain-boundary embrittlement. A direct consequence of high-temperature deformation and failure modes is that the strength of ice is rate sensitive and loading history becomes important in any load-deformation tests.

Consider conventional laboratory strength tests first. These are generally performed on cylindrical specimens under constant cross-head displacement rates, $\dot{x}$, or nominal strain rates, $\dot{\varepsilon}_n = \dot{x}/\ell$, where ℓ is the length of the specimen. Specimens are either unconfined or subjected to confinement. The author examined conventional tests in detail, performing then on both fresh-water ice (Sinha, 1981) and young and old sea ice (Sinha, 1984). In spite of the imposed constancy for cross-head rate, strain rate in the specimens increased monotonically with time, approaching a constant peak strain rate only after reaching maximum, or failure, stress for upper-yield type of failure. The initial strain rates could be significantly (orders of magnitude) less than the subsequent peak strain rate. Peak strain rate, $\dot{\varepsilon}_p$, compared well with the corresponding $\dot{\varepsilon}_n$. In conjunction with microstructural investigations, these observations indicate that virgin ice (undamaged) provides maximum resistance to cross-head movement, resulting in low strain rate in the specimen during the initial period. The observations indicate, as well, that the testing machine can impose the chosen deformation rate ($= \dot{\varepsilon}_n$) only when the specimen acquires a damage level, depending on loading rate, at which it ceases to offer increase in resistance with increase in deformation. Thus, in a conventional test, upper yield type of failure can be defined not only by the occurrence of peak stress but also by the onset of constant peak strain rate in the specimen.

Consider next the borehole jack test. It is the hydraulic pumping pressure applied to the piston that one attempts to maintain constant as a first measure. The parameter in such borehole jack tests that is the closest equivalent of the specimen strain rate in conventional tests is the "diametral strain rate" defined as $\dot{\varepsilon}_D = \dot{u}_D/D$, where $\varepsilon_D (= u_D/D)$ is the diametral strain and $\dot{u}_D$ is plate displacement rate. Questions arise about how a borehole jack system responds during a test, and what the characteristics of $\dot{u}_D$ are during the loading cycle. Most borehole jack tests have been performed in the field using a hand pump, with which it is impossible to control hydraulic pressure adequately. In this investigation, an electrohydraulic pump was used to provide pressure, and plate pressure and diametral displacement were recorded separately as functions of time.

FIELD TEST

Mould Bay, Prince Patrick Island, N.W.T., Canada, has proved to be an ideal site for conducting investigations on sea ice, primarily because of the High Arctic Weather Station located there (76°N, 119° 20'W) and the close proximity of the ice to the station (Sinha, 1984; 1985a). It was decided to carry out borehole jack tests as part of the fourth Radarsat field trip to Mould Bay in March-April 1984.

The southern half of the bay, which is 30 km long and more than 10 km wide at some locations, was covered with numerous (large and small) multi-year ice floes. Various sites were investigated to provide basic data for interpreting a Synthetic Aperture Radar (SAR) image of the ice conditions in the bay. These included the ten stations in first-year ice customarily set up along an east-west line across the bay (Sinha 1984). Borehole jack tests were conducted at three sites representing (1) first-year columnar-grained ice, (2) multi-year ridge, and (3) multi-year columnar-grained ice in a large floe.

The first site was at Station 9 on an east-west line about 1 km from the western shore. Here the ice cover was extremely flat and covered with snow 0.1 m in depth. Except for 0.11 m of snow ice at the surface, the ice was columnar-grained through its entire depth of 1.93 m (Fig. 2). The c-axes of the grains were in the horizontal plane (±5 deg) parallel to the surface of the ice cover; their mean

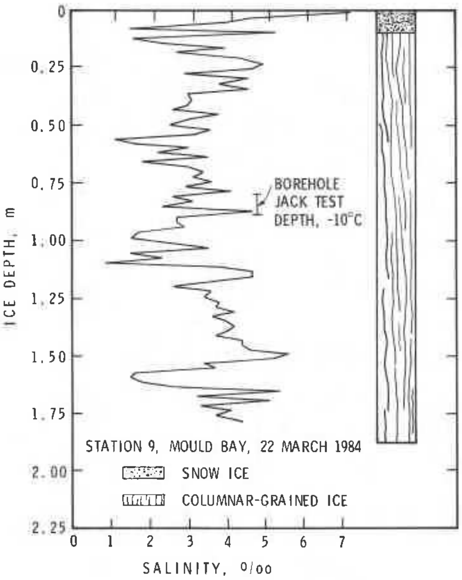

Fig. 2 Vertical salinity and texture profile of first-year ice

in the horizontal plane tended to be parallel (±15 deg) to the western shoreline and hence probably to the direction of tidal current. This type of anisotropy in the fabric of the ice in Mould Bay had been observed earlier (Sinha, 1984, 1985a).

As the ice was anisotropic in texture as well as fabric, it was necessary to use the following coordinate system. Coordinates x_1 and x_2 were chosen in the plane of the ice cover (horizontal plane) and x_3 parallel to the axes of the columnar grains (in the vertical plane). For simplicity, the direction of x_1 was taken as parallel to the mean c-axis orientation of the grains. Borehole jack tests were conducted with the load axis (σ_1) at angles α and γ to x_1 and x_3, respectively. As the tests were carried out in vertical holes, γ = 90 deg in the present tests. In all, 15 tests were conducted at this site, with three different orientations of α. Five tests were carried out at each of three orientations, i.e., α = 0, α = 45 and α = 90 deg.

Temperature measurements in the ice on the day of the tests at Station 9 (9 April 1984), just prior to borehole jack testing, showed that the ice was at -10°C at a depth of 0.85 m, an almost ideal situation. Here the average salinity was about 3.5% (Fig. 2). Because the ice cover was 1.9 m thick at this site, the test depth of 0.85 m was symmetrical with regard to the top and bottom surfaces of the ice cover. A number of uniaxial strength tests had been carried out in the past at a temperature of -10°C on ice of this type and from this general region.

A large block of ice extending to a depth of about 1 m was recovered from the site, using a chain saw for cutting. Specimens for the laboratory tests were later prepared from this block. Borehole jack tests were then performed in 15 holes drilled in the ice cover round the area from which the block had been taken. The distance between holes was kept to 2 m in order to avoid any damaged zone created in the ice by the tests. Although the jack was lowered to a depth of only 0.85 m, each hole was drilled to a depth about 1.20 m, the extra depth providing a reservoir for ice chips that could not be removed during drilling. To avoid any change in the thermal regime of the ice, each hole was drilled immediately before the test, which was carried out as rapidly as possible. From the beginning of drilling to the end of the tests, the total time was less than 6 min, including one test that took about 2 min. Such efficient procedures required considerable practice by a test crew of four. The tests were made on a calm cloudy day, with day-time air temperature between -26 and -28°C.

After completing the tests at Station 9, the test crew travelled a distance of 4.7 km east to a small floe designated "4-Peg Floe," part of an old ridge or rubble field containing a number of different types of ice. Only five tests were conducted at a relatively flat area on a hummock in the middle of this floe. Again, the jack tests were performed at a depth of 0.85 m, where the temperature was measured at -20°C. The ice was more than 7.9 m thick. No attempt was made to orient the jack in a particular direction. Two vertical ice cores (76 mm in diameter and 5.0 m long) were recovered from this site prior to the jack tests. One was used for determining the salinity profile and the other for determining ice type (Fig. 3). The second core also provided a number of cylindrical specimens (about 0.25 m long) that were used later for strength tests at -20°C to match the experimental temperature of the jack tests.

The third site was a relatively flat area in the middle of a large multi-year floe (1 km in diameter), designated "Norland Floe," in the south of the bay 5.3 km from the "4-Peg Floe." Here the ice cover was 5.0 m thick, columnar-grained through its entire depth, and showed anisotropy in texture and fabric similar to that in the ice at Station 9. There were several interfaces, however, containing air bubbles and frazil crystals embedded within the columnar grains, possibly indicating different growth seasons (Fig. 4). A considerable amount of information about the strength and structure of the ice at this site was obtained in the field prior to jack testing. Both confined and unconfined strength and deformation tests were conducted at -10°C, but none at lower temperatures. Blocks of ice were recovered before the jack tests were performed. Only four tests could be carried out, however, as one of the connectors to the pressure hose started to leak, with heavy loss of hydraulic fluid. Of the four tests, one was at α = 0°, one at α = 45°, and two at α = 90°. All were carried out at a depth of 0.8 m, where the ice temperature was -20°C. A few uniaxial laboratory tests were then conducted at -20°C on horizontally oriented samples to match the jack tests.

The uniaxial compression tests were carried out at -10°C and -20°C in a field laboratory on the eastern shore of Mould Bay. The procedures for unconfined tests on horizontally oriented samples were essentially similar to those described by Sinha (1984), except that the present tests were carried out on 100 × 100 × 250-mm specimens. Procedures described by Sinha (1985a) for measuring confined (biaxial) strength and deformation of second-year ice were strictly followed. Tests on the vertical samples of ridge ice were carried out at -20°C using procedures also described (Sinha 1983a). The universal test machine used was a 50-kN capacity, conventional screw-driven machine (Wykeham Farrance, Model WF-10053) capable of delivering a maximum cross-head rate, $\dot{x}$, of 6 mm/min or an equivalent of

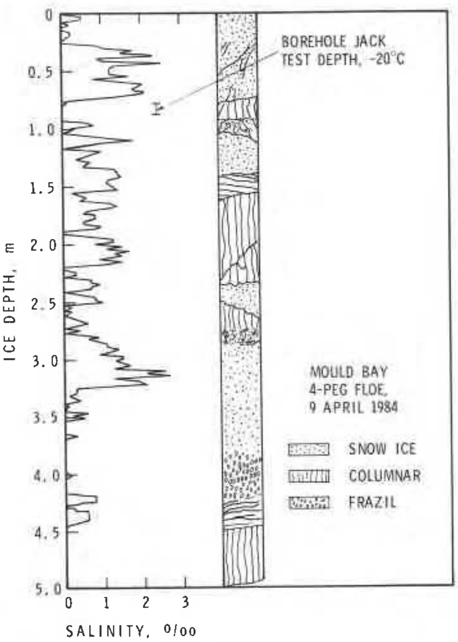

Fig. 3 Vertical salinity and texture profile of multi-year ridge ice

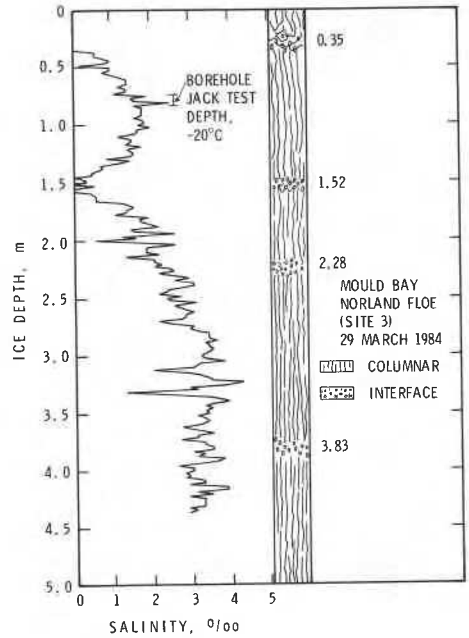

Fig. 4 Vertical salinity and texture profile in large multi-year flow

4×10^{-4} s^{-1} for nominal strain rate, $\dot{\varepsilon}_n = \dot{x}/\ell$, where ℓ is the specimen length. This machine was slightly faster than the one used during previous field trips. The temperature of the laboratory (a mobile trailer) and hence the test, was controlled (±0.5°C) by a commercially available heating/refrigerating unit operating in the heating mode.

RESULTS AND ANALYSIS

A set of in situ stress-displacement, σ_1-u_D (or stress-strain, σ_1-ε_D) diagrams obtained for first-year columnar-grained ice at -10°C is shown in Fig. 5 for $\alpha = 0°$, $\alpha = 45°$ and $\alpha = 90°$. Figure 6, on the other hand, shows all the results obtained for one of the three α orientations. The dependence of stress on displacement or diametral strain for the five tests on multi-year ridge ice at -20°C is presented in Fig. 7. Four tests performed on multi-year columnar-grained ice are presented in Fig. 8.

In all the stress-displacement or stress-strain curves in Figs. 5 to 8 stress gradually reaches a peak value, σ_{1f}, after which it decreases slowly

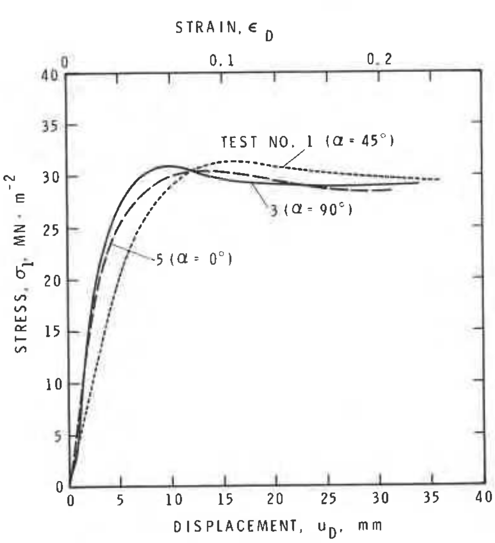

Fig. 5 Stress-displacement diagrams for borehole jack tests in different orientations, first-year columnar-grained ice, -10°C

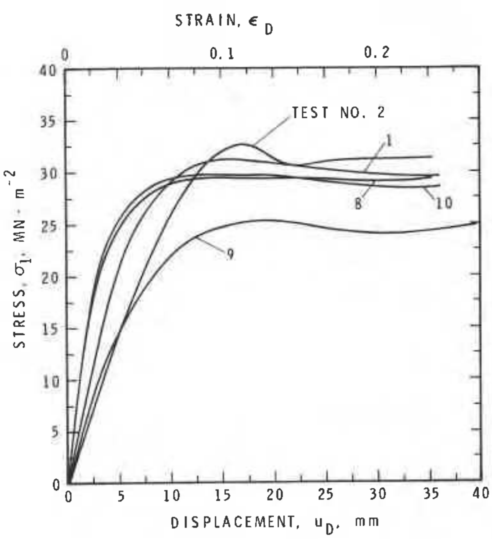

Fig. 6 Stress-displacement digrams for borehole jack tests with the same orientation, first-year columnar-grained ice, -10°C

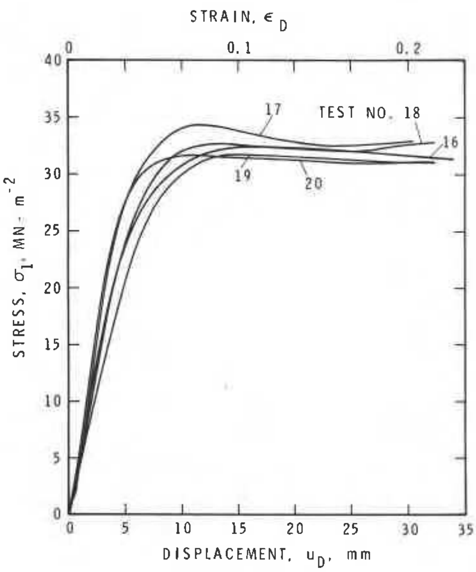

Fig. 7 Stress-displacement diagrams for borehole jack tests in multi-year ridge ice (4-Peg Floe), −20°C

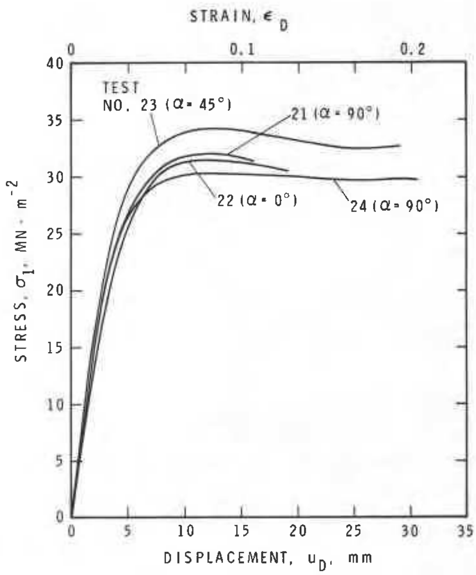

Fig. 8 Stress-displacement diagrams for borehole jack tests in multi-year columnar-grained ice (Norland Floe, site 3), −20°C

with further displacement. There is a tendency for load to increase again at larger displacement. All the σ_1–u_D (or σ_1–ε_D) diagrams show curved characteristics almost immediately after the initiation of loading, a type of curvature common in stress-strain diagrams in laboratory tests. The mean value of the peak stresses in first-year ice is 28.6 ± 2.3 MN·m^{-2} for the 15 tests, giving the standard deviation as 8% of the mean. The average σ_{1f} for the five tests in old ridge ice gives a value of 32.6 ± 1.1 MN·m^{-2}. Here the scatter is only 3% of the mean. The mean, σ_{1f}, of the multi-year floe ice was 32.1 ± 1.7 MN·m^{-2}, giving a scatter of 5%. The failure strains for all the ice were in the range of 5 to 10%. If peak stress is used as a measure of in situ strength, then one would conclude that the jack gives a fairly consistent index value. One would also conclude that strength is greater at lower temperatures, particularly when the results for Station 9 ice are compared with those at Norland; ice at both stations is similar and contained a fair amount of salt. It may also be seen that the colder ice shows a larger initial slope of the σ_1–u_D curve and hence greater effective modulus than the warmer ice. Figures 5 and 8 show that the orientation of the load with respect to the principal crystallographic axes of the grains in the horizontal plane does not affect the borehole jack peak values. Such non-dependency has also been observed in confined laboratory tests on oriented, second-year columnar-grained ice (Sinha, 1985a). Thus the jack is capable of giving information, at least in a relative sense, on some basic characteristics of ice. The σ_1–u_D or σ_1–ε_D curves without known history, however, are of limited use in the analysis of material behaviour at high homologous temperatures such as are involved in ice engineering (Sinha, 1981; 1982) where loading history plays a dominant role.

Examples of loading history are given in Fig. 9–11 for the three types of ice tested. The feature common to all is the displacement rate, $\dot{u}_D$, or the diametral strain rate, $\dot{\varepsilon}_D$; this is not constant but increases gradually during a test, only becoming constant when the load reaches peak value. The peak displacement rate, $\dot{u}_{Dp}$, is significantly greater than the initial rate, and is about twice the average displacement rate to failure, $\dot{u}_{Df} = u_{Df}/t_f$. This is contrary to common expectation, i.e., that the hydraulic system would lose its pumping capacity and lead to a decrease in $\dot{u}_D$ as load increases.

These observations bear almost one-to-one correspondence with the results obtained in uniaxial tests (constant cross-head displacement rate) on Station 9 ice (Fig. 12), in which the specimen strain rate approached a constant value after maximum load had been reached. Moreover, the peak strain rate compared well with the nominal rate; it was about three times the average strain rate, in this case $\dot{\varepsilon}_{1f} = \varepsilon_{1f}/t_f$, to the point of maximum or upper yield stress. A similar situation, though not so pronounced, may be seen in Fig. 13, which

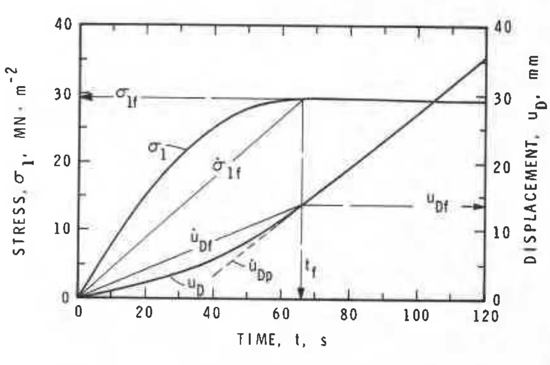

Fig. 9 Stress and displacement histories for borehole jack test No. 8 (α=45°, γ=90°), first-year columnar-grained ice, −10°C

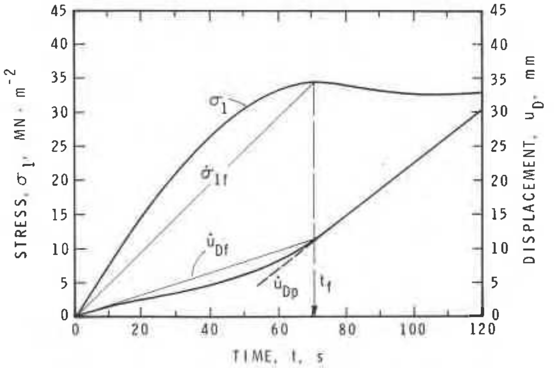

Fig. 10 Stress and displacement histories for borehole jack test No. 17 (α=?, γ=90°) in multi-year ridge ice (4-Peg Floe), -20°C

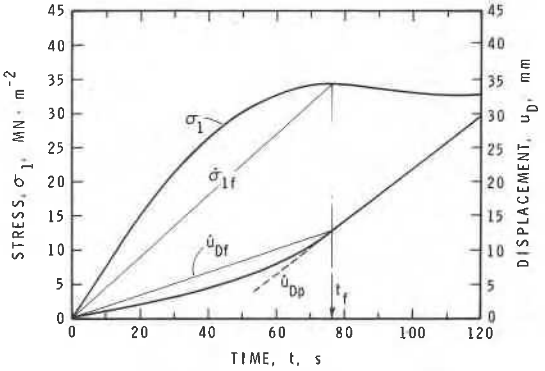

Fig. 11 Stress and displacement histories for borehole jack test No. 23 (α=45°, γ=90°) in multi-year columnar-grained ice (Norland Floe, site 3), -20°C

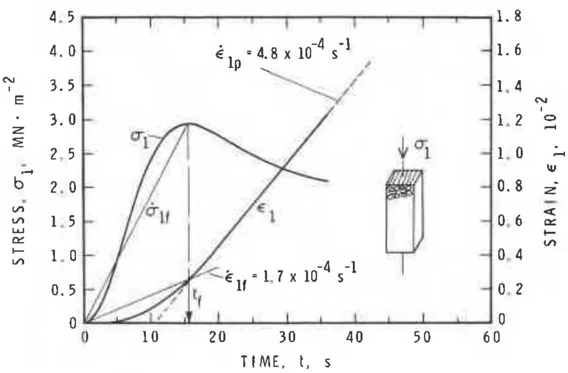

Fig. 12 Stress and strain histories for uniaxial unconfined test No. 240 (α=0°, γ=90°) for first-year columnar-grained ice, -10°C and $\dot{\varepsilon}_n = 4 \times 10^{-4}\ s^{-1}$

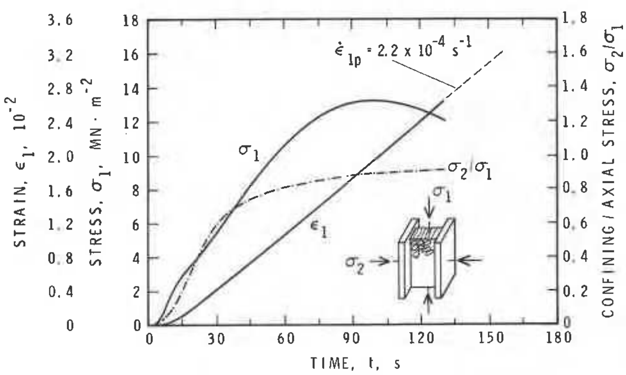

Fig. 13 Stress, strain and stress ratio histories for confined test No. 231 (α=45°, γ=90°) for first-year columnar-grained ice, -10°C and $\dot{\varepsilon}_n$ 3 × $10^{-4}\ s^{-1}$

illustrates a confined test on ice from the same site. Similar observations involving conventional test machines were also made earlier using laboratory-made fresh water ice (Sinha, 1981) and natural sea ice (Sinha, 1984, 1985b) under unconfined conditions, and second-year sea ice under confined conditions (Sinha, 1985a).

The simplest and most practical relation that can be examined from the experimental results is the dependence of upper yield or failure stress on the corresponding failure time. According to previous analyses, whether tests are conducted on fresh-water ice or sea ice, under constant cross-head rates or closed-loop, controlled strain or stress rates, (e.g., Sinha, 1981; 1982; 1984) a satisfactory relation is given by

$$\frac{t_f}{t_o} = C \left[\frac{\sigma_{1f}}{\sigma_o}\right]^{-\theta} \qquad (1)$$

where t_o is the unit or reference time (= 1 s) and σ_o is the unit or reference stress (= 1 MN•m^{-2}). Figure 14 shows that equation (1) applies not only to the data obtained for uniaxial and biaxial tests, which were carried out at deliberately different rates, but also to the in situ borehole jack tests. The results of regression analysis of the data are shown in Table 1.

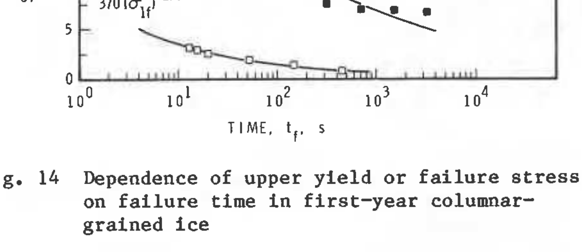

Fig. 14 Dependence of upper yield or failure stress on failure time in first-year columnar-grained ice

The simplest evaluation of the rate sensitivity of strength may then be obtained by using the average stress rate to failure, $\dot{\sigma}_{1f} = \sigma_{1f}/t_f$. It can be shown using equation (1)

TABLE 1. Results of regression analysis for field tests at -10°C, Mould Bay, March-April 1984

Test	C	θ
Borehole jack α=0,45,90°, γ=90°	5.92×10^4	2.08
Unconfined α=0°, γ=90°	370.5	2.78
Confined α=45°, γ=90°	2.80×10^6	4.06

that

$$\frac{\sigma_{1f}}{\sigma_o} = C^{\frac{1}{1+\theta}} \left[\frac{\dot{\sigma}_{1f}}{\dot{\sigma}_o}\right]^{\frac{1}{1+\theta}} \qquad (2)$$

where $\dot{\sigma}_o$ is unit stress rate defined as σ_o/t_o.

Substitution in equation (2) of the values of C and θ from Table 1 gives, for -10°C

$$\begin{aligned} \sigma_f &= 4.8\ (\dot{\sigma}_{1f})^{0.27} && \text{unconfined} \\ \sigma_f &= 18.8\ (\dot{\sigma}_{1f})^{0.20} && \text{confined} \qquad (3) \\ \sigma_f &= 35.4\ (\dot{\sigma}_{1f})^{0.32} && \text{in situ} \end{aligned}$$

Equation 3 is illustrated in Figure 15 along with the experimental points. It should be pointed out that Equation 3 should not be extrapolated beyond the experimental ranges.

Pressure, exerted by jack plates on the ice, and time are the two quantities that can be measured without ambiguity. Moreover, they can be measured without any electronic equipment, which may often malfunction under field conditions. Analysis based on average stress rate is clearly the simplest and probably the most appropriate method of examining the results obtained with a borehole jack. Figure 15 shows that loading rate was not fixed, but varied as much as 300%. The jack therefore interacted with the ice body differently from hole to hole, depending on local conditions (temperature, contact, etc.) and variations in quality. Such a large variation in actual loading conditions can even occur in laboratory-made ice under the best test conditions where cross-head rate, $\dot{x}$, is maintained constant by means of a closed-loop feedback system (Sinha, 1983b). It would appear that variation in jack strength results was caused primarily by variation in the imposed loading rate and hence by rate sensitivity of the ice. Scatter in the in situ results (Fig. 15) is comparable to (if not less than) that obtained in the laboratory when the results take into account the rate of loading. Also note the similarity in the rate sensitivity of strength, i.e., the stress rate exponent in Equation 3 given by the in situ and unconfined tests and 0.34 for vertical strength by Sinha (1983a).

For purposes of comparison, a stress rate of $0.3\ MN \cdot m^{-2}\ s^{-1}$ may be considered as a common rate for both in situ and laboratory tests. At this rate the jack strength is almost twice that of the confined test, which in turn is about four times greater than corresponding unconfined tests. It should perhaps be mentioned that the unconfined strength depends on α and is strongest when α = 0°, as in the present case, and significantly weaker when α = 45° (Wang, 1979).

Results obtained for multi-year ridge and floe ice are presented together in Fig. 16 because of similar experimental temperatures and the absence of sufficient data points for any systematic study. Moreover, the uniaxial tests on ridge ice represent a variety of loading conditions, resulting from different types, qualities and orientations of the ice, as would be expected from Fig. 3. Higher strengths (>8 $MN \cdot m^{-2}$) were obtained on samples with

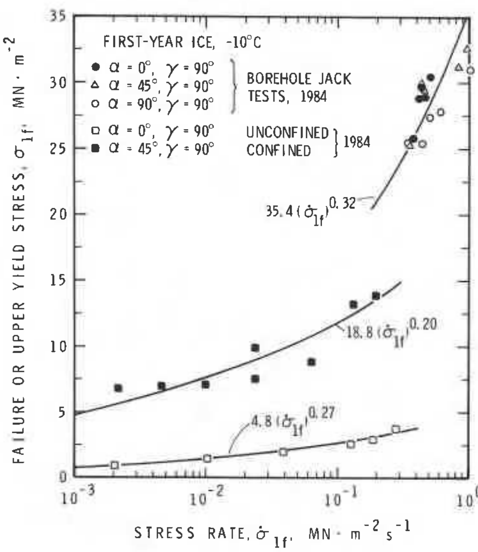

Fig. 15 Dependence of upper yield or failure stress on average stress rate to failure for first-year columnar-grained ice

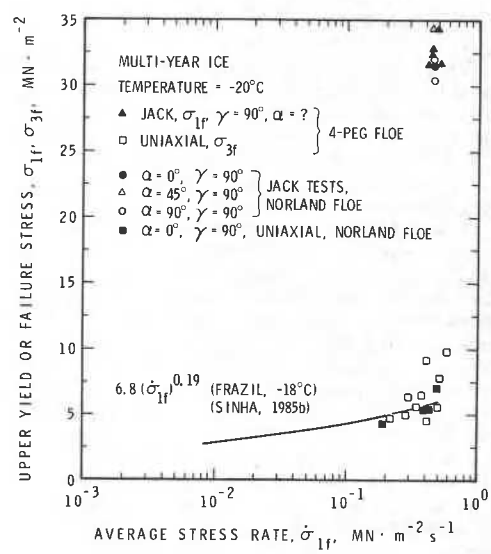

Fig. 16 Dependence of upper yield or failure stress on average stress rate to failure for multi-year ice

vertical columnar grains. The appropriate uniaxial results for comparison with in situ results would perhaps be those for samples in which granular ice was present (granular ice above and below but not at the jack test depth). These samples had strengths in the range 5-6 $MN{\cdot}m^{-2}$ and, in fact, agreed well (Fig. 16) with previous observations on congealed young frazil ice at -18°C at Mould Bay in 1981 (Sinha, 1985b). At a stress rate of 0.45 $MN{\cdot}m^{-2}\ s^{-1}$ the mean borehole jack strength is about 5.5 times greater than the uniaxial strengths. This comparison, however, should be accepted with caution. The area where the jack actually applied pressure at "4-Peg Floe" contained a 0.15-m zone of vertically-oriented columnar-grained ice containing little brine. The jack applied load at right angles to these columns, a loading condition similar to that obtained at the "Norland Floe." Perhaps this is why both sets of borehole jack results agree well with each other. This hypothesis is supported by the fact that the unconfined strengths of both 4-Peg ice and Norland ice agree with each other, as may be seen in Fig. 16. Though the number of tests is not large, Figures 15 and 16 indicate that the uniaxial strength of multi-year (Norland) ice is greater (about 30%) than that of first-year ice at the same rate of loading. The salinity of the first-year ice, tested at -10°C, was about 3°/oo (Fig. 2), whereas that of the old ice, tested at -20°C, was about 1.5°/oo (Fig. 4). Thus the higher strength of the older ice was due to the combined effects of lower salinity and lower temperature. Whatever the underlying reasons, it may be seen that the jack also provides a measureably higher strength index (about 20% at $\dot{\sigma}$ = 0.45 $MN{\cdot}m^{-2}s^{-1}$) for the old ice than for the new ice.

CONCLUSION

In situ tests in first-year and multi-year sea ice in the High Arctic, under winter conditions, show that the response of an existing test system (as indicated by plate pressure and diametral strain history) bears a one-to-one correspondence to the response of uniaxial, unconfined and confined (biaxial) tests in a conventional universal test machine. Virgin ice offers maximum resistance to load, resulting in lower displacement rate during the initial period of a borehole jack test. The displacement rate increases monotonically as the ice approaches failure and then remains constant.

Upper yield type of failure is associated with the onset of constant displacement rate. Jack strength is sensitive to both rate of loading and temperature. Loading rate, however, depends on quality and temperature, etc., of the ice. Apparently similar tests could therefore result in different values for strength. Loading history and temperature can and must be taken into account in any analysis. Average stress (plate pressure) rate to failure is appropriate for this purpose. Stress rate sensitivity for jack strength is the same as that of unconfined tests. For the same type of structure, multi-year ice may appear to be stronger than first-year ice, but this may be due to its lower brine volume and (usually) lower temperature. Both jack strength and confined strength are independent of loading direction in oriented, columnar-grained ice when load is applied normal to the columns. Jack strength can be twice as great as confined strength for columnar-grained ice and can be an order of magnitude greater than the uniaxial, unconfined strength (depending on orientation) at the same rate of loading. Hand pumping should never be used because it is nearly impossible to control the rate of loading. An improved borehole jack should have the capability of varying rate of hydraulic pumping and of controlling diametral displacement rate. Ideally, microstructural examination of thin sections should be carried out in stages as stress increases, but this was impossible because of time constraints.

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