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RÉSUMÉ

On a mesuré la résistance à la compression de plusieurs échantillons de glace d'eau de la mer de Beaufort confinés par des plaques verticales (type A) et latérales (type B). Les résultats montrent que la résistance en compression dépend nettement de la structure de la glace. Pour la glace granulaire, la résistance en compression
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CONFINED COMPRESSIVE STRENGTH OF SEA ICE

ABSTRACT

The confined compressive strength has been measured for both vertical (A-type) and lateral (B-type) confinement conditions for sea ice from the Beaufort Sea. The results show that the confined compressive strength is extremely sensitive to the structure of the ice. For granular ice, the confined compressive strength for both A and B type confinement is 19% higher than for unconfined compressive strength. For columnar ice, the compressive strength for A-type confinement can be four times as high as the strength of unconfined or B-type confined compressive strength. These results are explained in terms of basal-plane glide in the ice. The results of the tests are used to evaluate the coefficients of an n-type yield function from plasticity theory. The functional form of the yield surface for the cases of plane strain and plane stress in the plane of the ice cover are presented and compared to the corresponding functions for freshwater ice.

INTRODUCTION

When an ice sheet interacts with a structure, the stress field in the ice can be complex. In certain situations, in the plane of the ice cover, the ice can be in a confined loading state. As such, information on the behaviour of ice under confined conditions is extremely important. This is especially so since columnar ice is an anisotropic material with pressure sensitive mechanical strengths which are different for tension and compression. Because of this, von Mises and Tresca yield functions are not appropriate to describe ice behaviour under bi-axial stress conditions. In spite of its importance, the confined strength has been tested under limited conditions only for freshwater ice /1,2/, saline ice /3/ and model ice /9/ but not for sea ice. In this first attempt to measure this property under field conditions, the confined strength of sea ice has been determined for different confining directions and depths in the ice sheet (i.e. different grain size and type) for one nominal strain rate and one temperature. The results of the tests have been used to determine the numerical value of the coefficients for an n-type yield function postulated for sea ice.

EXPERIMENTAL

The ice tested in these experiments was obtained in January 1982 from a rafted solid block of ice which was in the rubble field around Tarsiut Island, Gulf/Dome's concrete-caisson island in the Beaufort Sea. Six ice blocks were cut through the depth of the ice and transported to a small laboratory in the Dome Petroleum base camp in Tuktoyaktuk where the final sample trimming and testing was performed. The structure of the ice was typical of sea ice from the Beaufort Sea. In the upper 2-3 cm there was a layer of fine-grained snow ice (1-2 mm grain diameter). Below this the grain size increased. With increasing depth there was a gradual change to a columnar structure of average grain diameter of 7mm. The grains were columnar below a depth of about 30 cm with distinct banding along the length of the core. There was a very strict columnar grain structure of the ice at depths of 30-50 cm and an abrupt change at about 50 cm to a 6 cm thick band of a finer-grained mix of granular and columnar crystals. Below this the ice became strictly columnar again.

Figure 1 shows a photograph of the sub-press used to create the confinement conditions. Basically it consists of an aluminum base to which one reinforced side wall is firmly secured. The other side wall is free of the base and, by using six screw-clamps (three per side) it provides firm confinement of the ice. The upper platen was attached to the circular platen of the Soiltest press (0.05 MN capacity) which was used to generate the pressure. Since the circular platen of the press is on a swivel head, this compensates for any irregularities in parallelism of the sample. The use of the sub-press requires careful sample preparation since the sample has to be a specified size. For this sub-press, the upper platen width is 5.0 cm and the height of the confining walls is 19.5 cm. As such, the ice pieces were trimmed with a band saw to a width of 5.5 cm and a height of 19.2 cm. Using a portable table planer, the sides of the samples were carefully planed to a thickness of 5.1-5.2 cm. The extra 1-2 mm width of the sample was used to compensate for any slight non-parallelism of the sample. After

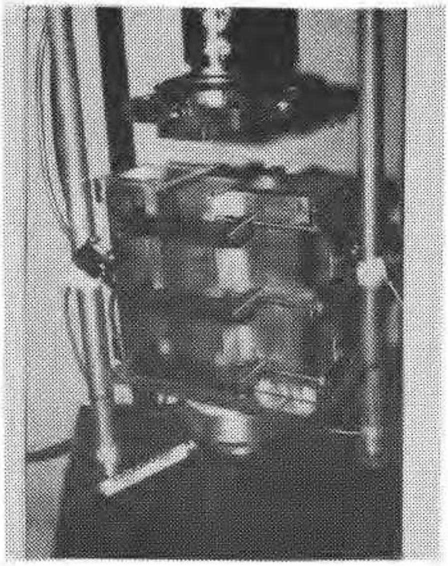

FIGURE 1 : ICE PIECE SANDWICHED BETWEEN CONFINING PLATES IN SUB-PRESS

cutting and planing the ice to size, it was carefully packaged and stored overnight in a small freezer at a temperature of -11°C. During testing, only a small number of samples were taken to the test lab at any one time in order to try to keep them at the warmer temperature for the test.

Three different confinement configurations were used. Since the specimens were cut so as to load them in the horizontal direction of the original ice sheet, confinement is possible on (A) the vertical sides of the sample, (B) the top and bottom of the sample, and (C) on none of the sides of the sample (i.e. uni-axial compression). These types of confinement are designated A-type, B-type and C-type respectively /2/. Since the ice macrostructure changes from a granular type to columnar type with increasing depth, this allows a comparison of results obtained on these two grain structures for different confining configurations. In all cases, the press was set at a nominal cross-head rate of 4×10^{-2} mm - s^{-1}. This corresponds to a nominal strain rate of 2×10^{-4} s^{-1} for the samples.

TEST RESULTS

Figure 2 shows stress as a function of time for types A, B and C confinement for samples with a granular structure. The stress was calculated using $\sigma = P/A$ where P is the applied load and A is the initial cross-sectional area on which it is applied. In all three cases a ductile-type failure occurred. For granular ice, results of A and B type confinement are equivalent. The results of all tests in this layer (2 A-type, 2 B-type, 4 C-type) show that the average yield stress for the confined tests (5.1 MPa) is 19% higher than that measured for the unconfined (uni-axial) tests (4.3 MPa). This difference seems reasonable since the confinement would tend to inhibit deformation in some grains which, without confinement, would contribute to the failure of the ice sample. This granular ice, which has a reasonably isotropic structure, can be compared to the plane strain tests done on freshwater T-1 (snow) ice /2/. In these laboratory tests, for a strain rate of 10^{-4} s^{-1} and at a temperature of -10°C, the measured strengths were 5.2 MPa and 6.8 MPa for the unconfined and confined test respectively. The confined strength was therefore 31% higher than the unconfined strength, in reasonable agreement with that observed for granular sea ice. Note, however, that the absolute values of the yield strength for the freshwater ice are higher.

Figure 2 also shows the stress as a function of time for types A, B and C confinement for samples with a <u>columnar</u> structure. In this case, both B and C-type failed in a ductile fashion at comparable yield stresses (i.e. strengths) of 2.0 MPa, whereas type A exhibited a significantly different stress-time curve. For A-type confinement, the stress initially increased at the same rate as that observed for B and C-type samples, but after a loading time of ≈15 s, the loading stress-rate decreased as the stress increased to levels 3-4 times higher than for the B and C type confinement. These high

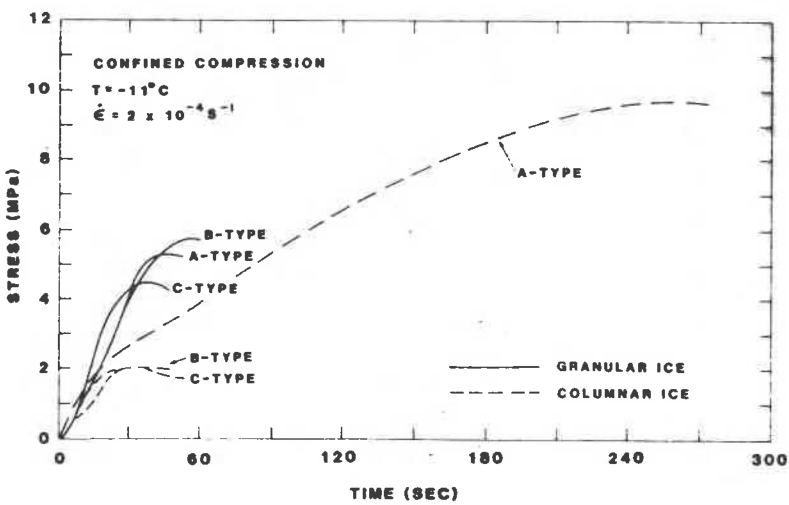

FIGURE 2 : STRESS-TIME CURVES FOR CONFINED COMPRESSION

strength values for this type of confinement clearly shows the anistropic failure mode for this columnar ice.

The structural anisotropy of this ice is characterized by a preferred basal-plane orientation and grain boundary direction such that deformation is two dimensional in the plane of the ice cover. In A-type confinement, the confining plates and loading platens are oriented so as to prevent deformation in this plane. As such, this deformation is inhibited and the ice must deform in the long direction of the grains. Since the grain boundaries and basal planes are not oriented to accommodate this, an elongation of the columns requires some type of non-basal glide. This type of deformation, however, requires stresses much greater than those associated with basal glide /4/. Therefore, the stresses required for yield of the columnar ice with A-type confinement are significantly higher than for unconfined or B-type confinement where deformation with basal glide is allowed. For similar reasons, there is no significant difference in strength between B and C-type confinement for columnar ice.

The depth dependence of the results of the A, B and C type tests are shown in Figure 3. This figure clearly shows the trends discussed above; viz. the comparable results for B and C-type confinement for granular ice, the higher strengths for both confined conditions as compared to the uni-axial case for the granular ice, the comparable results for B and C types confinement for the columnar ice, and the significantly higher strengths observed for A-type confinement of the columnar ice. In addition to these, however, there are several other features to note from this graph. With increasing depth, the strength for A-type compression increases whereas the strength for B and C-type compression decreases. This reflects the change from a granular structure to columnar structure with increasing depth. The most striking feature of the graph, however, is the "dip" in the A-type strength and the rise in the B-type strength for depths of 46-56 cm. This depth corresponds to the depth of the band of granular ice observed in the examination of the structure of the ice. This dramatically demonstrates the sensitivity of yield stress to ice structure and load conditions.

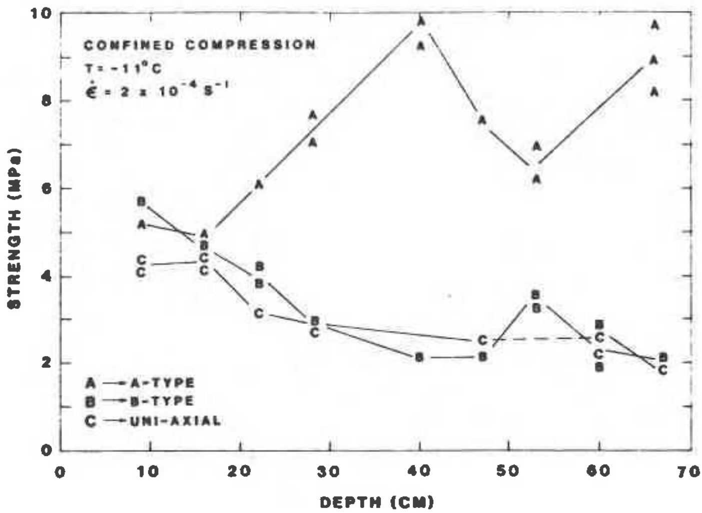

FIGURE 3 : CONFINED COMPRESSIVE STRENGTH VERSUS DEPTH IN THE ICE SHEET

APPLICATION OF RESULTS TO PLASTICITY THEORY

Plasticity theory provides a means of theoretically predicting the ice crushing forces in a dynamic ice-structure interaction. This theory was initially developed to describe the deformation and failure of metals, soils and rocks, and has recently been applied to ice problems. As a basic part of plasticity theory, a suitable yield function which describes the strength behaviour of the material must be formulated. The results of the present tests can be used to help evaluate the types of yield functions which are most suitable for describing ice strengths, and in determining the appropriate values of the yield function coefficients. **Ralston and Reinicke /5,7/ have** discussed the use of confined compression tests for selecting appropriate yield functions, and more recently, have applied this approach to calculate ice forces on indenters /8/ and conical structures /6/. Their analysis, however, was based on the tests results on confined freshwater ice. For sea ice, the brine in the ice reduces the strength. This will alter the values of the yield function coefficients. Coefficients appropriate for sea ice at the test temperature and strain rate can be obtained from the present test results.

In brief, yield functions for elastic-perfectly plastic materials are usually presented in the form $f(\sigma_{ij}) = 0$ where $f(\sigma_{ij})$ is some algebraic combination of stress components σ_{ij}. For $f<0$, the stress state is elastic, whereas for $f=0$, the material is at yield (i.e. in the plastic state). Ralston /5/ has shown that for ice, which is an anisotropic material, an n-type yield function of the following form is appropriate

$$\begin{aligned} f(\sigma_{ij}) = {} & a_1 \left[(\sigma_y-\sigma_z)^2 + (\sigma_z-\sigma_x)^2\right] + a_3 (\sigma_x-\sigma_y)^2 \\ & + a_4 (\sigma_{yz}{}^2+\sigma_{zx}{}^2) + a_6 \sigma_{xy}{}^2 + a_7 (\sigma_x+\sigma_y) \\ & + a_9 \sigma_z - 1 \end{aligned} \qquad (1)$$

where $a_6 = 2(a_1+2a_3)$ and the values of the coefficients a_1, a_3, a_7 and a_9 can be determined from the uni-axial compressive (C_x) and tensile (T_x) strengths and the A (σ^A) and B (σ^B) type confined strengths. Following Ralston's /5/ analysis yields four equations for the four unknown coefficients. Solving the equations using the strength values for sea ice of C_x=2.2 MPa, T_x=0.5 MPa, σ^A=9.0 MPa and σ^B=2.2 MPa gives a_1=0.19 MPa^{-2}, a_3=0.72 MPa^{-2}, a_7=1.55 MPa^{-1} and a_9=-0.82 MPa^{-1}.

This result is applicable to several problems. One such problem, that of the indentation of an ice sheet by a flat vertical indenter is of particular interest in ice mechanics. This problem involves two limiting situations: the condition of plane strain corresponding to a narrow indenter in a thick ice sheet and plane stress corresponding to a wide indenter in a thin ice sheet. Based on the generalized yield function (equation (1)) with the appropriate coefficients and Ralston's /5/ analysis, the yield functions for the special case of plane strain in the plane of the ice sheet is

$$f(\sigma) = 0.82\ (\sigma_x-\sigma_y)^2 + 1.14\ (\sigma_x+\sigma_y) - 1.44 \qquad (2)$$

and for plane stress in the plane of the ice sheet

$$f(\sigma) = 0.19\ (\sigma_x{}^2+\sigma_y{}^2)+0.72\ (\sigma_x-\sigma_y)^2+1.55\ (\sigma_x+\sigma_y)\ -1 \qquad (3)$$

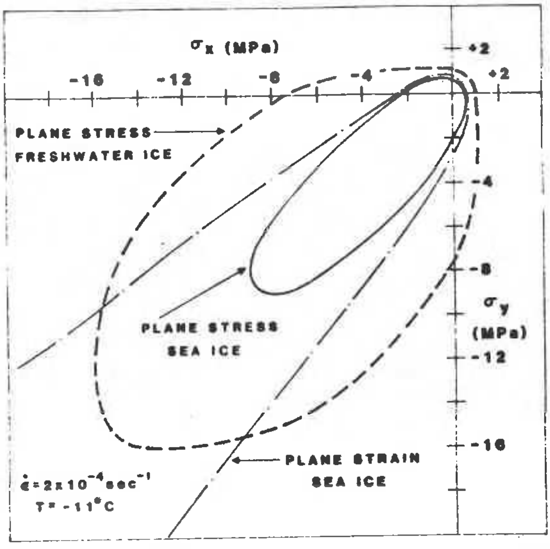

FIGURE 4 : YIELD SURFACES FOR SEA ICE AND FRESHWATER ICE AT A COMPARABLE LOADING RATE AND TEMPERATURE

These yield function envelopes are shown in Figure 4. Included in this figure is the corresponding plane stress ellipse for freshwater ice at the same strain rate and temperature based on Frederking's /2/ results. Comparing the plane stress ellipses for sea ice and freshwater ice it is clear that although they are qualitatively similar, they are quantitatively very different. In any analysis of the indentation of an indenter in sea ice using plasticity theory, the use of the yield function derived in this analysis should give more reliable results.

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REFERENCES

1 Croasdale, K.R., Morgenstern, N.R. and Nuttall, J.B. (1977), "Indentation tests to investigate ice pressures in vertical piers", J. Glac. 19, No. 81, pp. 301-312.

2 Frederking, R.M.W. (1967), "Plane-strain compressive strength of columnar-grained and granular snow ice", J. Glac. 18, No. 80, pp. 505-516.

3 Hausler, F.U. (1982), "Comparison between different failure criteria for saline ice". Annals of Glac. 4 (in press).

4 Higashi, A. (1967), "Mechanisms of plastic deformation in ice single crystals", in Ouru, H. ed., Physics of Snow and Ice, Part I, pp. 277-289, Bunyeido Printing Co., Sapporo, Japan.

5 Ralston, T.D. (1978), "An analysis of ice sheet indentation", in Proc. IAHR Symposium on Ice Problems, Vol I, pp. 15-31, Lulea, Sweden.

6 Ralston, T.D. (1980), "Plastic limit analysis of sheet ice loads on conical structures", in Tryde, P. ed., Physics and Mechanics of Ice, pp. 289-308, Springer-Verlag, New York.

7 Reinicke, K.M. and Ralston, T.D. (1977), "Plastic limit analysis with an anisotropic, parabolic yield function", Int. J. of Rock Mech., Mining Sci. and Geomech. Abstracts, 14, pp. 147-154.

8 Reinicke, K.M. (1980), "Analytical approach for the determination of ice forces using plasticity theory", in Tryde, P. ed., Physics and Mechanics of Ice, pp. 325-341, Springer-Verlag, New York.

9 Timco, G.W. (1982), "Uni-axial and plane-strain compressive strength of model ice". Annals of Glac. 4 (in press).