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MID-WINTER MECHANICAL PROPERTIES OF ICE IN THE SOUTHERN BEAUFORT SEA

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SOMMAIRE

Pendant les essais du brise-glace "CANMAR KIGORIAK" durant l'hiver 1979-1980, on a mesuré les propriétés de la glace de la banquise côtière près de McKinley Bay dans le Sud de la mer de Beaufort. On a effectué des analyses cristallographiques pour déterminer le type de glace et sa structure, établir des profils de température et de salinité et réaliser des essais de résistance à la compression axiale et l'essai brésilien. Le travail a été effectué à bord du brise-glace pendant les essais. Parmi les échantillons testés, il y avait des glaces de première année et de glaces comprimées depuis de nombreuses années. On trouvera dans cette étude les descriptions des techniques de mesure et d'échantillonage. Les valeurs de résistance obtenues sont comparées selon les conditions d'essais (salinité, charge, structure des cristaux, orientation de l'échantillon, et position de l'échantillon dans la couche de glace). Les résultats sont en général voisins de ceux de la littérature traitant du sujet.

MID-WINTER MECHANICAL PROPERTIES OF ICE IN THE SOUTHERN BEAUFORT SEA

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Ice property measurements were carried out during ice breaking trials of the "CANMAR KIGORIAK" during the winter of 1979-80, primarily in landfast ice in the Southern Beaufort Sea in the vicinity of McKinley Bay. They included crystallographic analysis to establish ice type and structure, temperature and salinity profiles, and uniaxial compression and "Brazil" strength tests. The work was performed on board ship at the time of the trials.

The ice under study included samples of first-year ice covers and multi-year pressure ridges. Sampling and measurement techniques are described. The strength results are discussed in terms of salinity, loading rate, grain structure, sample orientation and position in the ice cover. Strength results were found to agree generally with values in the literature.

In assessing the ice breaking performance of vessels it is necessary to have a complete knowledge of ice properties. Thickness, temperature, salinity where applicable, friction coefficient and flexural strength are normally of interest. In January 1980 the National Research Council of Canada collaborated with Dome Petroleum Ltd. during the ice breaking trials of the Canmar Kigoriak in a program that included grain fabric analysis to determine ice structure, type, grain size and orientation; ice temperature and salinity measurements for brine volume determinations; and compressive and "Brazil" strength tests. Measurements were carried out at the time of the trials in an improvised cold room on board ship.

The primary test area was in the Southern Beaufort Sea in the vicinity of McKinley Bay. The ice cover in this area was dynamic, with frequent movements into December, but it was landfast at the time of the January trials. Samples of ice from the trials area (first-year ice) were analysed, as was multi-year ice collected during a probe into the polar pack in October 1979. Measuring techniques are described, selected data presented, and strength results discussed in terms of salinity, loading rate, grain structure, and position in the ice cover. Complete results of the measurements appear in an earlier report [1].

Experimental Procedures

A total of 17 vertical cores of first-year sea ice were collected and analysed. Core diameter was 75 mm. In some cases temperatures and salinities were measured along the core immediately after retrieval in order to obtain representative profiles through the ice cover. Initial analysis involved a visual description of the core, including ice colour, air bubble content, brine drainage channels and sediment bands. Following this a decision was made on the further analyses to be performed. The cores were then marked and cut into appropriately sized pieces depending on whether specimens for thin section studies, salinity or strength measurements were required. All work was done in the improvised cold room on board ship, where temperature was a few degrees warmer than the ambient temperature, which ranged from -35 to -25°C.

Thin sections were made to determine general grain structure, size and orientation. A warming plate was used to prepare the thin sections, which were observed and photographed between crossed polaroids.

The compression and Brazil tests were done on a 50 kN capacity, motorized screw-drive test machine (Figure 1). Although this press is capable of cross-head rates from 3×10^{-3} to 5×10^{-2} mm/s, only a nominally constant rate of 3×10^{-2} mm/s was used for these tests. Load was measured with a 50 kN capacity load cell and recorded continuously. The ends of the specimens were cut on a band saw, care being taken to make the ends perpendicular to the axis of the cylinder, parallel to each other and flat. Compression specimens were typically 120 mm long by 75 mm diameter cylinders.

No further end preparation was done, other than brushing the cylinder clean. The length and diameter of each specimen were measured. "Maraset" compliant platens (2) were used to minimize the effect of irregularities and to reduce the radial stresses at the ends of the specimens. Loading was monotonic to yield or brittle failure. Strength was calculated from the maximum load each specimen was able to support and its cross-sectional area. From the continuous records of load versus time, loading stress rates [3] were determined for each test. The Brazil tests were performed on cylinders about 30 mm long by 75 mm in diameter. Load was applied perpendicular to the axis of the cylinder. Brazil strength, σ_B, was calculated using $\sigma_B = 2K \frac{P}{\ell \pi d}$ where K is concentration factor (assumed to be 6 in this case), P is failure load, ℓ is length, and d diameter. After testing, the salinity of each specimen was measured.

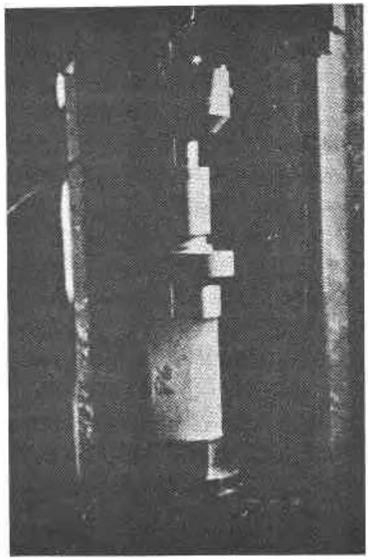

Figure 1

Loading frame of test machine showing compression sample between compliant platens

Results and Discussion

Numerical results of over 60 strength tests conducted on samples of first-year sea ice are presented in Tables I and II. As all specimens were obtained from vertical cores, the loading direction was parallel to the ice growth direction for compression tests, and perpendicular to ice growth direction for Brazil tests.

All the compression tests were run at a nominal strain rate of $2.5 \times 10^{-4}\ s^{-1}$ and a temperature of -26 ±1°C. It should be borne in mind that the test temperatures were much lower, particularly for the deeper samples, than the naturally occurring temperatures in the ice cover. Several trends were apparent from the results. First, there is a general increase in strength with increasing sample depth in the ice cover. Secondly, there is a pattern of ductile yield in the upper part of the ice cover and brittle failure in the lower part. Figure 2 illustrates a thin section of a typical core. Grain structure analysis showed the upper part of the ice cover to be small-grained (approximately 2 mm diameter) granular ice, and the lower part to be larger-grained (approximately 10 mm diameter) columnar-grained ice. A typical temperature

TABLE I. Uniaxial Compression Tests - First-Year Ice Vertical Cores

Test temperature = -26°C; Stress rate = 0.13 - 0.30 $MPa \cdot sec^{-1}$;
Strain rate = 2.5×10^{-4} sec^{-1} (nominal)

Sample Depth, cm	Ice Salinity, ‰	Stress Rate, $MPa \cdot sec^{-1}$	Time to Failure, sec	Compressive Strength, MPa
5	8.1	0.24	40	8.3
16	8.5	0.21	50	9.0
31	5.4	0.24	56	10.9
46	6.6	0.24	58	11.5*
57	5.8	0.26	55	13.3*
5	10.6	0.14	85	7.9
16	8.8	0.17	55	7.6
28	6.9	0.20	68	10.4
43	3.2	0.23	55	10.2
55	5.9	0.28	50	10.0*
5	10.5	0.14	80	7.9
16	9.0	0.19	52	8.1
28	7.8	0.21	59	10.2
44	4.0	0.23	69	11.9*
55	5.2	0.24	61	13.2*
11	8.2	0.13	59	5.6
27	5.4	0.18	50	7.2
40	5.2	0.19	53	8.4
52	5.4	0.19	43	4.4*
65	5.1	0.19	62	8.0*
77	4.6	0.21	56	9.2
11	6.3	0.19	51	8.6
24	5.1	0.17	51	7.1
36	5.2	0.18	53	7.5
49	4.3	0.22	63	10.5
65	4.6	0.23	65	12.2*
77	5.4	0.19	58	8.5
11	8.6	0.20	58	8.5
27	6.2	0.17	67	7.9
39	5.1	0.23	71	12.5
51	4.4	0.22	58	10.3*
12	4.3	0.21	60	9.0
25	3.5	0.30	78	16.7*
37	3.8	0.28	77	19.2*
53	3.6	0.28	95	22.2*
65	3.5	0.27	70	15.1*
76	4.4	0.14	72	7.9
23	6.5	0.15	55	5.4
36	4.9	0.18	53	7.0
62	4.2	0.21	60	12.0*
23	4.2	0.13	59	5.7
44	-	0.13	55	5.3
63	4.8	0.24	75	13.2*
80	4.2	0.25	62	12.2*
19	4.8	0.13	45	4.4
54	4.5	0.14	55	5.9*

* brittle type failure

TABLE II. Brazil Tests - First-Year Ice Vertical Cores

Test temperature = -20°C; Stress rate = 0.15 - 0.42 MPa·sec^{-1}

Sample Depth, cm	Ice Salinity, ‰	Stress Rate, MPa·sec^{-1}	Time to Failure, sec	Brazil Strength, MPa
3	6.4	0.25	17	3.4
6	4.0	0.42	14	3.8
9	3.6	0.35	18	3.5
48	4.6	0.21	15	1.9
51	4.4	0.22	13	2.1
54	4.8	0.15	11	1.2
69	4.6	0.39	11	2.2
72	5.3	0.26	8	1.7
2	3.0	-	-	2.4
7	5.2	0.21	10	1.9
30	5.4	0.29	12	2.1
70	4.9	0.19	20	2.5
3	5.1	0.32	15	3.2
10	3.8	0.24	14	2.9
26	4.8	0.39	8	2.1
29	5.6	0.33	14	2.8
35	5.2	0.36	9.5	2.4
61	4.1	0.36	8.5	1.8

and salinity profile is given in Figure 3. In general, the top 20 cm of the core had an average salinity of 10-15‰ and the remainder an average salinity of 5-6‰. Similar profiles have been observed for first-year sea ice in the Beaufort Sea [4].

Brine volume is often used as an independent variable in evaluating the strength properties of sea ice [5]. The compressive strength results have been presented on this basis in Figure 4a. A gradual decrease in strength with increasing brine volume is evident, but it is not particularly strong. Recent investigations of the mechanical properties of ice have shown that they are load history dependent [3]. The same results, plotted versus stress rate in Figure 4b, show less scatter and indicate a trend towards increasing strength with increasing stress rate.

Peyton [6] has found a similar strength trend for first-year sea ice. The specimens have been categorized in two groups to make comparison with Peyton's results easier: "top ice," granular ice from the top 20 cm of the ice cover; and "bottom ice," large-grained, columnar-grained ice from the lower part of the ice cover. Also shown in Figure 4 are strength values of multi-year ice [7]. In terms of brine volume, multi-year ice is weaker than first-year sea ice, whereas in terms of stress rate its strength is indistinguishable from that of first-year sea ice. The strong influence

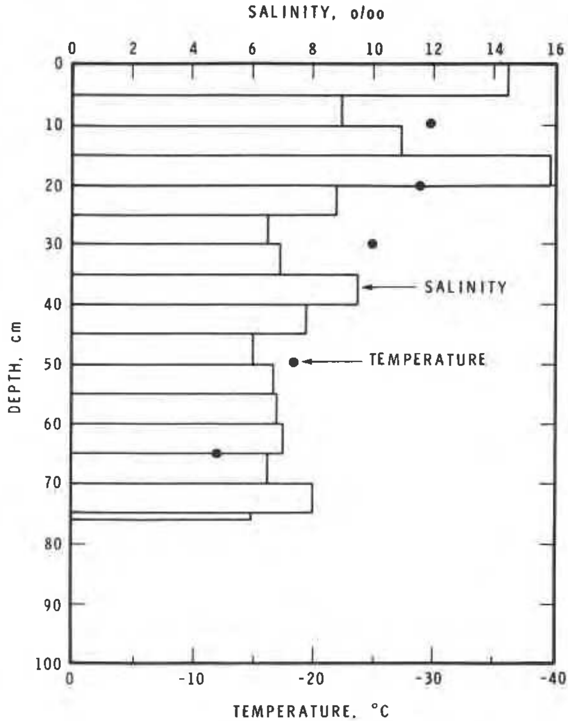

Figure 3

Typical temperature and salinity profile of first-year sea ice, Beaufort Sea, January 1980

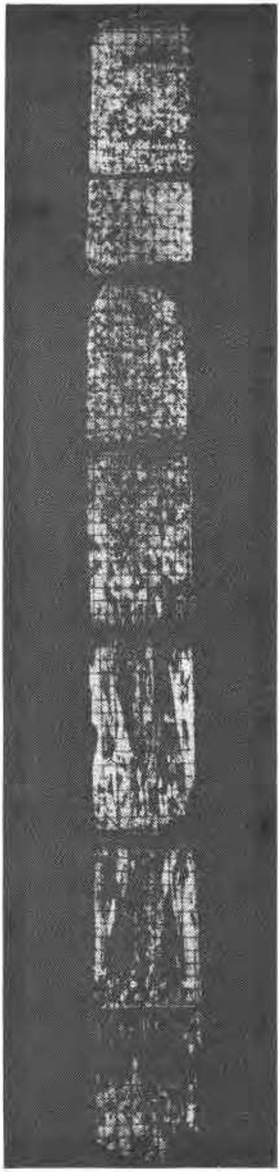

Figure 2

Vertical thin section of first-year sea ice showing grain structure variations with depth
(Total core length ~0.85 m, Beaufort Sea, January 1980)

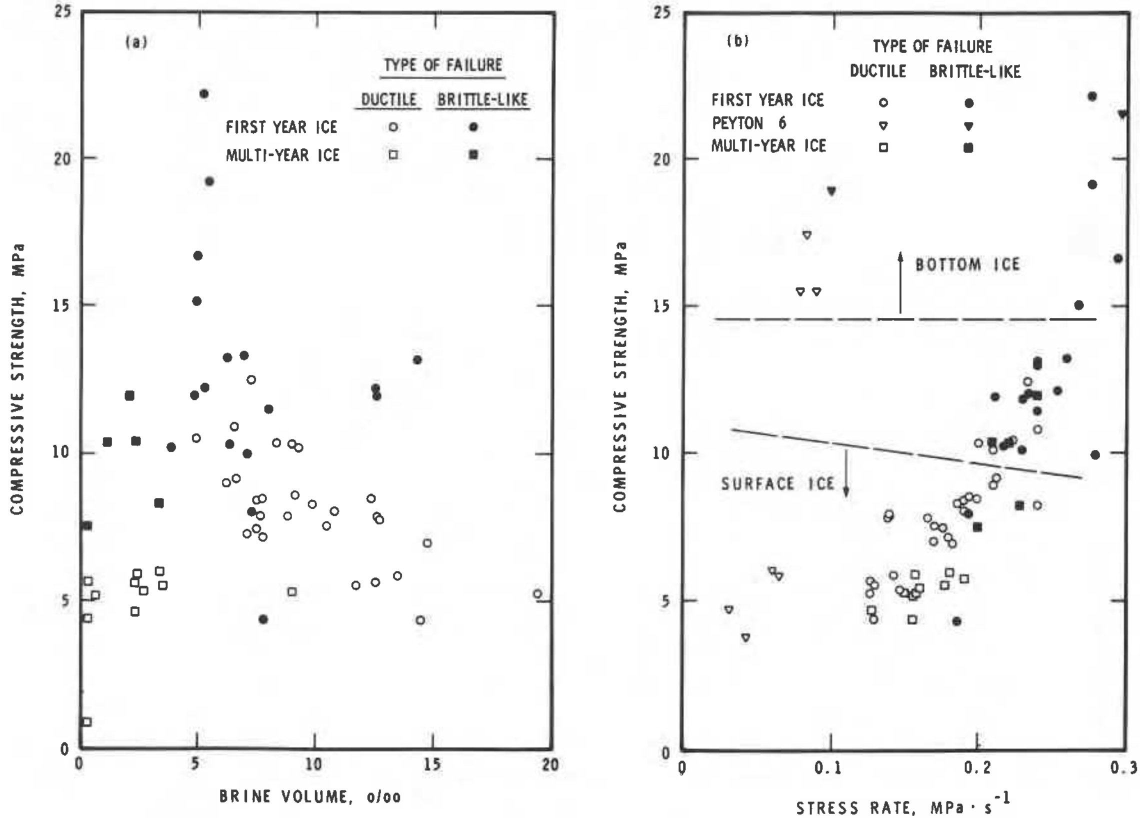

Figure 4. Compressive strength vs (a) brine volume and (b) stress rate; test temperature -20°C to -27°C, nominal strain rate 2.5×10^{-4} s^{-1}

of stress rate on compressive strength shows the importance of this factor in comparing the strength values reported by various investigators.

With regard to the Brazil tests, the results indicate strengths of the order of 3 MPa for granular ice and 2 MPa for columnar ice. This is in good agreement with other measurements of Brazil strength for sea ice of comparable brine volume [8].

Figure 5a presents the stress-time curves from two tests; the solid line illustrates ductile yield of granular ice, the dashed line, brittle failure of columnar-grained ice. Also shown are straight lines approximating the loading stress rate for each case. Sinha [9] has suggested that it is possible, with an appropriate rheological model and a knowledge of ice characteristics (temperature and grain size), to generate a stress-strain curve from stress history. This approach has been applied to the actual stress histories shown in Figure 5a, and the resulting stress-strain curves are presented in Figure 5b. Unfortunately, strains were not measured during

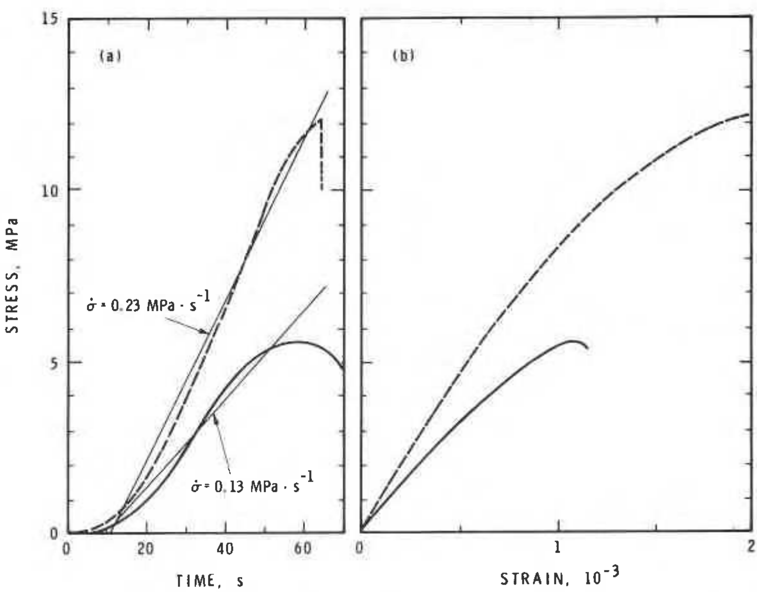

Figure 5

Representative stress histories (a) and calculated stress-strain responses (b) for first-year sea ice, -26°C (solid line ——, 2 mm grain diameter; dashed line - - -, 10 mm grain diameter) the tests now reported so that it is not possible to verify these predictions. Peyton [6] indicated strain modulus values of up to 5 GPa at a temperature of -21°C and loading rates comparable to those shown in Figure 5, indicating that the predictions are of the right order. There is a real need, however, for stress-strain-time data to help in developing a constitutive equation for sea ice that takes into account grain structure and size, temperature, and salinity. In future field tests it is planned to obtain strain-time in addition to stress-time data.

Conclusions

(1) Compressive strength and Brazil strength values determined in this study show general agreement with comparable data in the literature.

(2) Compressive strength and failure behaviour of vertically loaded specimens of first-year sea ice vary through the depth of the ice cover in a systematic fashion that appears to be related more to grain structure than to salinity or brine volume, at least for test temperatures less than -20°C.

(3) Stress rate appears to be an appropriate basis for the measurement and interpretation of compressive strength under relatively uncontrolled field test conditions.

(4) Measurements of ice characteristics and properties can be carried out successfully on board ship in improvised facilities, thereby reducing the problems associated with transporting ice samples to "southern" laboratories.

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