High Strain-Rate Compression Tests on Ice

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Received: October 11, 1996; In Final Form: January 17, 1997[⊗]

High-speed uniaxial compression tests were conducted in the strain-rate range 10^{-1}−10^{1} s^{-1}, at −11 °C, on freshwater ice and "Baltic" sea ice of mean salinity 2.4 ± 0.7 ppt. Two different testing machines were used to check for machine stiffness effects. The results showed that for both types of ice, the strength, σ, increased with strain rate, $\dot{\epsilon}$, consistent with a power law, $\sigma = A\dot{\epsilon}^{m}$, where $A = 8.9$ and $m = 0.15$ for fresh water ice, and $A = 6.0$ and $m = 0.19$ for the "Baltic" sea ice. At a strain-rate of 10^{1} s^{-1}, the freshwater ice was a factor of only 1.3 times stronger than the sea ice. Results are compared to literature values at lower strain rates.

Introduction

The Joint Research Project Arrangement #6 (JRPA 6) between Canada and Finland required, among other things, that Canada conduct high-speed mechanical tests on ice in an effort to obtain the strength of ice at speeds typical of ice-propeller interaction. These speeds are estimated to be about 30 ms^{-1}. It was decided, therefore, to conduct uniaxial compression tests at speeds as high as possible with the available equipment, approximately 1 ms^{-1}, corresponding to a strain rate of about 10^{1} s^{-1}. While this was not as high as when impacted by a propeller, it was at least 10 times higher than most results in the literature.[1−5] Earlier work[1,2] had shown an apparent peak in the strength of ice at a strain rate of about 10^{-2} s^{-1}, followed by a significant decrease, and it was considered important to check if this decrease continued to higher strain rates. Recent results of Hopkinson bar tests[6] at even higher strain rates, 10^{1}−10^{2} s^{-1} were not available when this work started.

Previous research at this institute[7] had tested freshwater ice and sea ice (∼6 ppt salinity) at high strain rates and had made this work possible. That work,[7] however, did not vary strain rate over a wide range, which is the main thrust of this paper. It had found evidence of possible dynamic effects with the equipment, and so it was decided to investigate those effects in more detail using freshwater, columnar grained ice with two different testing machines. Also, it was decided to test sea ice similar to that found in the Baltic Sea, which typically has a salinity of 3−8 ppt (parts per thousand) in the surface sea water and 0.5−3 ppt in melted sea ice.

Ice Preparation

The tests required bubble-free, columnar-grained ice grown from either fresh water or diluted sea water. The sea water used had a salinity similar to the Baltic Sea. Both types of ice were tested to compare compressive strengths. Details are given elsewhere[8] and the method resulted in columnar ice with a c-axis horizontal orientation, usually referred to as S2 ice.[9]

Test Samples

It was considered important to prepare uniform samples with flat, parallel, end faces so that nonuniform stresses did not give rise to premature fracture. Specimens measuring 6 × 6 cm in cross section and 12.5 cm in length were used for the tests. Considerable care was taken in the preparation of the samples,[8] and the resulting misalignment of the end faces was measured with a dial gauge and surface plate and found to be less than 0.025 mm.[8]

Testing Apparatus and Procedure

The uniaxial compressions were performed on two MTS machines—a "low-speed machine" and a "high-speed machine", in uniaxial compression. Both machines were in the same cold room maintained at a nominal −10 °C. The actual temperature at each test time was noted. The "low-speed machine" was an MTS Model 244.31, with a frame capable of ±1 MN load, but with a load cell limited to ±250 kN. The maximum speed of the actuator in this machine was 13 cm s^{-1}. The high-speed machine was smaller and lighter than the low-speed machine, with a frame capable of ±250 kN load. However, it was capable of a higher speed of compression of about 2 ms^{-1}. The low-speed machine was a factor of 2 stiffer than the high-speed machine. To measure the loads at such high speeds a PCB Quartz Force Link load cell was used, connected to a charge amplifier. A conventional strain-gauge load cell has a response time which is too slow at these strain rates. Strain was calculated as displacement divided by original length. The strain rate used in the analysis was this strain divided by the time to failure. The detailed testing procedure is given elsewhere,[8] and thin sections showed that the ice was indeed columnar S2, with a grain size that increased from about 4 mm diameter at the top to about 8 mm at the bottom. The tests at the highest speeds, strain rates greater than 5 s^{-1}, were impact compression. The ice was placed on the lower platen of the testing machine, and the actuator was positioned so that the top of the sample was backed off from the top platen approximately 1 cm. This allowed the machine to reach its top speed before crushing the ice sample.

Results

Visual Observations. Because of the high speed of the tests, the samples shattered into many small pieces on impact and it was impossible to see how cracks were nucleated or propagated. Video pictures recorded at 1000 frames s^{-1} were still too slow to be of significant help in direct observation.

Compressive Strength Data. The original data were collected as plots of load against time and were then converted to plots of stress against strain. From these plots, peak stress was determined, as well as the speed of the actuator during loading (i.e., from the time the load was applied until peak load was

[⊗] Abstract published in *Advance ACS Abstracts,* June 1, 1997.

S1089-5647(96)03162-8 CCC: $14.00 Published 1997 by the American Chemical Society

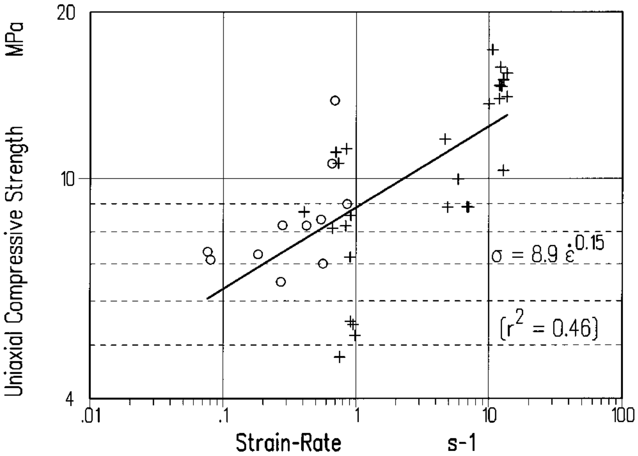

Figure 1. Uniaxial compressive strength of freshwater columnar grained ice loaded vertically at −11 °C: (○) data from low speed machine; (+) data from high-speed, but softer, machine.

reached). These values were used to calculate the maximum compressive stress from the maximum load divided by cross sectional area, and the strain rate given by the speed of actuator divided by original length of sample.

The data were then plotted as uniaxial compressive strength against strain rate on a log−log scale, both for the freshwater ice, shown in Figure 1, and for the "Baltic" sea ice (not shown). There is a significant amount of scatter but nevertheless some conclusions can be reached.

Effect of Machine Stiffness. From these plots the effects of the stiffness of the testing machines were analyzed. We conducted tests on two different machines, of different stiffness, at the same strain rate. The low-speed machine was about a factor of 2 stiffer than the high-speed machine. The two sets of data overlap at strain rates of about 1 s^{-1}, as shown by the circles and crosses in Figure 1. Taking the mean and standard deviation of the strengths between 0.5 and 1 s^{-1} for both types of ice gave

Fresh-water ice:

mean $\sigma = 9.8 \pm 2.6$ MPa (5 points) low-speed machine

mean $\sigma = 7.8 \pm 2.4$ MPa (11 points) high-speed machine

"Baltic" sea ice:

mean $\sigma = 6.3 \pm 2.3$ MPa (24 points) low-speed machine

mean $\sigma = 5.4 \pm 1.3$ MPa (6 points) high-speed machine

Within the standard deviations therefore, there was no difference in the results. We conclude that the machine stiffness was not an important factor in our results.

Effect of Strain Rate. The effect of strain rate can be seen in Figure 1. The compressive strength increased with strain rate over the range tested. The rate dependence was similar for the two types of ice and was consistent with a power law of the form

$$\sigma = A\dot{\epsilon}^m$$

where $A = 8.9$ and $m = 0.15$ for fresh water ice, and $A = 6.0$ and $m = 0.19$ for the "Baltic" sea ice. At a strain rate of 1 s^{-1}, the freshwater ice was a factor of 1.5 stronger than the "Baltic" sea ice; at a strain rate of 10 s^{-1} it was a factor of 1.3.

Effect of Salinity. We did not vary salinity in a systematic way, so little can be said from our results. The mean value of salinity of the 63 samples, measured by melting the samples after testing, was 2.4 ± 0.7 ppt. with the lowest being 1.6 and the highest 3.2 ppt.

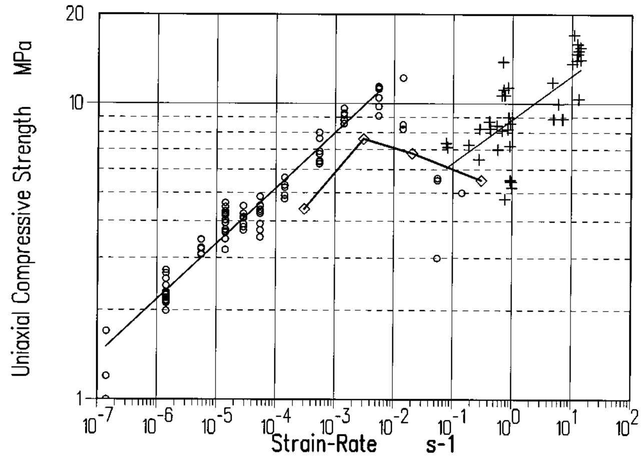

Figure 2. Present results for freshwater ice (+) compared to data in the literature: (○) Jones;[1] (◇) Schwarz.[2]

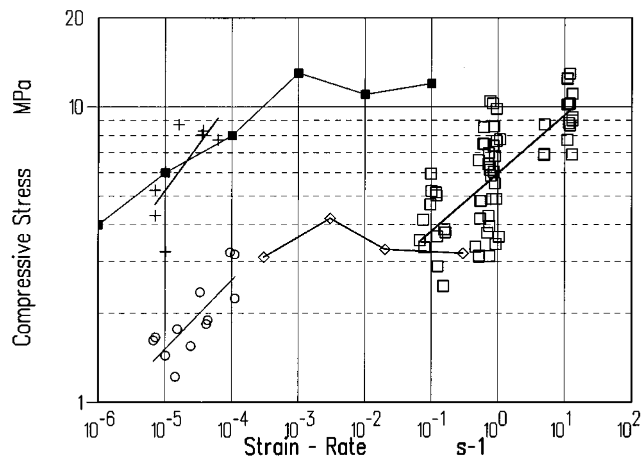

Figure 3. Present results for "Baltic" sea ice (□) compared to data in the literature: (○) and (+) Frederking and Timco;[4] (◇) Schwarz;[2] (■) Kuehn and Schulson.[5]

Discussion

The freshwater ice results can be compared to literature results at lower strain rates. Figure 2 shows a compilation of earlier results on polycrystalline ice over a wide range of strain rates,[1] and columnar ice compressed vertically,[2] with the columnar results presented here. The earlier work showed a tendency for the strength to peak at 10^{-2} s^{-1} and then decrease at higher strain rates. Similar work by others[3] showed the same tendency. One of the original reasons for conducting this work was to confirm if this decrease continued to higher strain rates. The present work shows that a continued decrease is not justified and that the strength continues to increase with strain rate or at least to remain steady. The data show greater scatter in the brittle range, than in the ductile range, as has been found by others. Unfortunately, these results do not seem to be in agreement with recent Hopkinson bar tests[6] which gave no indication of a continued increase in strength with strain rate. Further work is necessary to sort out this apparent discrepancy.

Figure 3 shows a comparison between our "Baltic" sea ice data and sea ice data at lower strain rates[2,4,5] collected at the same temperature (−10 °C or close) and similar grain size. I have replotted some data[4] as a function of strain rate instead of the stress rate used by the authors. Our results are all for vertical loading, *i.e.,* load perpendicular to the *c* axis of the columns, and so should be compared to that case. There is some discrepancy between the previous sets of data shown in Figure 4, for unknown reasons. The present results show a significant strain-rate dependence which was not found by the others at these rates. Again there is considerable scatter, as is normally found in the brittle range, but even so we conclude that the strength does not drop off at the high strain rates but continues to increase.

The strength of our freshwater ice was about 1.4 times that of our "Baltic" sea ice. This is consistent with results from lower strain rates for this vertical orientation. Most workers[4,5] have found horizontally loaded S2 sea ice to be weaker by a factor of about 3 than vertically loaded, but one data set[2] showed sea ice to be slightly weaker when loaded vertically than horizontally. Similar results have been found for freshwater ice, in which case *all* workers have found ice to be stronger in vertical loading. This is due to the morphology of the S2 sea ice in which brine channels are naturally vertical, and the fact that in horizontal loading some grains will be oriented for easy glide on the (0001) plane, whereas in vertical loading all grains have their basal planes aligned in, or close to, the loading direction, making basal glide difficult.

Conclusions

The strength of freshwater ice and low-salinity "Baltic" sea ice does not decrease at high strain rates but continues to increase within the range $10^{-1}-10^{1}$ s^{-1}.

Machine stiffness was not a significant factor in our experiments.

Freshwater ice is about 1.4 times stronger than "Baltic" sea ice at these strain rates, when loaded vertically, a result which is consistent with previous work.

Acknowledgment. Financial support for JRPA #6 was provided by Transport Canada and the Program of Energy Research and Development (PERD), as well as the National Research Council. Technical assistance was ably provided by T. Slade and J. Sweeney, to whom I am extremely grateful. I am also grateful to B. Parsons for access to his unpublished data.

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