TENSILE STRENGTH OF MULTI-YEAR PRESSURE RIDGE SEA ICE SAMPLES

by

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ABSTRACT

Thirty-six constant strain-rate uniaxial tension tests were performed on vertically oriented multi-year pressure ridge samples from the Beaufort Sea. The tests were performed on a closed-loop electro-hydraulic testing machine at two strain rates (10^{-5} and 10^{-3} s^{-1}) and two temperatures (-20 and -5°C). This paper summarizes the sample preparation and testing techniques used in the investigation and presents data on the tensile strength, initial tangent modulus, and failure strain of the ice.

INTRODUCTION

Data on the mechanical properties of multi-year sea ice are needed to effectively design offshore structures in the exposed areas of the Beaufort and Chukchi Seas. Data are now available on the unconfined compressive strength of multi-year sea ice (1,2,3,4). Limited data on the tensile and confined compressive strength of ice samples from a multi-year floe have also recently been obtained (3). Unfortunately, prior to this investigation, there were no data available on the tensile strength of ice samples from multi-year pressure ridges. We are particularly interested in the tensile strength of multi-year pressure ridges, as long multi-year pressure ridges will likely fail in bending as they move against conical shaped, offshore arctic structures.

This paper presents data on the uniaxial tensile strength, modulus, and failure strain of ice samples obtained from vertical cores from multi-year pressure ridges. Factors affecting the failure and strength of the ice are also examined. While horizontally oriented test specimens would have been more desirable for this work, they are very difficult to obtain. Examination of vertical ice samples was deemed to be a cost-effective approach for an initial investigation of the tensile strength of multi-year pressure ridges.

ICE DESCRIPTION

The tensile specimens tested in this program were derived from two multi-year pressure ridges in the Beaufort Sea, just northwest of Prudhoe Bay, Alaska. The test specimens had an average salinity of 0.787 ± 0.885 o/oo and an average density of 0.846 ± 0.037 Mg/m^3 at -20°C. Test specimen porosities varied from 25 to 228 o/oo. Most of the test specimens consisted of mixtures of granular and columnar grains and can be designated as ice structure Type III according to the multi-year sea ice structure classification scheme proposed by Richter and Cox (5). Representative thin-section photographs illustrating the structure of the test samples are given in Figures 1 and 2. Sample structures actually varied from 100% columnar grains to 100% granular grains; however, 80% of the samples had mixtures of both ice types. Generally, the granular ice crystals were randomly oriented and varied in size from less than 1 to about 5 mm. The columnar grains were usually coarser, 5 to 20 mm, and sometimes were oriented in a preferred direction. Information on the morphology of the sampled pressure ridges and data on the individual test specimens can be obtained in Cox et al. (6). A general discussion on the salinity, density, and structure of multi-year pressure ridges is also presented in companion paper in this volume (7).

TEST METHODS

Thirty-six constant strain-rate tension tests were performed on vertically oriented multi-year pressure ridge samples. The tests were conducted at two strain-rates (10^{-5} and 10^{-3} s^{-1}) and two temperatures (-20 and -5°C). Nine tests were done at each test condition.

Dumbbell test specimens were prepared from 10.7 cm diameter cores. Samples were first rough-cut on a band saw, and the ends were milled square on a milling machine to produce 25.4 cm long test specimens. End caps were then bonded to the samples and the samples were turned on a lathe to a dumbbell shape having a neck diameter of 8.9 cm. The form tool used to

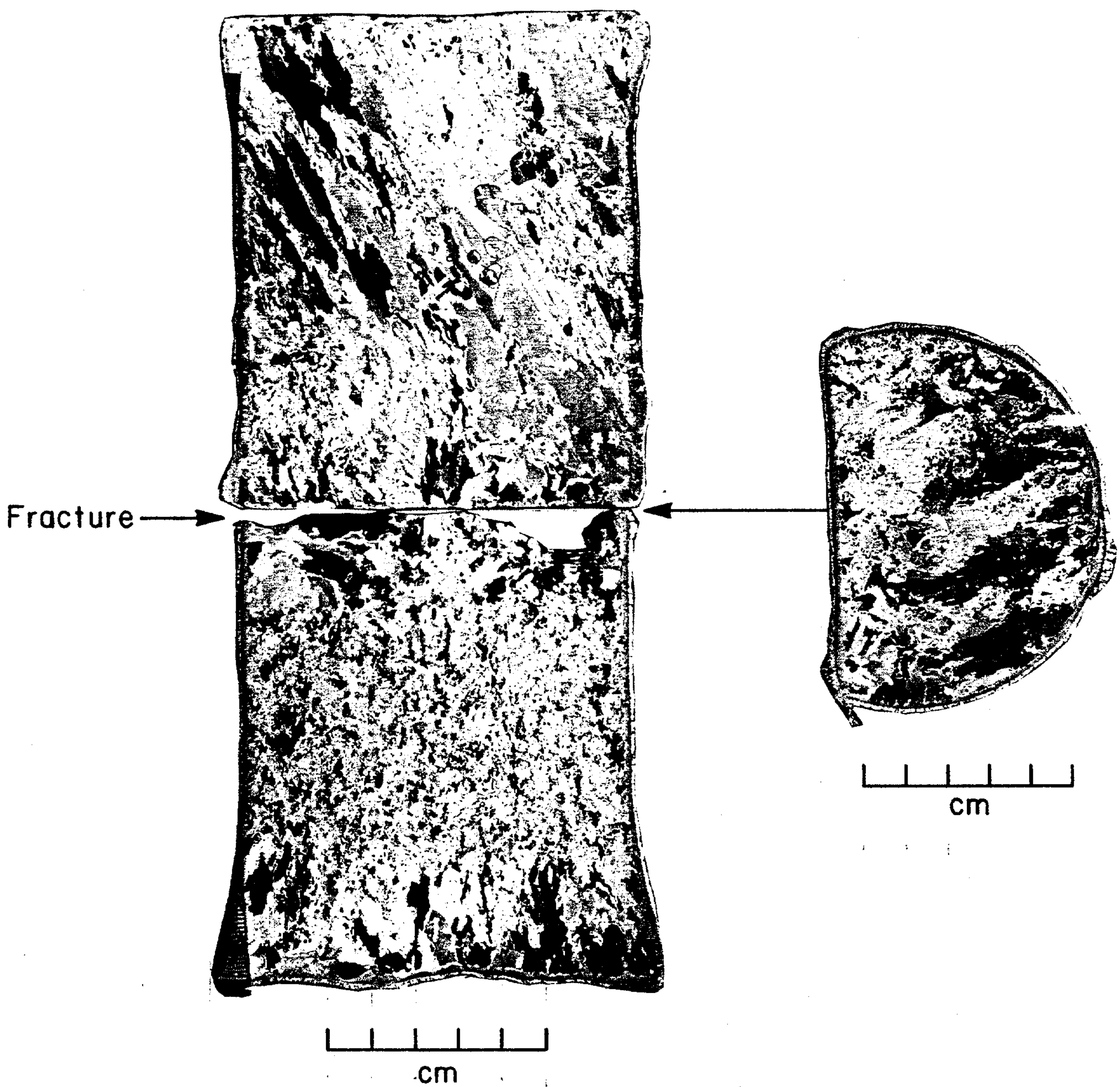

Figure 1. Photographs of ice thin-sections taken in crossed polarized light to illustrate ice structure.

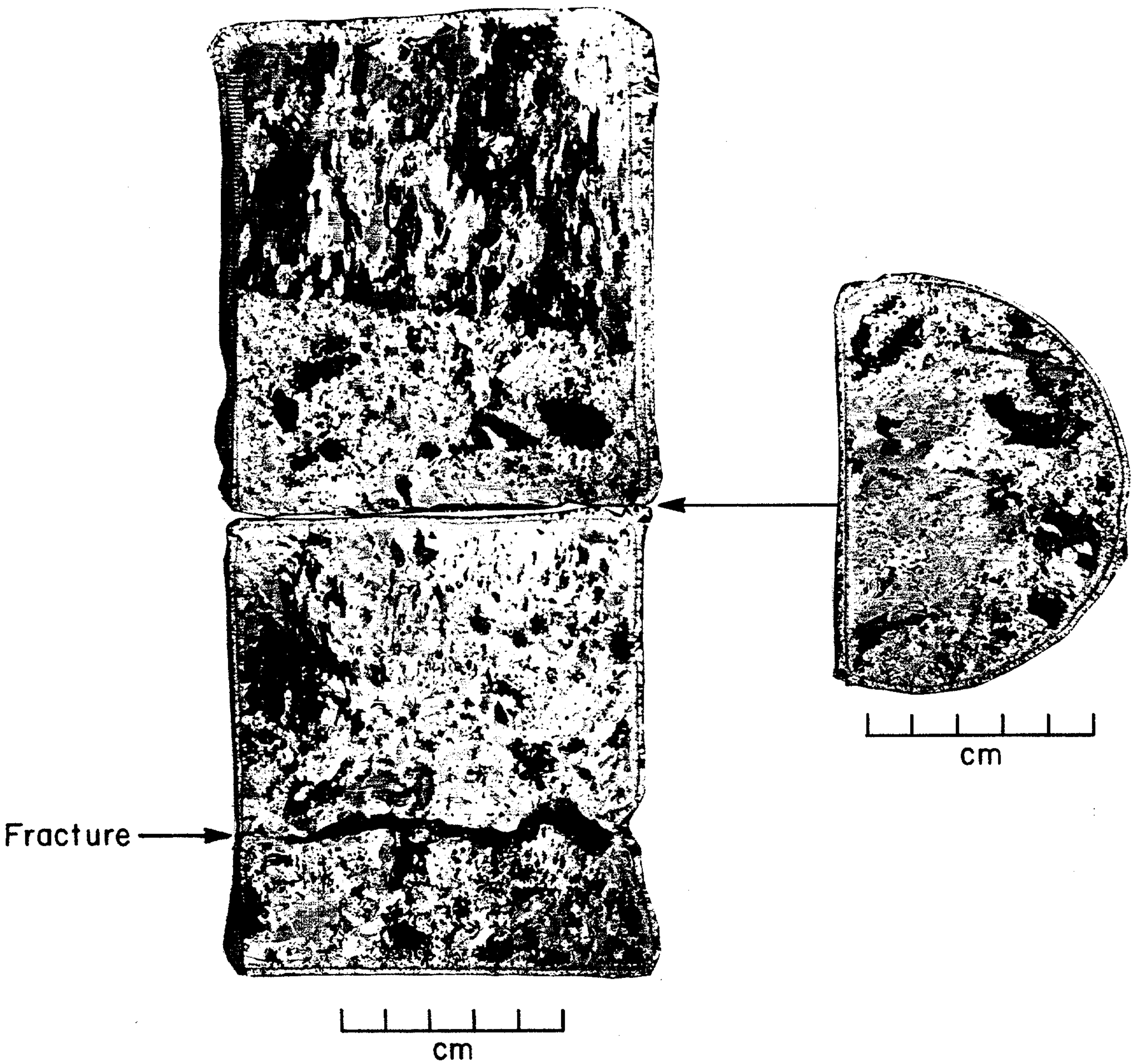

Figure 2. Photographs of ice thin-sections taken in crossed polarized light to illustrate ice structure.

prepare the dumbbell tension specimens had a radius of curvature of 17.8 cm, twice the diameter of the finished neck. This radius was chosen to minimize stress concentrations near the sample end planes. Every effort as made to produce properly sized, precision-machined test samples utilizing recommended methods (8,9).

All of the tension tests were performed on a closed-loop electro-hydraulic testing machine. The machine had two actuators with capacities of 1.1 and 0.11 MN and fast-response, high-flow-rate servo-values. The tension tests were conducted using the lower capacity, faster 0.11 MN actuator. The load frame of the machine had a capacity of 2.2 MN. Strain-rates were controlled by monitoring the full sample strain with an extensometer, which was attached to the end caps bonded to the test specimen (Fig. 3). Strains on the neck of the specimens were also monitored with a pair of DCDTs to provide accurate strain, strain-rate, and modulus data. The specimens were attached to the testing machine by threaded steel rods screwed into tapped holes in the end caps. The steel rods contained spherical universal joints to compensate for slight imperfections in end plane parallelism (10). Test temperatures were controlled to within 0.5°C by placing the sample in an environmental chamber mounted between the columns of the testing machine. Load and sample strain rate data were recorded on an XY plotter, several strip charts, and a FM magnetic tape recorder. Detailed information on our sample preparation and testing techniques can be found in Mellor et al. (11).

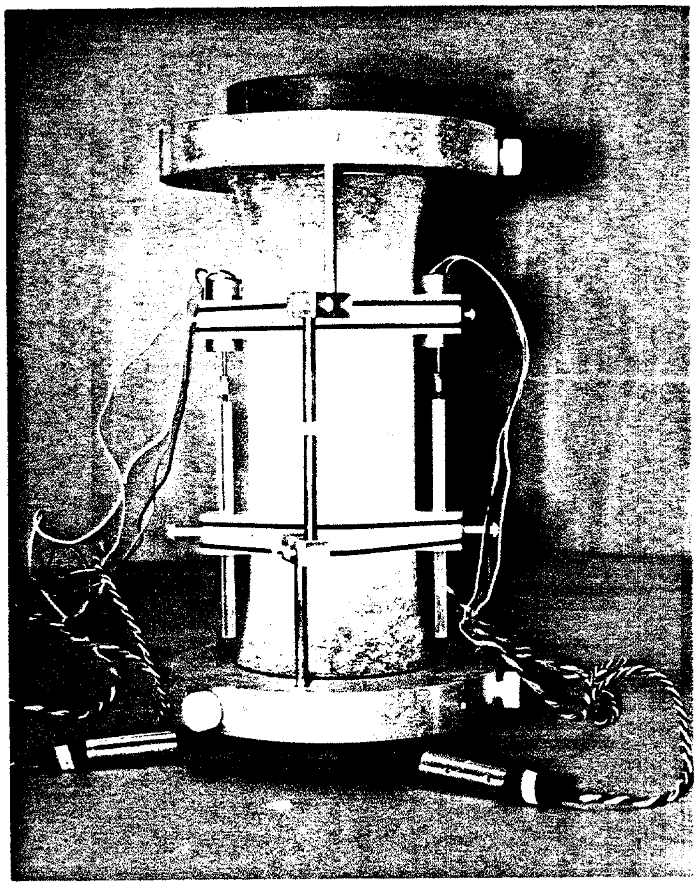

Figure 3. Instrumented uniaxial tension specimen.

TEST RESULTS

Summaries of the strength, failure strain, and initial tangent modulus data for each of the four test conditions are given in Tables 1 through 3. Modulus values were determined from the initial slope of the force-displacement curves. Strength and modulus data are plotted against strain-rate and ice porosity in Figures 4 through 11. Ice porosites were calculated from the salinity, density, and temperature of each sample (2).

DISCUSSION

Strength

In general, the mean tensile strength shows no significant variation with strain-rate or temperature. This behaviour is consistent with data on the tensile strength of fresh water polycrystalline ice summarized by Mellor (13). At strain-rates greater than 10^{-5} s^{-1}, the tensile strength of fresh water polycrystalline ice shows little or no variation with strain-rate, and from -5 to -20°C, the strength only shows a very small increase. In contrast, the results from Dykins (14) uniaxial tensile tests on first year sea ice do show a strong temperature dependency. However, this large strength variation is not due to changes in temperature of the pure ice matrix, but rather a change in the ice brine volume or porosity. As the salinity of the multi-year test specimens is very low, the brine porosity and strength of the ice show little variation with temperature.

The tensile strength is plotted against ice porosity in Figures 6 and 7. Due to large variations in the ice structure between different specimens, the data exhibit considerable scatter. Despite this scatter, there appeared to be a tendency for the ice tensile strength to decrease

Table 1. Summary of tensile strength data.

Uniaxial Tensile Strength

	Maximum (MPa)	Maximum (lbf/in.^{2})	Minimum (MPa)	Minimum (lbf/in.^{2})	Mean (MPa)	Mean (lbf/in.^{2})	Mean Porosity (ppt)	Samples
-5°C (23°F)								
10^{-5} s^{-1} V	1.03	149	0.57	82	0.82±0.17	119±24	78	9
10^{-3} s^{-1} V	0.83	120	0.41	60	0.61±0.16	89±23	108	9
-20°C (-4°F)								
10^{-5} s^{-1} V	0.92	134	0.49	71	0.71±0.16	103±23	82	9
10^{-3} s^{-1} V	0.92	134	0.48	69	0.75±0.16	109±23	77	9

V - Vertical

Table 2. Summary of tensile failure strain data.

	Failure Strain (%)			
	Maximum	Minimum	Mean	Samples
-5°C (23°F)				
10^{-5} s^{-1} V	0.022	0.014	0.019±0.002	9
10^{-3} s^{-1} V	0.013	0.007	0.010±0.002	9
-20°C (-4°F)				
10^{-5} s^{-1} V	0.022	0.009	0.013±0.004	9
10^{-3} s^{-1} V	0.012	0.009	0.011±0.001	9

V - Vertical

Table 3. Summary of tensile initial tangent modulus.

	Initial Tangent Modulus							
	Maximum		Minimum		Mean			
	(GPa)	(lbf/in.^{2}x10^6)	(GPa)	(lbf/in.^{2}x10^6)	(GPa)	(lbf/in.^{2}x10^6)	Mean Porosity (ppt)	Samples
−5°C (23°F)								
10^{-5} s^{-1} V	7.59	1.100	5.42	0.786	6.39±0.68	0.927±0.099	78	9
10^{-3} s^{-1} V	8.32	1.207	4.25	0.616	6.60±1.19	0.957±0.173	108	9
−20°C (−4°F)								
10^{-5} s^{-1} V	7.82	1.134	4.17	0.604	6.54±1.12	0.949±0.162	82	9
10^{-3} s^{-1} V	8.12	1.177	6.59	0.955	7.31±0.54	1.060±0.079	77	9

V - Vertical

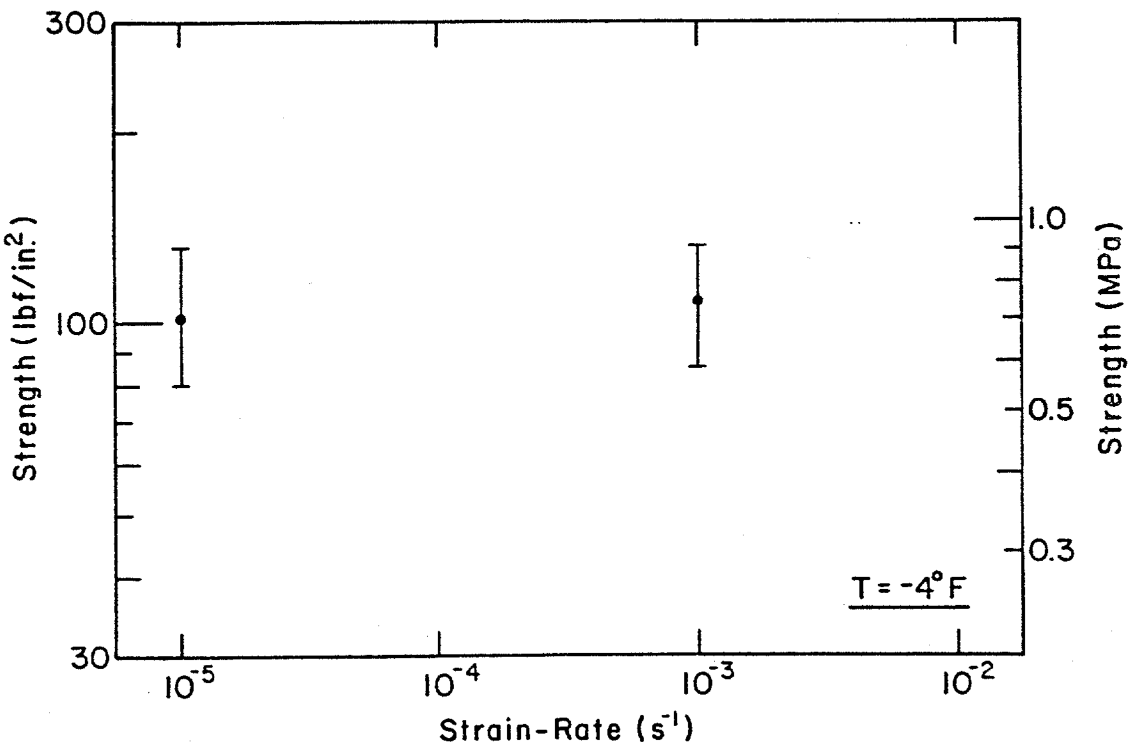

Figure 4. Uniaxial tensile strength versus strain-rate for those tests conducted at -20°C (-4°F). The bars denote one standard deviation.

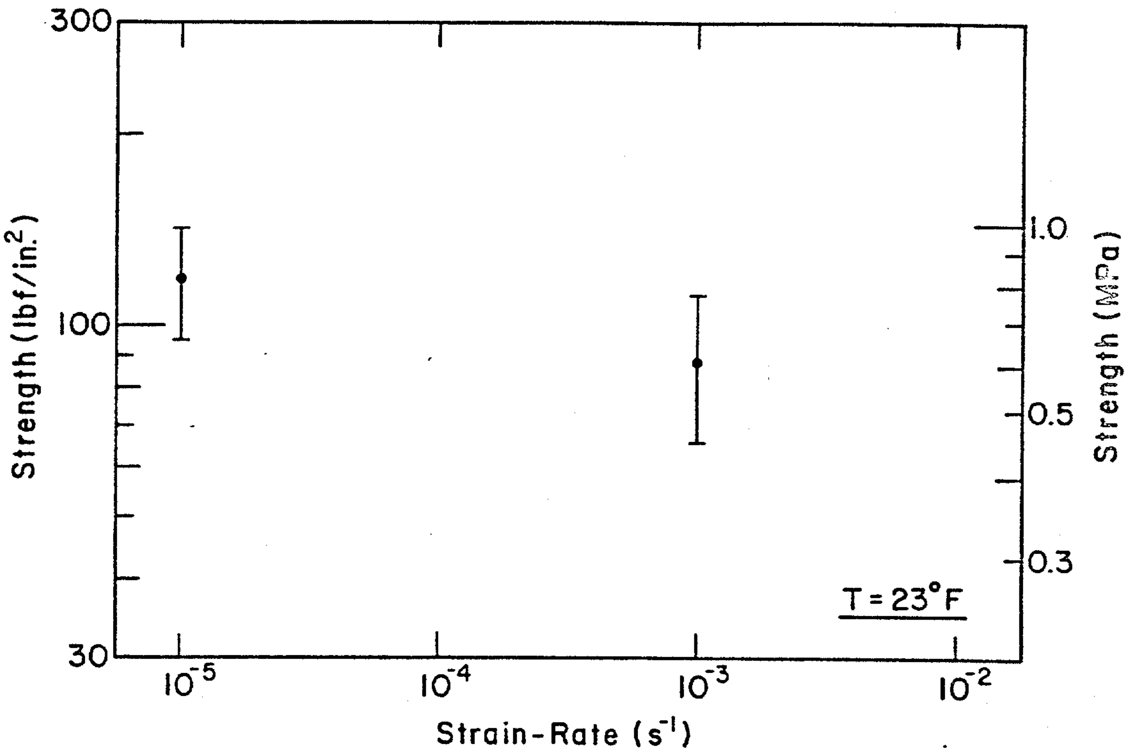

Figure 5. Uniaxial tensile strength versus strain-rate for those tests conducted at −5°C (23°F). The bars denote one standard deviation.

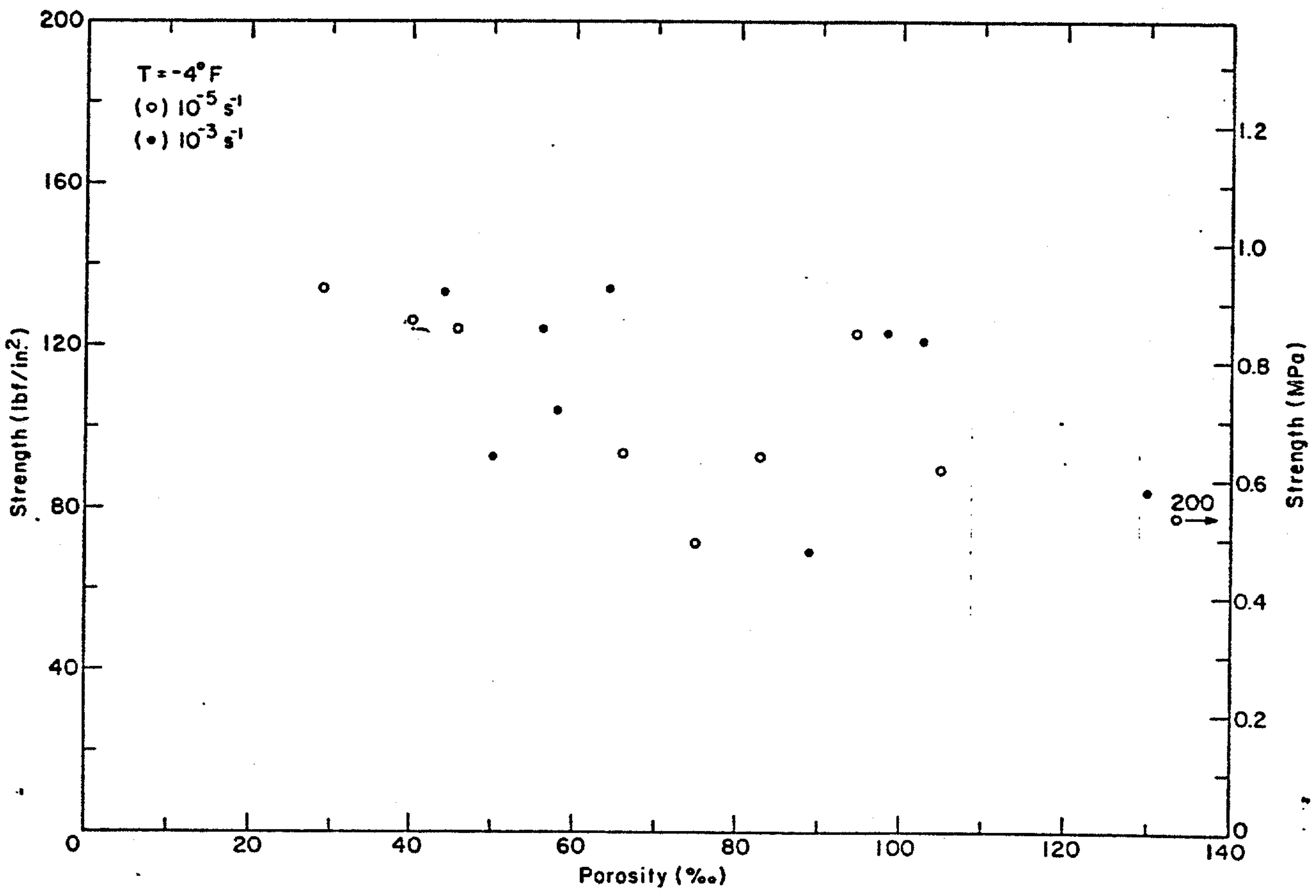

Figure 6. Uniaxial tensile strength versus ice porosity for those tests conducted at -20°C (-4°F).

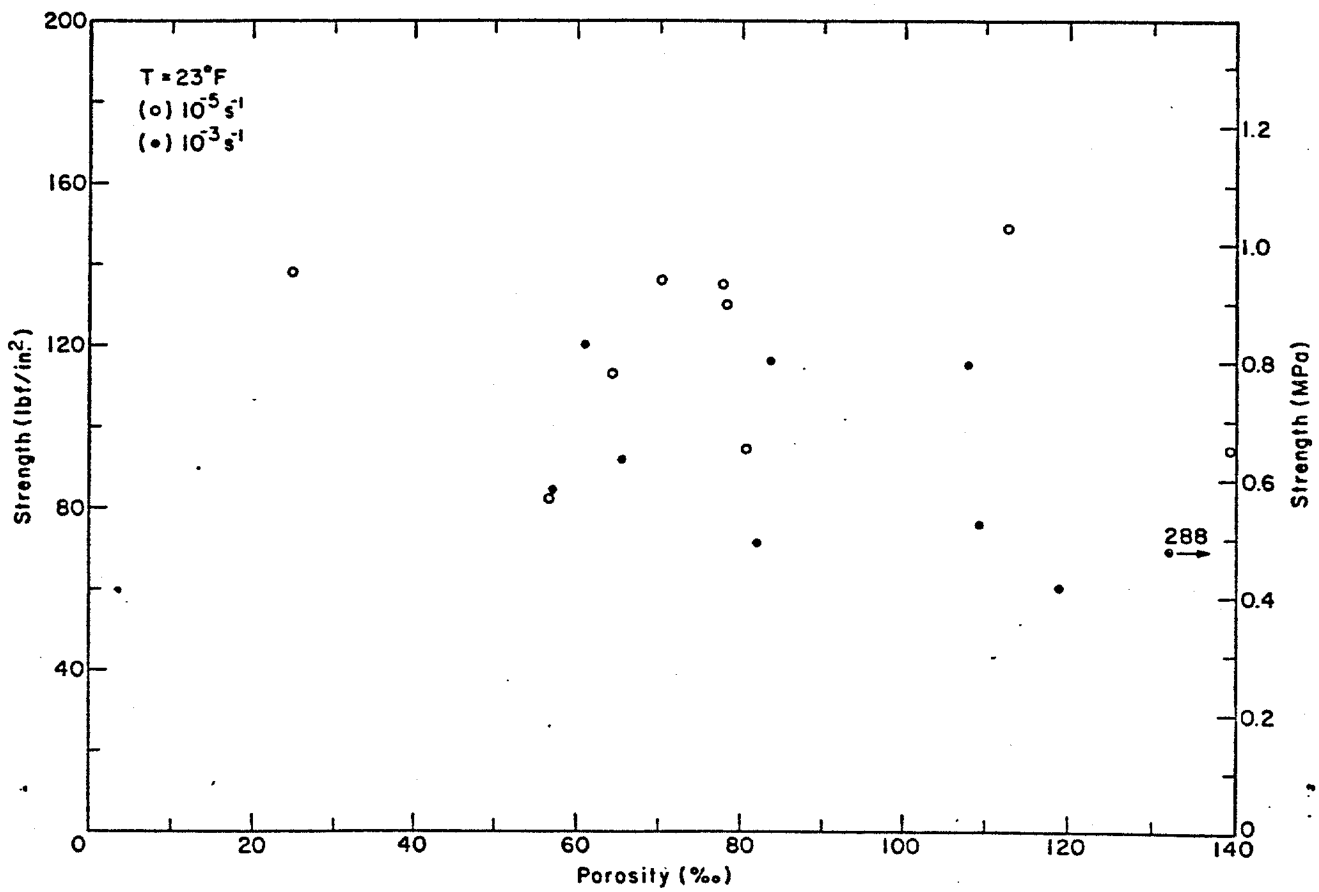

Figure 7. Uniaxial tensile strength versus ice porosity for those tests conducted at −5°C (23°F).

with increasing porosity. For a given porosity, strength values are in general agreement with those obtained by Dykins for first-year sea ice.

Richter and Cox (5) have shown that the uniaxial compressive strength of multi-year pressure ridge ice samples depends on the structure of the test specimens. We would also expect to see a similar dependency of the ice tensile strength on ice structure. Peyton's (15) tensile test results on oriented first year sea ice show that variations in the ice crystals' c-axis orientation with respect to the direction of the applied load can affect the magnitude of the tensile strength by a factor of three (0.7 to 1.9 MPa). Later tests by Dykins on horizontal and vertical sea ice samples support his findings. No work has yet been performed on the effect of grain size on the tensile strength of sea ice. However, based on the results from tensile tests on fresh water polycrystalline ice, variations in grain size can also vary the tensile strength by a factor of four, from 0.5 to 2.0 MPa (15,16,17).

Due to the structural variability both within and between test specimens, the test results of this study are not suited for a rigorous analysis of the effect of ice structure on the tensile strength of sea ice. However, a few general comments can be made. For all test conditions there was a definite tendency for the ice to fail in that part of the specimen containing the coarsest grains; but, there were exceptions. For example, in a few tests containing brecciated ice (ice composed of columnar fragments in a granular matrix), failure occurred in the finer grained granular ice when the columnar fragments were oriented in the hard fail direction with respect to the applied load. In some ice samples containing both fine and coarse grains, failure was not associated with grain size. Instead, flaws in the specimen such as large voids and structure discontinuities controlled the fracture location. Low strength values were usually associated with large voids and cavities in the specimen.

Failure Strain

Average tensile failure strains at the peak or maximum stress for each test condition are given in Table 2. In general, the samples failed in a brittle manner at strains of 0.01 to 0.02%. There was also a tendency for the failure strain to decrease with increasing strain-rate and decreasing temperature. Failure strains were about an order of magnitude lower than those observed on similar multi-year ice tested under uniaxial compression at the same temperatures and strain-rates (3).

It should be noted that the failure strains reported in this investigation were at least two to three times lower than those reported by previous investigators (15,16,17). This is because strains were measured directly on the neck of the sample and did not include deformation of the sample end caps or machine loading train. Because the measured strains were lower, initial tangent modulus values were higher in this program than those reported in earlier studies.

Initial Tangent Modulus

A summary of the initial tangent modulus data for each test condition is given in Table 3. The results are plotted against strain-rate in Figures 8 and 9 and against porosity in Figures 10 and 11. The initial tangent modulus data show a slight increase with increasing strain-rate, and a slight decrease with increasing temperature and porosity. As the

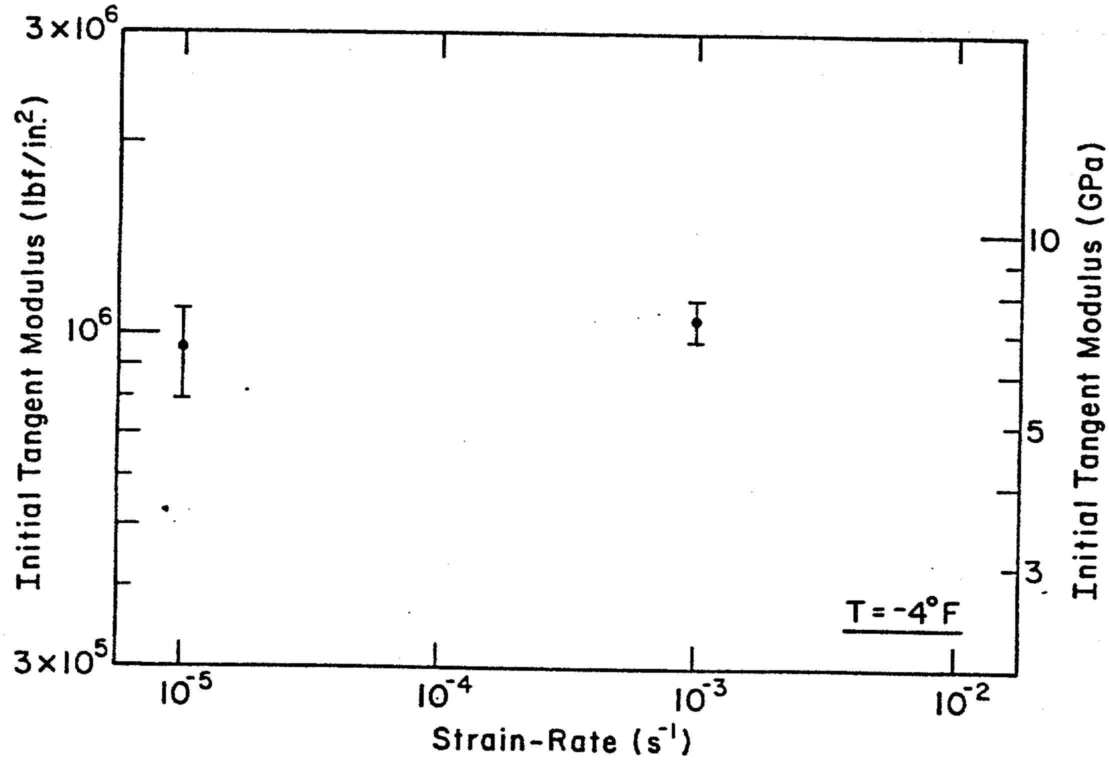

Figure 8. Initial tangent modulus in tension versus strain-rate for those tests conducted at -20°C (-4°F).

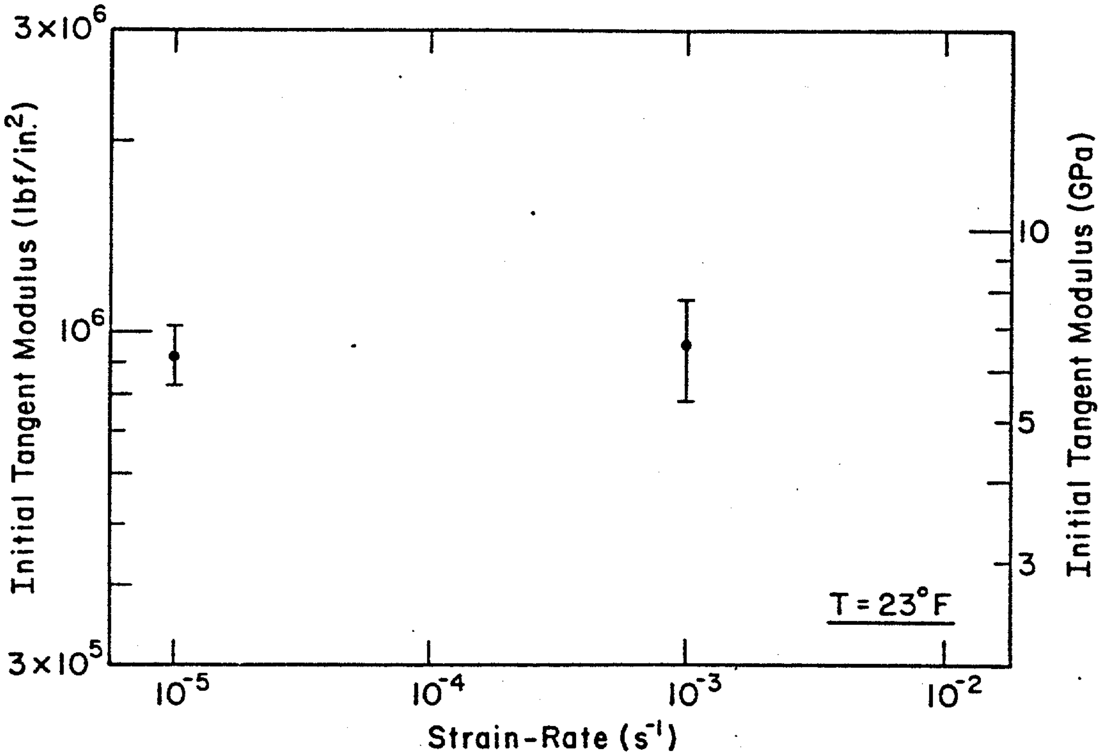

Figure 9. Initial tangent modulus in tension versus strain rate for those tests conducted at -5°C (23°F).

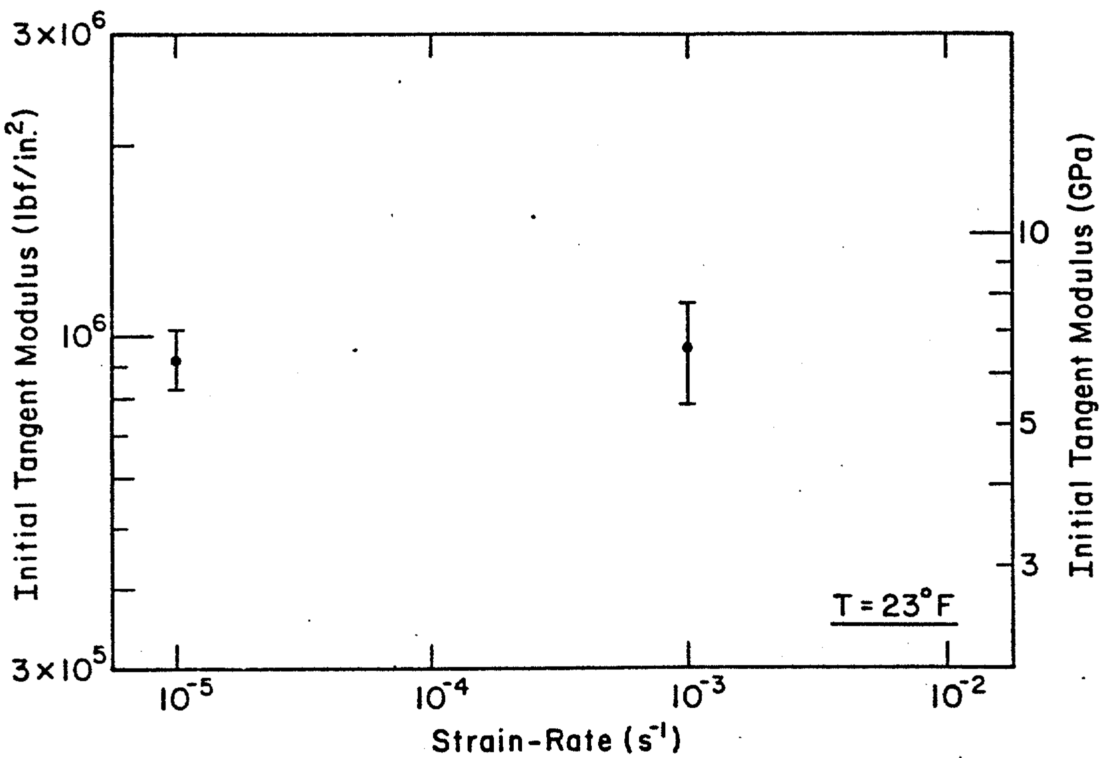

Figure 9. Initial tangent modulus in tension versus strain rate for those tests conducted at −5°C (23°F).

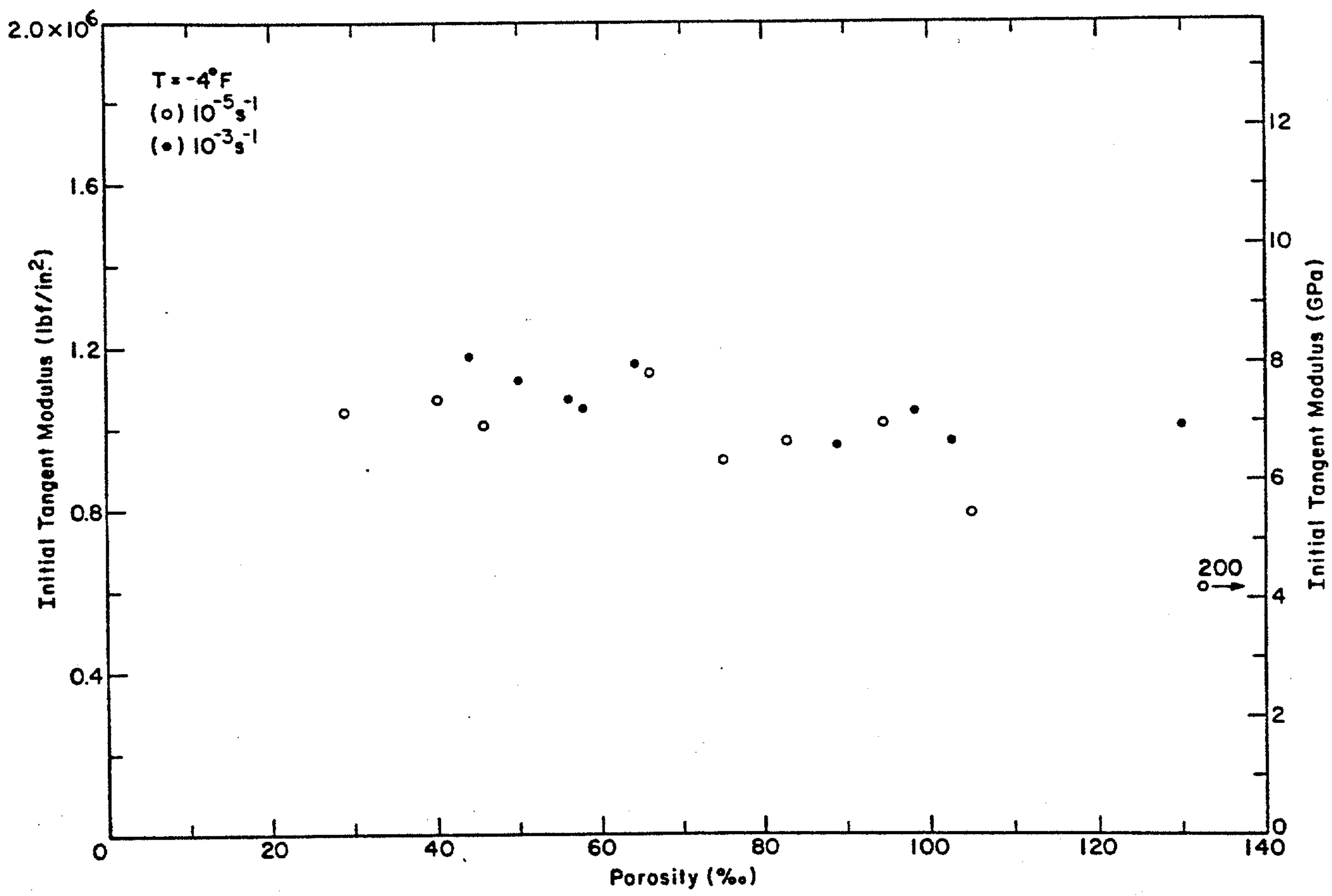

Figure 10. Initial tangent modulus in tension versus porosity for those tests conducted at −20°C (−4°F).

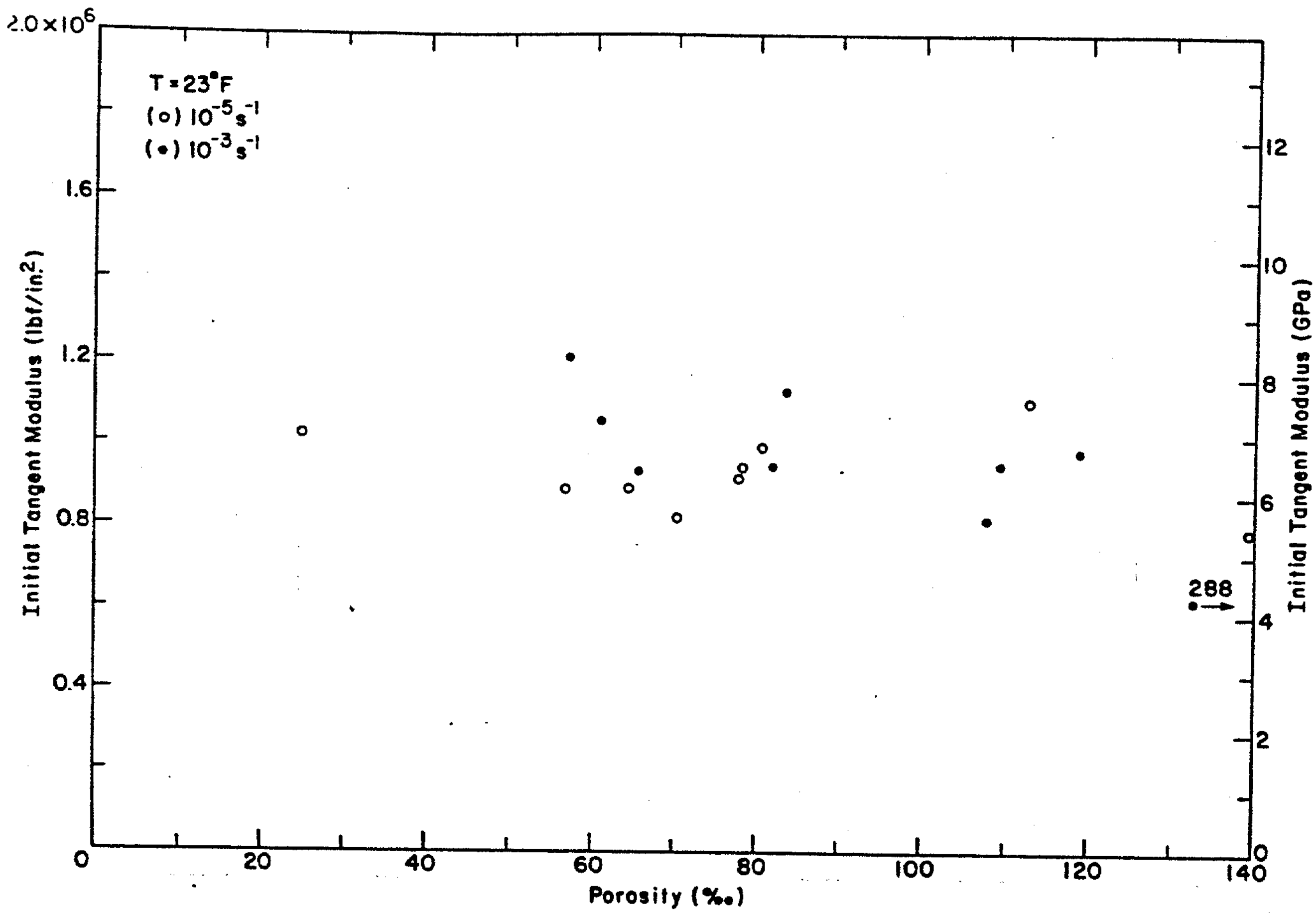

Figure 11. Initial tangent modulus in tension versus porosity for those tests conducted at −5°C (23°F).

temperature and porosity decrease, and the strain-rate increases, the ice behaves in a more brittle manner.

Frequently in ice engineering problems requiring an effective modulus value, compression modulus data are used even if the ice in the problem fails in tension. This is largely due to the fact that there is little data on the modulus of ice in tension. When the results of this study are compared to effective modulus values obtained from compression tests on similar ice, it is apparent that at low strain-rates (10^{-5} s^{-1}), the modulus in tension is noticeably greater. Only at high strain-rates (10^{-3} s^{-1}) are they similar. This is because at 10^{-5} s^{-1}, ice loaded in compression behaves in a ductile manner, whereas ice loaded in tension is still brittle. At 10^{-3} s^{-1} the ice is brittle in both tension and compression. In selecting an effective modulus value for an ice engineering problem, in addition to the ice stran-rate and temperature, the ice failure mode should be considered.

SUMMARY AND CONCLUSIONS

Thirty-six uniaxial tension tests were performed on vertical multi-year pressure ridge ice samples using state-of-the-art laboratory sample preparation and testing techniques. Tests were performed at two strain-rates (10^{-5} and 10^{-3} s^{-1}) and two temperatures (-20 and -5°C). Nine tests were performend at each test condition.

The specimens had an avergae tensile strength of 0.72 ± 0.17 MPa and showed little variation with either strain-rate or temperature. Due to variations in the ice structure between specimens, the data exhibited considerable scatter. However, despite this scatter, there appeared to be a tendency for the ice strength to decrease with increasing porosity. Generally, the ice failed in that part of the specimen containing the coarsest grains, at a structural discontinuity, or at a large void or cavity. Low strength values were usually associated with large voids or cavities in the specimen.

Mean failure strains for each test condition varied between 0.01 and 0.02% and showed a tendency to decrease with increasing strain-rate and decreasing temperature.

Mean initial tangent modulus values for each test condition varied between 6.39 and 7.31 GPa. The mean values showed a slight increase with increasing strain-rate, and a slight decrease with increasing temperature. Modulus values usually decreased with increasing porosity at a given test condition.

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