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Conseil national de recherches Canada

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Reprinted from
Proceedings 1982 SESA/Japan Society for Mechanical Engineers
Honolulu/Maui, Hawaii, May 1982. Part II.
p. 767 - 772

DBR Paper No. 1052
Division of Building Research

Price $1.00 OTTAWA NRCC 20610

Canada

Résumé:

La formation de fissures dans la glace a été étudiée à partir d'observations à l'oeil nu et par enregistrement d'ondes sonores. On a utilisé un système de localisation composé de deux détecteurs et d'un système permettant de mesurer les déformations à l'aide de deux appareils. On a observé que la formation d'ondes sonores de basse amplitude était rapidement suivie de fissures visibles se traduisant par des signaux d'une intensité relativement grande. On fait des commentaires sur la relation contrainte - déformation en fonction des signaux sonores associés aux fissures visibles; puis on l'a comparée avec la sensibilité lors d'un essai de résistance en tension. Enfin, on a analysé les relations entre l'intensité des signaux sonores et le temps, la contrainte et la déformation ainsi que la vitesse de déformation.

ACOUSTIC EMISSION AND MICROCRACKING IN ICE

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Abstract:

Cracking activity in ice has been monitored visually and by recording acoustic emissions. A locator system composed of two detectors and a deformation measuring system utilizing two gauges was used. The onset of low amplitude acoustic emissions was observed to precede very closely the onset of visible cracks giving relatively large signals. The strain and stress rate dependence of the stress level for the onset of acoustic emissions associated with visible cracks is discussed and correlated with the rate sensitivity of tensile strength; and the dependence of acoustic emission rate on time, stress, strain and strain rate is examined.

Introduction:

The acoustic emission (AE) technique, known also as microseismic activity (MA), for monitoring cracking activity in rocks has been known for more than forty years.(1,2) Today, the technology of detecting AE/MA is well established and has found wide application for non-destructive testing.(3-6) Efforts are now being made to standardize AE procedures.(7)

Monitoring AE in ice was carried out first by Gold(8) in 1960 when he reported a correspondence between signal received and formation of a visible crack in columnar-grained S-2 ice in constant load creep. He resorted, however, to counting visible cracks in his later work, mainly because the interpretation of the observations was more direct. Further AE studies of columnar-grained ice were made in Russia by Zaretsky et al., (9,10) who confirmed many of Gold's results. It seems clear that these studies were limited to the audible frequency range.

AE technology is a rapidly advancing field and it is possible to undertake studies today that were impossible only a few years ago. An improved method has been applied recently by St. Lawrence, (11) to granular snow ice undergoing constant load creep; but no AE studies have yet been made of columnar-grained ice under variable loading conditions such as those employed during strength tests.

Cracking activity during uniaxial compressive strength testing of columnar-grained ice was initially monitored by visual examination of crack formation.(12) While this method was useful during low strain rate tests, it was impossible to continue it at high loading rates when the cracks were too numerous and formed too rapidly for human response. It was necessary therefore to resort to AE studies.

Test Procedure:

Experimental details have been described (12) for selection, preparation and testing of large transparent specimens (5 × 10 × 25 cm) of transversely isotropic, columnar-grained ice. The specimens were subjected to uniaxial compressive loads applied perpendicular to the long direction of the grains at constant cross-head rates. Acoustic emission was observed by means of a matched pair of piezoelectric transducers with a resonant frequency of 0.37 MHz and an off-shelf AE system (AET Corporation, Model 3000 - The Locator) having a frequency band width of 0.1 to 0.6 MHz. It could amplify signals from the transducers by 60 to 100 dB and was capable of on-line real-time displays of one-dimensional AE source location, total events and signal level output simultaneously. The post-amplified threshold level for detecting an event was set at 1 V. This is equivalent to a signal of 110 μV at the output of the transducer if the total gain is 80 dB. The instrument can resolve events separated by more than 5 ms.

Detectors equipped with rubber pads were frozen to the specimen near each end and all the electronics were kept outside the cold room. The effective position of the detectors relative to the end platens was established by means of a pulse generator provided with the system. This procedure permitted evaluation of the quality of the bond between the specimen surface and the transducers. If the transducers were poorly frozen to the specimen, the position determined for the signal source was found to be erratic. Although great care was taken in preparing the specimen end surfaces,(12) it was necessary to be very particular about the cleanliness of the specimen ends and the surfaces of the two platens to eliminate noises from the specimen-platen interfaces. For consistent results, therefore, the platens were cleaned after each test and coated with a thin layer of vaseline.

The present work is a continuation of previous tests [12] and was undertaken primarily to investigate the effects of temperature and grain size on the rate sensitivity of the compressive strength of ice. Monitoring of AE was an integral part of each test, and AE data are considered preliminary in nature, although they are already providing new insight into material behaviour.

Results:

In a series of compressive strength tests conducted at -30°C the average cross-sectional grain size, normal to the length of the columns, was in a range of 4 to 5 mm. Figure 1 shows the time dependence of stress, σ, strain, ε, and accumulated AE events, N, for one of the slow tests in which the formation of cracks was also monitored visually inside the cold room and marked on a chart recorder by pressing a remote-event marker. Figure 2 shows the AE signals received in the first 3 h of testing. Signals with more than 100 mV (79 dB gain) were usually identified as visible cracks.

Figure 1 shows that as stress approached maximum or upper yield value the axial strain rate approached a peak value, $\dot{\varepsilon}_p$, equivalent to the nominal strain rate, $\dot{\varepsilon}_n = \dot{x}/L$, where L is specimen length and $\dot{x}$ is the applied constant cross-head rate. This shows that the rate of increase in the AE events, N, also approached a quasi-constant value as peak stress was reached. The characteristics in the axial strain rate, particularly nonconstancy in $\dot{\varepsilon}$ during most of the loading, was consistent with previous observations at -10°C.[12,13] The dependence of stress and N on strain for the above test is shown in Fig. 3. An approach to linear dependence between ε and N and hence $\dot{\varepsilon}$ and $\dot{N}$ is also evident.

The advantage of using transparent polycrystalline ice is that cracks can be seen as they form, their size can be estimated, and their position within the specimen located visually with appropriate lighting. The size and the shape of the visible cracks were compatible with the geometry of the constituent grains. The cracks were a few mm wide and from a few mm to a few cm long, and parallel to the long axis of the grains. Figures 4 and 5 show, respectively, the test specimen under discussion (after the test) and the locations of AE events. This particular example was chosen because of the visible nonuniformity of crack distribution; Fig. 5 illustrates the capability of the locater system. Usually, cracks were fairly uniformly distributed. Figure 5 also shows that the platen-sample interfaces were rather quiet.

A few low-amplitude AE events were recorded (see Fig. 1) before a visible crack formed, producing a relatively large signal. This was noticeable not only at -30°C in the coarse-grained ice 4 to 5 mm in diameter but also during another series of tests on fine-grained ice of average grain diameter of 2 mm at -10°C. Comparison is made in Fig. 6 between stress, σ_{fae}, at which the first acoustic emission was recorded, and average stress, σ_{fc}, for the emissions that could be associated with the first three visible cracks. This approach was chosen because of the difficulty of recording manually the exact time of formation of the first crack under the low temperature condition of the laboratory.

It may be seen in Fig. 6 that the first AE events were recorded when stress exceeded about 0.4 $MN \cdot m^{-2}$ and emissions corresponding to visible cracks formed at stresses greater than about 0.8 $MN \cdot m^{-2}$.

Discussion:

AE associated with a visible crack indicated, in this material, the creation of an opening comparable in size to the grains. The significance of the first visible cracks is discussed below.

Although the strain to the first cracks, ε_{fc} (see Fig. 1 for clarity of definition), was practically independent of load rate, the corresponding time, t_{fc}, varied greatly with loading conditions. Rate sensitivity of σ_{fc} was also noticeable. As neither stress rate nor strain rate was constant during the early loading period (Fig. 1), it was decided to examine the results on the basis of average loading conditions. The dependence of σ_{fc} on the average strain rate to the first cracks, $\dot{\varepsilon}_{fc} = \varepsilon_{fc} / t_{fc}$, and the corresponding average stress rate, $\dot{\sigma}_{fc} = \sigma_{fc} / t_{fc}$, are presented in Figs. 7 and 8, respectively. The figures also include the results of previous tests in which cracking activity was monitored only visually.

Formation of the first large crack during compression does not determine ultimate strength. It indicates, however, the beginning of internal damage that may lead to fracture in tension if the applied stress is sufficient to propagate the crack.[14] An estimation of the applied load, σ_f, for such failures can be made using Griffith's criterion,

$$\sigma_f = \left(\frac{2E\gamma_{vs}}{\pi \ell} \right)^{1/2} \quad (1)$$

where E is Young's modulus, 2ℓ is crack length, and γ_{vs} is the surface-free energy of the solid with respect to vapour.

If $\gamma_{vs} = 0.109\ Jm^{-2}$ (15) and $E = 9.5\ GN{\cdot}m^{-2}$, (16) then equation (1) gives σ_f of 1.2 and 0.5 $MN{\cdot}m^{-2}$ for crack lengths of 1 and 5 mm, respectively. Note that the size of the first cracks actually seen and the level of stresses at which they formed (Fig. 6) are consistent with the above calculations. Tensile failure can be expected when the first significant crack forms under tensile mode of loading.

Direct tensile strength data are rare even for columnar-grained ice, which is by far the most common type of natural ice. Surprisingly, the only work to date with sufficient information to provide comparison was carried out in 1939-41 for the South Manchurian Railway Company (SMRC) (17) by Dr. Y. Kubo, chief engineer. Tests were performed on dog-bone type tensile specimens of columnar-grained river ice with 3 × 3 × 12 cm gauge section. The load was applied perpendicular to the long axis of the columns and the applied stress rate was varied in the range of 3.3×10^{-4} to $3.3 \times 10^{-2}\ MN{\cdot}m^{-2}\ s^{-1}$. The dependence of tensile strength, σ_T, on stress rate, $\dot{\sigma}_T$, for the test temperature, T, of -10°C is given (on conversion to the present units) by

$$\sigma_T = \dot{\sigma}_T / (6.0 \times 10^{-4} + 0.7\ \dot{\sigma}_T) \qquad (2)$$

This work was declassified and translated into English but has never been discussed in the open literature. Equation (2) is shown in Fig. 8, the solid part of the curve indicating the range in stress rate.

Effect of temperature on tensile strength was investigated by Kubo (17) at a stress rate of $7 \times 10^{-3}\ MN{\cdot}m^{-2}\ s^{-1}$. Strengths of 0.8, 1.22, 1.36 and 1.54 $MN{\cdot}m^{-2}$ were obtained at -4, -11, -24 and -32°C, respectively (Fig. 8). Butkovich (18) was aware of this information but discussed only the temperature dependence of the observed tensile strength. He performed a series of tensile tests on cylindrical samples of cross-sectional area of 3 cm^2 made from a commercially available block of ice having columner-grained structure. Load was applied perpendicular to the columns and a linear dependence of strength on temperature observed in the temperature range 0 to -40°C. Butkovich provided no information on either load or strain rate, but he did mention the nondependence of tensile strength on stress rate above $1.6 \times 10^{-2}\ MN{\cdot}m^{-2}\ s^{-1}$ reported in Reference (17). For this reason Butkovich's results are shown in Fig. 8.

Michel (19) has discussed the tensile strength data of columnar-grained S-2 ice in the temperature range 0 to -30°C. Strength values of 0.8 to 1.2 $MN{\cdot}m^{-2}$ for natural St. Lawrence River ice and of 1.0 to 1.4 $MN{\cdot}m^{-2}$ for laboratory-made ice were reported. The absence of any measured loading conditions makes it difficult to compare these results in a positive manner. They are presented in Fig. 8 only to show the observed range in tensile strength; the stress-rate position is arbitrary.

Average stress, σ_{fc}, for the first three cracks is also shown in Fig. 8. As the first crack would actually form at a lower stress than σ_{fc}, tensile strength should be below σ_{fc} and hence closer to Kubo's results. On the other hand, Kubo used natural river ice, which could contain inherent flaws and could be weaker than laboratory-made ice. Procedures for sample preparation could also contribute to differences. In all, however, results shown in Fig. 8 are encouraging, particularly the rate effect shown in Kubo's work and the numerical magnitudes obtained by later investigators.

Conclusions:

Monitoring AE activities in conjunction with visual observation is a potentially significant method of examining the state of ice during compressive strength testing. For a constant cross-head displacement rate, AE rate approaches a constant value, along with axial strain rate, as the upper yield is reached.

First AE activity was recorded only after stress exceeded 0.4 $MN{\cdot}m^{-2}$, and emissions corresponding to the first visible cracks did not form until the stress was over 0.8 $MN{\cdot}m^{-2}$. These stresses exhibited rate sensitivity (with their corresponding times), but the associated strains ($\approx 2.5 \times 10^{-4}$) were not significantly affected by loading rate. There was an indication of higher stress at lower temperature. No significant differences were noticed, however, for fine-grained or coarse-grained ice. The size of the visible cracks and the stress, σ_{fc}, at which they form were shown to satisfy Griffith's criterion of fracture for tensile mode of loading. Rate sensitivity of σ_{fc} was analysed in terms of measured strain and stress rate.

The value of σ_{fc} and its dependence on stress rate were shown to be close to a few available tensile strength results on natural river ice. Direct tensile tests must be performed and stress and strain and their rates carefully documented before a more rational analysis can be made.

Acknowledgement:

The author would like to express his gratitude to Dr. Y. Kubo for his personal contact and encouragement and for the results of tests he performed in conjunction with the South Manchurian Railway Company's project; the author also wishes to acknowledge the technical assistance of D. Lavoie.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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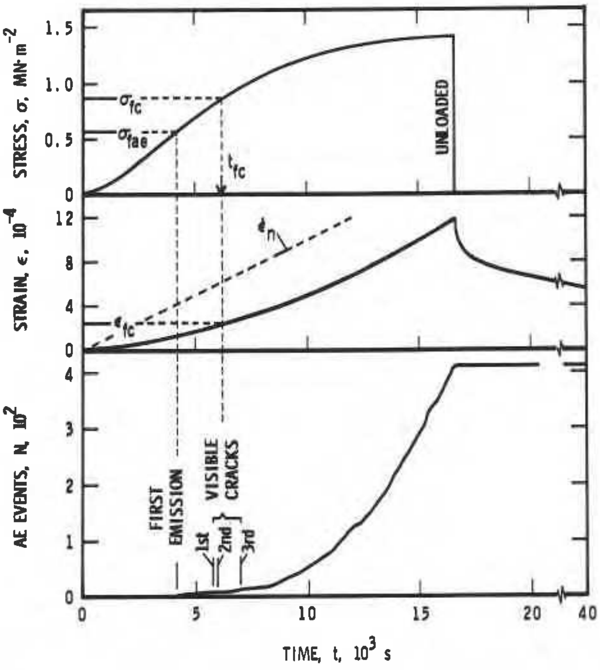

Fig. 1 Stress-time, strain-time and acoustic events-time results on columnar-grained S-2 ice at -30°C for a constant cross-head displacement rate of 2.5×10^{-6} cm s^{-1} or a nominal strain rate of 1×10^{-7} s^{-1}.

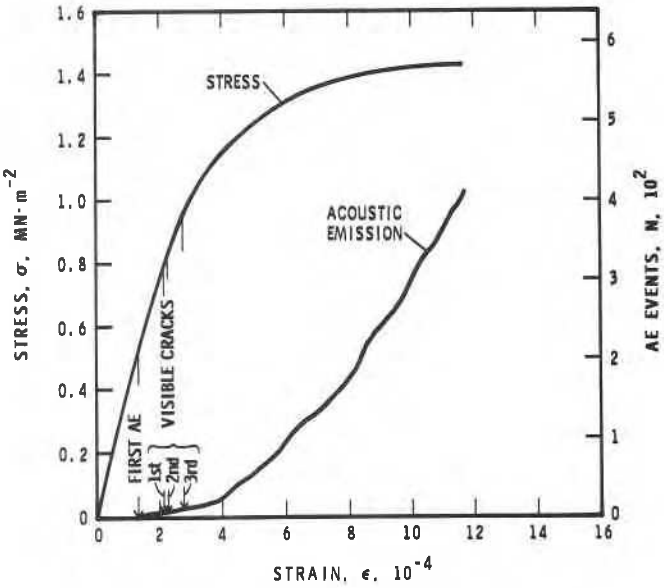

Fig. 3 Stress-strain and AE events-strain for test in Fig. 1.

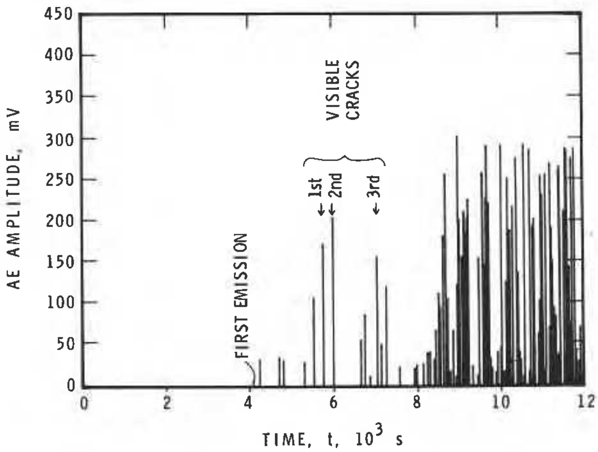

Fig. 2 Peak AE voltages and signals associated with first three visible cracks for test in Fig. 1.

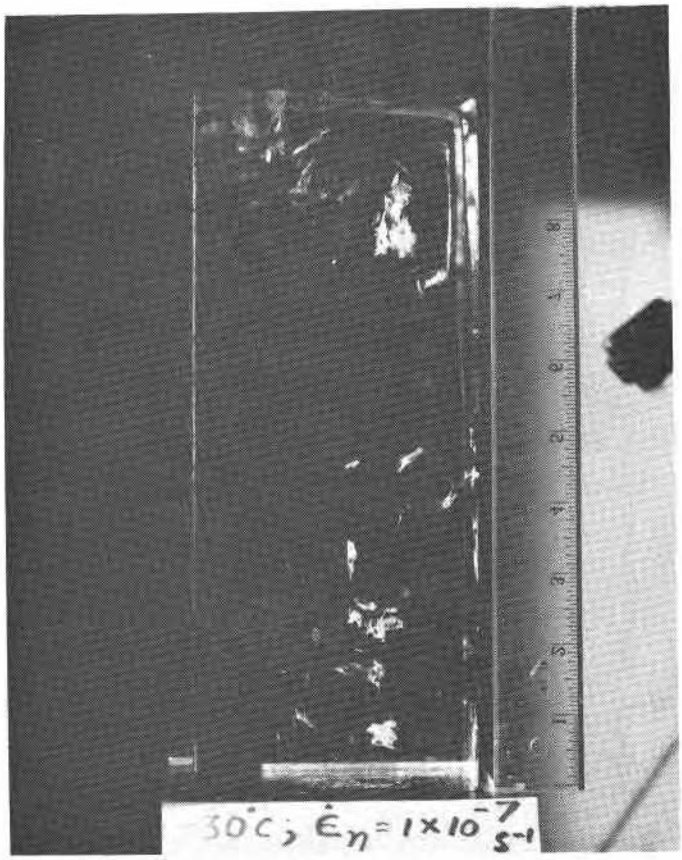

Fig. 4 Crack distribution in the sample after test of Fig. 1.

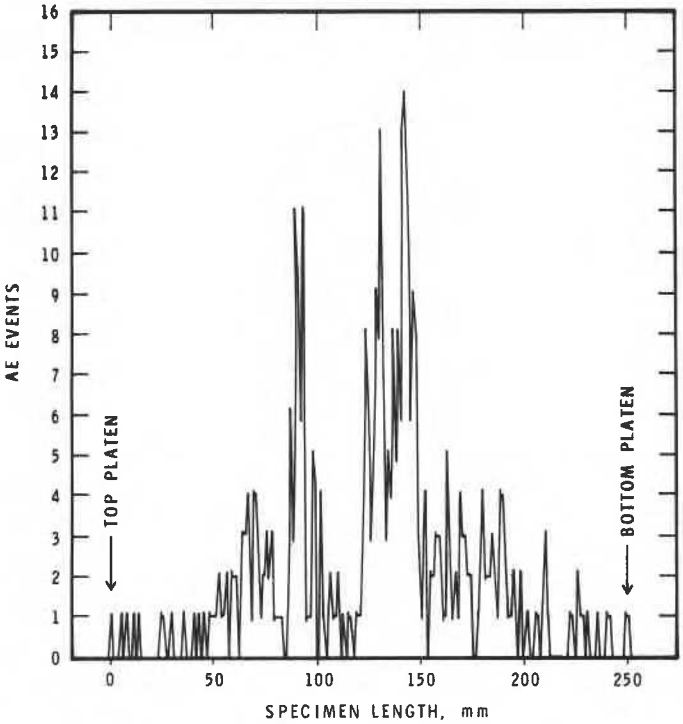

Fig. 5 One-dimensional locations of AE events recorded during test of Fig. 1.

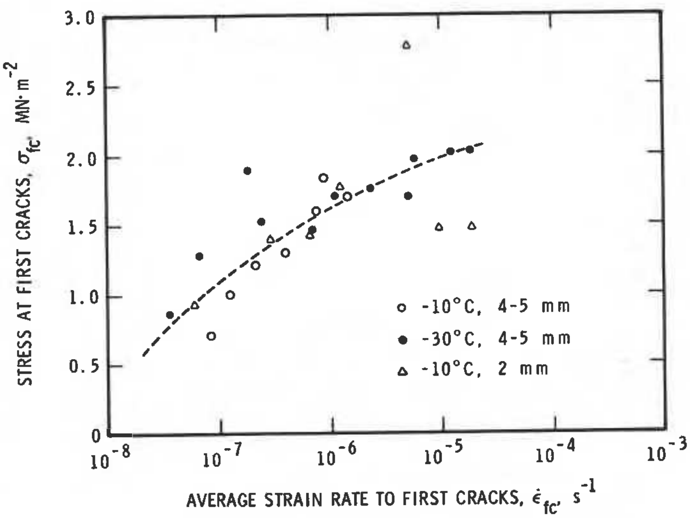

Fig. 7 Dependence of stress at first visible cracks on average strain rate to the formation of these cracks in columnar-grained S-2 ice subjected to various constant cross-head displacement rates.

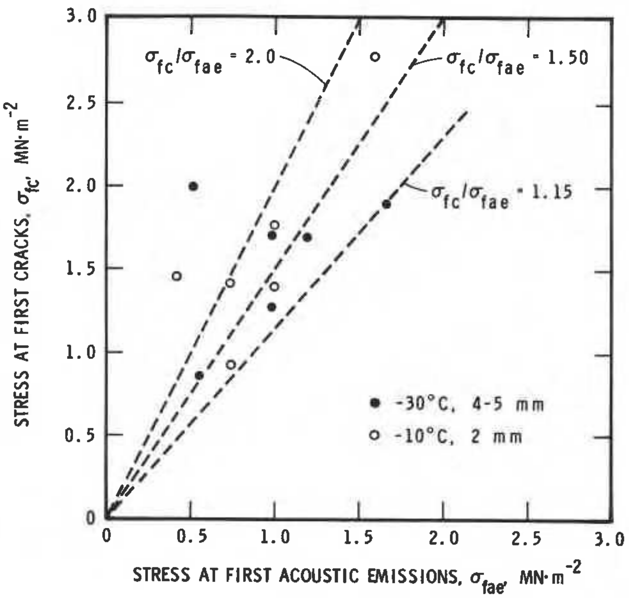

Fig. 6 Comparison of stresses at first acoustic emission and average stress for first three visible cracks.

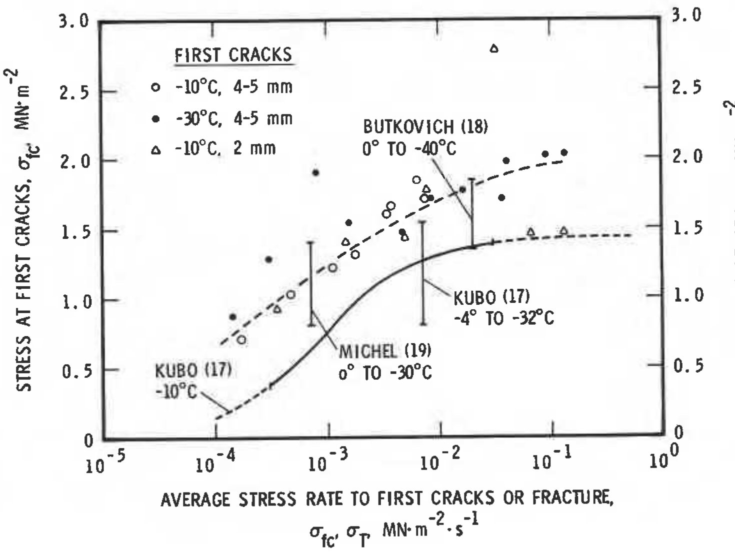

Fig. 8 Stress-rate dependence of stress at first visible cracks in laboratory-made columnar-grained S-2 ice. Tensile strength of natural river and laboratory ice are shown for comparison. Stress-rate for Butkovich (18) and Michel (19) are arbitrary (see text).