The strain rate and temperature dependence of Young's modulus of ice

Traetteberg, A.; Gold, L. W.; Frederking, R. M. W.

Publisher's version / Version de l'éditeur:

Proceedings, IAHR Third International Symposium on Ice Problems, 1975, pp. 479-486, 1975

National Research Council Canada | Conseil national de recherches Canada

THE STRAIN RATE AND TEMPERATURE DEPENDENCE OF YOUNG'S MODULUS OF ICE

by A. Traetteberg, L.W. Gold and R. Frederking

Reprinted from
Proceedings, IAHR Third International Symposium on Ice Problems
held 18 - 21 August 1975
Hanover, New Hampshire
p. 479 - 486

DBR Paper No. 667
Division of Building Research

Price 25 cents | OTTAWA | NRCC 15206

SOMMAIRE

Les auteurs mesurent le module de Young de la glace polycristalline à des vitesses de déformation entre 10^{-8} et 5×10^{-3} s^{-1} et à des températures de -10, -19.3, -29 et -39.5°C pour deux genres de glace: la glace granulaire naturelle et la glace colonnaire obtenue en laboratoire. La charge est appliquée à une vitesse de traverse constante jusqu'à une contrainte d'environ 5 kg/cm^2, puis enlevée immédiatement à la même vitesse. On détermine le module de Young d'après la partie linéaire de la courbe contrainte/déformation durant le chargement. Le module des deux genres de glace augmente en même temps que la vitesse de déformation augmente à toutes les vitesses de déformation étudiées.

Reprinted from

Proceedings

THIRD INTERNATIONAL SYMPOSIUM ON ICE PROBLEMS

18-21 August 1975
Hanover, New Hampshire

Guenther E. Frankenstein, Editor
USA CRREL

November 1975

International Association of Hydraulic Research
Committee on Ice Problems

THIRD INTERNATIONAL SYMPOSIUM ON
ICE PROBLEMS
Hanover, New Hampshire, USA

THE STRAIN RATE AND TEMPERATURE DEPENDENCE OF YOUNG'S MODULUS OF ICE

A. Traetteberg,* River and Harbour Research Laboratory, Technical University of Norway, Trondheim, Norway.
L.W. Gold, Assistant Director, Division of Building Research, National Research Council of Canada, Ottawa, Canada.
R. Frederking, Research Officer, Division of Building Research, National Research Council of Canada, Ottawa, Canada.

Measurements were made of Young's modulus of polycrystalline ice over the strain rate range of 10^{-8} to 5×10^{-3} s^{-1} at temperatures of -10, -19.3, -29 and -39.5 °C on two types of ice: naturally formed granular ice and laboratory grown columnar-grained ice. Load was applied at constant rate of cross-head movement until the stress was about 5 kg/cm^2, and then removed immediately at the same rate. Young's moduli were determined from the linear portion of the stress-strain curve during loading. The modulus for both types of ice increased with increasing strain rate over the full range of strain rate covered in the investigation.

* * * * *

The strain rate dependence of the strength of ice is important because of its role in determining the forces that ice can exert on structures. Observations by Gold (1958) of a significant temperature dependence for Young's modulus of columnar-grained ice when subject to a strain rate of about 10^{-5} s^{-1} in the temperature range of 0 to -40 °C, indicate that the modulus should also depend on the strain rate. Hawkes and Mellor (1972) presented evidence of this dependence for granular ice subject to a tensile stress. The work now reported was undertaken to further explore this dependence over the temperature range of -10 °C to -39.5 °C and strain rate range of 10^{-8} to 5×10^{-3} s^{-1}.

* Visiting scientist with the Division of Building Research, National Research Council of Canada, 1972-73.

Preparation of Test Specimens

The behaviour of two types of ice was investigated: naturally formed granular ice of grain size of about 1.4 mm and laboratory grown columnar-grained ice with grain area of about 20 mm^2 in the plane perpendicular to the long direction of the grains. The columnar-grained ice had a bias in crystallographic orientation such that the axis of hexagonal symmetry tended to lie in the plane perpendicular to the long direction of the grains.

Rectangular specimens 5 x 10 x 25 cm^3 were used for the measurements. They were cut from blocks using a band saw, and machined to their final shape with a milling machine. The columnar-grained specimens were cut so that the long direction of the grains was perpendicular to the 10 x 25 cm^2 face.

Method of Measurement

Young's modulus was determined by applying a compressive load to the 5 x 10 cm^2 faces of the specimens (i.e., perpendicular to the long direction of the grains for the columnar-grained ice) in a 10,000 kg capacity Instron testing machine. The testing machine applied the load under the condition of a nominally constant rate of cross-head movement until the stress was about 5 kg/cm^2, and then immediately removed it at the same rate of cross-head movement.

The load was measured with a 900 kg capacity load cell which was placed beneath the specimen. The strain was measured with an extensometer which was clamped directly to the specimen. The extensometer, which had a gauge length of 15 cm, contained two linear differential transformers that were located on either side of the specimen. Their outputs were added and, with the output of the load cell, recorded on a two channel, galvanometer type recorder with a full scale response time of less than 0.02 sec.

The specimens were prepared and the measurements determined in a cold room whose temperature could be controlled to within ±0.1 Celsius degrees. After machining, the specimens were stored in kerosene until the time of testing. Young's modulus was determined at the temperature of -10, -19.3, -29.0 and -39.5 °C. Specimens were maintained at the test temperature at least 24 hours prior to mounting in the testing machine. Precautions were taken to prevent sublimation when the time required for a measurement was sufficiently long for it to occur.

Results

A typical stress-strain curve determined from the load and strain record is shown in Fig. 1. In most cases, the stress-strain curve during loading was essentially linear; the curve representing unloading was parallel to it for part of its length. The Young's moduli presented in this paper were determined from the linear portion of the stress-strain curve during loading.

Young's moduli measured at -10 °C for both columnar and granular ice, are plotted against strain rate in Fig. 2. The strain rate was determined from the linear part of the strain-time record associated with each modulus. The results show that there is a decrease in modulus with decreasing strain rate for both the columnar-grained and granular ice over the full range of strain rate covered in the investigation. It was not possible to apply sufficiently high strain rates to clearly establish the maximum value of the modulus for the two types of ice. Measurements made by dynamic methods, however, show that the maximum value is about 10^{10} N m^{-2} (about 10^5 kg cm^{-2}).

When the strain rate was less than about 10^{-5} s^{-1}, permanent deformation occurred during a load cycle. A correction was made for this by assuming that the strain rate associated with it was proportioned to σ^2, where σ is the applied compressive stress. The strain correction as a function of time was calculated using the load-time curves with the condition that the strain correction equal the permanent strain remaining after relaxation at the end of a test. The assumed time dependent permanent strain contribution was subtracted from the measured strain before calculating Young's modulus.

Each curve in Fig. 2 is for one set of measurements. More than one set of measurements were usually made on a specimen. The first numeral in the identification number for each curve identifies the specimen and the second indicates the order in which the sets of measurements were made. For each set, the tests were conducted in order of increasing rate of cross-head movement, beginning with the lowest rate. Evidence which was obtained from one of the columnar-grained specimens that had not been subjected to prior loading, indicates that the moduli obtained from the first set of measurements on this ice type can be larger at a given strain rate than those obtained from subsequent sets of measurements (e.g., 5 -1, -2, -3, -4, Fig. 2).

The strain dependence of Young's modulus at temperatures of -19.3, -29 and -39.5 °C for one specimen of columnar-grained and one of granular ice, is shown in Figs. 3 and 4, respectively. These figures illustrate the general increase in Young's modulus with decreasing temperature that was observed for each specimen.

Discussion

The observations clearly show that Young's modulus of ice undergoes a relaxation in the strain rate range of 10^{-3} to 10^{-8} s^{-1}, the same range associated with the ductile to brittle transition in behaviour. Present understanding of the factors controlling crack initiation and propagation indicates that the relaxation processes involved probably play a significant role in the ductile to brittle transition.

The results are being analyzed assuming that ice behaves as a linear anelastic solid (Zener 1948, Gold and Traetteberg 1974). An investigation of the relaxation that occurred for each specimen at -10 °C after the load was removed suggests that the non-elastic behaviour is not determined by only one process with a constant relaxation time, but rather by two or more processes, one of these with a relaxation time of about 1 sec, and a second with a relaxation time that increases with time. Analyses to date indicate that the observed strain rate dependence of Young's modulus is determined primarily by the latter process. The time dependence of the relaxation of Young's modulus for a columnar-grained and granular specimen at -10 °C is given in Fig. 5. The theoretical analysis shows that, with the conditions under which the measurements were determined, Young's modulus is not essentially a function of strain rate but rather of time.

Young's modulus of ice should depend on the density. The values obtained from the first set of measurements on the granular specimens at -10 °C and strain rate of 10^{-5} s^{-1} are plotted against density in Fig. 6. There appears to be a well defined dependence, which, if valid, would account for much of the difference that was found between the Young's moduli of the various granular specimens.

Conclusions

Young's modulus of granular and columnar-grained ice, with the axis of hexagonal symmetry of each grain tending to be perpendicular to the long direction of the grains, undergoes a relaxation in the range of strain rate of 10^{-3} to 10^{-8} s^{-1}. This relaxation is both time and temperature dependent and probably plays a significant role in the ductile transition that occurs in the same range of strain rate.

* * * * *

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.

References

Gold, L.W., 1958. Some Observations on the Dependence of Strain on Stress for Ice. Can. J. Phys., Vol.36, pp. 1265-1275.

Gold, L.W. and A. Traetteberg, 1974. Young's Modulus of Ice and Ice Engineering Problems. Proc., Second Symposium on Applications of Solid Mechanics, Dept. Mech. Eng., McMaster Univ., Hamilton.

Hawkes, I. and M. Mellor, 1972. Deformation and Fracture of Ice under Uniaxial Stress. J. Glaciol., Vol. 11, pp. 103-132.

Zener, C.M., 1948. Elasticity and Anelasticity of Metals. University of Chicago Press, Chicago.

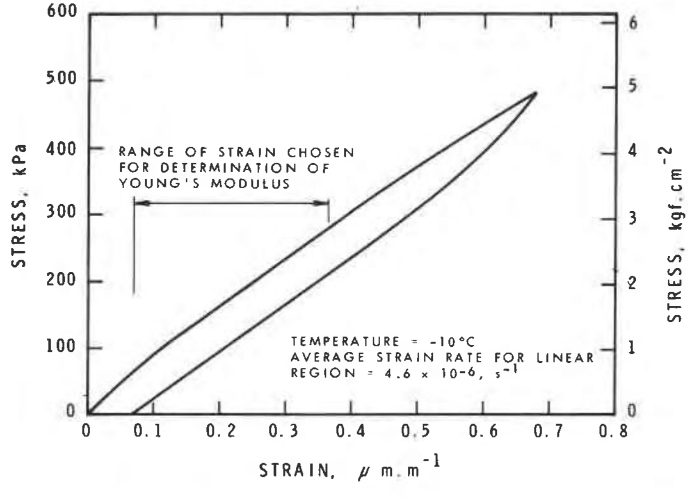

FIGURE 1

STRESS - STRAIN CURVE FOR COLUMNAR - GRAINED ICE

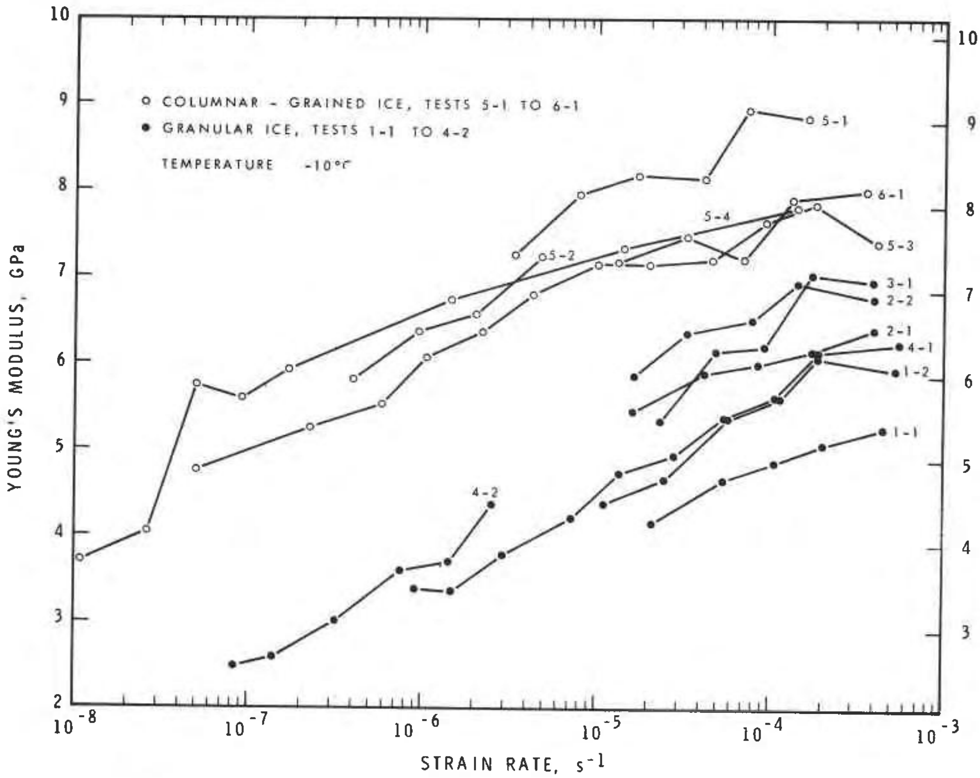

FIGURE 2

STRAIN RATE DEPENDENCE OF YOUNG'S MODULUS

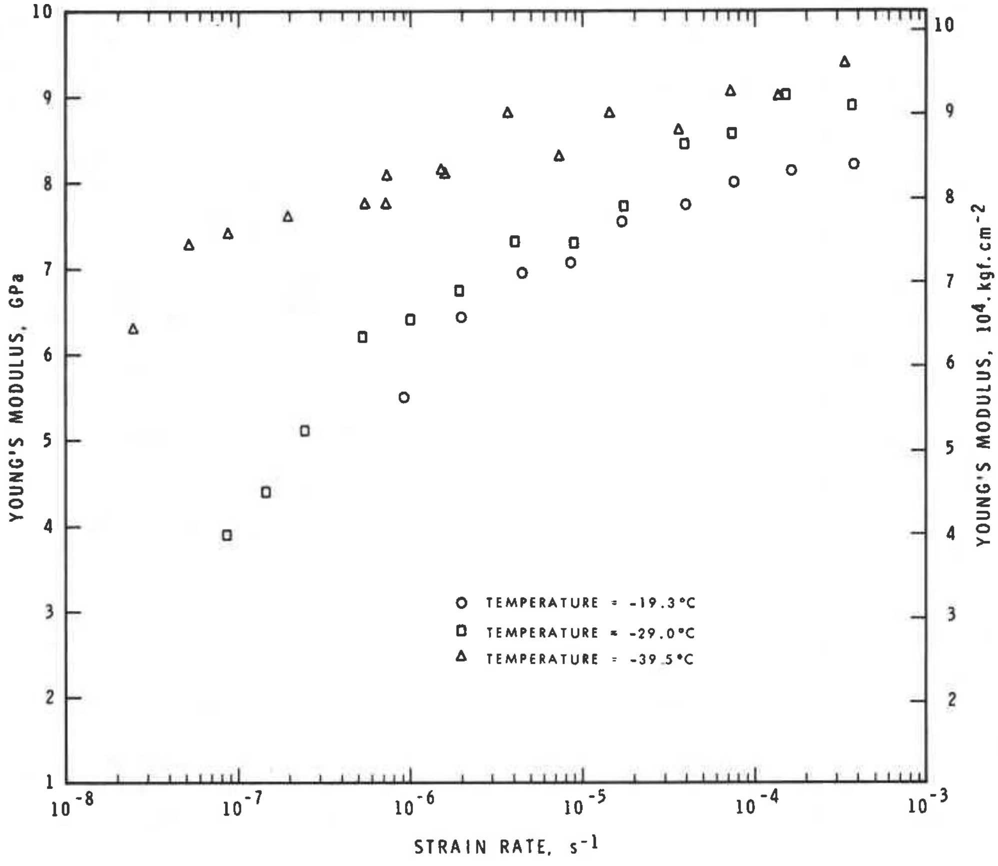

FIGURE 3

TEMPERATURE AND STRAIN RATE DEPENDENCE OF YOUNG'S MODULUS OF COLUMNAR-GRAINED ICE

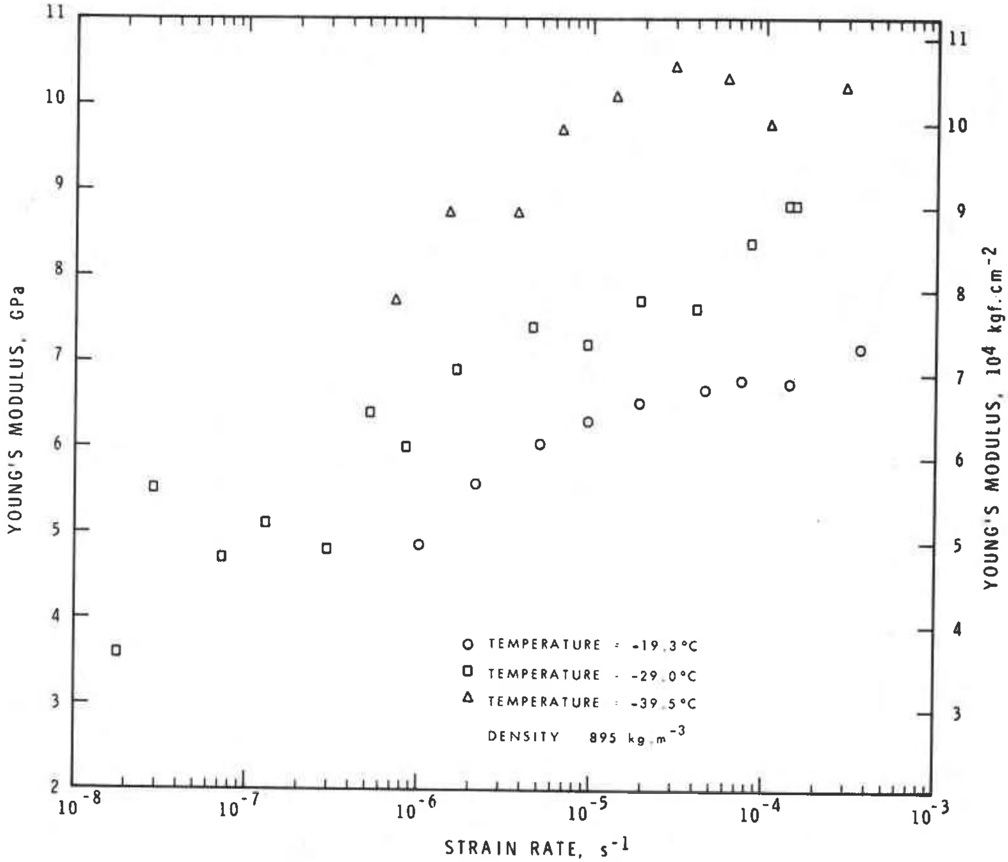

FIGURE 4

TEMPERATURE AND STRAIN RATE DEPENDENCE OF YOUNG'S MODULUS OF GRANULAR ICE

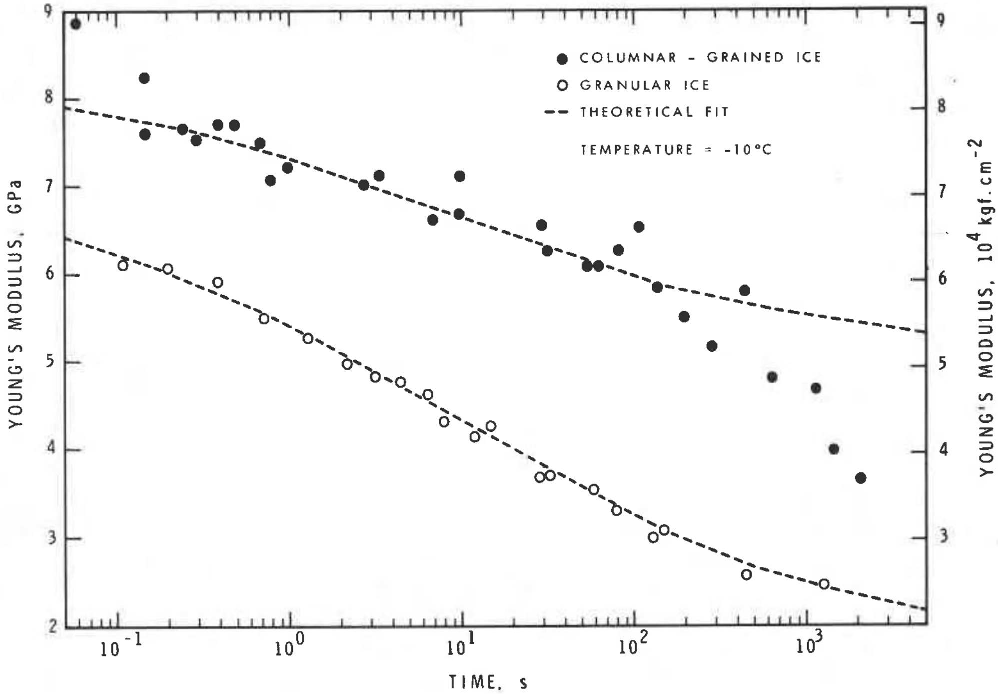

FIGURE 5

TIME DEPENDENCE OF YOUNG'S MODULUS

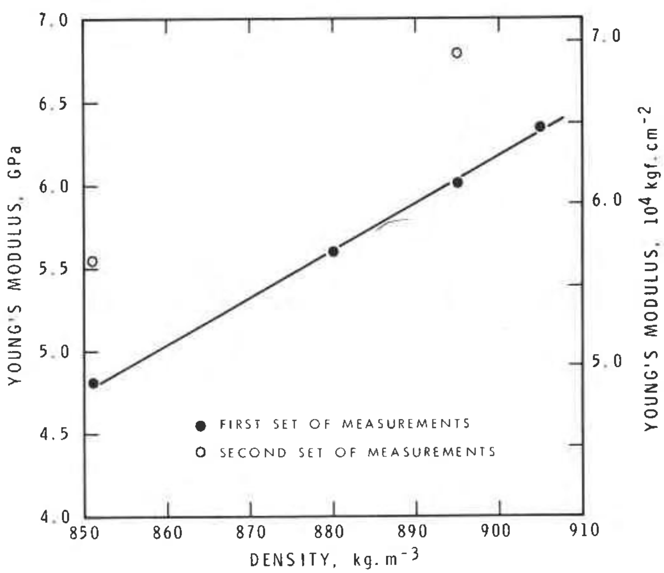

FIGURE 6

DENSITY DEPENDENCE OF YOUNG'S MODULUS OF SNOW ICE