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Canadian Journal of Physics, 38, 9, pp. 1137-1148, 1960-09

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THE CRACKING ACTIVITY IN ICE DURING CREEP

BY

L. W. GOLD

Reprinted from
CANADIAN JOURNAL OF PHYSICS
VOL. 38, NO. 9, SEPTEMBER 1960, p. 1137

RESEARCH PAPER NO. 103
OF THE
DIVISION OF BUILDING RESEARCH

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THE CRACKING ACTIVITY IN ICE DURING CREEP[1]

L. W. GOLD

ABSTRACT

Observations were made at one temperature on the cracks that form in ice during creep under constant compressive load. The ice had a hexagonal symmetry with respect to the grain boundaries. The load was applied perpendicular to the long axis of the grains. A piezoelectric crystal was used to detect the cracking activity in the ice.

Two stages of cracking were observed. The first occurred during the transient period of the creep, and the plane of these cracks tends to be parallel to the grain boundaries and to the direction of the stress. The rate at which these cracks formed decreased very markedly as the creep rate approached a constant value. Above a certain stress, the creep rate continuously increased with time. Under this condition the second stage of cracking was observed. These cracks tend to be more irregular in direction and to occur in planes that are at 45° to the applied stress.

INTRODUCTION

Observations on the elastic and creep behavior of ice under constant compressive stress have been carried out by Brown (1926). At lower stresses he observed a creep rate which, after the initial transient stage, tended to decrease with time to a constant value characteristic of the stress. At a critical stress range, between 190 and 200 p.s.i. for the temperature and load conditions of the experiment, the character of the creep–time curve changed radically from one for which the creep rate decreased with time to one for which it increased with time. The period of observation was never more than $3\frac{1}{2}$ hours.

Throughout his paper, Brown refers to internal cracking of the ice and associated audible "crackling" that occurred during a load test. Qualitatively, his comments indicate that the intensity of "crackling" depends on the temperature and on the magnitude of the applied stress.

The creep of ice and its general dependence on stress, temperature, and time is similar to that observed for many materials. Glen (1958), in his review of such investigations, found that the minimum observed strain rate is related to the applied stress according to the law:

$$\dot{e} = kc^n \qquad (1)$$

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[1] Manuscript received May 10, 1960.

Contribution from the Snow and Ice Section, Division of Building Research, National Research Council, Ottawa, Canada.

Issued as N.R.C. No. 5763.

where $\dot{e}$ is the strain rate, c is the applied stress, and k is a constant. The exponent n is observed to increase with c within the range $1.85 < n < 4.16$ for $1.0 < c < 15$ kg/cm^2. Glen (1955) observed that until accelerating creep occurs, ice obeys the Andrade law with the initial transient in the creep curve being proportional to the cube root of the time.

Cracking activity has been reported in other materials during compressive loading. Obert (1945) conducted investigations in the laboratory to see if the microseismic activity, which he observed in rock in the field, could also be detected with rock specimens subject to compressive loads in the laboratory. He observed a high "microseismic rate" when the load was between 1/8 to 1/2 the ultimate strength of the rock. This rate had decreased to a minimum when the load reached 1/2 to 3/4 the ultimate strength. As the load was increased, he observed that the rocks that tended to shatter showed a marked increase in "microseismic" activity at about 8/10 of the crushing strength, whereas the rocks that tended to crush showed comparatively little increase in activity. He was able to show that the first maximum in his observed "microseismic" activity was due to the geometry of loading. If he held the load constant at stresses up to 9/10 the ultimate load, the activity rate in the sample decreased with time to a constant value which depended on the magnitude of the load.

Bridgman (1949) attributed anomalies in the volume change during loading for loads approaching the ultimate strength of the material to the forming of internal cracks or interstices at grain boundaries, mechanical impurities, or around dislocations in the lattice.

Jones (1952) observed that the velocity of an ultrasonic pulse transmitted through a concrete specimen in a direction perpendicular to the applied compressive load began to decrease when the load was about 25 to 30% of the ultimate strength. He attributes this decrease to the formation of internal cracks. Because the velocity of a pulse propagated in the direction of the stress did not change, he concluded that the plane of the cracks must be parallel to the direction of the stress.

Rüsch (1959) using a crystal pickup, recorded the internal cracking in concrete subject to compressive loads. For loads within 85% of the 1-minute ultimate strength, he observed a high rate of cracking when the load was first applied. This rate dropped off but increased again rapidly just before failure occurred.

The purpose of the observations reported in this paper was to investigate at one temperature and under constant compressive load, the cracking activity that occurs in ice during creep. In particular, it was desired to investigate the sudden transition that Brown reported in the character of the creep–time curve and to see if this transition was in some way related to the internal cracking.

EXPERIMENTAL PROCEDURE

The observations were carried out on rectangular ice specimens 5×10 cm and 20 cm long prepared at −10° C with a standard metal cutting lathe and a wood planer. A small, manually driven testing machine (Hounsfield

PLATE I

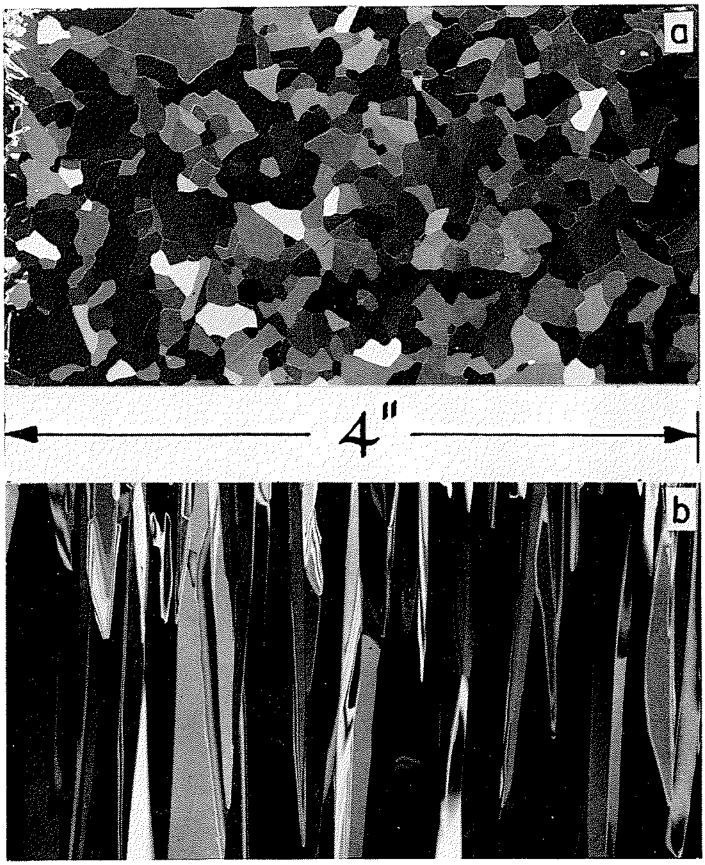


FIG. 2. Thin sections of test specimen viewed with polarized light: (*a*) section perpendicular to direction of growth, (*b*) section parallel to direction of growth.

tensometer) with a capacity of 2000 kg was used for applying the load. The test pieces were mounted between special loading heads one of which is shown in Fig. 1. The silicone grease, separated from the ice by the silicone rubber diaphragm, ensured that the applied compressive stress was uniform over the test piece.

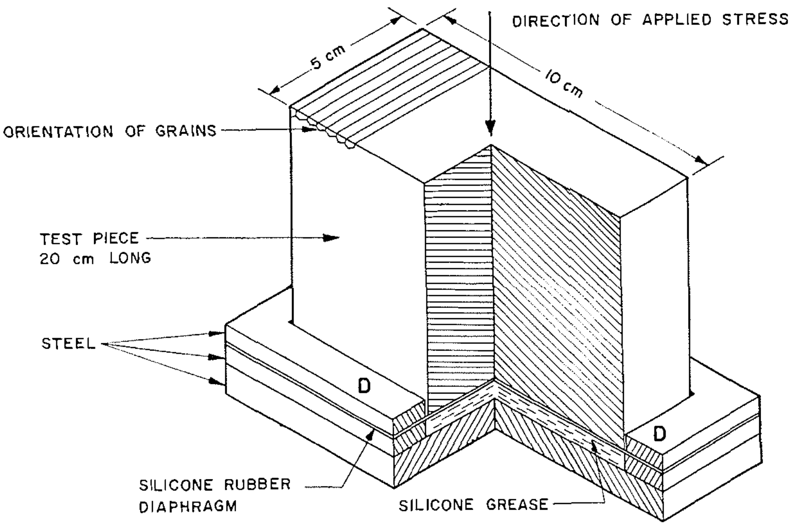


FIG. 1. Sketch of loading head construction.

To keep the silicone rubber from shearing during an experiment, water was frozen in the small space between the test piece and D of the loading heads. The frozen bond between the ice and D failed as soon as a load was applied but the ice was constrained from deforming laterally. This constraint influenced the distribution of cracks in the vicinity of the loading head as will be shown later.

An extensometer with a 2-in. gauge length and a strain magnification of 3300 was used for measuring the creep. The gauge had to be remounted periodically because of its limited range. The creep was recorded on a Baldwin X-Y recorder, model MD-2. The pen of the recorder automatically and continuously traversed the chart paper at a constant rate of $2\frac{1}{4}$ inches per minute. The creep–time curve was constructed by aligning the measured sections on the known time base.

The ice used in the observations was prepared from ordinary tap water in a cylindrical container about 1 meter in diameter. The direction of freezing was perpendicular to the water surface. When the water surface cooled to 0° C, ice grains were sprinkled on the surface to act as centers of nucleation. The resulting grain structure as seen with polarized light is shown in Fig. 2. Figure 2*a* is a thin section cut parallel to the ice surface and Fig. 2*b* is a section cut perpendicular to the surface. The columnar structure is typical for multigrained ice often encountered under natural conditions.

The test specimens were cut so that the long axis of each grain was perpendicular to the 10×20 cm face and therefore perpendicular to the applied compressive stress as shown in Fig. 1. The stress applied to the test specimen was kept constant to ±1% of the applied load during the test.

To measure the cracking activity in the ice during creep, a piezoelectric crystal was frozen to one face of the test piece. The output from the crystal was fed into a high-gain amplifier and then recorded. Each time a disturbance occurred within the ice that would set up a shock wave, the event caused a deflection of the recorder pen.

The observations were carried out in a cold room maintained at $-10\pm0.5°$ C. The test pieces were stored in the room in kerosene for at least 24 hours before they were loaded in the testing machine.

OBSERVATIONS

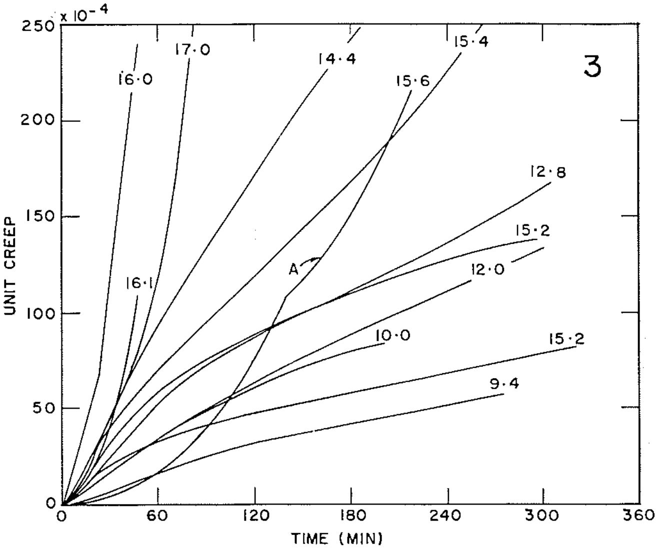
Cracking Activity

Figure 3 shows that the observed creep–time curves for all tests exhibit an initial increase in creep rate with time. Those subjected to a stress less than about 16 kg/cm^2 had a decreasing creep rate with time after about the first half hour. Two of these showed a tendency to a later period of increasing creep rate with time.

Figure 4 shows the observed dependence of the total cracking activity on time for three test pieces subject to the applied stress given in the figure. Also shown are the associated creep–time curves. At a stress of 10 kg/cm^2, very little internal cracking occurred; at a stress of 15.2 kg/cm^2 the cracking activity was appreciable. Most of the activity occurred in the first hour during the transient portion of the creep–time curve. After $1\frac{1}{2}$ hours, practically no further cracking occurred. When the stress was greater than about 16 kg/cm^2, and the creep rate showed no tendency to decrease with time, the cracking activity greatly increased.

Some of the details in the cracking–time curves are shown in Fig. 5 where the number of disturbances that occurred in a 5-minute interval are plotted against time. The resulting curve is an approximation to the rate of cracking activity. One further set of observations made at a stress of 15.4 kg/cm^2 is shown to illustrate the oscillatory character of the rate of cracking activity after the first maximum. The cracks seem to occur in bursts as though a critical situation developed within the test piece, which then was relieved by the formation of cracks. Figure 5 shows also that even when the applied stress was great enough that no decrease was observed in the rate of creep, a decrease was observed in the cracking rate but then the rate increased beyond the original maximum.

In Fig. 6, the logarithm of the total cracking activity that occurred during the first hour, which amounted to at least 60% of the total cracking activity observed, is plotted against the applied stress. The line drawn is the least squares fit to all the observations made. This figure shows the marked dependence that the cracking activity has on the applied stress.



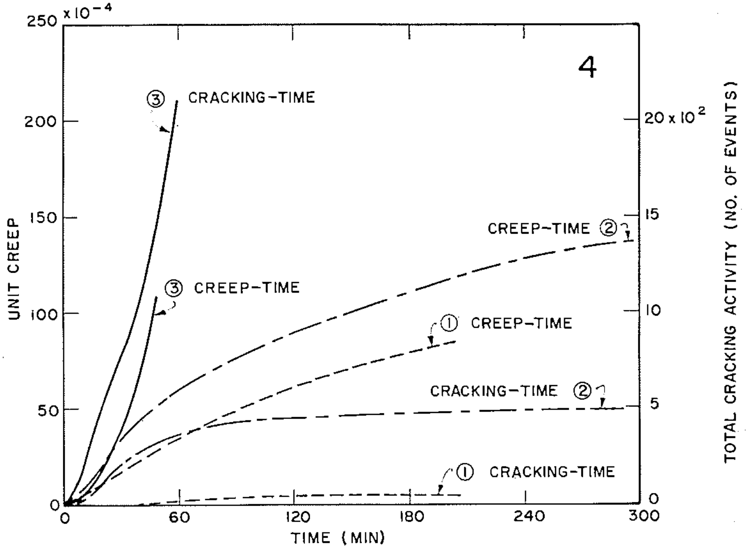


FIG. 3. Creep–time curves. The stress in kg/cm² is given for each curve.

FIG. 4. Three typical examples of the dependence of the total cracking activity and the creep on time at the applied stress given. (1) - - - stress = 10 kg/cm²; (2) — — — stress = 15.2 kg/cm²; (3) ——— stress = 16.1 kg/cm².

Crack Formation

The cracks were observed to propagate parallel to the long direction of the grain boundaries and perpendicular to the applied stress. This is shown in Fig. 7*b* where each light mark is a crack. The edge view shows that in some cases the cracks will propagate from face to face. For stresses below about 15 kg/cm², the crack distribution, which resulted during the period of loading,

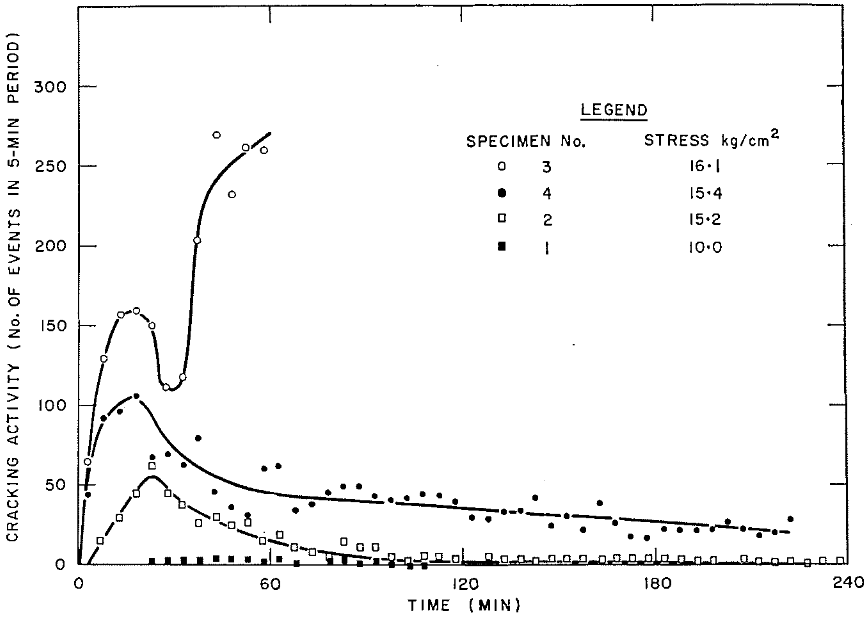


FIG. 5. Time dependence of the rate of cracking activity.

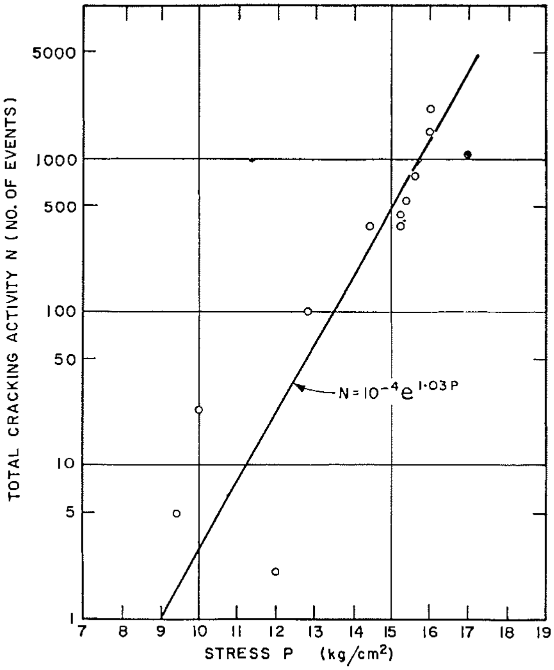


FIG. 6. Stress dependence of total cracking activity which occurred during the first 60 minutes.

PLATE II

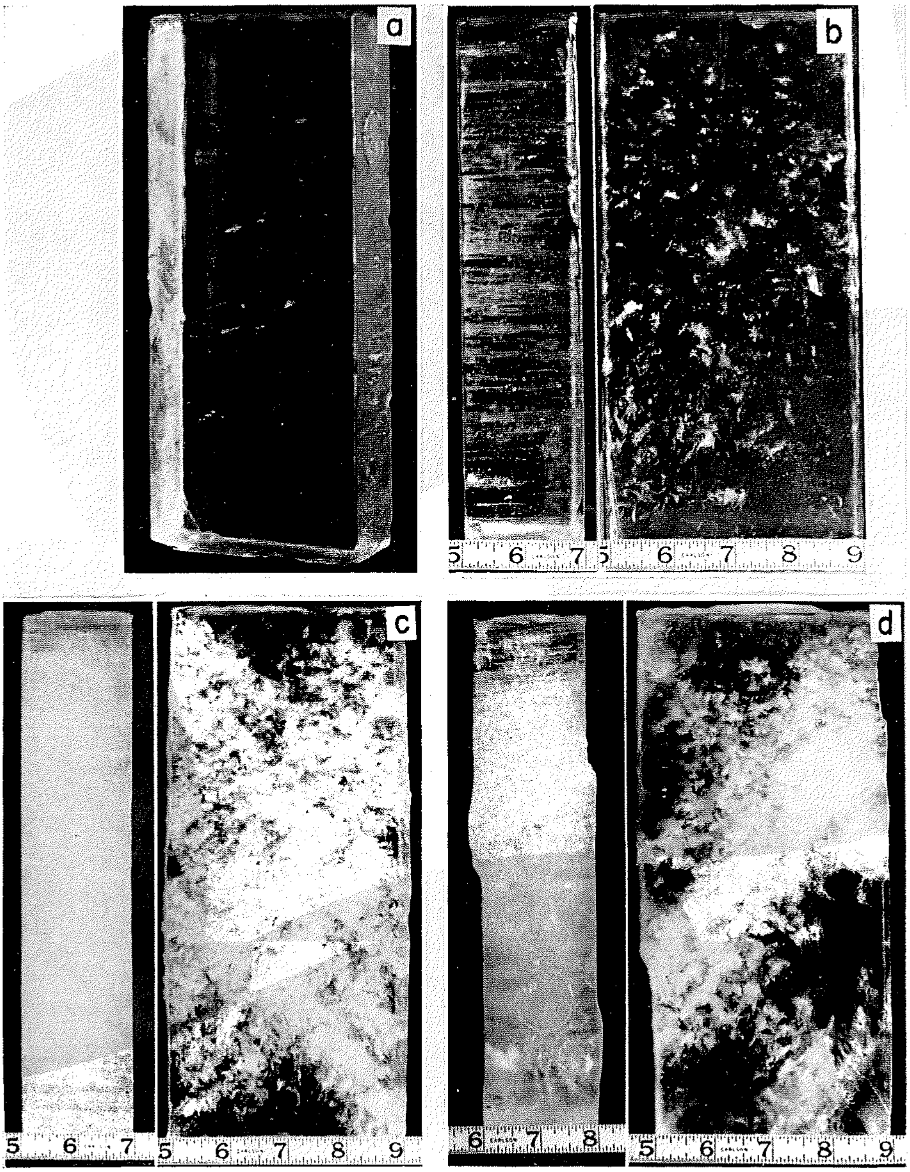


FIG. 7. Examples of crack development in ice during creep (scale in inches): (*a*) stress, 10 kg/cm^2; duration of load, 180 minutes; (*b*) stress, 15.2 kg/cm^2; duration of load, 300 minutes; (*c*) stress, 16 kg/cm^2; duration of load, 50 minutes; (*d*) stress, 15.6 kg/cm^2; duration of load, 225 minutes.

was fairly uniform as shown in Figs. 7*a* and 7*b*. For stresses greater than about 15.5 kg/cm^2, a marked change occurred in the character of the cracking and this change was associated with the increase in the cracking rate shown in Fig. 5 for specimen 3. In these cases, after an initial cracking period of 15 to 30 minutes, during which the cracks formed uniformly throughout the test piece, the cracks tended to form in planes that were about 45° to the applied stress and parallel to the grain boundaries as shown in Fig. 7*c*. In only one case out of the five in which these cracking planes developed was the plane not parallel to the grain boundaries. This is shown in Fig. 7*d*; its creep–time curve is designated by A in Fig. 3.

Most of the test pieces were quite free of cracks in a triangular zone adjacent to the loading heads as shown in Fig. 7*c*. This is thought to be due to the confining influence of the loading heads.

Two test pieces were subjected to stresses of the order of 14 kg/cm^2 and allowed to deform until a number of cracks had developed. The angle between the plane of each crack and the direction of the stress was measured. The resulting distribution diagram for 56 cracks observed, which is shown in Fig. 8, shows that there is a definite preference for a crack to form with its plane parallel to the direction of the applied stress. No cracks were observed with their plane at an angle greater than 45° to the stress. As already mentioned, the long direction of the cracks is parallel to the grain boundaries.

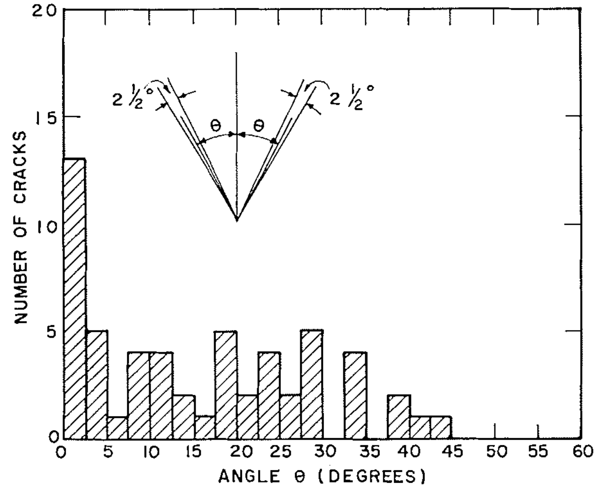


FIG. 8. Number of cracks in 2½-degree interval with plane of crack at angle θ to stress.

Out of 74 cracks studied, 22 occurred at grain boundaries. An additional eight occurred at grain boundaries but were also partly transcrystalline. The remainder were completely transcrystalline.

The water molecules in ice are loose-packed and the single crystal has an hexagonal symmetry. An attempt was made to see if there was any correlation between the direction of the axis of hexagonal symmetry and the direction of the plane of those cracks that were transcrystalline. An etching technique described by Higuchi (1958) was used to determine the crystallographic orientation. No positive correlation was found because it proved to be almost impossible to form an etch pit in grains containing a crack using Higuchi's technique.

It was realized during the etch-pit observations and later confirmed by observations using polarized light that there was a bias in the crystallographic orientation of the grains. It had been hoped that seeding with snow would result in a random orientation. Hillig (1958) has shown that ice crystals grow more quickly perpendicular to the axis of the hexagonal symmetry than parallel to it. As a result, crystals with their symmetry axis perpendicular to the direction of growth tend to squeeze out those that are parallel. In the present experiments, no crystals were observed that had their axis of hexagonal symmetry within 45° of the direction of growth. Thus, the easy slip plane of the grains tended to be parallel to the grain boundaries. Because the symmetry axis tended to be normal to the grain boundaries and therefore parallel to the ice surface, it was impossible with the apparatus available to determine its direction accurately with polarized light. It was observed that at least 12 of the 44 transcrystalline cracks were either parallel or perpendicular to the symmetry axis and therefore parallel or perpendicular to the easy slip plane.

Deformation of the Test Pieces

Measurements were made on one specimen that had been subject to a stress of 17 kg/cm^2 to determine the change of volume that occurred over the section where the creep was measured. An increase in volume of approximately 3% was observed. This increase is probably due to the formation of the cracks. When the sample was immersed in kerosene for storage after the observations, air bubbles were observed to issue from some of the cracks.

All of the lateral deformation of the specimen was observed to be normal to the grain boundaries. No significant creep in the direction parallel to the long axis of the grains was observed in any of the tests. The ice deformed in a way similar to a pile of logs subject to a load perpendicular to the long dimension of the logs. At the completion of a test, the edges of most of the test pieces were very irregular and it was possible to recognize individual grains because of their displacement relative to their neighbors.

DISCUSSION

In an earlier paper, Gold (1958) presented evidence which indicated that when ice, at a temperature between 0° C and −40° C, is subject to a uniaxial compression normal to the grain boundaries, there is a relaxation of the shear stress at the grain boundaries. Consider the array of hexagonal grains shown in Fig. 9. If the shear stress relaxes at the grain boundaries, a tensile stress will be developed across the planes nearly parallel to the applied stress, such as A–A, whose average value is given approximately by

$$p = c(1-a\cos^2 b) \tag{2}$$

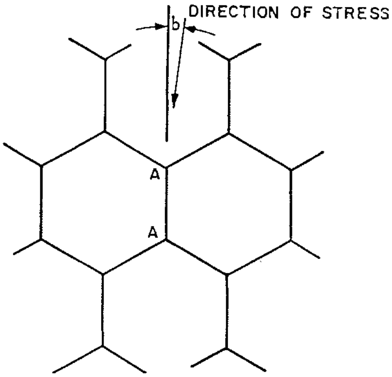


FIG. 9. Array of hexagonal grains.

where p is the average tensile stress,

c is the compressive stress,

$0 < a < 1$ is the proportion of shear stress still effective at the grain boundary,

b is the angle between the applied stress and the plane under consideration. For $b = 0°$,

$$p = c(1-a).$$

This demonstrates that under conditions of uniaxial compression, if the shear stress can relax at the grain boundaries, each grain will be subject to both compressive and tensile stresses. The magnitude of these stresses at each point will depend on the value of the applied stress, the local geometry of the grain boundaries, and their orientation with respect to the applied stress. In the present case, the stress field is biaxial because of the columnar nature of the grains. Under these conditions, one would expect cracks to form parallel to the grain boundaries with their plane tending to be parallel to the direction of the applied stress, that is, to form in planes across which tensile stresses can develop. Furthermore, it would be expected that the number of such sites available for crack formation would be limited and would depend on the magnitude of the stress as was observed (Fig. 4).

Figures 4 and 5 show that the initiation and extension of a crack in ice is time dependent. If one considers the conditions necessary for the development of a crack according to the theory put forward by Griffith (1924), this would imply that (*a*) the stress across the rupture plane increases with time, (*b*) imperfections in the single crystal or at the grain boundaries coalesce until in time a nucleus of the right size has formed from which a crack can develop (Cottrell 1959), or (*c*) both processes occur together.

Cottrell states that for holes at incoherent grain boundaries to grow, the following relation must be satisfied:

$$p = 2d/r, \tag{3}$$

where p is the tensile stress normal to the boundary,
d is the surface energy of ice per unit area,
r is the radius of the hole.

Figure 7 shows that for the duration of load associated with the observations, the compressive stress has to be greater than about 9 kg/cm^2 for a crack to develop. Assuming that the shear stress has completely relaxed at the grain boundary, this would give for p a value of about 9 kg/cm^2. The value of 120 ergs/cm^2 for d (Skapski *et al.* 1957) gives, for the critical radius, $r = 2.7\times10^{-5}$ cm. This value for r is a little smaller than that used by Cottrell in calculations of the critical tension p for metals.

Figure 4 shows that the transient portion of the creep–time curve occurs during the period when the cracking is maximum. Glen (1955) has attributed this transient stage, and the condition of an increasing creep rate with time, to recrystallization. In the present experiments it is apparent that the formation of cracks and the resulting disruption of the lateral constraint on the grains must make a significant contribution to the observed creep rate. The increasing creep rate with time at the start of the test would support the thesis that the tensile stress concentration across planes, such as A–A in Fig. 9, tends to increase with time. The formation of a crack would relieve the tensile stresses locally and thus change the stress distribution. This change in stress distribution would tend to decrease the creep rate of the grains involved. It would appear that under the conditions of the present experiments, during the first few minutes at least, Andrade's law for creep is not obeyed.

Steinemann (1954) gives evidence of the recrystallization of ice during the creep process. The ice used in his experiments had a granular rather than a columnar structure. It is possible that for compressive stresses less than about 9 kg/cm^2 at a temperature of $-10°$ C, creep and recrystallization of the grains ensures that concentrations of stress and imperfections will not develop to the magnitude necessary for the initiation of a crack.

Although the evidence indicates that it is the grain boundaries that control the formation of the cracks and the direction of the creep of multigrained ice, the possible influence of the easy slip direction, which tends to be parallel to the direction of the grain boundaries because of the bias in the crystallographic orientation, cannot be ruled out. This bias may certainly have been a contributing factor to the lack of creep in the direction of the long axis of the grains. It would also contribute to the ability of each grain to deform under the constraints imposed by its neighbors.

Each time a crack forms, the internal structure of the ice is altered. In the present situation it would appear that when enough cracks form, the ability of the ice to withstand shear stresses is lowered to the extent that large movements accompanied by extensive crack formation occur along preferred planes in which the shear stress is a maximum. When this condition is reached the ice can be considered to have failed. The cracking associated with the planes of shear failure is responsible for the high cracking rate observed after the first ½ hour for those test pieces that showed a continually increasing creep rate with time. It is probable that, if the tests at lower stress had been continued long enough, failure along the planes of maximum shear would have developed in these cases also, resulting in a sudden increase in the cracking rate and a corresponding increase in the creep rate similar to that observed in concrete by Rüsch (1959).

Because of the movement that occurs at the planes of cracking in Fig. 7*c* and 7*d*, the creep measured by an extensometer similar to that used would depend on the location at which it is mounted. An obvious example of this is curve A in Fig. 3. It was also observed that if the cracking tended to occur on one side of the test piece, the creep would be greater on that side, that is, the test piece would develop a bow. These factors are responsible in part for the irregular dependence of the creep on the applied stress as seen in Fig. 3. Even so, the observed dependence of the creep rate on the stress does agree well with the dependence found by Steinemann (1954) for granular ice.

CONCLUSIONS

The purpose of these observations was to investigate, at one temperature and under constant compressive load, the cracking that occurs in ice during creep. In particular, it was desired to investigate the sudden transition in the creep–time curve that had been reported earlier and to see if this transition was in some way related to the internal cracking. From the present observations the following conclusions are drawn:

(1) During creep under uniaxial compressive stress greater than about 9 kg/cm^2 applied perpendicular to the grain boundaries of ice at $-10°$ C, internal cracks form in the ice. The rate of formation of these cracks depends on the time and on the magnitude of the stress. For stresses below about 16 kg/cm^2, this rate goes through a maximum within the first hour after the application of the load and then decreases. The cracks tend to be long and narrow with their plane parallel to the direction of the grain boundaries and to the applied stress.

(2) The formation of these cracks is due to a tensile stress which is developed perpendicular to the applied stress because of the relaxation of shear stresses at the grain boundaries.

(3) The transient portion of the creep–time curve is due, in part, to the formation of internal cracks.

(4) The formation of internal cracks weakens the structure until a condition is attained where the specimen will fail along the planes of maximum shear.

(5) Because of the logarithmic dependence of the rate of cracking on the stress, this condition is attained very rapidly at stresses of about 16 kg/cm^2 and is responsible for the sudden change in the character of the creep–time curve that is observed in this stress range.

(6) Once failure begins along the planes of maximum shear the cracking activity greatly increases, the cracks forming primarily in the failure plane.

ACKNOWLEDGMENTS

The author acknowledges with gratitude the assistance of R. Wallace in obtaining the observations that form the basis of this paper. This paper is a contribution from the National Research Council of Canada, Division of Building Research, and is published with the approval of the Director.

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