

EFFECT OF TEMPERATURE ON THE CREEP OF ICE

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ABSTRACT. Creep tests on homogeneous, isotropic polycrystalline ice gave an apparent activation energy for creep of 16.4 kcal/mol (68.8 kJ/mol) over the temperature range -10° to -60°C . Above -10°C the Arrhenius relation for temperature dependence is invalid, and creep rate becomes progressively more temperature dependent as the melting point is approached. Between -20° and -50°C the apparent activation energy for creep of a single crystal of ice was found to be 16.5 kcal/mol (69.1 kJ/mol). A complete creep curve for a single crystal loaded in uniaxial compression parallel to the basal plane was qualitatively similar to the classical creep curve; creep rate at all stages was very much faster than for polycrystalline ice under the same conditions. Creep tests on polycrystalline ice at 0°C gave a stress/strain-rate relation for that temperature, but its precise meaning is unclear, since recrystallization complicated the results.

RÉSUMÉ. *Effet de la température sur le fluage de la glace.* Des expériences de fluage d'échantillons de glace polycristalline et isotrope donnent une énergie apparente d'activation pour le fluage de 16.4 kcal/mol (68.8 kJ/mol) pour tout l'intervalle de température de -10° à -60°C . Au-dessus de -10°C , la relation Arrhenius en fonction de la température n'est plus valable et la vitesse de fluage devient progressivement plus dépendante de la température que l'on s'approche du point de fusion. Entre -20° et -50°C , l'énergie apparente d'activation de fluage pour un monocristal de glace était de 16,5 kcal/mol (69,1 kJ/mol). Une courbe de fluage complète pour un monocristal sous contrainte compressive uniaxiale parallèle au plan de base était qualitativement similaire à la courbe de fluage classique; la vitesse de fluage pour tous les stades était plus grande que pour de la glace polycristalline dans les mêmes conditions. Des expériences de fluage de la glace polycristalline à 0°C donnèrent une relation entre contrainte et vitesse de déformation pour cette température, mais sa signification précise n'est pas claire, comme un phénomène de recristallisation complique les résultats.

ZUSAMMENFASSUNG. *Einfluss der Temperatur auf das Kriechen des Eises.* Kriechuntersuchungen mit homogenem, isotropem, polykristallinem Eis ergaben im Temperaturbereich von -10° bis -60°C eine scheinbare Aktivationsenergie von 16,4 kcal/mol (68,8 kJ/mol). Über -10°C ist die Arrhenius-Beziehung der Temperaturabhängigkeit ungültig; die Kriechgeschwindigkeit wird, je näher man dem Schmelzpunkt kommt, immer stärker temperaturabhängig. Zwischen -20° und -50°C wurde die scheinbare Aktivationsenergie für einen einzelnen Eiskristall mit 16,5 kcal/mol (69,1 kJ/mol) bestimmt. Eine vollständige Kriechkurve für einen Einkristall, der durch einachsigen Druck parallel zur Basisebene beansprucht wurde, war der klassischen Kriechkurve qualitativ ähnlich; die Kriechgeschwindigkeit war in jedem Stadium erheblich schneller als die des polykristallinen Eises unter denselben Bedingungen. Kriechversuche mit polykristallinem Eis bei 0°C ergaben eine Druckspannungs-Relation für diese Temperatur, deren wirkliche Bedeutung jedoch unklar ist, weil Rekristallisation die Ergebnisse kompliziert.

INTRODUCTION

Creep tests were made on polycrystalline ice in order to establish a firm relationship between secondary creep rate and temperature. Particular attention was paid to creep at temperatures between -10°C and 0°C , and many tests were made at 0°C for a broad range of stresses. A rather high stress level, 12 kgf/cm² (1.18 MN/m²), was used in the main group of tests, partly out of practical necessity but partly to provide data which could be related to creep rupture studies on the same type of ice. Tests were also made on ice monocrystals to find a temperature relationship applicable to the straining of monocrystals, to compare creep rates for single crystals and polycrystalline ice, and to observe in some detail the shape of the creep curve for a single crystal.

TEST PROCEDURES

Preparation of ice samples

The polycrystalline ice was prepared by packing sieved ice grains into cylindrical moulds, saturating with distilled degassed water, and freezing. The method was evolved originally (Mellor and Smith, 1967) to simulate polar glacier ice formed by dry compression of snow, but a more refined technique is now used to produce fine-grained, homogeneous, isotropic ice of consistent quality without particular regard to simulation of any special type of natural ice.

The ice used in these tests had a grain size of approximately 1 mm, and the crystals were randomly oriented (Fig. 7). Small bubbles, about 0.5 mm in diameter, were dispersed uniformly through the material, and bulk density of the various samples ranged from 0.86 to 0.90 Mg/m³. For tests below 0°C samples were 5.77 cm in diameter and 16 cm long. For tests at 0°C the samples were 8.8 cm diameter and approximately 25 cm long. The ice was prepared from distilled water of conductivity $10^{-6} \Omega^{-1} \text{cm}^{-1}$, measured at 25°C and 60 Hz. Contamination occurred during handling and moulding, and the melt water from samples had conductivity of approximately $5 \times 10^{-5} \Omega^{-1} \text{cm}^{-1}$ at 25°C and 60 Hz.

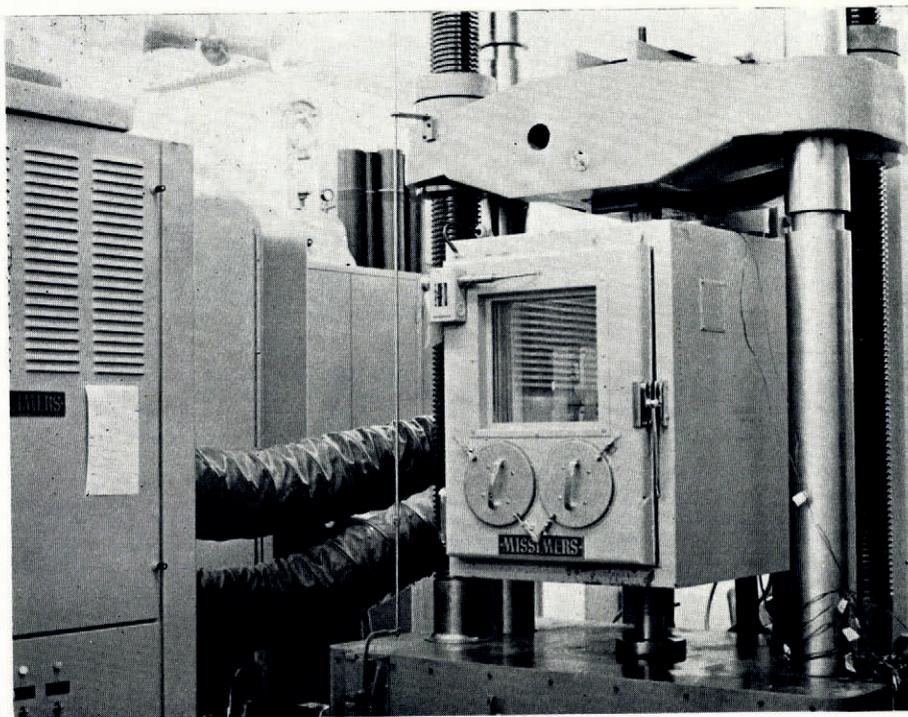


Fig. 1. Environmental chamber installed between cross-head and table of universal testing machine.

The single crystals were grown by R. O. Ramseier using the zone-melting method.* The monocrystals used for creep testing were cylindrical, 5.73 and 8.9 cm in diameter and approximately 11 and 23 cm long. Prior to loading, the *c*-axes of the crystals were approximately normal to the axis of symmetry of the cylindrical sample. The monocrystals were prepared from distilled, deionized water of conductivity between 5×10^{-7} and $10^{-6} \Omega^{-1} \text{cm}^{-1}$, measured at 25°C and 60 Hz.

For tests below 0°C the sample ends were faced-off in a lathe, and the platens of the testing machine were applied directly to the ice. The 0°C samples, which were too big for the lathe, were trimmed in a jig on a bandsaw. Plates of bonded bakelite were placed between the ice and the platens of the testing machine to minimize any possible heat flow.

* The tests on monocrystals were made in collaboration with R. O. Ramseier, who wished to compare creep activation energy with activation energy for self-diffusion in monocrystals (Ramseier, 1967).

Loading and temperature control

In all of the creep tests, cylindrical samples were loaded axially in compression without lateral restraint. The first pilot tests were run on a Tinius–Ohlsen universal testing machine, utilizing the load-hold feature of the machine to make constant load tests. The machine operated satisfactorily, but the cold room in which it was housed was subject to unacceptably wide temperature fluctuations, and the lowest temperature to which the room could be cooled was not low enough to satisfy the requirements of the test program. The work was then moved to a Riehle universal testing machine which could be operated in conjunction with a special environmental chamber (Fig. 1). The main machine stood in a warm laboratory, but the test sample and the loading platens were surrounded by the cold chamber, which could be cooled to -73°C by its own refrigerating unit.

In the early stages, considerable difficulty was experienced with the Riehle machine, since it was being used to apply small loads very close to the lower limit of its design range. Eventually the machine was induced to hold small loads constant, and no further trouble occurred. Many tests were run before a fully satisfactory mode of operation became established, but the results of these abortive tests proved useful in planning the final tests, since they established the magnitude of strain and time for onset of secondary and tertiary creep.

For tests at 0°C , the temperature of the environmental chamber was set to 0°C and the sample was completely surrounded by a large mass of wet crushed ice. A sample enclosure was formed with compartmented cans filled with wet crushed ice, and wet crushed ice was packed around the loading platens (Fig. 2). Wet ice was also placed in the throat through which refrigerated air entered the chamber. The sample itself was made as large as possible so as to minimize the effect of possible surface melting, and it was introduced into the test chamber while at a temperature of approximately -10°C . Temperature of the air space immediately adjacent to the sample was monitored by two copper-constantan thermocouples, but no measureable deviation ($< \pm 0.1^{\circ}\text{C}$) from 0°C was detected.

Testing methods

To establish the effect of temperature on creep rate the influence of other variables has to be kept to a minimum, and an attempt was made to compare creep rates for the same ice at the same amount of total strain. Thus a sample was subjected to creep under constant load (approximating constant stress) at a high temperature, secondary creep was established, and then the temperature was progressively lowered in a series of steps without relaxation of the applied load. After thermal equilibrium had been established at each new temperature, the sample was allowed to strain until a strain-rate for that temperature had been determined by a sequence of readings on a dial micrometer which gave displacements to 10^{-4} inches (2.54×10^{-3} mm) directly, with estimates between graduations to 10^{-5} inches (2.54×10^{-4} mm).

This system worked well for the polycrystalline ice at temperatures from -5°C downward when the applied stress was 12 kgf/cm^2 (1.18 MN/m^2). If an attempt was made to start at a higher temperature, too much straining occurred in the initial stages, especially in the intervals during which sample temperature was adjusting to change. For temperatures above -5°C , separate samples were tested.

With monocrystals the problem was more difficult, as accelerating creep developed almost immediately after load was applied, and creep was much faster than that in the polycrystalline ice under corresponding conditions. The method of step temperature changes was judged to be reasonably satisfactory for temperatures below -10°C when the stress was 6 kgf/cm^2 (0.59 MN/m^2); in the second such test, the load was removed in the intervals during which the sample was adjusting to a new temperature.

For tests at 0°C the sample was taken from storage in a -10°C room and placed between the loading platens. The wet ice jacketing was closed, and the sample was allowed to warm up to 0°C . Load was applied, and after a secondary creep rate was established the load was

changed to give a different stress in the same sample. Most samples were strained at three different stresses; in some cases the test started at a high stress and stress was successively reduced in two steps, while other tests started at low stress and stress was then increased in two steps. The Riehle press was used to apply stresses from 0.5 to 12 kgf/cm² (49 to 1180 kN/m²), and direct dead load was used to apply stresses from 0.22 to 0.36 kgf/cm² (22 to 35 kN/m²).

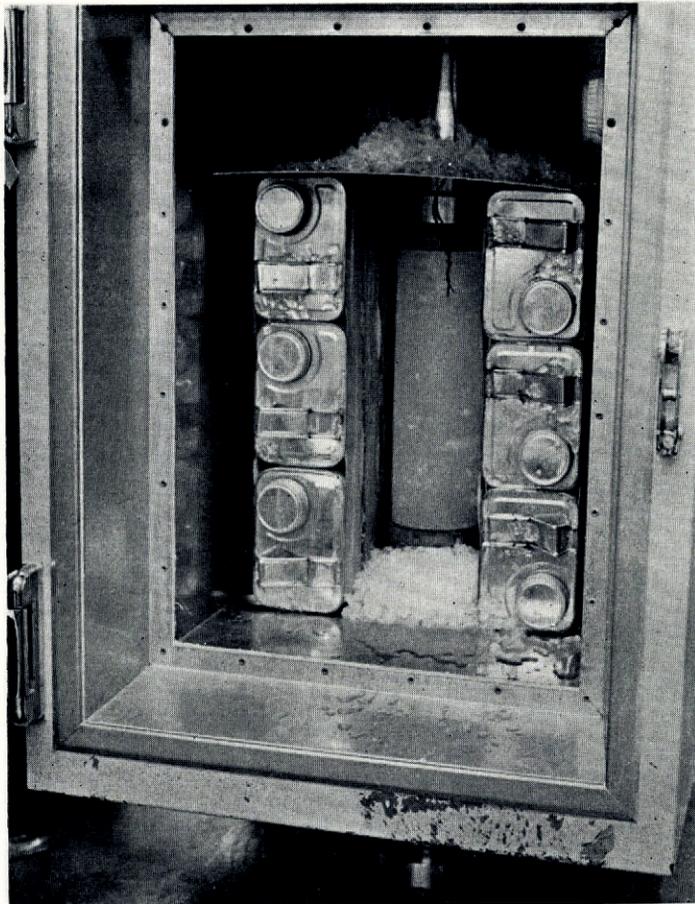


Fig. 2. Ice sample positioned for testing at 0°C. Cans of wet crushed ice form complete barrier around sample. Loading platens are packed with wet crushed ice.

TEST RESULTS

The results of the tests on polycrystalline ice with an axial compressive load of 12 kgf/cm² (1.18 MN/m²) are given in Table I. The strain-rates given were measured at total axial strains from 2×10^{-2} to 4×10^{-2} .

In Figure 3 the data from Table I are used to plot the logarithm of strain-rate against the reciprocal of absolute temperature.

Four monocrystals were tested: the first failed very rapidly under an axial stress of 12 kgf/cm² (1.18 MN/m²), the second was used to obtain a complete creep curve at a single stress and temperature, while the third and fourth were tested over a range of temperatures.

TABLE I. SECONDARY CREEP RATE OF POLYCRYSTALLINE ICE AT VARIOUS TEMPERATURES
Axial stress = 12 kgf/cm² (1.18 MN/m²)

| Sample | Diameter cm | Length cm | Bulk density Mg/m ³ | Temperature °C | 1/T (°K) ⁻¹ | Axial strain-rate s ⁻¹ |
|-----------------------------------|----------------|--------------|-----------------------------------|-------------------|---------------------------|--------------------------------------|
| P1 | 5.77 | 15.9 | 0.90 | -5.5 | 3.74 × 10 ⁻³ | 5.91 × 10 ⁻⁷ |
| P1 | 5.77 | 15.9 | 0.90 | -9.9 | 3.80 × 10 ⁻³ | 2.87 × 10 ⁻⁷ |
| P1 | 5.77 | 15.9 | 0.90 | -22.1 | 3.98 × 10 ⁻³ | 5.84 × 10 ⁻⁸ |
| P1 | 5.77 | 15.9 | 0.90 | -30.4 | 4.12 × 10 ⁻³ | 1.83 × 10 ⁻⁸ |
| P1 | 5.77 | 15.9 | 0.90 | -45.9 | 4.40 × 10 ⁻³ | 1.79 × 10 ⁻⁹ |
| P1 | 5.77 | 15.9 | 0.90 | -61.0 | 4.71 × 10 ⁻³ | 1.48 × 10 ⁻¹⁰ |
| P2 | 5.77 | 15.8 | 0.90 | -1.7 | 3.68 × 10 ⁻³ | 2.42 × 10 ⁻⁶ |
| P3 | 5.77 | 16.7 | 0.90 | -5.0 | 3.73 × 10 ⁻³ | 9.26 × 10 ⁻⁷ |
| Composite (see Figs. 6 and 10) | 8.8 | 25 | 0.86 to 0.90 | 0 | 3.66 × 10 ⁻³ | 4.06 × 10 ⁻⁶ |

The very rapid deformation of the first monocrystal (M1) when it was stressed to 12 kgf/cm² (1.18 MN/m²) at -10°C was unexpected, and in the resulting confusion no useful strain data were obtained. However, the appearance of the deformed crystal is interesting in itself (Fig. 4). Ramseier studied the sample in some detail, and observed that the *c*-axis had been rotated by approximately 20° during deformation of the crystal.

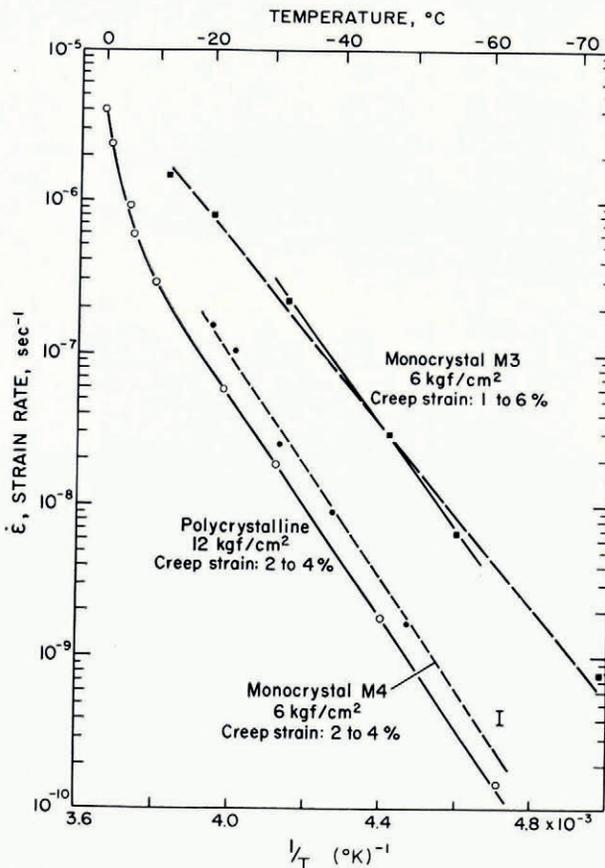


Fig. 3. Logarithm of strain-rate as a function of $1/T$ for polycrystalline ice and single crystals.

The second monocrystal (M₂) was subjected to an axial stress of 6 kgf/cm² (0.59 MN/m²) at -20.3°C, and was allowed to creep to an axial strain of 7 per cent. For comparison, a polycrystalline sample of similar size was tested in the same equipment at the same stress and temperature. The resulting creep curves are shown in Figure 5.

Samples M₃ and M₄ were stressed to 6 kgf/cm² (0.59 MN/m²), and temperature was changed in a series of steps. Sample M₃ was first loaded at a temperature of -3.7°C; the temperature was taken down to -72.5°C in steps, and load was maintained for the full duration of the test, even in the intervals when the sample was adjusting to a new temperature. The results of this test, given in Table II and Figure 3, are considered to be unsatisfactory in view of the large strains which occurred at the higher temperatures. Sample M₄ was first loaded at -20.3°C and the temperature was taken down to -61.5°C in steps; load was

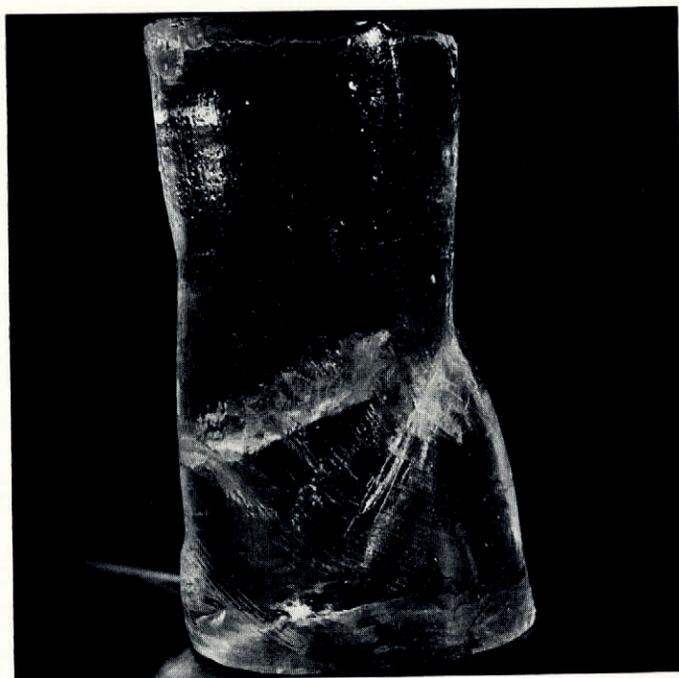


Fig. 4. Ice monocrystal after rapid creep failure.

relaxed and reapplied in the intervals during which the sample was adjusting to a new temperature. After straining at the lowest temperature, the sample was warmed again to -24.0°C to check the effect of strain increase. The results of this test, which are given in Table III and Figure 3, are considered more reliable than those yielded by Sample M₃.

The results of the creep tests on polycrystalline ice at 0°C are summarized in Table IV.

To check for grain growth during tests at 0°C, 5 special samples were prepared, tested, sectioned, and photographed by transmitted polarized light. The test conditions are given in Table V, and a sample of the resulting thin-section photographs is shown in Figure 6.

DISCUSSION

For temperatures below -10°C the variation of creep rate with temperature for the polycrystalline ice can be described nicely by the Arrhenius equation with an apparent activation energy of 16.4 kcal/mol (68.8 kJ/mol). The data for single crystals are less satis-

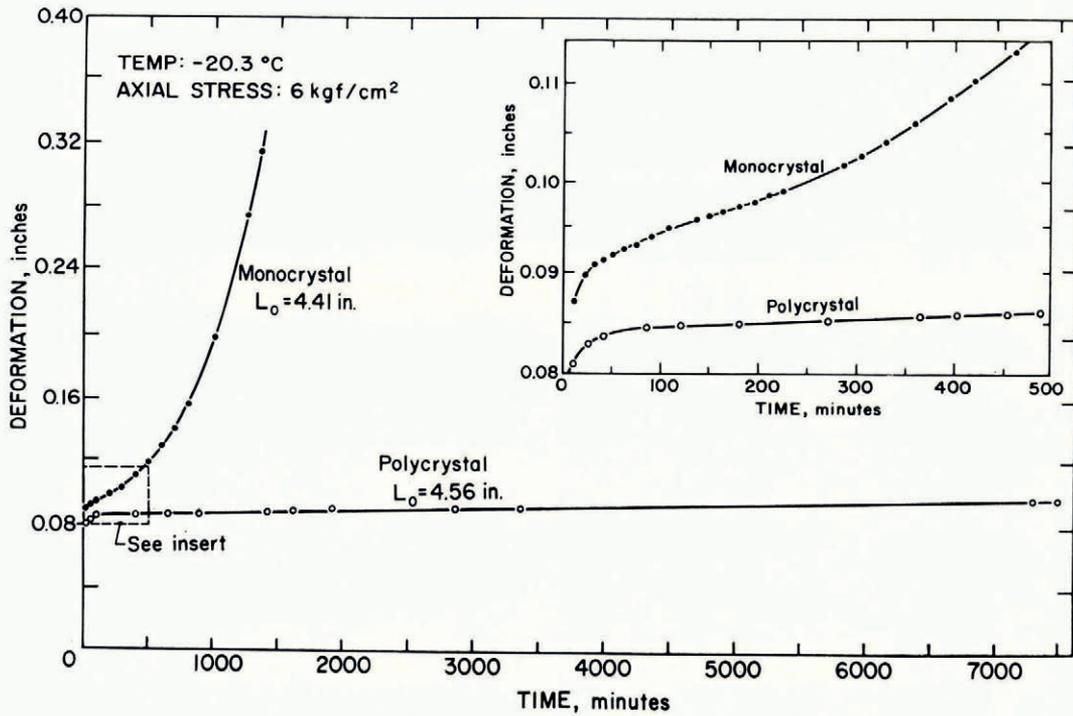


Fig. 5. Creep curves for polycrystalline ice and a single crystal.

TABLE II. CREEP OF MONOCRYSTAL M₃ AT VARIOUS TEMPERATURES

Sample size: 8.9 cm dia. 23.4 cm long
Crystal orientation: *c*-axis approximately normal to cylinder axis
Axial stress: 6 kgf/cm² (0.59 MN/m²)

| Temperature °C | $1/T$ °K ⁻¹ | Axial strain-rate s ⁻¹ |
|-------------------|---------------------------|--------------------------------------|
| -3.7 | 3.72×10^{-3} | 1.06×10^{-6} |
| -11.9 | 3.83×10^{-3} | 1.49×10^{-6} |
| -19.8 | 3.95×10^{-3} | 7.98×10^{-7} |
| -32.0 | 4.15×10^{-3} | 2.20×10^{-7} |
| -46.4 | 4.42×10^{-3} | 2.92×10^{-8} |
| -55.5 | 4.60×10^{-3} | 6.57×10^{-9} |
| -72.5 | 4.98×10^{-3} | 7.66×10^{-10} |

TABLE III. CREEP OF MONOCRYSTAL M₄ AT VARIOUS TEMPERATURES

Sample size: 5.73 cm dia. 11.3 cm long
Crystal orientation: *c*-axis approximately normal to cylinder axis
Axial stress: 6 kgf/cm² (0.59 MN/m²)

| Temperature °C | $1/T$ °K ⁻¹ | Axial strain-rate s ⁻¹ |
|-------------------|---------------------------|--|
| -20.3 | 3.95×10^{-3} | 1.53×10^{-7} |
| -31.3 | 4.13×10^{-3} | 2.48×10^{-8} |
| -39.1 | 4.27×10^{-3} | 9.05×10^{-9} |
| -49.6 | 4.47×10^{-3} | 1.64×10^{-9} |
| -61.5 | 4.72×10^{-3} | 3.7 to 4.6×10^{-10} (Poor data) |
| -24.0 | 4.01×10^{-3} | 1.06×10^{-7} |

TABLE IV. CREEP OF POLYCRYSTALLINE ICE AT 0°C

Sample size: 8.8 cm dia. 25 cm long

| Sample | Bulk density Mg/m ³ | Axial stress kgf/cm ² | Axial strain-rate s ⁻¹ |
|--------|-----------------------------------|-------------------------------------|--------------------------------------|
| PO1 | 0.88 | 8.0 | 1.52 × 10 ⁻⁶ |
| | | 4.0 | 5.37 × 10 ⁻⁷ |
| | | 0.5 | 3.24 × 10 ⁻⁷ |
| PO2 | 0.86 | 1.0 | 2.79 × 10 ⁻⁷ |
| | | 2.0 | 3.74 × 10 ⁻⁷ |
| | | 6.0 | 9.56 × 10 ⁻⁷ |
| | | 12.0 | 6.83 × 10 ⁻⁶ |
| | | 8.0 | 1.41 × 10 ⁻⁶ |
| PO3 | 0.86 | 10.0 | 2.63 × 10 ⁻⁶ |
| PO5 | 0.86 | 5.0 | 6.87 × 10 ⁻⁷ |
| | | 1.5 | 3.73 × 10 ⁻⁷ |
| | | 7.0 | 1.77 × 10 ⁻⁶ |
| PO10 | 0.86 | 3.0 | 6.75 × 10 ⁻⁷ |
| | | 1.25 | 4.24 × 10 ⁻⁷ |
| | | 11.0 | 3.97 × 10 ⁻⁶ |
| PO11 | 0.86 | 7.0 | 1.82 × 10 ⁻⁶ |
| | | 3.0 | 5.45 × 10 ⁻⁷ |
| | | 12.0 | 4.06 × 10 ⁻⁶ |
| PO12 | 0.86 | 2.5 | 5.33 × 10 ⁻⁷ |
| | | 0.75 | 2.28 × 10 ⁻⁷ |
| | | 8.0 | 1.23 × 10 ⁻⁶ |
| PO14 | 0.87 | 0.22 | 3.12 × 10 ⁻⁷ |
| | | 9.0 | 3.36 × 10 ⁻⁶ |
| | | 5.0 | 1.30 × 10 ⁻⁶ |
| PO15 | 0.86 | 0.5 | 6.09 × 10 ⁻⁷ |
| | | 9.0 | 2.10 × 10 ⁻⁶ |
| | | 4.0 | 6.28 × 10 ⁻⁷ |
| PO16 | 0.86 | 0.5 | 3.14 × 10 ⁻⁷ |
| | | 6.0 | 1.73 × 10 ⁻⁶ |
| | | 2.5 | 7.37 × 10 ⁻⁷ |
| PO17 | 0.86 | 0.75 | 3.58 × 10 ⁻⁷ |
| | | 0.36 | 2.51 × 10 ⁻⁷ |
| | | 4.0 | 6.12 × 10 ⁻⁷ |
| PO18 | 0.86 | 0.34 | 3.70 × 10 ⁻⁷ |
| | | 0.22 | 2.02 × 10 ⁻⁷ |
| | | 10.0 | 1.89 × 10 ⁻⁶ |
| PO19 | 0.86 | 0.22 | 6.30 × 10 ⁻⁸ |
| | | 0.89 | |
| | | 0.22 | |

factory, since temperature changes were imposed for a non-linear portion of the creep curve. The best results, for monocrystal M₄, give an apparent activation energy of 16.5 kcal/mol (69.1 kJ/mol) when the uncertain data obtained at -61.5°C are left out of account. The dubious results given by monocrystal M₃ give an overall activation energy of about 14 kcal/mol (58.3 kJ/mol), but if a value is taken only from the creep rates obtained between -32° and -55°C (where strain did not change much) the activation energy is 15.6 kcal/mol (65.1 kJ/mol).

TABLE V. TEST CONDITIONS FOR SAMPLES SHOWN IN FIGURE 6

Sample size: 8.8 cm dia. 25 cm long

Bulk density: 0.90 Mg/m³

Test temperature: 0°C

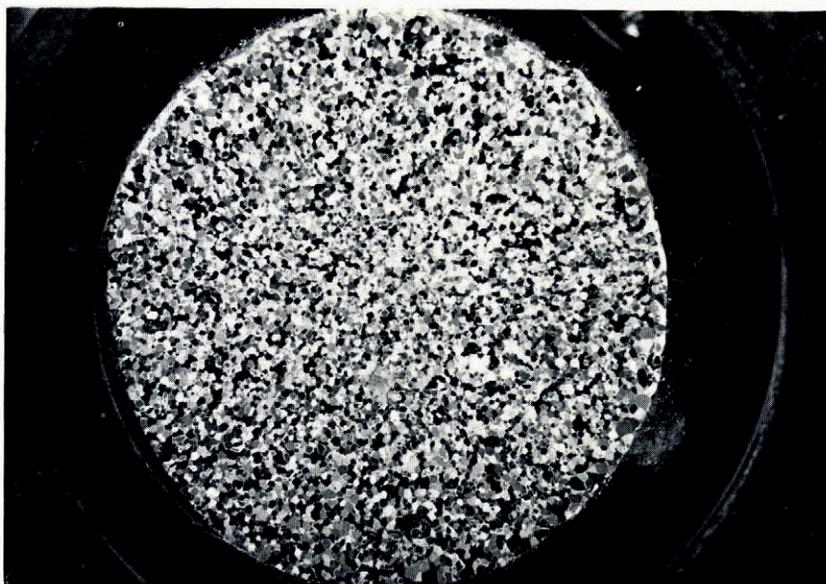
| Sample | Axial stress kgf/cm ² | Total strain | Test duration min | Minimum strain-rate s ⁻¹ |
|--------|-------------------------------------|--------------|----------------------|--|
| A | 8 | 0.0182 | 200 | 1.20 × 10 ⁻⁶ |
| B | 4 | 0.0118 | 225 | 1.81 × 10 ⁻⁷ |
| C | 0 | 0 | 0 | — |
| D | 4 | 0.0179 | 200 | 3.70 × 10 ⁻⁷ |
| E | 0.22 | 0.00136 | 335 | 5.01 × 10 ⁻⁸ |

The above values are slightly higher than the values of activation energy which have been found for self-diffusion in ice monocrystals (Table VI).

The values found here for creep activation energy of single crystals are in reasonable agreement with the value 15.9 kcal/mol (66.3 kJ/mol) determined by Higashi and others (1964), who used a constant strain-rate tensile technique between -15° and -40°C .



(a)



(b)

Fig. 6. Thin sections of ice strained at 0°C (see Table V for test conditions). (a) Sample B loaded for 225 min at 4 kgf/cm^2 . (b) Control Sample C (see Table V).

TABLE VI. ACTIVATION ENERGY FOR SELF-DIFFUSION IN ICE MONOCRYSTALS

| Investigator | Activation energy kcal/mol |
|------------------------------|-------------------------------|
| Dengel and Riehl (1963) | 13.5 |
| Dengel and others (1966) | 14.5 |
| Blicks and others (1966) | 14.4 |
| Ramseier (1967) | 14.1 to 14.4 |
| Itagaki (1964) | 15.7 |
| Itagaki (1966) | 12.6 to 15.4 |
| Delibaltas and others (1966) | 15.7 |

The relation between creep strain and time for the monocrystal is broadly similar to earlier results (Glen and Jones, 1967; Higashi, 1967). Up to a creep strain of 0.9 per cent, creep strain ϵ was proportional to t^m , where t is time and m is a constant equal to 1.7. Above 0.9 per cent creep strain, the value of m changed to 2.4.

Comparison between the present data for polycrystalline ice and most previous data has to be approached with caution in view of the apparent non-linearity of $\ln \dot{\epsilon}$ with $1/T$ for temperatures above -10°C (Figure 3). If this departure from linearity is real, it helps to explain certain discrepancies in earlier results, since most previous testing has been carried between 0°C and -25°C .

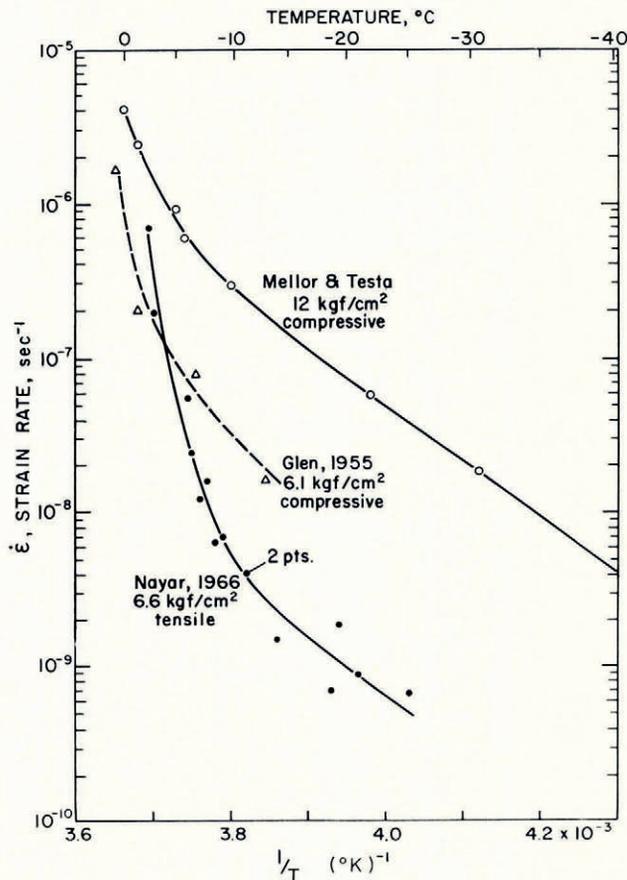


Fig. 7. Logarithm of strain-rate as a function of $1/T$ for polycrystalline ice at high temperatures.

In Figure 7 the present data for polycrystalline ice at the higher temperatures are compared with some other results which tend to confirm that creep of the material becomes more strongly temperature dependent as temperature rises above -10°C , at least for high stresses. The effect exists for both compressive and tensile loading.

Voytkovskiy (1957) made a large number of flexural creep tests on ice beams between -1° and -10°C , as well as some torsional creep tests on hollow cylinders over the same temperature range. The stress magnitude for the beam tests is hard to define, but under elastic stress distribution the extreme fibre stresses would have been $\pm 12 \text{ kgf/cm}^2$ ($\pm 1.8 \text{ MN/m}^2$). The torsion tests were made with a shear stress of 1 kgf/cm^2 (98 kN/m^2). When Voytkovskiy's deformation rates are plotted logarithmically against $1/T$ they show a slight but systematic curvature in the same sense as the present data; deformation rate increased by

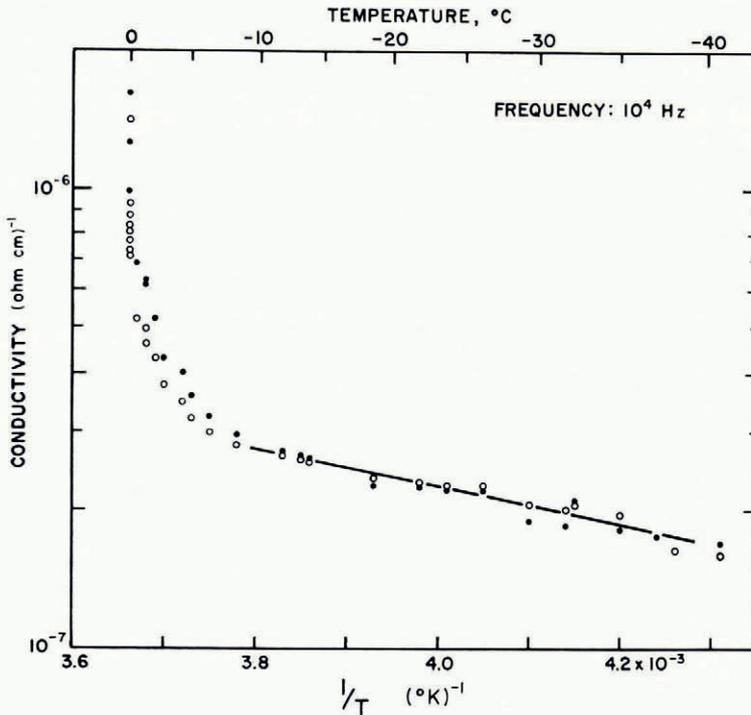


Fig. 8. Variation of electrical conductivity with $1/T$ for polycrystalline ice at high temperature.

factors of 3 to 4 (equivalent to apparent activation energies of 19 to 24 kcal/mol (80 to 100 kJ/mol)) as temperature rose from -10° to -2°C , compared with a factor of about 6.5 for the present results.

In a separate investigation (Mellor, unpublished), electrical conductivity was measured as a function of temperature for the same type of polycrystalline ice as was used for the creep studies. The results show that conductivity also rises quite sharply as temperature increases above -10°F (Fig. 8). It is suspected that grain-boundary melting may occur at temperatures above -10°C , and differential thermal analysis is planned for this type of ice.

The scatter in the data for creep at 0°C can probably be attributed in the main to grain-growth complications. At the higher stresses the creep rates for 0°C relate reasonably well to creep rates measured at lower temperatures, but at low stresses the 0°C creep rate is some two

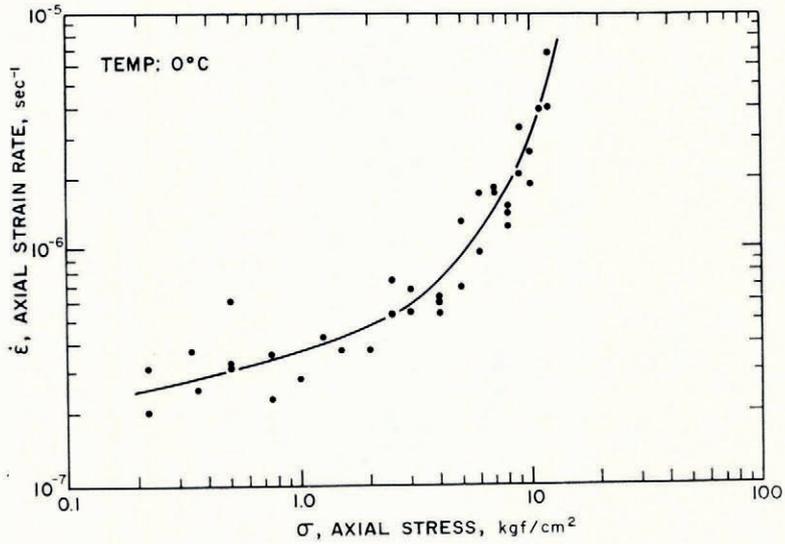


Fig. 9. Log-log plot of strain-rate versus stress for polycrystalline ice at 0°C. The line drawn tends to a slope of approximately 3 at high stress, but the slope at low stress is only about 1/4.

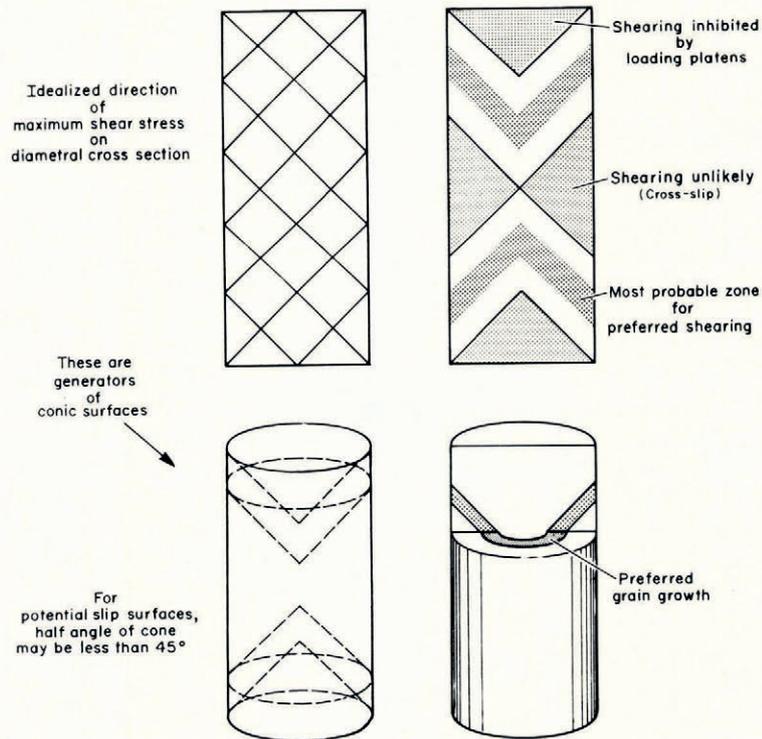


Fig. 10. Schematic distribution of shear stress and displacement in unconfined compressive test, which might give rise to preferred grain growth in selected conic zones.

orders of magnitude higher than corresponding creep rates measured a few degrees below the melting point. Another curious feature of the results (Fig. 9) is the relatively weak stress-dependence at the low end of the stress range.

Barnes and Tabor (1966) found an abrupt increase in the deformability of polycrystalline ice (measured by indentation methods) between -1.2° and 0°C , and noted that Glen's (1955) creep data show a corresponding feature. They presented a persuasive argument in favour of pressure melting as a creep augmentation process. In the present case, grain growth is undoubtedly a factor contributing to high strain-rates, but it does not seem necessary to invoke pressure-melting as a major determinant of grain growth. The few observations on ice fabrics after straining gave no obvious indication of a correlation between stress level and grain growth, and it is known that grain growth in ice is quite rapid at 0°C (Roos, 1966).

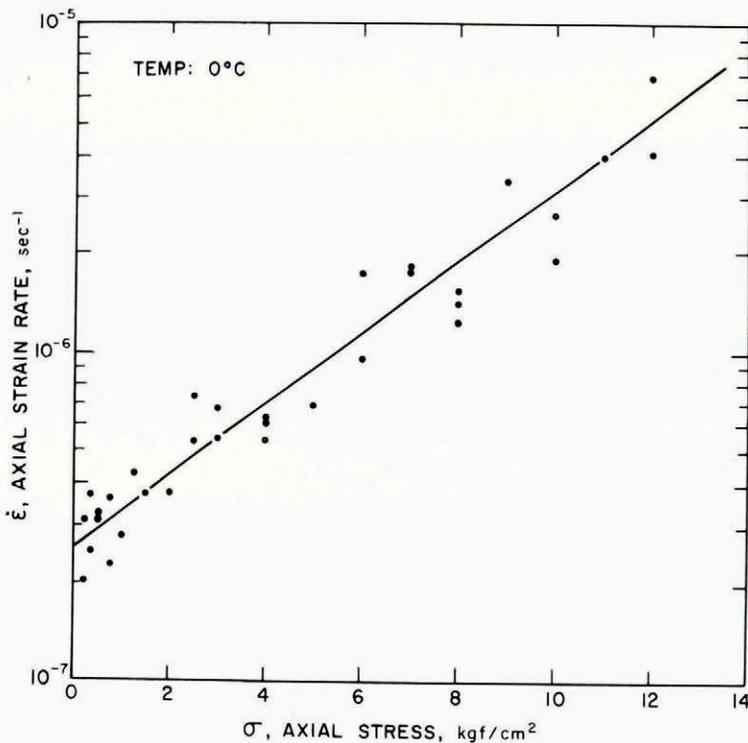


Fig. 11. Logarithm of strain-rate at 0°C plotted against stress.

It is unfortunate that the observations on grain growth were not more thorough. A more systematic program of sectioning could have given a three-dimensional picture of the grain-growth pattern, and the crystal orientations could have been measured. As it is, the only explanation of the curious ring structures (Fig. 6) which can be offered is that they represent preferred grain growth on conic surfaces of controlling shear stress (Fig. 10).

There is a further point which tends to support the idea of grain growth under a biasing stress as a dominant creep process at low stress and 0°C : extrapolation of the data to zero stress gives a positive strain-rate intercept, suggesting that strain-rate remains appreciable as stress tends to zero. To determine this apparent intercept a semi-logarithmic plot was used, and it is noted that such a plot linearizes the data (Fig. 11), suggesting an exponential relation between strain rate $\dot{\epsilon}$ and stress σ of the form $\dot{\epsilon} = \dot{\epsilon}_0 \exp(\sigma/\sigma_*)$, where $\dot{\epsilon}_0$ is strain rate at zero

stress and σ_* is a constant. Nayar (unpublished) found that such a plot linearized his data for creep of polycrystalline ice containing 1 per cent by volume of colloidal (150 Å) silica particles, with a temperature of -12°C .

CONCLUSION

Between -10° and -60°C the secondary creep rate of polycrystalline ice varies with temperature according to the Arrhenius equation. The present value of 16.4 kcal/mol (68.8 kJ/mol) for apparent activation energy is somewhat higher than most previous determinations, especially those made at lower stress levels. In the past, temperature effects have usually been determined by comparing creep rates from separate tests at different temperatures, and there must be some question as to whether secondary creep was actually established for low temperatures and low stresses in those cases.

Above -10°C , creep rate becomes progressively more temperature-dependent in polycrystalline ice, perhaps because of grain-boundary melting caused by concentration of impurities there or because of inherent "liquidity" of the surface layers.

The creep curve for a single crystal showed a stage of decelerating creep, followed by an inflexion stage during which strain was temporarily proportional to time, and finally a stage of accelerating creep. At all stages the monocrystal strained very much faster than polycrystalline ice with random crystal orientation.

The best value of creep activation energy for the monocrystal between -20° and -50°C was 16.5 kcal/mol (69.1 kJ/mol). Better results could be obtained by using the present technique at lower stress.

Creep at 0°C is influenced strongly by grain growth and perhaps crystal reorientation. To obtain results more directly applicable to problems of glacier flow it would be desirable to run long-term creep tests at relatively low stress so that some measure of recrystallization equilibrium can be reached.

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