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Confined Creep Tests on Polar Snow

by

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and

George Hendrickson

U.S. ARMY MATERIEL COMMAND

COLD REGIONS RESEARCH & ENGINEERING LABORATORY

HANOVER, NEW HAMPSHIRE

PREFACE

This report describes work done as part of the CRREL program of snow studies in Antarctica, a project supported in part by the National Science Foundation under grants NSF (G-17894) and (GA-2). This part of the work was under the direction of Mr. Malcolm Mellor, Civil Engineer, Experimental Engineering Division, USA CRREL. U. S. Army project personnel for the 1961-62 field season were Pfc. P. Morelli and Pfc. V. Aleksandravicius, and for the 1962-63 season were Pfc. G. Hendrickson, Pfc. R. Rowland, and Pfc. T. Pavlak.

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2. Snow--Density--Temperature factors
3. Snow--Antarctic regions
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SUMMARY

Snow was sampled from various depths below the surface of the ice sheet at Byrd and Amundsen-Scott Stations, Antarctica. The samples were obtained either by sawing blocks from trench and tunnel walls or by coring with the CRREL hand auger. The creep specimens were introduced into their stainless-steel cylinders by "screwing" the saw-edged cylinders into larger sample blocks. The cylinders were standard CRREL snow-sampling tubes, lined with silicone grease to reduce friction and adhesion. The tubes were set vertically on a bench, and pressure was applied axially with a loose piston loaded by a guided yoke, deformations being read periodically from dial micrometers. The mechanics of creep is discussed and the data are tabulated and graphed with respect to temperature and density effects. At the lower densities, the compressive viscosities are in reasonable agreement with those deduced from depth-density profiles. At the higher densities, the viscosities are significantly lower than those calculated from depth-density profiles. It is suggested that at least part of the discrepancy may be attributed to the strain history of the snow. The creep tests suggest a functional relationship between viscosity and density different from that suggested by analyses of natural snow densification.

CONFINED CREEP TESTS ON POLAR SNOW

by

Malcolm Mellor and George Hendrickson

Introduction

Snow was sampled from various depths below the surface of the ice cap at Byrd Station and the South Pole, Antarctica. Cylindrical samples of bonded snow were fitted into smooth-sided tubes and loaded in compression by a piston, deformations being read periodically from dial micrometers. Tests were conducted at the ambient temperatures of chambers excavated below the ice cap surface.

Results of the tests are analyzed here for the effect of density on strain rate, in an attempt to give data applicable to problems in applied glaciology.

Creep of snow

When dense, bonded snow is subjected to a moderate compressive load there is an immediate elastic strain on application of the load, followed by a transient stage of decelerating strain rate, referred to as "primary creep" or "delayed elasticity". Eventually a more or less constant strain rate develops (secondary creep), the rate at any given time depending upon the stress and upon the snow type, as described by density, temperature, and grain structure. Actually the snow compresses and strain-hardens, so that the "steady state" creep rate slowly decreases over a period of time.

Experiments suggest that an exponential relationship describes the dependence of strain rate* on stress (Bader, 1962; Landauer, 1957). At low stresses snow exhibits linear (Newtonian) viscosity, while at high stresses it tends towards the behavior of an ideal plastic solid, in which strain rate tends to infinity when critical stress is reached. Strain rate and stress can be conveniently related by a hyperbolic sine function:

$$\dot{\epsilon} = \frac{1}{\eta_C} \sigma_0 \sinh\left(\frac{\sigma}{\sigma_0}\right) \qquad (1)$$

where

$\dot{\epsilon}$ = strain rate,
σ = stress,
σ_0 = an empirical constant (which actually may be expected to vary with temperature and density to some extent), and
η_C = a constant for given density and temperature, which may be termed the "coefficient of compressive viscosity".

When $\frac{\sigma}{\sigma_0}$ is small, the first term of the series for $\sigma_0 \sinh \frac{\sigma}{\sigma_0}$ dominates, so that there is almost linear proportionality between $\dot{\epsilon}$ and σ (Fig. 1). The value of σ_0 for snows of the density and temperature found in the upper layers of an ice cap seems to be about 700 g/cm^2; with the value of σ adopted for the Antarctic creep tests, 488 g/cm^2, the assumption of linear proportionality between strain rate and stress introduces an error of less than 8%.

For given stress and temperature, strain rate is dependent on the grain texture of the snow (i.e. on grain shape, size, and grading), on grain packing, and on the structural connections between grains. The only practical index of grain structure currently available is density, which seems to give a good indication for dry snow in which intergranular bonds are well developed (fully "age-hardened"). Previous investigators

* From here on strain rate is "steady state" creep rate taken over a period sufficiently short for the densification effect to be neglected.

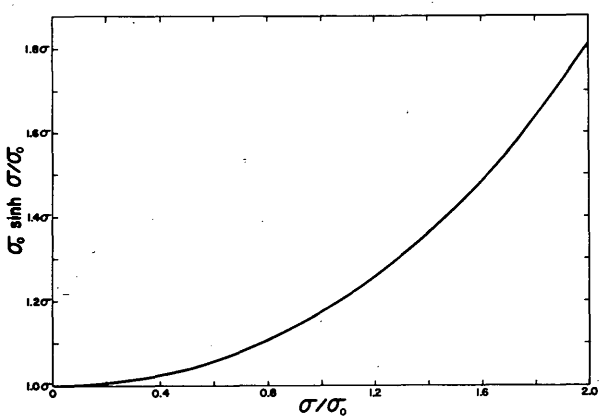

Figure 1. Plot of σ_0/σ sinh $\left(\frac{\sigma}{\sigma_0}\right)$ against $\left(\frac{\sigma}{\sigma_0}\right)$.

(Bader, 1962a; Landauer, 1957a; Kojima, 1958) have chosen to relate strain rate (or viscosity) with density by exponential equations; only Bader (1962a) appears to have considered boundary conditions. For the present analysis a power law capable of fulfilling reasonable boundary conditions and amenable to linear regression is adopted.

While recognizing that different mechanisms may control straining in different density ranges, it seems desirable to try first a relation between compressive viscosity η_c and density γ which satisfies the following boundary conditions:

$$\gamma = 0, \qquad \eta_c = 0, \qquad \frac{d\eta_c}{d\gamma} = 0$$

$$\gamma = \gamma_{ice}, \qquad \eta_c = \infty, \qquad \frac{d\eta_c}{d\gamma} = \infty.$$

Such an expression is

$$\eta_c = a \left(\frac{\gamma}{\gamma_{ice} - \gamma}\right)^n \tag{2}$$

where a and n are constants for a given temperature and snow type. The reference viscosity a is expected to be temperature-dependent; n may vary only with grain structure.

Further comment on the value of γ_{ice} might be made. If tests were made *in vacuo*, γ_{ice} would have a value of 0.917 g/cm^3, but with tests made in air, straining will cease and η_c will thus become infinite when the pressure in the bubbles of entrapped air equals the external pressure on the sample. Assuming a seal-off density of 0.82 g/cm^3, and applying the gas law, it is found that straining would cease for the present tests at $\gamma = 0.85$ g/cm^3 for Byrd Station and $\gamma = 0.86$ g/cm^3 for South Pole. Nevertheless, a value $\gamma_{ice} = 0.917$ g/cm^3 may be used as a consistent parameter, since the tests are entirely below the snow-ice transition density.

It is customary to account for the temperature effect on creep in snow by an equation based on physical reasoning, as distinct from the empirical equations 1 and 2 above. Bader (1962b) and others use the equation

$$\dot{\epsilon} = b\, e^{-\frac{Q}{RT}} \tag{3}$$

where $\dot{\epsilon}$ = strain rate,
b = a constant for given stress and density,
Q = an activation energy,
R = the gas constant ($\sim$ 1.987 cal/mole °K), and
T = absolute temperature (°K).

Beyond noting that eq 3 does not apply at temperatures close to the melting point, no further comment on its form will be made. It should be pointed out, however, that previous work shows rather broad variations for determinations of Q, which might be attributed to changes in surface/volume ratio, to impurities, or to other physical factors.

Test method

Snow samples were obtained either by sawing blocks from trench and tunnel walls or by coring with the CRREL hand auger. The creep specimens were introduced into their stainless-steel confining cylinders by "screwing" the saw-edged cylinders into larger sample blocks. The cylinders were standard CRREL snow-sampling tubes, 18.9 x 7.1 cm diam, coated inside with silicone grease to reduce friction and adhesion. Initial density was doubly determined by measuring and weighing both the large sample block and the specimen in the cylinder. Initial length of the sample was recorded.

The tubes were set vertically on a bench, and pressure was applied axially by a loose piston (not air-tight) which was loaded by means of a guided yoke (Fig. 2). Deformation was read periodically from dial micrometers permanently attached to each apparatus.

Data

Creep curves were drawn in the usual way, plotting displacement against time. Figure 3 gives examples of creep curves. Strain rates were obtained from the secondary creep portions of the creep curves, the slope of the curve being divided by appropriate sample length according to

$$\dot{\epsilon}_{\frac{t+\Delta t}{2}} = \frac{1}{L_{\frac{t+\Delta t}{2}}} \left(\frac{L_{t+\Delta t} - L_t}{\Delta t} \right).$$

where t = time (sec); L = sample length (cm).

The corresponding density was taken to be

$$\gamma_{\frac{t+\Delta t}{2}} = \frac{L_0}{L_{\frac{t+\Delta t}{2}}} \cdot \gamma_0 .$$

Underlying the analysis is the tacit assumption that the sample densifies uniformly through its length; this is perhaps justifiable, since the ratio of length to diameter is only about 2.5:1.

At the South Pole there was little variation of the test temperature, but at Byrd seasonal temperature changes were felt in the undersnow test chamber. The Byrd values for strain rate were adjusted to a mean temperature of -23C, assuming an activation energy Q = 14,000 cal/mole for the relatively small corrections according to eq 3.

South Pole creep tests

(Loading: 488 g/cm^2; Mean temperature: -48C)

Test (Sample no.)	Mean test density (g/cm^3)	Mean strain rate, $\dot{\epsilon}$ (Adjusted to -48C) (sec^{-1})	Compressive viscosity, η_c (g cm^{-2} sec)
1	0.453	3.21×10^{-10}	15.2×10^{11}
2	0.584	2.56×10^{-10}	19.1×10^{11}
3	0.632	1.01×10^{-10}	48.5×10^{11}
4	0.554	3.09×10^{-10}	15.8×10^{11}
5	0.384	6.65×10^{-10}	7.33×10^{11}
8	0.361	13.7×10^{-10}	3.56×10^{11}
9	0.385	6.49×10^{-10}	7.51×10^{11}

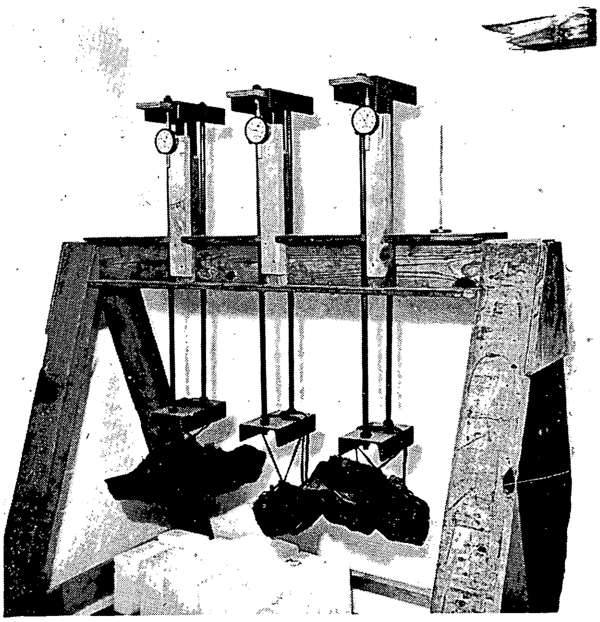

Figure 2. Apparatus for making confined compressive creep tests.

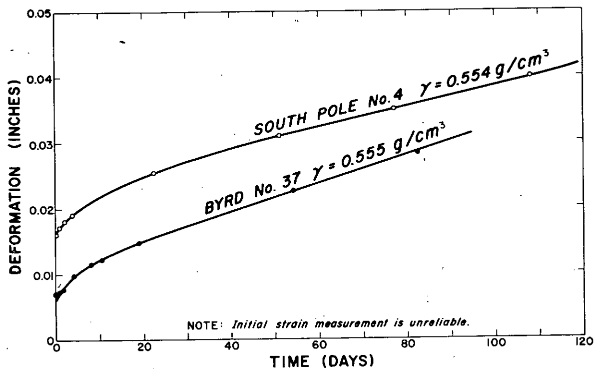

Figure 3. Typical creep curves.

Byrd Station creep tests

(Loading: 488 g/cm^2; Mean temp: -23C)

Test (Sample no.)	Mean test density (g/cm^3)	Mean strain rate, $\dot{\epsilon}$ (Adjusted to -23C) (sec^{-1})	Compressive viscosity, η_c ($g\ cm^{-2}\ sec$)
1	0.416	60.4×10^{-10}	0.807×10^{11}
3	0.594	2.68×10^{-10}	18.2×10^{11}
5	0.476	55.6×10^{-10}	0.878×10^{11}
14	0.526	7.26×10^{-10}	6.72×10^{11}
29	0.465	12.7×10^{-10}	3.85×10^{11}
30	0.436	14.8×10^{-10}	3.29×10^{11}
31	0.487	13.7×10^{-10}	3.56×10^{11}
32	0.460	14.0×10^{-10}	3.49×10^{11}
33	0.558	12.3×10^{-10}	3.96×10^{11}
34	0.521	8.37×10^{-10}	5.82×10^{11}
35	0.526	10.9×10^{-10}	4.48×10^{11}
36	0.552	4.10×10^{-10}	11.9×10^{11}
37	0.555	5.04×10^{-10}	9.67×10^{11}

Density effect

Figure 4 gives a plot of logarithmic strain rate against density for Byrd and South Pole Stations. An inverse correlation is evident, but the data show serious scatter.

In Figure 5, the logarithm of compressive viscosity, $\log \eta_c$, has been plotted against $\log\left(\frac{\gamma}{\gamma_{ice} - \gamma}\right)$. Values of η_c were computed on the assumption of a linear relation between strain rate and stress. The straight lines drawn through each set of data were fitted by the method of least squares to give the following relationships.

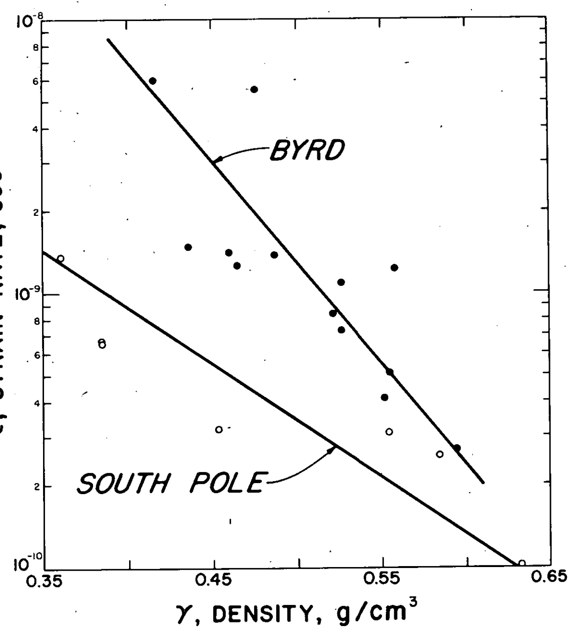

Figure 4. Logarithmic strain rate plotted against density.

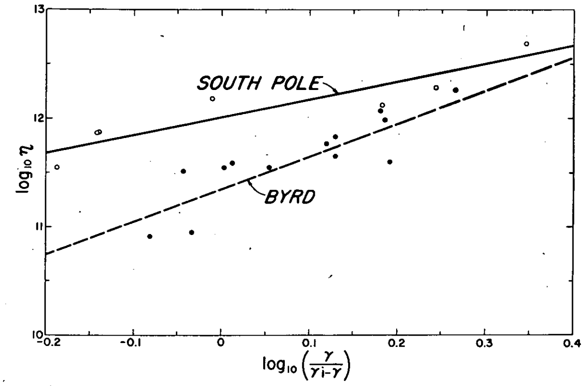

Figure 5. Plot of data and regression lines for log η and log $\left(\frac{\gamma}{\gamma_i - \gamma}\right)$.

Byrd Station:

$$\eta_c = 2.27 \times 10^{11} \left(\frac{\gamma}{\gamma_i - \gamma}\right)^{3.03} \text{ g cm}^{-2} \text{ sec.} \tag{4}$$

(Correlation coefficient = 0.804; Standard deviation of log η = 0.241.)

South Pole:

$$\eta_c = 1.04 \times 10^{12} \left(\frac{\gamma}{\gamma_i - \gamma}\right)^{1.53} \text{ g cm}^{-2} \text{ sec.} \tag{5}$$

(Correlation coefficient = 0.909; Standard deviation of log η_c = 0.165.)

The difference between the exponents for the two stations is greater than might have been expected. If the difference is real, there is no ready explanation for the wide discrepancy; it can only be suggested that it is due to difference of grain structure in the two types of snow.

Since the two curves intersect if extrapolated in accordance with eq 4 and 5, it is of interest to note the density at which compressive viscosity would be the same for both stations. Solving eq 4 and 5 as simultaneous equations it is found that viscosities for both stations would be equal for a density of 0.67 g/cm³.

Bader (1962a) expresses the relationship between compressive viscosity and density by

$$\eta_c = c \left(\frac{\gamma}{\gamma_i - \gamma}\right) e^{m\gamma}, \tag{6}$$

where c and m are constants for a given temperature and snow type. From analyses of depth-density profiles for the ice cap snows at Byrd and South Pole, Bader evaluates the parameters c and m, so that it is possible to calculate values of η_c. In Figure 6 the relationships between η_c and γ obtained by analysis of the present creep data and from Bader's densification theory are presented together.

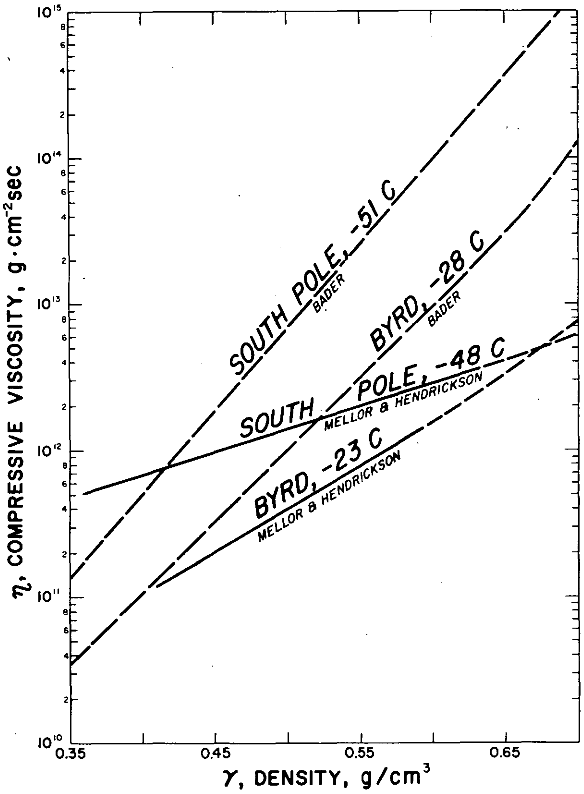

Figure 6. Logarithm of compressive viscosity as a function of density according to the present data, and calculated from Bader's snow densification data.

It is clear that η_c is a much stronger function of γ in Bader's relationships than in the relationships derived from the present tests. A review of the literature provides support for Bader's expressions; other investigators of snow densification under natural field conditions find η_c to be a similarly strong function of density for the range covered in the creep tests described here ($0.35 < \gamma < 0.65$). The results of both Landauer (1957a) and Kojima (1958) show that, as density increases from 0.4 to 0.5 g/cm^3 viscosity increases by approximately one order of magnitude. Data from other creep tests, however, show some correspondence with the present findings. Bucher's data for low-density snow (Bucher, 1956), when re-plotted exponentially, give a line roughly parallel to ours for the South Pole (Mellor, in prep.). Ramseier (1964) breaks his data for unconfined creep tests at the South Pole into three ranges, $0.41 < \gamma < 0.48$, $0.48 < \gamma < 0.62$, and $0.62 < \gamma < 0.65$ g/cm^3. For the middle range, 0.48 - 0.62, there is a lower rate of viscosity increase with density than that found in the present tests, although the outer ranges suggest strong density dependence comparable to Bader's relation. It may be noted in passing that the present data can be interpreted to give a weak indication of a similar trend.

Ramseier's data for unconfined creep tests at Camp Century, Greenland, and Byrd Station, Antarctica, lie chiefly in the range $0.46 < \gamma < 0.55$, and for this range give a rate of viscosity increase with density similar to ours for the South Pole.

Some possible sources of error in the present tests are easy to imagine (e.g., side friction in the tubes, uneven stress distribution in the samples), but they all tend to increase the apparent coefficient of compressive viscosity. The principal discrepancy lies in the fact that the tests give lower values than the densification theory over the higher part of the density range. Bader's data are for slightly lower temperatures than the creep data, but the effect of this is small. The only suggestion which can be offered here is that, in the ice cap, the higher-density snows are subjected to greater stresses than those applied in the creep tests; lower strain rates may permit recrystallization of the ice grains to keep pace with the deformation, thus maintaining orientations favorable to easy glide. If this is the case, samples loaded perpendicular to the original stratification* should strain more easily than samples of the same snow loaded parallel to the original stratification. Data from unconfined creep tests made by Ramseier at Camp Century show that this does indeed occur.

Temperature effect

Had the curves for Byrd and South Pole been close to parallel, it might have been reasonable to attribute the separation solely to temperature, and to calculate a value for the activation energy in accordance with eq 3. Since the test curves converge, such a calculation would be meaningless, but an evaluation from the data of Bader (1962a) may be of interest. Substituting appropriate values into eq 3 for densities of 0.4, 0.5 and 0.6 g/cm^3 gives:

*The present tests were all made with load normal to the original snow stratification.

Density (g/cm^3)	Activation energy (cal/mole)
0.4	7500
0.5	9200
0.6	11,000

Conclusion

The test results probably give an adequate description of the behavior of ice-cap snow under the conditions imposed by the tests. At the lower densities ($0.35 < \gamma < 0.45$), the compressive viscosities measured from the tests are in reasonable agreement with those deduced from depth-density profiles. At the higher densities, the measured viscosities are significantly lower than those calculated from depth-density profiles, and hence the tests lead to a different relationship between viscosity and density.

It is suggested that at least part of the discrepancy can be attributed to the strain history of the snow. The high density test samples, having been taken from the ice cap, had previously been subjected to considerable vertical strain, and the constituent crystals would therefore have some preferred orientation. In the undisturbed ice cap, crystal reorientation must lag behind the creep stages, being a consequence of strain.

One implication of a strain history effect is that new (but fully age-hardened) Peter snow should exhibit a higher viscosity than ice-cap snow compacted naturally to the same density when both are loaded vertically.

It has been found that mechanical tests on snow can only be relied upon for reproducible results when multiple testing is carried out, and by this token the present series is deficient. We also have misgivings about the adequacy of density alone as an index of grain texture and structure. However, with these reservations we must conclude that creep tests suggest a different functional relationship between viscosity and density than do analyses of natural snow densification, at least for the mid-range of density. Three independent studies of snow densification (Bader, 1962a; Landauer, 1957a; and Kojima, 1958) tend to be mutually supporting, and show compressive viscosity to be a relatively strong function of density. Three independent investigations involving compressive creep tests (Ramseier, 1964; Bucher, 1956; and this investigation) give contrary data showing compressive viscosity to be a much weaker function of density in a certain range. The rheological implications of this should be studied further; creep mechanisms in the different density ranges might be considered.

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2. Snow--Density--Temperature factors
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4. Snow--Plasticity--Test results

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