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Is Minimum Creep Rate a Fundamental Material Property?

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Résumé

Les problèmes de génie des glaces exigent des solutions pour ce qui est des limites particulières de contrainte, de déformation ou d'endommagement. Les ingénieurs doivent connaître l'interdépendance des contraintes, de la déformation, du degré d'endommagement et du temps, dans le cas d'une masse de glace, pour une distribution des températures et une histoire de chargement données. Il est d'usage courant, lorsqu'il s'agit de déterminer les propriétés mécaniques de la glace, d'évaluer l'influence de la vitesse sur la contrainte maximale ou la dépendance de la «vitesse minimale de fluage» à l'égard de la contrainte. Cette vitesse minimale de fluage (on parle aussi de fluage «secondaire» ou «en régime permament») et les lois de vitesse, exposants de contrainte et coefficients correspondants ont une valeur limitée en ce qui concerne les conditions effectives de service. Ils ne sont pas très utiles non plus pour construire des équations constitutives permettant d'analyser des problèmes complexes de génie des glaces. L'ingénieur doit plutôt se concentrer sur les phénomènes transitoires liés à la structure et à la texture, sur la cinétique des dommages causés par les fissures et sur les effets attachés, dans le tout premier pour-cent de déformation par fluage.

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IS MINIMUM CREEP RATE A FUNDAMENTAL MATERIAL PROPERTY?

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Abstract

Ice engineering problems require solutions in terms of specific design stress, strain or damage limits. Engineers must know the interdependence between stress, strain, damage state and time for a given ice body at a given temperature distribution and loading history. Common practice of determining the mechanical properties of ice is to evaluate the rate sensitivity of maximum stress or the stress dependence of minimum creep rate. 'Minimum creep rate' (also known as 'Secondary' or 'steady-state') and the corresponding rate laws, stress exponents, and coefficients are of limited value with respect to actual service conditions. Neither are they of much use in building constitutive equations for analyses of complex ice engineering problems. The engineer must focus instead on the structure and texture-sensitive transient phenomena, kinetics of crack damage and the associated effects within the very first percent of creep deformation.

Introduction

Creep and fracture of polycrystalline ice is part of a larger field of study - deformation and failure of materials at high homologous temperatures. At temperatures greater than 0.3 T_m, where T_m is the melting point in Kelvin, total strain, ε, can be described phenomenologically in terms of elastic strain, ε_e, delayed elastic strain, ε_d, and permanent or viscous strain, ε_v,

$$\varepsilon = \varepsilon_e + \varepsilon_d + \varepsilon_v \qquad (1)$$

An engineering structure or component can be designed to function properly and to achieve the required life under specified operating conditions without failure if the creep, creep damage and fracture characteristics of a material are known and Eqn. 1 is formulated for any loading history taking account of the physical processes involved. To date most treatments for engineering design, including ice engineering, are empirical in nature and based on oversimplified ideas. These ideas have been challenged recently. Examination of the physical phenomena governing creep deformation and the kinetics of creep damage has given new directions that are discussed in this paper.

Constitutive Equations

Most theoretical treatments, for simplicity, are based on the notion of a steady-state matrix creep rate, $\dot{\varepsilon}_{std}$, and an idealized form of Eqn. 1,

$$\varepsilon = \varepsilon_e + \varepsilon_d + \dot{\varepsilon}_{std}\, t \qquad (2)$$

Since steady state creep rate, $\dot{\varepsilon}_{std}$, is synonymous with 'minimum creep rate', $\dot{\varepsilon}_{min}$, Eqn. 2 is replaced by,

$$\varepsilon = \varepsilon_e + \varepsilon_d + \dot{\varepsilon}_{min}\, t \qquad (3)$$

where $\dot{\varepsilon}_{min} = A\,\sigma^n$ (4)

where A and n are constants, σ is stress. Eqn. 4, known as Norton's law or simply the power law, was used by Glen (1955) for ice. Since it breaks down at high stresses, Barnes et al. (1971) adopted the unifying Garofalo (1965-proposed for metals) equation, where b is another constant,

$$\dot{\varepsilon}_{min} = A\,[\sinh(b\sigma)]^n \qquad (5)$$

Following the ideas of Garofalo (1965) and others that there must be interrelationships between primary and secondary creep in metals, Ashby and Duval (1985) introduced the following expression in ice mechanics,

$$\varepsilon = \varepsilon_e + \varepsilon_d(\dot{\varepsilon}_{min}) + \dot{\varepsilon}_{min}\, t \qquad (6)$$

and proposed a 'modified Sinha equation' in terms of $\dot{\varepsilon}_{min}$. Eqn. 6 is based on the popular Monkman and Grant (1956) type expression, where t_m is the time to reach $\dot{\varepsilon}_{min}$,

$$\dot{\varepsilon}_{min} t_m = \text{constant} \qquad (7)$$

One of the consequences of the governing Eqn. 4 or 5 and the underlying concept of steady-state is the development of the idea that a 'maximum stress', σ_{max}, should be obtained if a constant strain rate, $\dot{\varepsilon}$, is applied,

$$\dot{\varepsilon} = M\,\sigma_{max}^m \qquad (\text{or} = M\,[\sinh(c\sigma_{max})]^m) \qquad (8)$$

Polycrystalline Ice

Any body containing several crystals is a polycrystalline body. The crystals are commonly referred to as grains and can have substructures. Polycrystalline ice, including sea ice, can be grouped essentially into three major types: - granular, columnar and frazil. A brief description follows on the type of polycrystalline ice encountered in nature and the tests performed to determine mechanical properties.

Columnar-grained ice consists of long pencil-like crystals with one dimension many times longer than the others. This type of ice develops as a result of unidirectional freezing of a water body. Frazil ice consists of needle or disc type crystals and it forms from the freezing of congealed frazil slush. Granular ice could best be described as ice with grain structure other than those of frazil and columnar. Granular ice forms from a number of processes - freezing of saturated snow or ice particles, sintering process, recrystallization, etc. It is rather confusing and often misleading that even today the glaciological literature is full of examples where the term polycrystalline ice is strictly applied for granular, isotropic, equiaxed ice. To many researchers 'polycrystalline ice' incorrectly brings to mind solely a picture of isotropic, equiaxed material.

As for granular ice, the situation is rather complicated. It has been shown that the 'easy' glide crystal orientation of granular ice in compression is a fabric with a small circle girdle (Gao and Jacka, 1987; Jacka and Budd, 1989) as shown in Fig. 1d.

Mechanical Tests

Two commonly applied experiments to determine material properties of ice at a constant temperature for engineering applications are the uniaxial constant stress (CS) creep and the uniaxial constant strain or deformation rate (CD) tests. Ideally a stress is suddenly imposed and held constant in the CS tests; in the CD tests, a strain rate is suddenly imposed and held constant.

In the CS tests, it is usually the load, not the stress, that is maintained constant. The usual practice is to record strain/time curves from which instantaneous strain rate is determined as a function of time, t. The presentation of test results, as required by Eqn. 4, is almost invariably limited to the dependence of minimum strain rate, $\dot{\varepsilon}_{min}$, on initial stress, σ.

Fig. 1 Some commonly observed crystal orientation fabrics of ice.

Ice Fabric - Shapes and Arrangements of Crystals

Physical properties of ice depend on the structure, texture, fabric, impurities and inclusions of the ice (see Members, 1980 for definitions), and the nature of the stress state with respect to the crystal structure. A few common crystal orientation fabrics, excluding the multiple maxima, are shown in Fig.1

The crystals in one of the most common type of ice, S1 type columnar-grained (Michel and Ramseier, 1971), are oriented to have their optic or c-axis tending to be parallel to the length of the columns - parallel to the vertical plane in an ice cover. This ice, therefore, has a fabric with a single maximum (Fig. 1a). Maximum resistance to flow in this ice develops if a load is applied parallel to the long axis of the grains or c-axis. This loading configuration is equivalent to a 'hard' glide. Because the basal planes of the grains coincide with the plane of the ice cover, a uniaxial load application in a plane at about 45° to the axis of the grains is equivalent to an 'easy' glide, i.e. the maximum shear stress being parallel to the basal plane. Similarly, 'easy' glide corresponds to a load application in a plane at about 45° to the long axis of the grains for transversely isotropic, columnar-grained, S2 type ice (Fig. 1b) because the basal planes of the grains in this ice tend to be parallel to the length of the grains.

'Hard' or 'easy' glide modes of loading can occur, relatively speaking, in the same plane (horizontal) in oriented S-3 type landfast, columnar-grained sea ice (Fig. 1c) in which the c-axis of the grains is in the horizontal plane but tending to be parallel to the water current below the ice cover.

Information is usually not provided on the magnitude of axial strain, lateral strain and volumetric strain, or any interdependence between strain components, strain rate and time, and their dependence on stress, grain size, structure, texture, etc.

In CD tests, it is usually the displacement rate of the cross-head or the actuator (excepting a few recent tests using closed-loop systems), not the specimen strain rate, that is maintained constant. As required by Eqn. 8, maximum stresses are reported in terms of nominal strain rates estimated from the cross-head rate and specimen length. Vital information on stiffness characteristics of test systems and histories of stress, specimen strain, cracking activities, etc., are usually not measured, reported or discussed.

Problems

A large number of CS studies have been carried out on granular ice. Most of these studies are difficult to understand and analyze because the minimum creep rates were reported without providing a comprehensive picture of the creep-time data. Tests were often conducted over a wide range of stresses and temperatures involving stress- and temperature-dependent complex kinetics of microfracturing and cavitation. Moreover microstructural studies were rarely carried out after the tests.

The tests could, however, be divided into two major groups based primarily on whether any microcracking activities are involved during deformation. Since high temperature embrittlement processes play dominant roles at uniaxial stresses above about 5 x 10^{-5} E, where E is the Young's modulus, tests at stresses below about 0.5 MN.m^{-2} could be considered as low stresses for ice.

Minimum Creep Rate at Low Stresses

The concepts of steady state and Eqn. 2 are idealizations. The transformation of Eqn. 2 to Eqn. 3, is a result of practical necessity for describing the pre-tertiary creep regime. Usual forms of Eqn. 3 do, however, give the impression that creep rate is 'believed' to decrease with time approaching a prolonged, quasi steady-state, 'secondary-creep' regime, associated with a 'minimum creep rate'.

Recent experimental observations at the University of Melbourne have given an understanding of the creep response of granular ice for low stresses relevant to the deformation of land-based natural ice masses. Initially isotropic ice (Fig. 1e) shows a monotonically decreasing strain rate until a minimum creep rate of 1.2 x 10^{-8} s^{-1} is reached, at an octahedral strain of about 0.6% (at-3.3°C and 0.2 MN.m^{-2}), and then the strain rate increases again to a quasi-constant strain rate at a strain of about 10% (Jacka and Budd, 1989). However, an initially anisotropic ice, exhibiting a small circle crystal orientation fabric (Fig. 1d), exhibits a monotonically decreasing strain rate during loading leading to a minimum octahedral creep rate of 3.5 x 10^{-8} s^{-1} at octahedral strain of about 10%. Both types of ice exhibit similar final crystal fabric patterns with a small circle girdle. **Minimum creep rate for isotropic ice, therefore, is of transitory nature and does not signify a steady state.** These and other observations led Jacka and Budd (1989) to conclude that the concept of a steady state secondary creep condition is invalid for initially isotropic ice because of the development of crystal anisotropy during deformation. It seems that the tertiary flow rates for anisotropic ice are more appropriate for ice sheet flow than the minimum strain rate is for isotropic ice (Jacka and Budd, 1989).

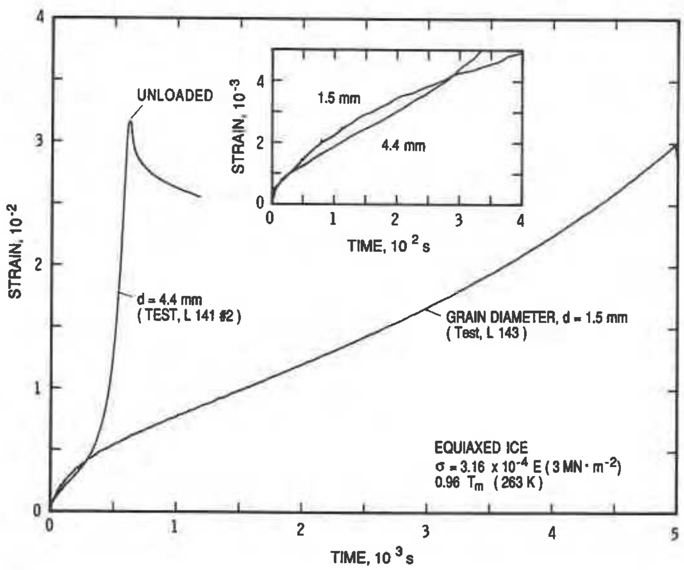

Fig. 2 Observed grain size effect on creep in isotropic ice.

Minimum Creep Rate at High Stresses

A significant number of CS studies have been carried out on mechanical properties of ice for stresses, greater than about 0.5 MN.m^{-2}, relevant to many engineering applications (for example, Glen, 1955; Barnes et al., 1972; Gold, 1965; Mellor and Cole, 1982; Sinha, 1989a,c). Mechanical response of polycrystalline ice in this range is affected by grain-facet size microcracking activities (Cole, 1986, Sinha, 1989b). **There is, however, a tendency towards reporting only rudimentary details on the microstructural characterization. Such limited detail is essentially useless.**

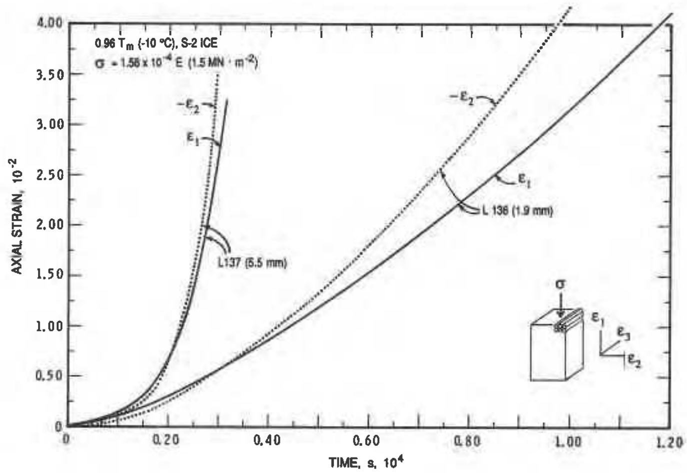

Fig. 3 Observed grain size effect on creep in tansversely isotropic columnar-grained ice.

For isotropic, equiaxed, granular ice, the total strain shows a decelerating or primary creep stage followed by a secondary quasi steady state and an accelerating or tertiary stage as can be seen in Fig. 2. A similar response has also been observed for transversely isotropic columnar-grained S2 ice (Fig. 3) loaded perpendicular to the columns. Microfracturing activities during deformation have been shown to affect axial deformation and volumetric strain (dilatation) in the material. Both granular ice (Fig. 4) and columnar-grained ice (Fig. 5) exhibit microfracturing and volumetric dilatation during deformation. **The entire creep curve of both granular and columnar-grained ice shows significant dependence on grain size** (Sinha, 1989a,b). Primary as well as tertiary creep rate are strongly influenced by grain size (Figs. 2,3). **A knowledge of $\dot{\varepsilon}_{min}$ provides neither the creep rate nor the creep strain during the primary creep period or the tertiary range.**

Columnar-grained ice, similar to S-2 type but with a slight anisotropy fabric (tending to be small circle girdle) in the plane normal to the length of the columns has been found to exhibit an accelerating primary creep period before going into decelerating creep (Sinha, unpublished). Initially increasing creep rate response in columnar-grained ice has also been observed by Gold (1965) at stresses in the range 0.4 to 1.3 MN.m^{-2} and strains up to 1 x 10^{-2}. The same specimens were, however, reported to exhibit lower creep resistance and 'normal' initial decreasing creep rate response on reloading of the damaged specimens. These observations also give clear indications that it would be difficult to formulate the overall creep response on the basis of any steady state creep concept.

The duration of the secondary creep regime decreases with increase in stress for stresses greater than 0.5 MN • m^{-2} in uniaxial tests (Figs. 4, 5). The secondary creep regime disappears with increase in stress and only a transitory minimum creep period followed by an accelerating tertiary creep regime is noticed at stresses of engineering interest as can be seen in Figs. 2 and 3. **The 'minimum creep rate' signifies only a point on the creep curve and Eqns. 4 or 5 applies only to this point.** The basic assumption of stable microstructure, ideally associated with the concept of steady state, is not valid for minimum creep regime at stresses of engineering importance. Moreover, experimental results showing significant grain-size effects raise questions to the validity of Eqn. 6. Since the usual Eqns. 4 or 5 for $\dot{\varepsilon}_{min}$ do not show any dependence on grain size and shape or the ice type, the question raised is: How useful is Eqn. 6 for real life ice problems?. Therefore, constitutive equations expressed in terms of $\dot{\varepsilon}_{min}$, such as Eqn. 6 are of little practical or physical value. In general it would be fair to say that:

- **creep is a continuous process and each regime depends on earlier creep history;**
- **use of the term 'minimum creep rate' synonymously for 'Steady-state creep rate' is a 'misuse' of language; 'minimum creep rate' does not always imply steady state condition.**

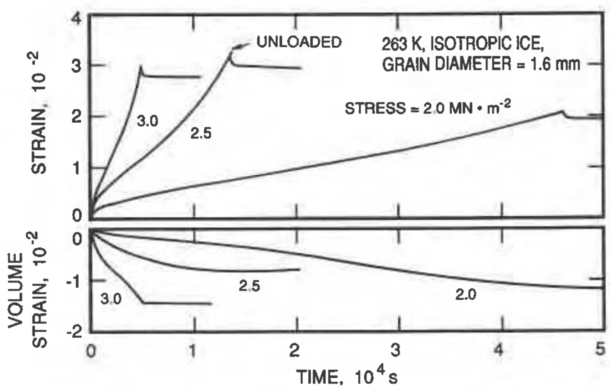

Fig. 4 Experimental observations on axial strain and volumetric strain under constant compressive load for isotropic ice.

The concept that the minimum creep rate is a basic quantity in engineering applications in man-made materials such as metals, alloys and ceramics has, however, found its way into ice mechanics. Analyses of innumerable problems (ice engineering no exception) have been carried out on the basis of $\dot{\varepsilon}_{min}$, ignoring the fact that **it actually occurs only 'momentarily' during a creep test**. Consequently, most experimental observations in polycrystalline metals, alloys, ceramics and ice have been conducted exclusively to find the stress and temperature dependence of $\dot{\varepsilon}_{min}$ using uniaxial constant load tests. Most theories in metals, alloys and ceramics have also been developed to satisfy stress and temperature dependence of $\dot{\varepsilon}_{min}$. A consequence of these practices is the profusion of either empirically developed or theoretically formulated mathematical equations to describe constant stress (CS) creep, as well as constant strain rate (CD) deformation experiments. These equations, inadvertently but inevitably have led to confusion.

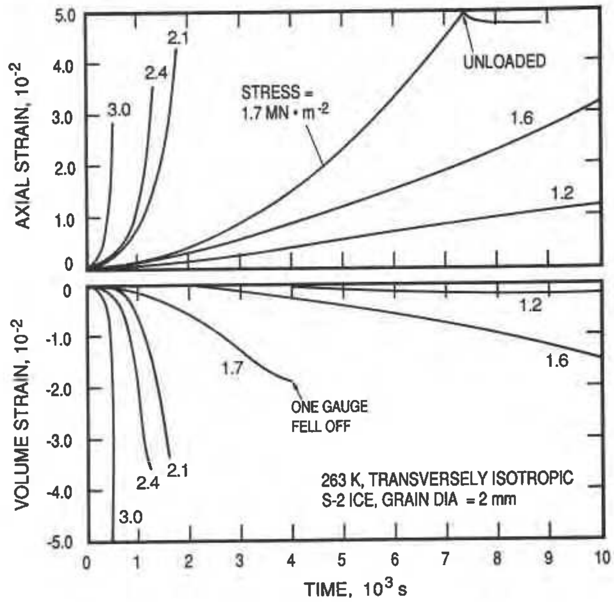

Fig. 5 Experimental observations on axial strain and volumetric strain under constant compressive load for transversely isotropic ice.

Constant Deformation Rate Test

Historically, it is the cross-head or the actuator displacement rate that is maintained constant in CD tests so that the experiments are conducted at constant 'nominal' strain rates, $\dot{\varepsilon}_n = \dot{x}/L_o$ where $\dot{x}$ is the cross-head displacement rate and L_o is the specimen gauge length. This tradition is so strong that often no distinction is made between specimen strain rate and $\dot{\varepsilon}_n$ or to draw attention that the tests are indeed not constant strain rate tests. In a CD test, the total displacement after a loading time, t, is given by the sum of the specimen displacement, x_s, and the machine/system displacement, x_m,

$$\dot{x} = (x_s + x_m)/t \tag{9}$$

If $\dot{\varepsilon}_{as}$ (= $x_s/(L_o t)$) is the average specimen strain rate to time, t, then Eqn. 9 gives the nominal strain rate as,

$$\dot{\varepsilon}_n = x_s/(L_o t) + x_m/(L_o t) = \dot{\varepsilon}_{as} + x_m/(L_o t) \tag{10}$$

If E_m is the spring constant of the test machine/system, A_o is the initial cross-sectional area of the specimen and P is the total load, then $x_m = P/E_m$ and $P = \sigma A_o$ where σ is the engineering stress. Eqn. 10 then gives,

$$\dot{\varepsilon}_n = \dot{\varepsilon}_{as} + \sigma A_o/(L_o t E_m) \tag{11}$$

According to Eqn. 11 the average specimen strain rate to t depends on the geometry of the specimen, stiffness of the test system and the time of loading. For a given test system and specimen geometry, $\dot{\varepsilon}_{as}$ approaches $\dot{\varepsilon}_n$ as t increases and equals $\dot{\varepsilon}_n$ at $t = \infty$, which, however, corresponds to infinite strain. Such a response has been observed in ice at strain rates less than 5×10^{-8} s^{-1}. A quasi-steady state deformation rate and a constant value of stress have been observed a long time after the beginning of loading, satisfying, therefore, the underlying concept for transposing Eqn. 4 to 8. These slow CD tests are similar to CS tests at stresses less than about 0.5 $MN.m^{-2}$, for which a quasi steady-state is reached eventually during loading, justifying the assumed equality between the idealization (Eqn. 2) and its practical reality (Eqn. 3). The long-term response of the slow CD tests is equivalent to the long-term part of low stress CS tests.

It should be mentioned here that a closed-loop test system, with the controlling displacement gauge mounted directly on the specimen, is equivalent to a machine with very high stiffness and gives $\dot{\varepsilon}_n = \dot{\varepsilon}_{ss}$ instantaneously. At low strain-rates the stress asymptotically approaches a maximum value. Nevertheless, the long term response provides neither any basis of analysis for the system response or any information on the shape of the stress-strain diagram.

For strain rates higher than 5 x 10^{-8} s^{-1}, of engineering interest, a finite time, t_{max}, and hence a finite strain, ε_{max}, is required to reach the maximum stress, σ_{max}. The maximum stress actually occurs only 'momentarily' during a CD tests on ice. A power-law has indeed been found to apply for upper-yield type of failures. This has strengthened the notions of steady-state creep and 'Ductile Failure', in spite of observed severe cracking activities. Consequently, premature fractures, that did not follow the expected power-law, were termed 'Brittle', leading to the concept of 'Ductile-to-Brittle' transition.

A review of experimental results on S-2 ice (Sinha, 1981) shows the value of m (3 to 4), in Eqn. 8, nearly equal to n (about 3), in Eqn. 4, but the value of M varies significantly (1.8 x 10^{-7} to 1.5 x 10^{-6} at -10°C) with the stiffness of the test system. M (Eqn. 8) was shown to decrease with an increase in system stiffness and to approach the numerical value of A (Eqn. 4) as the stiffness approaches infinity. The results obtained with a conventional machine of finite stiffness were also found to agree well with those of a closed-loop machine if average strain rate to upper-yield stress, $\dot{\varepsilon}_{amax} = \varepsilon_{max}/t_{max}$, is used for analysis. Premature failures were found to depend on specimen end finish and to occur at lower strain rates as the system stiffness increased.

Why is M not always equal to A? Why does it depend on external boundary conditions? Why does the ductile-to-brittle transition depend on system stiffness? Why do both failure time, t_{max}, and failure strain, ε_{max}, decrease with increase in stiffness of the system? What is the mechanism of ductile compressive failure? Why are ductile failure strains often less than 1 x 10^{-3}, similar to those of brittle failures when very stiff machines are used? Why does $\dot{\varepsilon}_{amax}$ provide a better description of the rate sensitivity of upper-yield stress than $\dot{\varepsilon}_n$? Why do the stress-strain curves show rate sensitivity? These and many other questions cannot be answered using conventional wisdom.

Most studies on ice, with a few exceptions (Sinha, 1981; Mellor and Cole, 1983), have paid attention only to the correspondence between m and n, and discussed the rate sensitivity of 'strength' in terms of 'secondary or steady-state' creep rate. As a consequence, a considerable amount of effort was made in the past in obtaining results to fit Eqn. 8 and answering irrelevant questions of the form - what is the strain rate during an ice-structure interaction? What is the failure envelope? It was ignored that the occurrence of **a maximum stress in a laboratory test is only an index - a transient phase that depends on loading history and complex interactions between the machine and the specimen.**

Inadequate Approach

In spite of a significant amount of information on the so-called strength and deformation of ice, methods of analysis of most ice engineering problems are inadequate. Too much emphasis has been placed on empirically developed equations that give no consideration to the structure and texture of the material or the physical processes occurring during the deformation.

Predictability of micromechanically based equations are based on simple ideas and assumptions of values for material constants. Material constants are often determined from experiments that seem simple. In fact, experimental conditions are often complicated by interactions between the test specimen and the testing system.

Engineering design incorporates some type of safety factor that is usually based on the allowable deformation or damage under actual operational conditions. Many important ice engineering problems are associated with relatively small strain, dynamic load and stress up to the failure value. The long term information does not provide any fundamental basis to analyze the short-term, transient response required for many engineering applications. Behaviour in the short term depends strongly on grain size, structure and texture. Ice in nature is so variable in structure, fabric and texture that a constitutive equation must include these factors or state variables. **The success of a creep or fracture model must therefore be judged** not only on its compatibility with the Eqns. 4 to 8, but also **on its ability to describe the entire creep curve, primary as well as tertiary**.

Alternate Approach

A more refined constitutive equation would be one that incorporates the state of the material and yet maintains the familiar phenomenological form - describing instantaneous recovery, time-dependent recovery and permanent deformation. A general form of Eqn. 1 would be one that expresses elastic, delayed elastic, and viscous components as functions of state variables (Sinha, 1989b), so that,

$$\varepsilon = \varepsilon_e + \varepsilon_d + \varepsilon_v$$

where
$$\varepsilon_e = \varepsilon_e(\sigma, T, t, V_i)$$
$$\varepsilon_d = \varepsilon_d(\sigma, T, t, V_i)$$
$$\varepsilon_v = \varepsilon_v(\sigma, T, t, V_i)$$
and
$$V_i = V_i(\sigma, T, t, ..) \quad (12)$$

where V_i represents internal and external variables that could be influenced by σ ,T and t. All the terms in Eqn. 12 are structure and texture sensitive; they could vary during deformation with alterations of the microstructure. A detailed discussion on this subject is outside the scope of this paper. The success of the approach can be judged from the fact that the failure processes can be described under a wide range of loading conditions, including CS as well as CD tests (Sinha, 1988; 1989a-c) and ice-structure interactions (Derradji-Aouat et al., 1990; Marcellus et al., 1990).

Equation 12 merely recognizes that a material at high homologous temperatures, like ice, experiences irreversible microstructural changes once it is deformed and that a number of interdependent micromechanisms operate simultaneously. These processes make creep and creep failures very complex. Experiments should be designed a) to measure the axial and lateral strains for estimation of volumetric deformations, b) to carry out measurements of the three strain components (ε_e, ε_d and ε_v) from strain history after sudden unloading, c) to record fabric, and microstructural details, including substructures and inclusions, before and after the tests, d) to record and to report shape change, if any, to insure the uniformity of stress or strain field, and e) to carry out measurements to quantify the damage processes during testing using metallographic, acoustic emissions and other techniques.

Recapitulation

Both 'minimum creep rate' ($\dot{\varepsilon}_{min}$), in constant stress tests, and maximum stress (σ_{max}), in constant displacement rate tests, represent only transitory phases under specific conditions. Engineers, not familiar with the details of material response, have used these quantities as fundamental material properties for the analysis of wide ranging engineering problems without realizing that the assumptions are not valid for the conditions under examination. The concept of 'strength' implies a specific material property. This low temperature concept does not apply at the elevated temperatures relevant to ice engineering. It has retarded growth in the understanding of failure processes in ice in general. Application of this concept has misleading implications, drawing attention away from one basic fact: transient or primary creep stage, involving microfracturing and damage accumulation, plays a dominant and decisive role in many engineering problems. Constitutive equations should be based on state variables to take account of the loading history and the effect of micro- and macro-structural changes during loading.

References

Ashby, M.F. and Duval, P. (1985). The Creep of Polycrystalline Ice, Cold Regions Sci. Tech. Vol. 11, p. 285-300.

Barnes, P., Tabor, D., and Walker, J.C.F. (1971). The friction and creep of polycrystalline ice. Proc. Royal Soc. London, Ser. A, Vol. 324, No. 1557, p. 127-155.

Cole, D.M. (1986). Effect of Grain Size on the Internal Fracturing of Polycrystalline Ice. U.S.Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Report No.86-5, 71 pages.

Derradji-Aouat, A., Evgin, E., and Sinha, N.K. (1990). Finite Element Calculations of Ice Pressure on Rigid Structures. Proc. 9th. Int. Conf. Offshore Mechanics and Arctic Eng. (OMAE/ASME), Houston, Texas, Feb.18-23, 1990.

Gao, X.Q., and Jacka, T.H. (1987). The Approach to Similar Tertiary Creep Rates for Antarctic Core Ice and Laboratory Prepared Ice. J. de Physique, Colloque Cl (Supplement to No. 3), Vol. 48, pp. 289-296.

Garofalo, G.(1965). Fundamentals of Creep and Creep-Fracture in Metals. Macmillan Company, New York, Chapter 2, p. 10.

Glen, J.W. (1955). The Creep of Polycrystalline Ice. Proc. Royal Soc., London, Ser. A, Vol. 228, No. 1175, pp. 519-538.

Gold, L.W. (1965). The Initial Creep of Columnar-Grained Ice, Part I: Observed Behavior, Part II: Analysis. Can. J. Physics, Vol. 43, pp. 1414-1434.

Jacka, T.H., and Budd, W.F. (1989). The Use of Tertiary creep Rates in Ice at High Strains in Compression and Shear. IUTAM/IAHR Symposium on Ice-Structure Interaction, August 14-17, 1989, St. John's, Newfoundland.

Marcellus, R.W., Sander, M., Sinha, N.K., and Shah, V.K. (1990). A Theoretical Dynamic Ice Structure Interaction Model for Crushing with Extraction. Proc. 9th. Int. Conf. Offshore Mechanics and Arctic Eng. (OMAE/ASME), Houston, Texas, Feb.18-23, 1990.

Mellor, M., and Cole, D.M. (1982). Deformation and Failure of Ice Under Constant Stress or Constant Strain-Rate. Cold Regions Science and Technology, Vol. 5, pp. 201-219.

Mellor, M., and Cole, D. M. (1983). Stress/Strain/Time Relations for Ice under Uniaxial Compression. Cold Regions Science and Technology, Vol. 6, pp. 207-230.

Members of ICSI working group. (1980). Mechanical Properties of Polycrystalline Ice: an Assessment of Current Knowledge and Priorities for Research. Cold Regions Sci. Tech., Vol. 3, pp 263-275.

Michel, B. and Ramseier, R.O. (1971). Classification of River and Lake Ice. Canadian Geotechnical J., Vol. 19, No. 1, pp. 36-45.

Monkman, F.C., and Grant, N.J. (1956). Proc. Am. Soc. Test. Mater., Vol. 56, p 593.

Sinha, N.K. (1981). Comparative Study of Ice Strength Data. Proc. IAHR Int. Symp. on Ice, Quebec, Canada, Vol. 2, pp. 581-595.

Sinha, N.K. (1988). Crack-enhanced Creep in Polycrystalline Material: Strain-rate Sensitive Strength and Deformation of Ice. J. Mater. Sci., vol. 23, No. 12, pp. 4415-4428.

Sinha, N.K. (1989a). Ice and Steel - a Comparison of Creep and Failure. Mechanics of Creep Brittle Materials - 1, Proc. Euromech - 239, 15-17 August,1988, Leicester, U.K., Edited by A.C.F. Cocks and A.R.S. Ponter, Elsevier Applied Science Publishers, London, pp. 201-212.

Sinha, N.K. (1989b). Microcrack-Enhanced Creep in Polycrystalline Materials at Elevated Temperature. Acta Metall., Vol. 37, No. 11, pp. 3107-3118.

Sinha, N.K. (1989c). Kinetics of Microcracking and Dilatation in Polycrystalline Ice. IUTAM/IAHR Symposium on Ice-Structure Interaction, August 14-17, 1989, St. John's, Newfoundland.