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Timco, G. W.; Frederking, R. M. W.

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by G.W. Timco and R.M.W. Frederking

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RÉSUMÉ

Il est bien connu que la rigidité des machines d'essai peut fausser les résultats des essais de compression uniaxiale de la glace. Cela provient du fait que les machines d'essai de compression conventionnelles ne sont pas suffisamment plus rigides que l'échantillon de glace soumis aux essais. Il en résulte donc un processus complexe d'interaction entre la machine et la glace. Cette communication présente un modèle simple de ce processus et les équations déterminantes. On obtient ainsi une formule correctrice qui permet de tenir compte de la rigidité de la machine. Le modèle est vérifié avec des échantillons de glace columnaire d'eau douce et de glace granulaire d'eau de mer en comparant les valeurs des résistances corrigées pour trois machines d'essai différentes avec celles obtenues en utilisant une machine d'essai à circuit fermé de forte capacité.

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A PROCEDURE TO ACCOUNT FOR MACHINE STIFFNESS IN UNI-AXIAL COMPRESSION TESTS

G. W. Timco and R. Frederking   National Research Council   Canada
Research Officers

ABSTRACT

It is well established that test machine stiffness can influence the results in uni-axial compression tests on ice. This comes about because the conventional compression machines are not substantially stiffer than the piece of ice under test; hence the test becomes a complicated ice-structure interaction process. In this note, a simple model of this process is outlined and the defining equations are established. This yields a correction formula which accounts for the stiffness of the test machine. The model is checked for both columnar freshwater ice and granular sea ice by comparing the corrected strength values for three different test machines with those measured using a high-capacity closed-loop test machine.

INTRODUCTION

In recent glaciological literature, there has been discussion on the influence of the test machine stiffness on the uni-axial compressive strength of ice which has been measured using constant cross-head rate test machines (Haynes, 1979; Sinha and Frederking, 1979; Sinha 1981a, 1981b, 1982; Frederking and Timco, 1983, 1984). Basically this problem arises because these conventional test machines are not considerably more rigid than the ice specimen being tested. Because of this, the test machine itself can deform elastically a significant amount during the test. This deformation of the test machine results in a lower applied strain rate on the sample than the nominal strain rate. Since the test results are usually interpreted in terms of the strain rate, and the compressive strength of ice is strain-rate dependent, this leads to an inaccurate interpretation of the test. Thus, a test of ice strength made on a machine which is not significantly more rigid than the ice sample will result in a lower strength than would occur for a true strain rate equal to the nominal rate. It has been shown, in fact, that for the same nominal strain rate, the apparent strength of ice increases with increasing test system stiffness (Sinha, 1981a).

To overcome this problem, recent tests of ice strength have been performed on "closed-loop" test machines. In these tests, the rate of deformation of the sample is measured and instantaneously fed back to the control system. This, in turn, adjusts the cross-head rate so as to maintain a true constant strain rate of the sample during the test. Using a test machine of this type, it is possible to investigate the strength of ice as a function of true constant strain rate; i.e. the influence of the test machine stiffness is eliminated. In any study investigating the physics or mechanisms of ice failure, a machine of this type should be used, if at all possible. Closed-loop machines, however, have several drawbacks since they are quite expensive, very large and not easily deployable for use in the field. For many engineering applications, therefore, a conventional test machine is used. Most of the information in the literature on the strength of ice has been obtained using such test machines. It would be highly desirable, therefore, to find a technique which would allow all this information to be compared by eliminating the influence of the machine stiffness. This technique would also facilitate field testing since lighter and more easily deployable test machines would still give results which could be interpreted in terms of strain rate.

In this note, a simple model is presented for the stiffness of a conventional test machine. This yields a correction formula which accounts for the machine stiffness. The model is checked by comparing strength values which were obtained for both columnar freshwater ice and granular sea ice using three different test machines and corrected using this formula, with those measured using a high capacity closed-loop machine.

DEFINING EQUATIONS

The model for the system of an ice sample in a test machine is shown in Figure 1. It consists of a series combination of two individual elements which represent the machine stiffness and the ice stiffness.

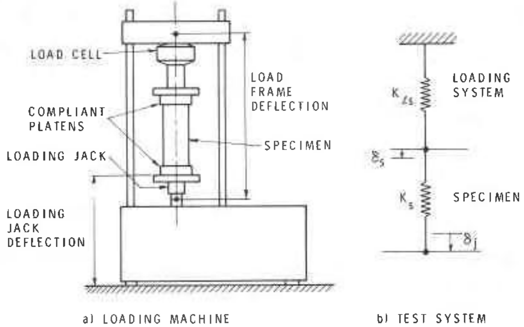

FIGURE 1 SCHEMATIC OF (a) COMPRESSION LOADING MACHINE AND (b) EQUIVALENT STIFFNESS ELEMENTS

It has previously been discussed by Frederking and Timco (1983). In brief, the loading system stiffness $K_{\ell s}$ is defined as

$$K_{\ell s} = \frac{\Delta P}{\delta_j - \delta_s} \qquad (1)$$

where ΔP is a load increment, δ_j is the corresponding displacement increment of the screw jack, and δ_s is the resulting deformation increment of the sample. δ_s is defined as

$$\delta_s = \frac{\Delta P \ell}{EA} \qquad (2)$$

where E is the elastic modulus of the specimen, ℓ is the length and A its cross-sectional area. Combining these equations and setting the sample stiffness $K_s = EA/\ell$, yields (per unit time)

$$\dot{\delta}_s = \frac{K_{\ell s}}{K_{\ell s} + K_s} \dot{\delta}_j \qquad (3)$$

This expression relates the displacement rate of the sample ($\dot{\delta}_s$) to the displacement rate of the cross-head of the machine ($\dot{\delta}_j$). Since the results of compression tests are usually discussed in terms of the strain rate ($\dot{\varepsilon}$) of the sample and $\dot{\varepsilon} = \dot{\delta}/\ell$, equation (3) yields a relationship between the strain rate in the sample ($\dot{\varepsilon}_s$) and the nominal strain rate of the test ($\dot{\varepsilon}_n$) as

$$\dot{\varepsilon}_s = \left[\frac{1}{1 + K_s/K_{\ell s}}\right] \dot{\varepsilon}_n \qquad (4)$$

This equation shows that the sample strain rate is less than the nominal strain rate, and that as the loading system stiffness becomes very large compared to the ice stiffness, $\dot{\varepsilon}_s$ approaches $\dot{\varepsilon}_n$, as expected. To use this equation, both the loading system stiffness and the ice stiffness must be known. The former is obtained by loading a specimen of known constant elasticity and measuring the load, movement of the screw jack, and load frame deflection (Frederking and Timco, 1983). The results for three different test machines which the authors have used (Instron, TTDM-L, 0.1 MN capacity; Tri-test 50, 0.06 MN capacity; Soiltest CT-405, 0.05 MN capacity) are shown in Figure 2. Note that the machine stiffness is not a constant, but a function of load at low loads, and for a given test machine, the stiffness is greater for steel platens than for compliant platens. For the analysis in this paper, the load dependence of the machine stiffness will not be taken into account in a rigorous fashion; instead, it is approximated as the average value of the machine stiffness up to the load level at which the ice yields. With regard to the ice stiffness, this is also not a constant for these tests since the specimen is loaded to its yield point. For low loads, the ice stiffness is given by EA/ℓ where E is the elastic modulus of the ice. With increasing load, the ice stiffness decreases such that, by definition, it is zero at the yield point. Similar to the machine stiffness, this load dependence will not be taken into account in a rigorous fashion; instead, the ice stiffness is approximated as the average of the ice stiffness during the test (assuming a linear decrease with load to yield; i.e. $\overline{K_i} = EA/2\ell$ where E is the elastic modulus of the ice for low loads). It should be noted that with increasing load, the stiffness of the test machine increases whereas the stiffness of the ice specimen decreases. Thus, the present approach greatly simplifies a complex interaction problem by using average values in a linear system to represent the situation. With this approximation, the reader is cautioned not to interpret the corrected strain rate $\dot{\varepsilon}_s$ as the true strain rate of the test. To verify the applicability of equation (4), it was used to correct strength measurements for two different cases. First, for measurements on columnar S2 freshwater ice which were made using a conventional machine with steel platens under carefully controlled laboratory conditions; and second, on granular sea ice made in the field using two different test machines with both steel and compliant platens. The corrected values were compared to the laboratory measurements on the same type of ice using a closed-loop test machine. In both cases, the test data was taken from previously published test results.

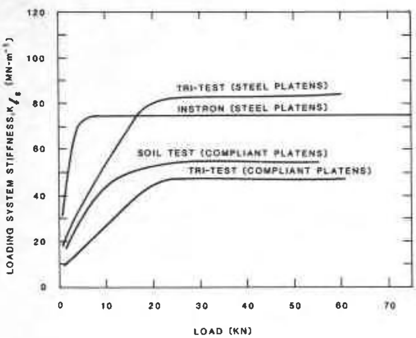

FIGURE 2
LOADING SYSTEM STIFFNESS
VERSUS LOAD FOR THREE
COMPRESSION TEST MACHINES

FRESHWATER ICE

The information on freshwater ice was taken from the published work of Sinha (1981a) who compared the results of compression tests by several investigators using a number of test machines. For this analysis, the results of his tests using the conventional Instron test machine are compared to his closed-loop test results. These results were presented in the form of a best-fit regression line through his data and they are shown in Figure 3. In order to apply equation (4) to his results, the loading system stiffness and elastic modulus of the ice must be known. The former is shown in Figure 2. An appropriate value for the elastic modulus of the ice for a given strain rate was taken from the results of Traetteberg et al. (1975) which gives the strain rate dependence of the modulus for both granular and columnar S2 freshwater ice. Using these values, the test results of Sinha were re-analysed using equation (4), and the result is shown in Figure 3. There is excellent agreement between the strength obtained using the conventional and the closed-loop machine.

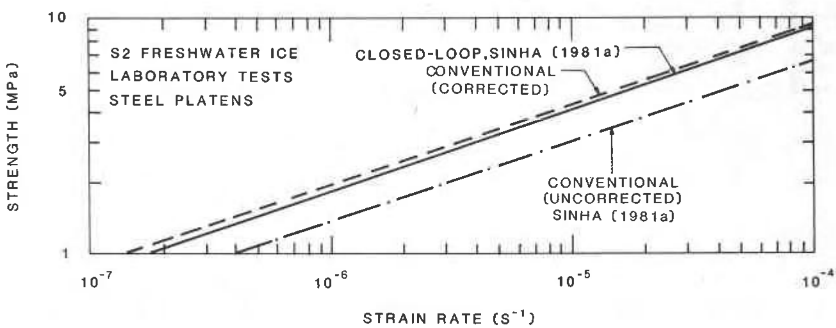

FIGURE 3 STRENGTH-STRAIN RATE RELATIONSHIP FOR S2 FRESHWATER ICE SHOWING SINHA'S RESULTS OBTAINED USING BOTH A CONVENTIONAL AND CLOSED-LOOP TEST MACHINE. THE DASHED LINE IS THE CONVENTIONAL MACHINE TEST RESULTS CORRECTED FOR MACHINE STIFFNESS USING THE PROPOSED MODEL

SEA ICE

For this type of ice, the results of compression tests performed by the authors in the field on granular sea ice using two different test machines (Soiltest CT-405; Tri-Test 50) with both compliant and steel platens (Frederking and Timco, 1983; 1984) were compared to the results of tests made by Wang (1979) on the same type of sea ice under laboratory conditions using a closed-loop test machine. In all cases, the test temperature was approximately -10°C, and the ice was of comparative salinity. The results for these tests are presented in Figure 4a. Similar to the results for the freshwater ice tests, the as measured strength of the ice is less than those for comparable strain rates obtained with the closed-loop machine. Since the elastic modulus of the ice was not measured in these tests, an estimate of it was made by using the relationship between the elastic modulus (E) and the brine volume

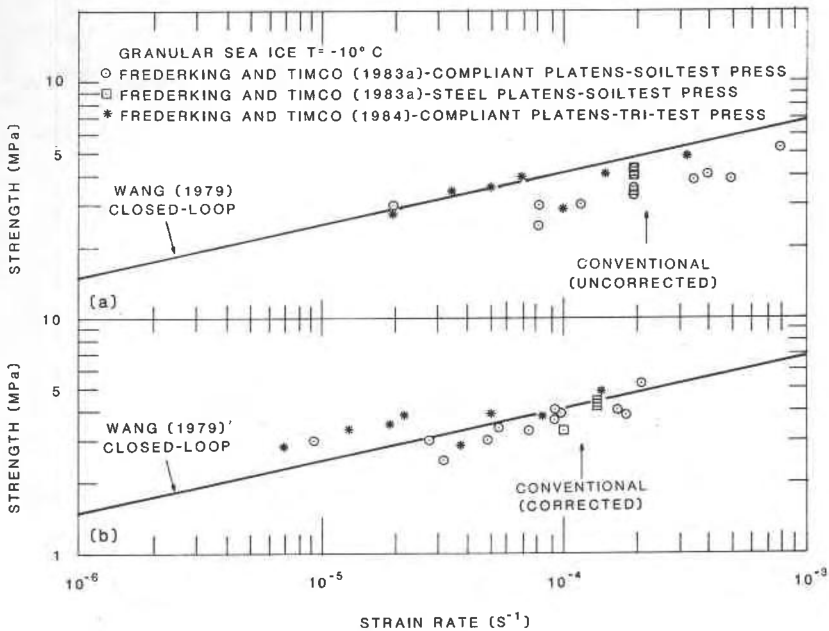

FIGURE 4 STRENGTH-STRAIN RATE RELATIONSHIP FOR GRANULAR SEA ICE SHOWING WANG'S LABORATORY RESULTS OBTAINED USING CLOSED LOOP MACHINE AND FREDERKING AND TIMCO'S FIELD RESULTS OBTAINED USING CONVENTIONAL MACHINES (a) UNCORRECTED, (b) CORRECTED FOR MACHINE STIFFNESS USING THE PROPOSED MODEL

(υ_b) determined for sea ice by Vaudrey (1977), $E = 5.32 - 13\sqrt{\upsilon_b}$ GPa. Using these values and equation (4), the results of the tests by Frederking and Timco were re-analysed and are presented in Figure 4b. The corrected values compare well with those of Wang.

SUMMARY

The method outlined in this note, based on a knowledge of the test system stiffness and specimen modulus, appears to provide a reasonable first approximation for correcting strain rates in strength tests. The technique can be applied to interpreting data already in the literature if the test machine stiffness is known. It also provides a rationale for using conventional test machines in field testing.

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