Recommended Standards for Small-Scale Ice Strength Tests
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by T. R. Butkovich

U. S. ARMY SNOW ICE AND PERMAFROST RESEARCH ESTABLISHMENT
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PREFACE

This report was prepared by Mr. T. R. Butkovich, physicist, Snow and Ice Basic Research Branch. The recommendations are results of work performed under SIPRE project 22.1-10, Ultimate strength of snow and ice, under the general supervision of Mr. J. A. Bender, branch chief.

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SUMMARY

The effects of specimen size and shape on the strength values obtained with small-scale unconfined compressive tests are shown. Results are given that show that a loading rate of 0.5 kg/cm²-sec is required for all small-scale strength tests to minimize plastic effects which accompany slow loading of ice. The ring test, which is a useful new type of test to measure the tensile strength of ice, is described. Recommended standards for specimen size, shape, and configuration along with loading rates and equipment are discussed.
RECOMMENDED STANDARDS FOR SMALL-SCALE ICE STRENGTH TESTS
by
T. R. Butkovich

INTRODUCTION

Every engineer and applied scientist interested in the bearing capacity of ice sheets will, at one time or another, either perform small-scale strength tests on the ice or accept some predetermined values that were so obtained. The strength values of ice depend upon two types of conditions: first, those imposed objectively, such as temperature, grain size, orientation, and salinity; and, second, those imposed subjectively by the observer. Most observers choose test techniques arbitrarily; the choice depends on tools, materials, and facilities available. However, such factors as size and shape of the test specimen and loading rate also affect the magnitude of the strength test results. Standards should be set up so that anyone may immediately see the differences between one type of ice and another, and know that these differences are real.

An important consideration in the selection of a type of test to measure strength is that the test should be easy to make in the field and in the laboratory. A minimum amount of sample preparation and the use of a more or less portable strength test apparatus is preferred.

Several criteria have been developed for use with ice, such as loading rates and test specimen size and shape, as well as a new technique for measuring tensile strength.

UNCONFINED COMPREHENSIVE STRENGTH

The compression test is principally used for testing brittle materials. Ice falls into this category. The first step prior to making these tests is to choose a shape for the test specimen. In testing brittle materials such as stone, concrete, and cast iron, cubical or cylindrical specimens are commonly used.

It is not widely known how the shape of the cross section of the test specimen influences the results obtained. One might suspect that different values would be obtained with circular and square cross-sections because of edge effects. A number of tests using commercial ice were made in the USA SIPRE laboratory on 10-cm² cross sections using a height to width ratio of 3 to 1. They were made on rough-cut prisms, with and without the end surfaces machined, on rough-cut octagonal prisms, and on machined cylindrical specimens. Keeping all other test conditions constant, the mean strengths with their standard deviations for 10 specimens at -10°C were:

- Square prisms, rough-cut (all sides) 61.8 ±7.9 kg/cm²
- Octagonal prisms, rough-cut (all sides) 64.7 ±7.8 kg/cm²
- Square prisms, rough-cut (machined ends) 70.8 ±4.0 kg/cm²
- Cylindrical (machined ends) 83.1 ±4.1 kg/cm²

Besides the greater values obtained, cylindrical and rough-cut prisms with machined ends show a considerably better degree of reproducibility and should be used when possible. It is suspected that the large differences could be reduced with larger cross sections.

The knowledge of how specimen size and ratio of length to width or diameter affects the magnitude of the results is also necessary. Previously, many observers used cubical specimens for measuring the unconfined compressive strength of ice. Because of the friction on the surfaces of contact between the specimen and the compressing head of the machine, the lateral expansion due to the effect of Poisson's ratio which accompanies compression is prevented at these surfaces. A usual method for eliminating the effect of these friction forces is to use longer specimens.
The middle portion of the specimen then approaches a condition of uniform compression. On the other hand, when the length of a specimen under compression is large in comparison with its transverse dimensions, failure tends to occur by buckling or lateral bending rather than by direct compression.

A large number of tests was made to determine the effect of specimen size (Butkovich, 1955). Rough-cut square prisms of clear lake ice cut with the long axis parallel to the ice sheet were used. Length to width ratios of 2 to 1 and 3 to 1 were tested because it was expected that end constraint would be a minimum and columnar action would not take place in this range. Figure 1, for the 3 to 1 ratio of length to width, shows that somewhat higher values of unconfined compressive strength are obtained with the smaller cross sections and, when the cross sectional area is greater than 10 in.$^2$ (64.5 cm$^2$), the magnitude of the results are more or less constant. Figure 2, for the 2 to 1 ratio of length to width, is a similar type of curve, but the dependence of strength upon area is somewhat less above 10 in.$^2$. This is probably due to some end constraint still being present.

Before the development and perfection of the USA SIPRE 3-in. diam ice-coring auger, it was difficult to make strength tests on cylindrical specimens. Sample preparation required special equipment, was extremely time consuming, and was confined to the laboratory. The 3-in. auger has been tried and proven to work equally well in fresh-water ice, sea ice, and high-density snow. Long uniform cores are consistently obtained. This ice auger has the added advantage of obtaining a near finished specimen in the field, requiring only a minimum amount of additional preparation. Its cross sectional area of more than 7 in.$^2$ (45.6 cm$^2$) comes very close to filling the requirement that the sample area be 10 in.$^2$ or greater in unconfined compression. With the ice auger, samples can be taken vertically deep into thick ice sheets and glaciers. Continuous cores have been taken to a depth of about 100 ft (30 m) into the Greenland Ice Cap. With the exception of beam tests, all strength tests have been adapted for use with a 3-in. diam cylindrical core.

Ice is usually considered a visco-plastic material, with small elastic effects. Consequently, the magnitude of the strength test results are dependent on the loading rate at the lower rates. If the loading is performed fast enough, the elastic effects mask the plastic effects and the stress-strain curve is linear to near the failure stress. Jellinek (1957) found a relationship between rate of stress application and tensile strength which shows that for rates greater than 0.5 kg/cm$^2$-sec, the magnitude of the results are no longer dependent on the loading rate (Fig. 3).

![Figure 1. Crushing strength vs area, Portage Lake Ice. 3:1 ratio of length to width. Parallel to ice sheet.](image1)

![Figure 2. Crushing strength vs area, Portage Lake Ice. 2:1 ratio of length to width. Parallel to ice sheet.](image2)

![Figure 3. Average tensile strength as a function of rate of stress application for snow-ice cylinders (height 2 cm, diam 2cm). (From Jellinek, 1957)](image3)
From these results, the following standards for unconfined compressive strength tests of ice are recommended:

<table>
<thead>
<tr>
<th>Specimen shape</th>
<th>cylindrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>3 in.</td>
</tr>
<tr>
<td>Ratio of length to diameter</td>
<td>2.5 - 3 to 1</td>
</tr>
<tr>
<td>Loading rate</td>
<td>greater than 0.5 kg/cm²-sec</td>
</tr>
</tbody>
</table>

TENSILE STRENGTH

A new test technique for use with high-density snow or ice, which is easily adapted to field work, has been tried by USA SIPRE (Butkovich, 1956a, 1956b). This test was previously used successfully for the determination of the tensile strength of rock, concrete, and other brittle materials. A ring of the material is caused to fail by applying a compressive load normal to its axis. The failure plane is always directed under and parallel to the direction of application of the load (Fig. 4). The theory for these tests is discussed in an article by Ripperger and Davids (1947).

Ring tensile strength as determined by failure of point 2 is determined by the equation

\[ \sigma_T = \frac{KP}{\pi r_0} \]

where \( P \) is the load per unit ring length and \( r_0 \) the outer radius of the ring. The constant \( K \), the concentration factor, depends only on the ratio \( \bar{r} = r_1/r_0 \), where \( r_1 \) is the inner radius of the ring. Theoretically, if the test is made on a solid cylinder \((r_1 = 0)\), the value of \( K \) is 1.0. However, if an infinitesimal small hole exists in the center of the cylinder, \( K \) passes discontinuously from 1.0 to 6.0. Figure 4 also shows how \( K \) varies with \( \bar{r} \). For a \( \frac{1}{2} \)-in. hole in the 3-in. diam core, \( \bar{r} = 0.166 \) and \( K = 7.1 \) approximately, and for the 1-in. hole in the 3-in. core, \( \bar{r} = 0.33 \), \( K = 10.9 \) approximately.

It has been found that the ring test consistently yields somewhat higher values of tensile strength than either flexural or direct tension tests. This is attributed to the fact that stress concentrations occur over extremely small volumes, and failure is forced upon a predetermined small volume.

After a load is applied, theoretically an infinite stress exists at \( r_0 \) directly under the load (point 4 in Figure 4). However, a finite stress at point 2 causes the failure. One explanation that is advanced is that a slight plastic deformation occurs under the load, and causes such a redistribution of load that the infinite stress over an infinitesimal area is changed to a finite stress over a finite area. If the material is strong in compression, such a redistribution would not materially affect the stress at an appreciable distance from the point of loading.

It can be expected that higher values of tensile stress would be obtained with smaller volumes. Jellinek (1957) and others have explained this on the basis of a distribution of imperfections in ice. The distribution is considered in relation to the strengths of the imperfections. Each imperfection can withstand stresses up to a certain value. When the critical stress is exceeded, a crack opens up which does not grow beyond a certain unspecified average size. Thus, there will be stress relief in the neighborhood of this crack, and the next strongest imperfection will open up.
The specimen will rupture when a cascade of cracks forms across the specimen. Since the probability of the weak imperfections existing is greater in larger volumes than in smaller volumes, small volumes will yield higher tensile strength values.

The application of the ring test for measuring tensile strength does make use of the assumption that the tested material is truly elastic. Therefore, as with the unconfined compression tests, the loading rates must be fast enough, that is greater than 0.5 kg/cm²·sec, so that the plastic effects are overshadowed by the elastic effects.

In the equation for determining ring tensile strength, the dependence of the failure on the specimen length has not been investigated. The length of the rings used has usually been about 3 in., primarily for testing convenience.

A group of tests was made on glacier ice to see if different results would be obtained with different size holes. Parallel tests were made using solid cylinders, 1/2-in. holes, and 1-in. holes in the 3-in. core. The results for the 1/2-in. and the 1-in. hole were the same within the standard deviations. However, not enough results are available at this time to recommend solid cylinder tests. The 1/2-in. hole in the 3-in. cylinder is preferred primarily because, with weak ice, larger loads are required to cause failure, and most load measuring devices are more accurate at higher loads.

The recommended standards for measuring tensile strength of ice with ring tests are:

1. 3-in. diam cores from 2 1/2 to 3 in. long
2. 1/2-in. hole drilled coaxially
3. Loading rate greater than 0.5 kg/cm²·sec

FLEXURAL STRENGTH

Historically, beam tests take precedence over ring tests. The values of tensile strength that most observers report in the literature are from beam tests. However, ring tests give values which are more nearly representative of the average tensile strength of ice.

The beam test is quite simple to make, although a greater amount of sample preparation is required. A block of ice is removed from the ice sheet and sawed into parallel slabs, which are sawed into beams. The flexural strength of simple beams is

$$\sigma = \frac{M}{S}$$

where $M$ is the moment and $S$ the section modulus. The moment at the center caused by the applied force is

$$M = \frac{P l}{4}$$

where $P$ is the force exerted on the ice beam and $l$ the beam span. The section modulus is

$$S = \frac{bh^2}{6}$$

where $b$ is the average width and $h$ the average height of the beam, both measured at the failure plane. In the case where the beam fails other than at the point of load application, the flexure strength is computed as

$$\sigma_c = \sigma (1 - \frac{2a}{l})$$

where $a$ is the distance off center where the break occurred. If the beam is large an additional correction is made for the stresses caused by the weight of the beam itself.

No specific size beams were tested, although the limits of width and height vary between 6 to 15 cm and 4 to 7 cm respectively. The beam spans used varied between
40 and 60 cm, with beam length between 50 and 80 cm. The most important consideration for these tests is that the loading rate be greater than 0.5 kg/cm²·sec.

As was previously mentioned, these tests yield results about 10% lower than ring tests, which is about the same as would be obtained in direct tension.

The main advantage of a beam test is that it does not require any special equipment. These tests can be performed by anyone with an ice saw and a "home made" beam breaker, which consists of supports and a load applying and measuring arrangement. The following standards are recommended for center-loaded simple beam tests:

<table>
<thead>
<tr>
<th>Paramter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam length</td>
<td>75 cm</td>
</tr>
<tr>
<td>Beam span</td>
<td>60 cm (50 or 40 cm as alternates)</td>
</tr>
<tr>
<td>Height</td>
<td>5 - 6 cm</td>
</tr>
<tr>
<td>Width</td>
<td>10 - 12 cm</td>
</tr>
<tr>
<td>Loading rate</td>
<td>Greater than 0.5 kg/cm²·sec.</td>
</tr>
</tbody>
</table>

**SHEAR STRENGTH**

A device to measure the shear strength of ice and high density snow has been used with varying degrees of success by USA SIPRE (Butkovich, 1956a, Fig. 4). It consists of a hollow tube, 3 inches ID to accept a 3-in. diam cylinder of the test material. The tube is 12 in. long, divided into three 4-in. segments. The two ends are fixed and the middle section is attached to a load-measuring device. Shear strength is determined by measuring the force required to punch out the middle section of the core.

Although the device yields itself rather nicely to field tests, there are serious faults in this testing technique. First of all, a flexure failure always occurs near the middle of the test specimen, similar to that obtained with simple beams in flexure. Secondly, failure is being forced upon arbitrary planes which are not necessarily the weakest planes. Test results show excellent reproducibility for a homogeneous granular material such as snow, but almost any results can be expected for ice. As far as is known, no good simple test exists in which ice can be made to fail in pure shear.

**REMARKS**

A hand-operated mechanical loading press employing a screw jack is preferred over either a hydraulic or a motor-driven press because a near-constant rate of stress application can be attained when the operator controls the movement of the crosshead. A hydraulic jack tends to apply the load in increments, and with a motor drive a constant speed of crosshead motion, or constant strain rate is achieved. In practice, the loading rate accelerates until about half the ultimate load is attained, where it becomes nearly constant.

It was found that a 15,000-lb capacity press is required to cause failure of the 3-in. diam sea-ice cores in unconfined compression at temperatures below -20°C. Load measuring devices should have at least two ranges, one for the maximum press capacity, and another of no greater than 1000 lb for use with ring tests. Another lower capacity proving ring (200-500 lb) should be provided for testing extremely weak ice, such as sea ice at or very near its melting point.

In addition, it should be emphasized that a complete description of the ice tested be given and, if applicable, the values of density, salinity, grain size, orientation, temperature, loading rate, and history of the ice should be given with the results. With these variables known, the results can be adequately interpreted.
REFERENCES


