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IN-SITU TENSILE TESTS OF SNOW-PACK LAYERS

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ABSTRACT. During the winter of 1987–88, an average of seven tensile tests was made for each of 66 snow layers in the Rocky Mountains of western Canada. The precision of the mean strength for seven tests, expressed in terms of the coefficient of variation, was 15% with 90% confidence. Snow with a faceted micro-structure was approximately half as strong as partly settled or rounded snow of the same density. Notch sensitivity in the strength data and critical strains of 1% or less indicate that the test fractures were essentially brittle.

INTRODUCTION

In-situ testing allows the properties of snow to be established with minimal risk of damage to specimens due to extraction from the snow-pack, transportation to a testing laboratory, and setting up in a testing device. It also facilitates the estimation of properties such as tensile strength using specimen cross-sections substantially larger than those feasible in laboratory work, thus reducing the severity of the specimen-size effect often prevalent in brittle fractures. However, *in-situ* testing does not permit control of variables such as snow temperature, ambient air temperature, or humidity. In addition, only rather imprecise control of stress rates is possible with the manual testing techniques presently available for *in-situ* work.

An *in-situ* tensile test based on a technique developed by Conway and Abrahamson (1984) was used in the present study. Over 450 tensile tests were made during the winter of 1987–88 in and near the Lake Louise Ski Resort in the Canadian Rocky Mountains.

PREVIOUS *IN-SITU* STUDIES

Roch (1966) measured the strength of 37 snow slabs by averaging the results of tensile tests repeated every 50 mm down the face of crown fractures. For each test, parts of the slab 30–60 mm thick were gripped with hollow samplers with cross-sections of 2×10^{-3}–$3 \times 10^{-2}\,\mathrm{m}^2$ and uniaxial tension was applied to the samplers with a spring gauge. As discussed subsequently, Roch's tests on these small cross-sections resulted in strengths generally higher and more variable than strengths from studies which used larger cross-sections.

Perla (1969) made approximately 250 cantilever beam tests on newly fallen snow. As with other bending tests, areas of maximum tensile stress at failure were small and indeterminate. Tensile strength was estimated by presuming tensile failure at the top of the failure surface; however, the shapes of the fracture surfaces suggested that some fractures may have involved shear effects (McClung, 1979). Also, the estimates of strength for a given density vary widely, in some cases by a factor of ten.

In 38 rolling-cart tests, McClung (1979) applied essentially uniaxial tension to specimens with cross-sections of approximately $0.12\,\mathrm{m}^2$. Each specimen was loaded to failure in 1–8 min by tilting the table under the rolling-cart. The results were not affected by the shape of the notches, which indicates that the fractures involved ductility. Also, the strengths from these uniaxial tests showed less variability than Perla's (1969) cantilever beam tests.

Conway and Abrahamson (1984) developed the "slip-plate" test method shown in Figure 1 and used in the present study. They made 32 tensile tests of snow slabs on avalanche slopes with loading times to failure of up to 15 s and cross-sections of approximately $0.1\,\mathrm{m}^2$.

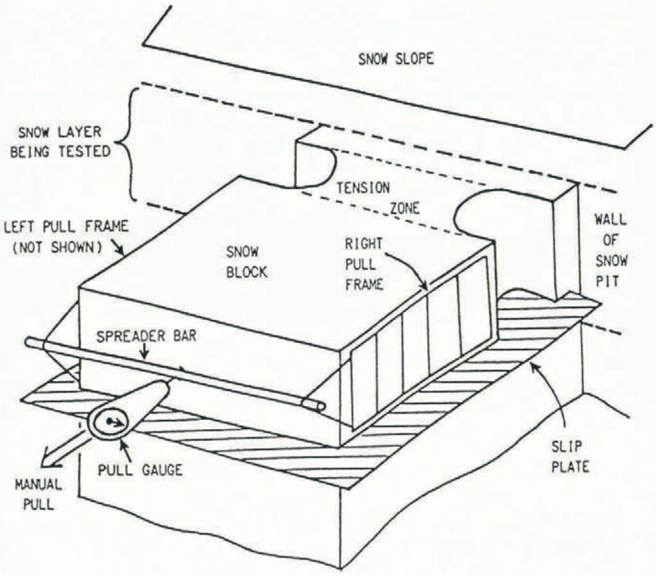

Fig. 1. Slip-plate tensile test with load applied parallel to the slope.

Rosso (1987) measured the strength of 13 snow slabs on steep slopes. For each test, a large trapezoidal block of a snow slab was under-cut parallel to the slope with a snow saw from the lower wider end toward the upper narrower end until it failed in tension. Cross-sections at the point of failure ranged from 0.04 to $0.24\,\mathrm{m}^2$. To support the under-cut part of the block and thus minimize bending stresses, a foam pad was trailed behind the saw to fill the gap left by the saw cut. This technique is more time-consuming than the slip-plate technique and can be done only on steep slopes.

TEST METHOD

The present study used the test method developed by Conway and Abrahamson (1984), since it applies essentially uniaxial tension to comparatively large cross-sections, requires only 10–15 min per test, and can be done on level or sloping terrain.

The test method involves isolating a block of snow which remains attached to the up-slope (or back) wall of a pit in the snow-pack as shown in Figure 1. The block is separated from its supporting column of snow by inserting a low-friction slip plate, and is gripped on either side by a metal pull frame. The snow attaching the block to the up-slope (or back) wall of the snow pit is narrowed by cutting a 50 mm radius notch behind each pull frame. Cords attach each pull frame to a spreader bar and tension is applied to the mid-point of the spreader bar by a manually operated spring gauge which records the maximum force. The load is applied parallel to the slope and is increased at an approximately constant rate until fracture occurs across the notched tensile zone.

In the present study, the tops of the blocks measured approximately 0.4 m by 0.4 m and the blocks were at least 0.1 m thick. Loading times ranged from 0.5 to 5 s with a mean of 2.2 s. Friction between the snow and the slip plate was measured by tilting the plate and measuring the "friction angle" at which a snow block on the plate began to slide. Friction angles for the snow blocks on the waxed slip plate ranged from 2° to 10° with a mean of 3.6°. These friction angles were obtained by waxing the plate with paste wax for skis. (Coating the plate with a no-stick spray for cooking pans or with a silicon-based spray for ski-bindings resulted in higher friction angles.)

Since the fractures occurred between the notches, the snow in the notched tensile zone was considered to be the specimen. Most specimens in the present study were contained within a single layer of the snow-pack. The grains in each layer were observed under low magnification and classified by predominant grain shape according to UNESCO/IASH/WMO (1970).

EQUIPMENT

Slip plate

Plates of 0.6 mm stainless steel were employed to undercut the snow blocks cleanly and were sufficiently stiff to resist denting and bending under normal handling. The size of each plate was 0.45 m across, 0.40 m in the down-slope direction, with 25 mm stiffening flanges on three sides at right-angles to the surface of the plate. The cutting edge without the flange was sharpened to facilitate gentle insertion under the snow block and minimize the risk of disturbance. Such plates proved adequate for all but extremely weak snow layers where premature failure occasionally occurred during insertion of the slip plate.

Pull frames

Frames soldered from 25 mm wide strips of 0.45 mm stainless steel proved adequately sturdy for testing snow with densities ranging up to 350 kg m^{-3}. The length of the frames was 0.28 m to allow for a 100 m notched zone at the back of the block and for a 10–20 mm gap between the snow block and the front flange of the plate. Four equally spaced cross-pieces were soldered in place. To ensure that the depth of the frames approximately spanned the depth of the snow layer being tested, frames with depths of 0.10, 0.20, and 0.30 m were used. The cutting edges of the frames were sharpened to permit penetration of the sides of the snow block with minimal disturbance.

Notching tool

The blade of this tool consisted of 0.7 mm stainless steel sheet metal bent into a semi-circle with a 50 mm radius. During the study of notch sensitivity, which is discussed subsequently, two other notching tools producing notch radii of 10 and 1 mm were also used.

CALCULATION OF TENSILE STRENGTH

During each test the following parameters were recorded: maximum pull force (P), loading time to cause fracture (t), length of the block down-slope (l_b), cross-slope width of the block (w_b), depth of the block (d_b), the corresponding dimensions of the tensile zone (w, d), slope angle (β), friction angle (ϕ) for the snow block on the plate, mean snow density (ρ), and the mass of the frames (m_f).

Equilibrium conditions just prior to fracture dictate that the average stress is:

$$\sigma = (W \sin \beta + P - W \tan \phi \cos \beta)/(wd) \qquad (1)$$

in which the weight of the block and frames is

$$W = (l_b w_b d_b \rho + m_f)g \, . \qquad (2)$$

INFLUENCE OF TESTING VARIABLES ON STRENGTH

Rate effects

Although manual loading does not allow precise control of the loading rate, the effect of the approximate stress rate on strength was investigated. The test method was repeated eight to 18 times using various loading rates on each of four different layers of rounded grains. The loading rate was maintained approximately constant during each test. However, for each set of tests on a particular layer, a range of loading rates was applied and loading times ranging from 1.5 s to more than 40 s were obtained. Approximate stress rates ($\dot{\sigma}$) were calculated from the stress at failure (σ) and the loading time (t):

$$\dot{\sigma} \approx \sigma/t \, . \qquad (3)$$

For each set of repeated tests, Table I shows linear correlation coefficients for the trend between strength and stress rate. Since the two correlations which are significant at the 95% level are negative, there appears to be a general trend for strength to decrease with an increase in stress rate.

TABLE I. EFFECT OF STRESS RATE ON STRENGTH

Date	*Density* kg m^{-3}	*No. of tests*	*Correlation coefficient*	*Significance level*
16 Mar 1988	203	19	–0.53	0.98
22 Mar 1988	295	8	–0.09	0.16
24 Mar 1988	298	11	–0.60	0.95
8 Apr 1988	228	15	–0.32	0.76

Although Table I uses linear correlation coefficients, the trend between strength and stress rate may not be linear for the range of approximate stress rates used to test these four layers. In Figure 2, strength is plotted against stress rate for the set of 11 tests made on 24 March 1988. For this particular range of stress rates, it appears that a reciprocal relationship between strength and stress rate may be more appropriate than a linear one.

To reduce variability associated with rate effects, tests with loading times greater than 5 s were screened from the results discussed subsequently.

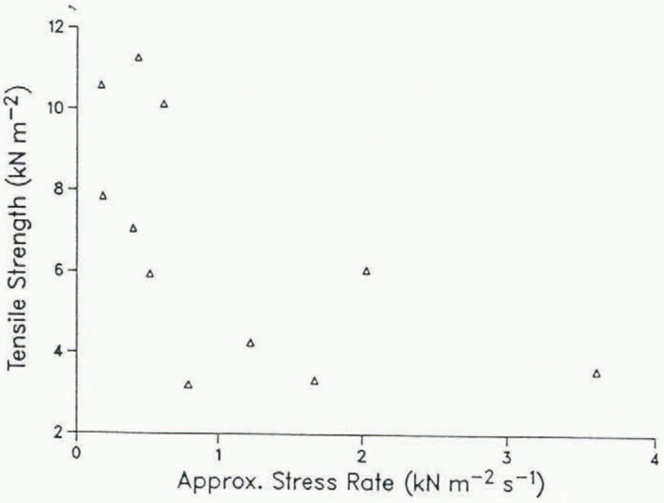

Fig. 2. Effect of stress rate on the strength of a layer of rounded grains with a density of 298 kg m^{-3}.

TABLE II. PREDICTOR VARIABLES FOR REGRESSION ANALYSIS

Test conditions	*Snow properties*	*Fracture characteristics*
Replicate number	Density*	Angle between plate and fracture
Loading time to failure*	Temperature	Fracture at front of notched zone*,†
Slope angle*	Moisture level†	Fracture at back of notched zone*,†
Fracture width*	Micro-structure*,†	Fracture crosses notched zone 20–40 mm forward of centre†
Fracture depth*		Fracture crosses notched zone 20–40 mm behind centre†
Friction angle for snow on plate		Fracture angles towards front of one notch†
Notch shape*,†		Fracture angles towards back of one notch†
Plate moved during loading†		Two fracture planes intersect at 10–20°†
		Two fracture planes intersect at >20°†
		Fracture bifurcates†
		Fracture at back of plate†
		Cup-shaped fracture†
		Protuberance on fracture surface†
		Fracture bypasses a V- or Y-shaped notch†

* Significant at 99% level.
† Categorical variable.

Notch shape

To study the effect of notch shape on the results, five different snow layers ranging in density from 184 to 338 kg m^{-3} were tested with 1 and 10 mm radii notches and with "standard" notches (50 mm radius). Fourteen tests with 10 mm radius notches were each matched with the standard test on the same layer that was physically closest and there was no significant difference in strength between matched tests at the 90% level. Nineteen tests with 1 mm radius notches were each paired with the closest standard test on the same snow layer and the mean difference in strength was significant at the 99% level. The strengths obtained with 1 mm radius notches were reduced an average of 22% from tests made with standard notches.

Screening of data

During the winter of 1987–88, a total of 555 tests was performed. The effect of various test conditions and fracture characteristics on the results was investigated by a multi-variate regression (Jamieson, unpublished). Several variables, including the location of the test pit, were excluded from the analysis because of strong correlations ($r > 0.65$) with other variables. The list of ten test conditions and 14 fracture characteristics included in the analysis is given in Table II. Many of the listed variables are categorical and each N-level categorical variable was represented by $N - 1$ dichotomous variables in the regression equation.

As indicated in Table II, density and micro-structure as well as five testing variables and two fracture characteristics were associated with increases in variability at the 99% level. The two fracture characteristics, fractures at the back of the notched zone and fractures at the front of the notched zone, were associated with a decrease in strength which averaged 11%. Two testing variables (notch radii of 1 mm and loading times greater than 5 s) have already been discussed. The other three testing variables (slope angle and the width and depth of the fracture surface) were accepted as sources of variability in the results as a whole. However, when the cross-sectional area of the notched zone was varied widely for 24 tests of a single layer at a particular study plot, significant size effects were not detected.

The following four factors: notch radii of 1 mm, loading times greater than 5 s, and fractures at the front or back of the notched zone, were considered to be unrelated to the field study of snow strength in terms of material properties, and the 98 tests associated with one or more of these factors were rejected, giving a refined set of 457 tests for studying the tensile strength of snow layers. The following sections of this paper are based on this refined data set.

For a total of 21 tests on four layers, the temperature of the snow specimen was 0°C and the free-water content was classified as slightly moist according to the "squeeze test" (UNESCO/IASH/WMO, 1970). The results of these 21 tests are included in the refined data set, since the regression analysis did not associate this moisture level with an increase or decrease in strength.

INFLUENCE OF SNOW CHARACTERISTICS ON STRENGTH

Density and microstructure

Typically, at a particular study site on a given day, the tensile stremgth of a snow layer was measured an average of seven times. Each set of repeated tests is considered to represent a distinct layer because the material properties of snow may change from day to day. The mean strength of each of the 66 sets of repeated tests is plotted against mean density in Figure 3.

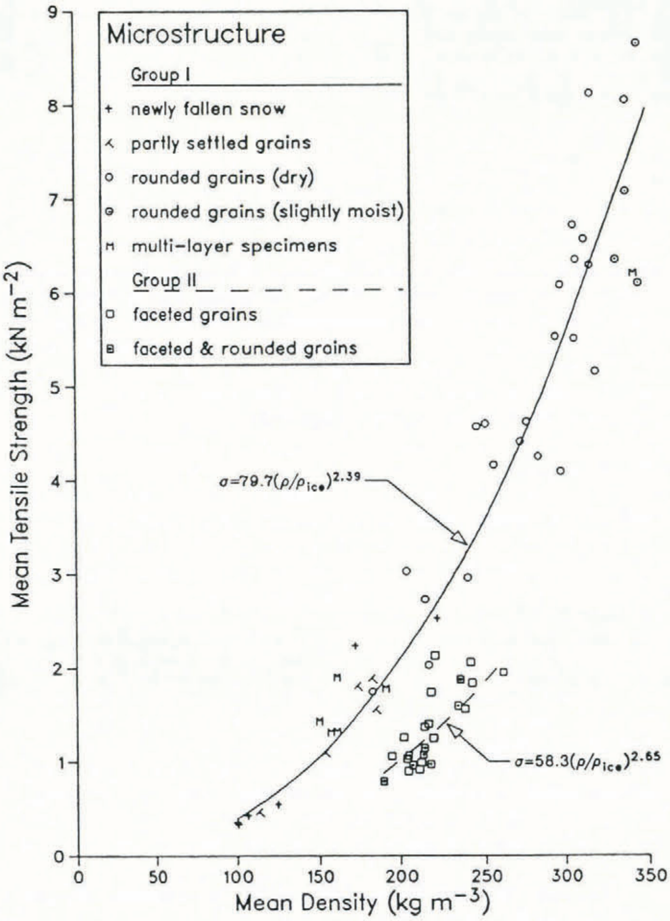

Fig. 3. Dependence of tensile strength on density and micro-structure.

Each layer is placed into one of two groups according to its micro-structure. Group I consists of layers of new snow, partly settled grains or rounded grains with no evidence of melting. Also included in group I are specimens which consist of more than one layer of new, partly settled or rounded grains. Group II consists of layers of faceted grains and of layers of grains which showed both faceting and rounding with no evidence of melting. Separate regression lines for group I and group II micro-structures are also shown in Figure 3. These two lines were obtained by regressing tensile strength (σ) on density (ρ) using the empirical equation:

$$\sigma = A(\rho/\rho_{\text{ice}})^{a} \qquad (4)$$

which is analogous to the equation used for shear strength by Perla and others (1982). In Equation (4), ρ_{ice} = 917 kg m^{-3}, a is a dimensionless constant, and A is a constant with units of kN m^{-2}. Values of a and A for the two regressions are shown in Table III, along with the range of density for which each group was tested.

TABLE III. REGRESSION COEFFICIENTS AND DENSITY RANGE

Micro-structure	*A*	*a*	*Density*
	kN m^{-2}		kg m^{-3}
Group I	79.7	2.39	100–345
Group II	58.3	2.65	190–260

For the density range of 190–260 kg m^{-3}, layers with group I and layers with group II micro-structures were tested. For any given density within this range, the strength of the group II layers was approximately half that of the group I layers. However, the results for group II layers may be biased upwards because a number of the weaker specimens broke before the load could be applied.

Comparison with the results of previous *in-situ* studies

In Figure 4, strength as a function of density is used to compare the individual test results of the present study with the results of previous *in-situ* tests from Roch (1966), Perla (1969), McClung (1979), Conway and Abrahamson (1984), and Rosso (1987). Faceted snow, wet snow, and moist snow are excluded from this comparison since there are only three tests on faceted snow (Rosso, 1987) and nine tests on wet snow (McClung, 1979) with which to compare the present results.

Roch (1966) used smaller cross-sections than the other studies and obtained higher and more variable strengths. Perla's (1969) cantilever beam tests, which involved small but indeterminate areas of maximum tensile stress, showed a similar amount of scatter. The remaining studies which applied uniaxial tension to larger cross-sections exhibit less variability.

Below a density of 250 kg m^{-3}, the present tensile strengths are consistent with the results of McClung (1979), Conway and Abrahamson (1984), and Rosso (1987). Above 250 kg m^{-3}, strengths from the present study appear lower than the few *in-situ* strengths reported by McClung (1979), Conway and Abrahamson (1984), and Rosso (1987). This reduction in strength is likely due to the rapid loading used in the present study.

Variability

Coefficients of variation of tensile strength were calculated for each set of more than one test on a particular layer. For the two largest sets (30 and 42 replicates), the coefficients of variation were both 0.20. For the different types of micro-structures, average values of the coefficient of variation ranged from 0.14 for partly settled grains to 0.23 for rounded grains, as shown in Table IV. The apparent increase in the average coefficient of variation for rounded grains compared to the value for other micro-structures may not be substantial and is in contrast with Sommerfeld (1973) who reported greater variability of faceted grains compared to other micro-structures.

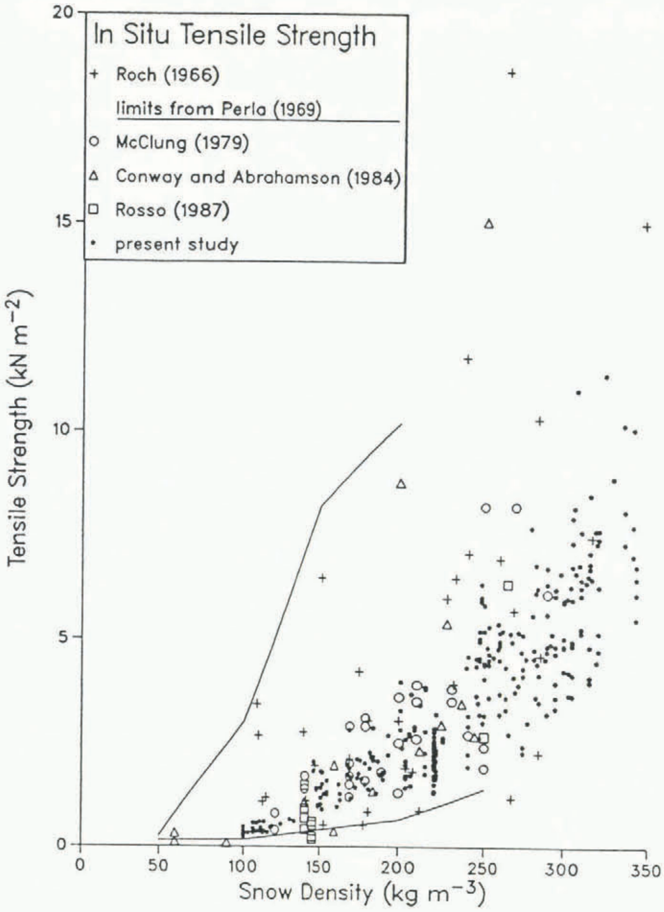

Fig. 4. Comparison with the results of previous in-situ studies. Results for moist or wet snow and for faceted grains are excluded from the comparison. One point from Roch (1966) falls above the top of the figure.

TABLE IV. COEFFICIENTS OF VARIATION OF TENSILE STRENGTH

Micro-structure	*No. of sets of replicates*	*Average*
Newly fallen snow	5	0.19
Partly settled	5	0.18
Rounded	23	0.23
Faceted	15	0.18
Faceted and rounded	8	0.14

Precision

Appropriate sample sizes for required levels of precision can be estimated from the coefficient of variation (v) of repeated tests on a particular layer of snow. The number of tests (n) which must be averaged to obtain precision (p) a the $1 - 2\alpha$ confidence level is given by

$$n = (t_{\alpha,n-1}v/p)^2 \, , \qquad (5)$$

in which $t_{\alpha,n-1}$ is the tabulated value from a Student's t-distribution with $n - 1$ degrees of freedom and which has a probability of α associated with each tail. Equation (5) is easily solved for n by trial and error and the results for a coefficient of variation of 0.20 are given in Table V.

An average of seven tests was made for each of 66 layers. With 90% confidence, the mean strength determined from seven replicates will have a precision of 15%.

Critical strain

Approximate values for the strain just before failure were obtained from a photographic technique which was applied to 15 tests. A scale graduated in 0.5 mm was placed across one of the two notches and this notch was photographed up to five times per second while the load

TABLE V. NUMBER OF TESTS FOR REQUIRED PRECISION

Required precision of mean, p	*Confidence level, 1 − 2α*	*Estimated number of tests, n*
%	%	
10	90	13
10	95	18
15	90	7
15	95	10

was increased manually. Loading times to failure for these 15 tests ranged from 1 to 14 s.

The deformation of the tensile zone before failure, as shown by the scale in the photographs, ranged from 0 to 1 mm with an average of 0.5 mm. Although the accuracy of this technique is only ±0.25 mm, the technique is useful for establishing an upper limit on the deformation. Since the length of the tensile zone is 100 mm, a deformation of 0.5 mm corresponds to a strain of 0.5%. Thus, the critical strains (just prior to failure) were less than 1%. This limit is used to determine the mode of failure, as discussed in the next section.

Mode of failure

In the laboratory, Narita (1983) observed that brittle tensile fractures occurred suddenly at strains of 0.8% or less and exhibited nearly planar fracture surfaces oriented perpendicular to the axial load. In the present study, fracture surfaces were approximately planar and averaged 91.5° from the axial load, and critical strains were 1% or less. This agreement between Narita's (1983) laboratory results and the present *in-situ* results, combined with the notch sensitivity discussed previously, indicates that the fractures in the present study were essentially brittle.

CONCLUSIONS

1. Tensile tests were made on a total of 43 layers of new, partly settled or rounded grains with no evidence of melting. An average of seven tests was made on each layer. In the density range of 100–345 kg m^{-3}, the brittle tensile strength, in kN m^{-2}, of these layers can be approximated by

$$\sigma = 79.7(\rho/\rho_{\text{ice}})^{2.39}.$$

An average of six tensile tests was made on each of 23 layers of faceted grains. In eight of these layers, the grains exhibited both faceting and rounding without evidence of melting. In the density range of 190–260 kg m^{-3}, the brittle tensile strength of the 23 layers can be approximated by

$$\sigma = 58.3(\rho/\rho_{\text{ice}})^{2.65}.$$

However, this empirical equation may be biased upwards because a number of weaker specimens of faceted snow broke before the load was applied. In the density range of 190–260 kg m^{-3}, layers of faceted grains were approximately half as strong as layers of partly settled or rounded grains.

2. In sheltered study plots, where snow-pack layers show less variability than in areas exposed to wind, coefficients of variation of tensile strength were typically 0.20. This implies that approximately seven tests are required for a precision of 15% with 90% confidence and approximately 13 tests are required to obtain a precision of 10% with 90% confidence.

3. An increase in the manually applied stress rate tended to decrease the strength for loading times ranging from 1.5 to 40 s.

For loading times of 14 s or less, the 100 mm long tensile zones elongated by 1 mm or less prior to fracturing. This apparent limit of 1% on critical strain is in agreement with Narita's (1980) laboratory results for brittle fractures.

4. When tests were made with notches with tip radii of 1 mm, strength was reduced by an average of 22% compared to tests made with notch radii of 50 mm. Such sensitivity to notch shape is expected for brittle fractures.

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