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SNOW AND ICE PROPERTIES AS RELATED TO ROADS AND RUNWAYS IN ANTARCTICA

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PREFACE

This work was performed by the U.S. Army Cold Regions Research and Engineering Laboratory in response to a request by the U.S. Naval Support Force, Antarctica, during "Operation Deepfreeze 65" at McMurdo, Antarctica.

The study was conducted by Messrs. Guenther Frankenstein and Gunars Abele, Research Civil Engineers of the Applied Research Branch (Mr. Albert F. Wuori, Chief) of the Experimental Engineering Division (Mr. Kenneth A. Linell, Chief), USA CRREL.

Pfc. Richard Haney, U.S. Army Research Support Group, assisted in the construction of the experimental runway section and participated in the performance of the field tests.

Mr. George Hendrickson, under contract with Dartmouth College, assisted in the field tests.

The report has been given pre-publication review by Dr. A. Assur and Messrs. A.F. Wuori, F.J. Sanger and M. Mellor.

USA CRREL is an Army Materiel Command laboratory.

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SUMMARY

During "Operation Deepfreeze 65" a study was performed on the mechanical properties of snow and ice at McMurdo, Antarctica, and the feasibility of snow and ice runway construction in this area.

The Peter plow (Peter snow miller) processing and LGP D-8 tractor compaction methods appear to be superior to the pulvimixer processing and roller compaction methods, as far as the effective depth of processing and compaction and the resulting mechanical properties of the snow pavement are concerned. The Peter plow method appears to be more difficult from an operational standpoint.

The automatic snow finegrader did not perform properly, apparently because of a hydraulic malfunction.

Snow runways capable of supporting a C-130 aircraft on wheels can be constructed either with the Peter plow or with the pulvimixer. However, the runway would be reliable only during comparatively low temperatures (< -15C).

The feasibility of supporting a C-121 on wheels on runways prepared by these methods appears to be marginal. Additional strengthening of the runway surface by other methods may be necessary.

The criteria for support of various types of aircraft on a snow runway are presented.

The study of ice properties consisted of dynamic and static tests. The dynamic tests were performed to determine the Young's modulus of sea ice, derived from longitudinal wave velocities measured with a soniscope. The static tests consisted of standard ring tensile strength and simple beam or flexural strength tests. The strength data were plotted on a base of the brine volume for each test. The test results indicate that the annual sea ice at McMurdo Sound is capable of supporting cargo type aircraft.

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INTRODUCTION

One of the main prerequisites for a successful operation in a remote polar area is reliable logistic support. An operation such as "Operation Deepfreeze" in Antarctica, because of its extremely remote location, depends heavily on air support for the transport of personnel and equipment. Effective air support can be maintained only with adequate runway facilities.

The terrain and climatic conditions do not permit standard runway construction methods in Antarctica. It is, therefore, necessary to investigate the potential of snow and ice as construction materials.

This report is on the mechanical properties of snow and ice at McMurdo, Antarctica, and the feasibility of snow and ice runway construction in this area. The field work was conducted during January and February 1965.

Detailed test results are presented in the Appendices.

STUDY OF SNOW PROPERTIES

Description of study

The phenomenon of "age hardening" of snow, after mechanical disaggregation, has been previously discussed by various authors (Bader *et al.*, 1939; Nakaya, 1959, 1961; Fuchs, 1960). The mechanical disaggregation of snow, which causes subsequent age hardening and significantly increased strength, is the fundamental method used in snow runway construction. Several types of equipment can be used to achieve this. Also, various methods can be used to produce additional compaction and thus further increase the ultimate strength of the processed snow.

USA CRREL's work in this field has dealt primarily with the development of design criteria theoretically and empirically (by using small, experimental test strips and simulated aircraft loads).

The concept developed by USA CRREL in the construction of snow runways is essentially the same as that used by the Naval Civil Engineering Laboratory (NCEL). However, the methods and equipment used vary in some respects. Since the depth of processing with the modified pulvimixer is limited to a depth of 40 to 50 cm, the processing of a snow pavement is done in layers. The Peter plow (Peter snow miller) is capable of processing to a depth of at least 130 cm.

The Peter plow snow processing and compaction methods (USA CRREL method) and results have been discussed by Wuori (1960, 1962a, 1963a). The snow mixer (a modified pulvimixer) method and compaction techniques used in Antarctica (NCEL method) have been described by Moser (1962, 1963, 1964) and Page (1964).

The original plan of study called for the construction of two or three small test strips, using the various processing, compaction and leveling methods. The age hardening process of the various snow pavements would be monitored and eventually taxiing tests with aircraft would be performed.

However, because of the need for emergency landing and take-off facilities at McMurdo after the annual ice runway becomes unusable, it was necessary to concentrate all efforts in the construction of a 3500 ft long cross-wind runway (oriented in the direction of storm winds) on the snow-covered sea ice at Williams Field (Fig. 1). The NCEL pulvimixer processing method was used for 2500 ft and the Peter plow (Fig. 2) method for the remaining 1000 ft.

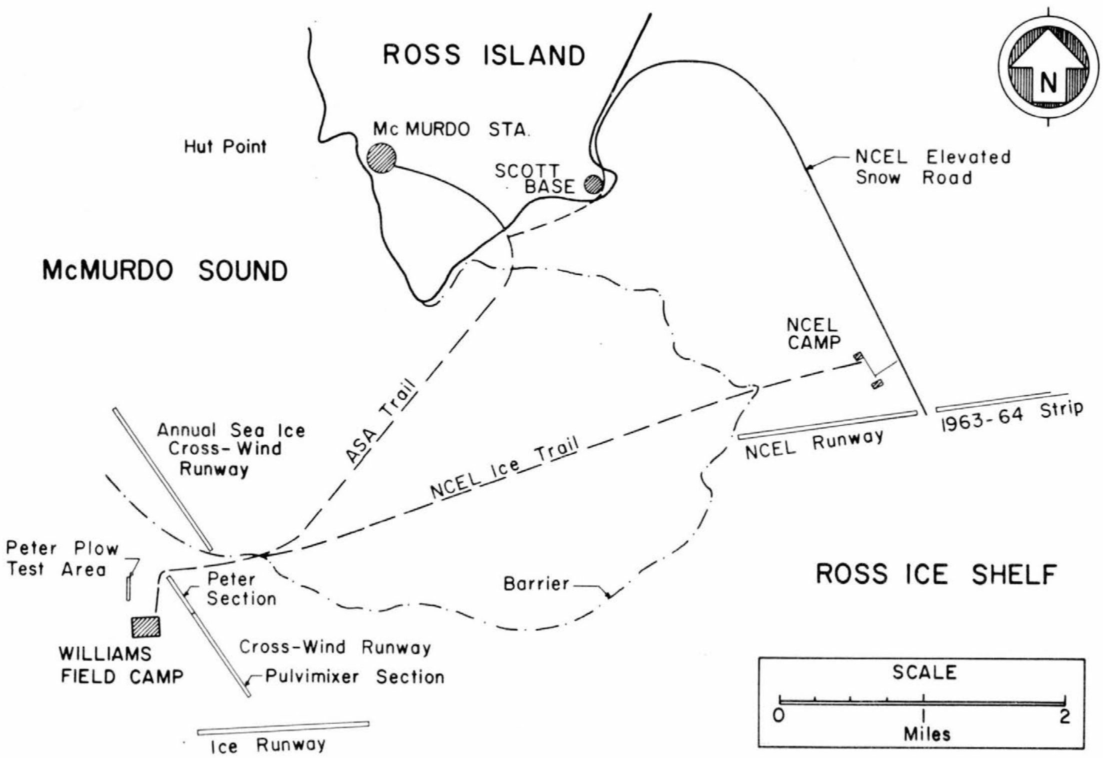


Figure 1. McMurdo Sound and surrounding area (after a map by NCEL).

Figure 2. Peter snow plow with backcasting chutes.

To minimize the snow drifting and thus decrease the work of maintenance, it is desirable to have the runway surface somewhat higher than the surrounding area. Since the average density (approx. 0.45 g/cm^3) of the natural snow was less than that expected of the processed and compacted snow pavement (usually between 0.55 and 0.65 g/cm^3), the final runway surface would be lower than the original surface. Because of this, the proposed runway site was first precompacted and processed with a pulvimixer. This constituted the bottom layer, 35 to 40 cm thick, of the pulvimixer processed runway section. Additional snow was blown on the surface to a height of 12 to 18 in., which was considered adequate.

Because of the unavailability of required equipment and qualified operators for most of the season, only a 70-ft width of the proposed 200 ft wide runway was processed with the Peter plow. The top layer of the pulvimixer processed section, using a steel roller for compaction and a land planer for leveling, was completed as planned.

A low ground pressure (LGP) D-8 tractor with blade was used for rough leveling and for compacting the Peter processed snow pavement. An automatic snow planer-finegrader (Fig. 3) was used for the final leveling.

The age hardening of the Peter processed snow runway section was observed by means of periodic ram hardness tests. Snow grain size distribution, density profile and flexural strength data were obtained. Unfortunately, this study could not be completed, because the entire Peter processed runway section, as well as approximately 500 ft of the pulvimixer processed section, broke off and drifted away into the Ross Sea 16 days after the construction of the runway began. Some important data, such as the unconfined compressive strength and ram hardness after 3 or 4 weeks of age hardening (when the snow has reached 70 to 80% of its ultimate strength), could not be obtained.

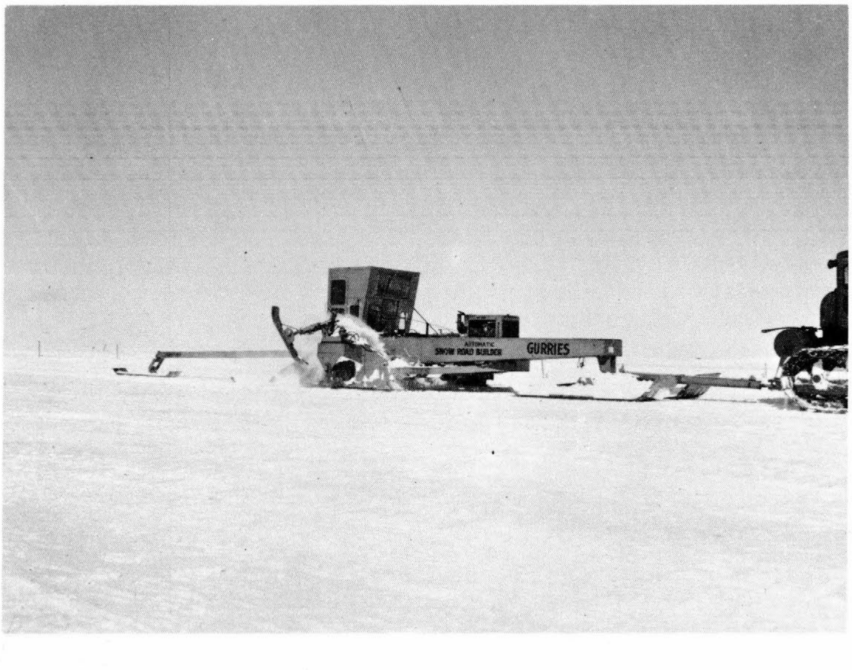


Figure 3. Automatic snow finegrader.

To evaluate the effectiveness of the compaction method used, a Peter processed, uncompacted test plot was constructed and the age hardening process monitored.

Strength data (flexural, unconfined compression, and dynamic Young's modulus) were also obtained on the NCEL runway, and actual landing, taxiing and take-off tests with a C-130 E aircraft were observed.

In order to aid in predicting the feasibility of constructing processed snow runways at South Pole Station, density observations and sieve analysis tests were performed on South Pole snow.

Results

Natural snow profile. The natural snow profile at the cross-wind runway is shown in Figure 4. The layered pattern caused by the annual snowfall and temperature variations is evident. Depth hoar, a loose, granular type of snow, is predominant in the Williams Field area, but less is found in the NCEL camp and runway area (Fig. 5).

At Williams Field a considerable amount of ice was encountered at depths of less than 100 cm.

Disaggregation of the natural snow deposit at Williams Field to obtain a broad grain size distribution which would promote a high rate of age hardening was difficult because of the large amount of ice and depth hoar. The natural snow in the NCEL camp area appeared to present fewer problems in this respect.

Construction of cross-wind runway section. It was planned to use two Peter plows simultaneously to produce a 16 ft wide strip (8 ft wide cut per plow), thus enabling the LGP D-8 tractor and the snow planer to begin compaction and leveling immediately after processing. However, because of persistent mechanical difficulties with one of the plows (which apparently had not been properly repaired after several years of operation in Greenland and in Michigan), processing had to be performed with only one plow, furnished by the U.S. Navy.

Some difficulties, nevertheless, were experienced with the control and maneuverability of this plow as well. The operators were unable to control the pitch and roll of the plow and also had difficulty in following a straight line. The result was a very rough, uneven surface, having as much as a 4-ft difference between crest and trough of the snow "waves." It was difficult to determine whether this was caused by the lack of experience of the operators or the mechanical condition of the plow, or, perhaps, a combination of both. On a few occasions low visibility may have been partly responsible.

If compaction is not performed within a few hours after processing, the effectiveness of compaction is usually confined to a depth of less than 1 ft. Furthermore, after a sufficient amount of bonding between the snow grains has occurred, compactive action will cause these bonds to break, and any increase in density may be offset (for a period of days or weeks, depending on temperature) by the weakening of the snow structure.

Since only one plow was available, compaction and leveling sometimes had to be delayed longer than desired. Frequently the LGP D-8 was not available when needed.

The average forward speed of the Peter plow while cutting was approximately 13 ft/min, or about 800 ft/hr.

Because of the extremely rough surface left by the Peter plow, leveling was difficult and time consuming. An experienced bulldozer operator was not available. It was, therefore, necessary to use a man who had never operated a bulldozer.

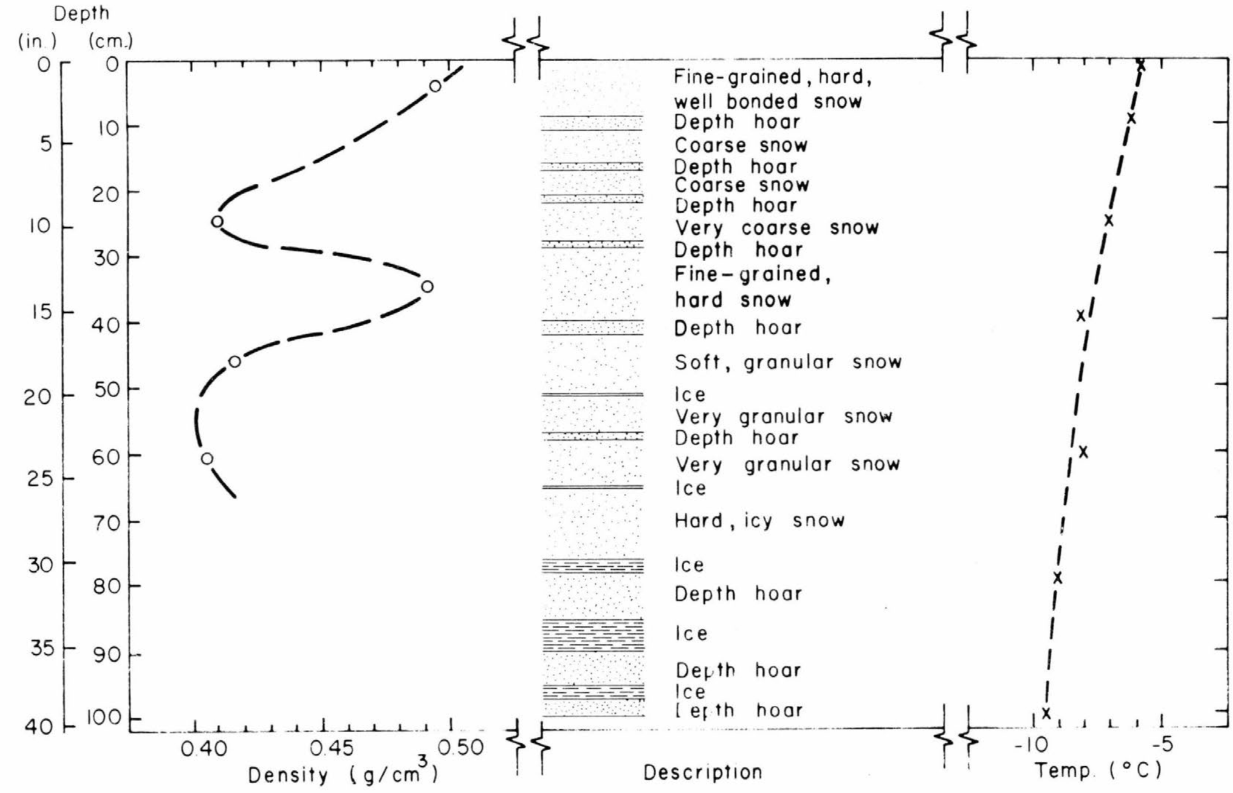


Figure 4. Natural snow profile, Williams Field.

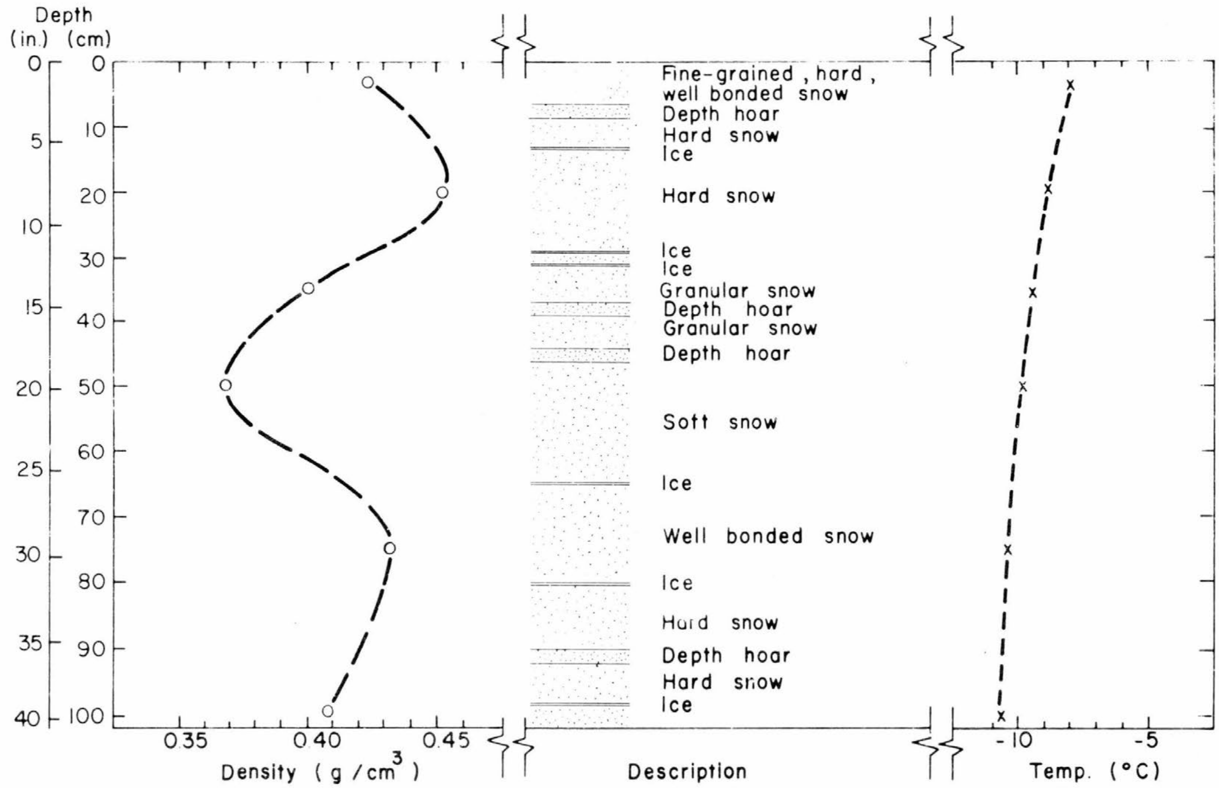


Figure 5. Natural snow profile, NCEL Camp.

The automatic snow finegrader did not perform as well as it had performed previously in Greenland and in Michigan (Abele, 1964c). This is a "finishing" leveler, and it is not very effective on an exceptionally rough surface. However, its performance on a comparatively smooth surface was also erratic. Whether or not a mechanical or a hydraulic malfunction was responsible could not be determined in the absence of a qualified mechanic.

While this runway test section made it possible to evaluate to a certain degree the mechanical characteristics of the snow pavement, the overall surface produced was not adequate for an operational runway.

Grain size distribution of processed snow. The age hardening process (the rate of property change with time, pertaining to all properties that depend on bond growth) is highly dependent on the snow particle size distribution. In general, under favorable environmental conditions, a higher percent of fine particles (less than 0.2 mm) in the material will result in a higher rate of initial age hardening. A broader particle size distribution (within certain limits) will result in a higher ultimate strength. That is, a fine-grained snow will harden more rapidly, but will not achieve as high an ultimate hardness or strength as a coarser but well-graded (broad grain size distribution) snow, provided a sufficient amount of fine particles are present.

The effect of the snow particle size distribution on the age hardening process has been discussed in detail by Waterhouse (1964b) and Butkovich (1962).

The grain size distributions of the Peter miller and pulvimixer processed snows are shown in Figure 6. The distribution is skewed. As far as range of particle sizes is concerned, the pulvimixer snow has a broader distribution, but contains a high percentage of coarse particles in comparison to the fine particle content. The Peter snow exhibits a somewhat narrower range, but a better coarse to fine particle proportion.

The same data are shown in the more familiar sieve analysis curve form (% finer by weight vs. size) in Figure 7. The pulvimixer snow is somewhat coarser, the median size (at 50% finer) being 0.9 mm as compared to 0.8 mm for the Peter snow. In comparison, the Peter snow obtained in Greenland is considerably finer (median size less than 0.6 mm) than the Peter snow at Williams Field. This is due to the larger amount of ice and depth hoar in the Williams Field natural snow profile.

Theory (Waterhouse, 1964b) and field data indicate that the strength of snow at a particular age is:

1) a function of the standard geometric deviation of the mixture distribution (indicated by the slope of the distribution curve in Figure 7);

2) a function of the mean surface diameter (indicated by the relative location of the distribution curve in Figure 6 or Figure 7);

3) a function of the relative proportional distribution of the particle sizes or the particle size ratios (indicated by the shape of the distribution curve in Figure 6 or Figure 7).

If the above theory is valid and other parameters such as temperature, density and particle shape are equal, then the following can be expected:

1) Snow processed with a Peter plow at Williams Field will age harden at a somewhat lower rate than snow processed with a Peter plow on the Greenland Ice Cap, but should reach a somewhat higher ultimate strength.

2) Snow processed with a pulvimixer at Williams Field will age harden at a somewhat lower rate and reach a somewhat lower ultimate strength than Peter snow. (The pulvimixer snow does not satisfy the requirement for the

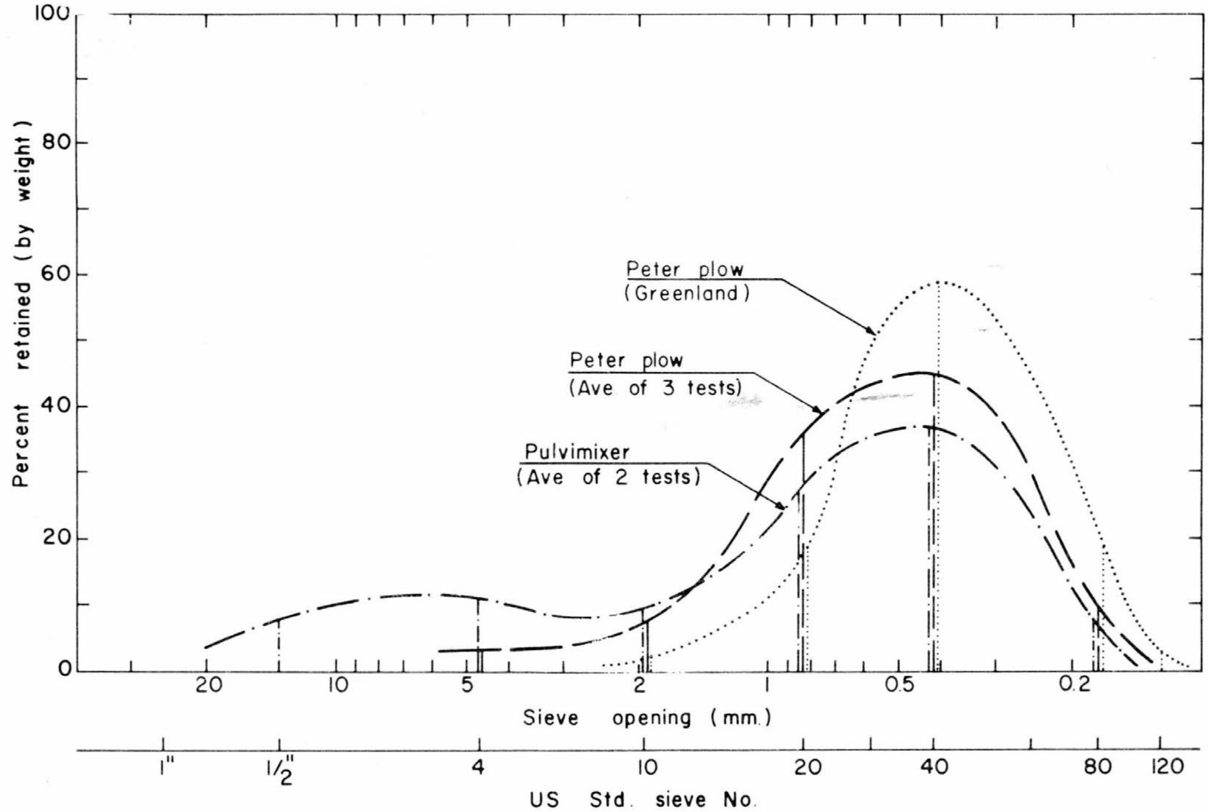


Figure 6. Histogram of particle size distribution of processed snow.

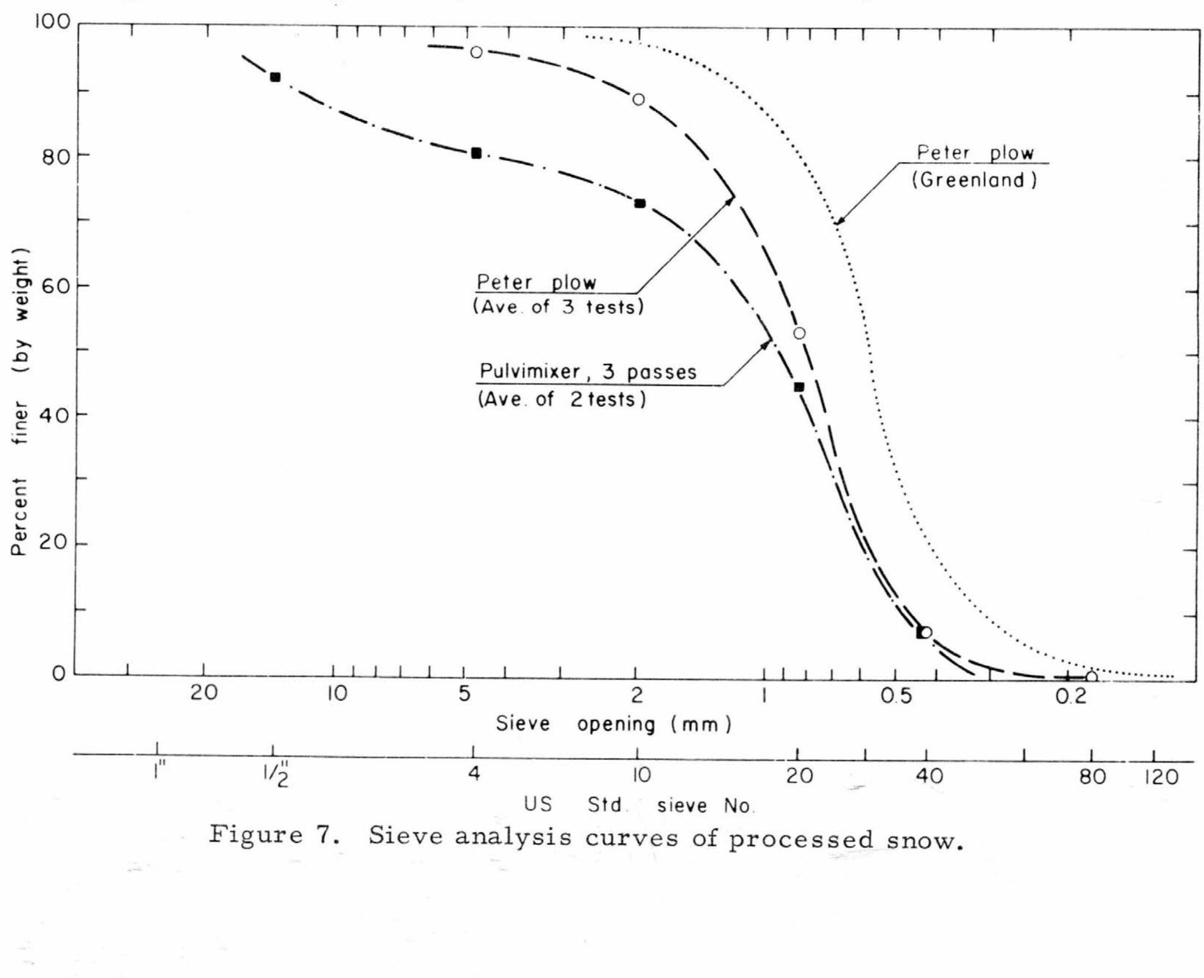


Figure 7. Sieve analysis curves of processed snow.

relative proportional size distribution as well as does Peter snow.) This, however, could not be verified from field data, since periodic age hardening data of the pulvimixer processed cross-wind runway section are not available.

On the basis of available data, the indications are that the Peter snow has slightly better age hardening characteristics than the pulvimixer snow. Conclusive evidence, however, is not available at the present. The optimum particle size distribution has not yet been determined.

If a portion of the coarse material (5 to 13 mm size) in the pulvimixer snow could be disaggregated to produce a higher amount of fines (in the 0.1 to 0.5 mm size range), this snow would be superior to the Peter snow as far as the resulting final strength is concerned. The presence of small particles or fines is of principal importance. Multiple passes with the pulvimixer (Page, 1964) do produce a breakdown of the coarse particles, but do not increase the amount of fines below the 0.5 mm size.

Density. The density profiles of the processed snow, both compacted and uncompacted, as well as of the natural snow (see Fig. 4, 5) are shown in Figure 8. The increase in density, due to processing with either the pulvimixer or the Peter plow, is quite evident. Compaction produces an additional increase in density.

Wuori (1960, 1963b) has indicated that an LGP D-8 tractor produces a more extensive compaction of processed snow than certain other standard compaction equipment, such as rollers, vibrators, etc.

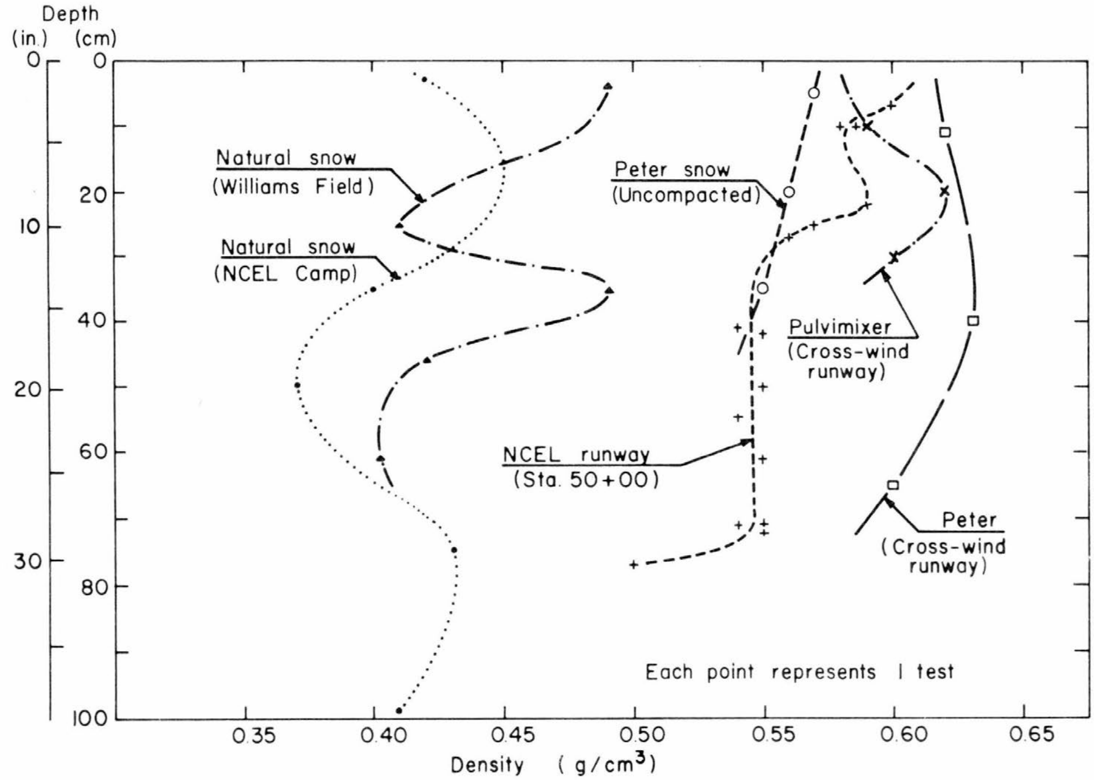


Figure 8. Density profiles of natural and processed snow.

Compaction with an LGP D-8 tractor was, therefore, used on the Peter snow cross-wind runway section. Densities of 0.60 to 0.64 g/cm^3 were obtained to a depth of more than 60 cm. In the pulvimixer section of the runway, densities between 0.59 and 0.62 g/cm^3 were obtained to a depth of 30 cm using a steel roller.

It is interesting to note that the density obtained in the pulvimixer section of the cross-wind runway with only limited compaction is higher than that of the NCEL runway which received more extensive compaction. The cross-wind runway construction was done during a comparatively warm period (mean daily temperatures between -5 and -12C), while the NCEL runway construction may have occurred during lower temperatures. Compaction, in general, is more effective at higher temperatures.

Density alone is not a reliable indicator of snow strength. Temperature, in particular, is a significant factor. Strength of processed snow cannot be estimated to any degree of reliability unless the temperature history during the age hardening period and the age of the snow (particularly if less than approximately 2 weeks) are known, as well as some idea of the original grain size distribution.

All other conditions being equal, a higher density snow will exhibit a higher strength.

Ram hardness and age hardening. The Rammsonde cone penetrometer (ram) hardness test, which indicates the resistance to penetration of a cone, is a convenient and comparatively fast method of determining the approximate strength of snow.

The correlation between ram hardness and a more familiar indicator of strength, the unconfined compressive strength, has been discussed in a previous report (Abele, 1963). The reliability and performance of the ram hardness instrument and suggested modifications have been discussed by Niedringhaus (1965).

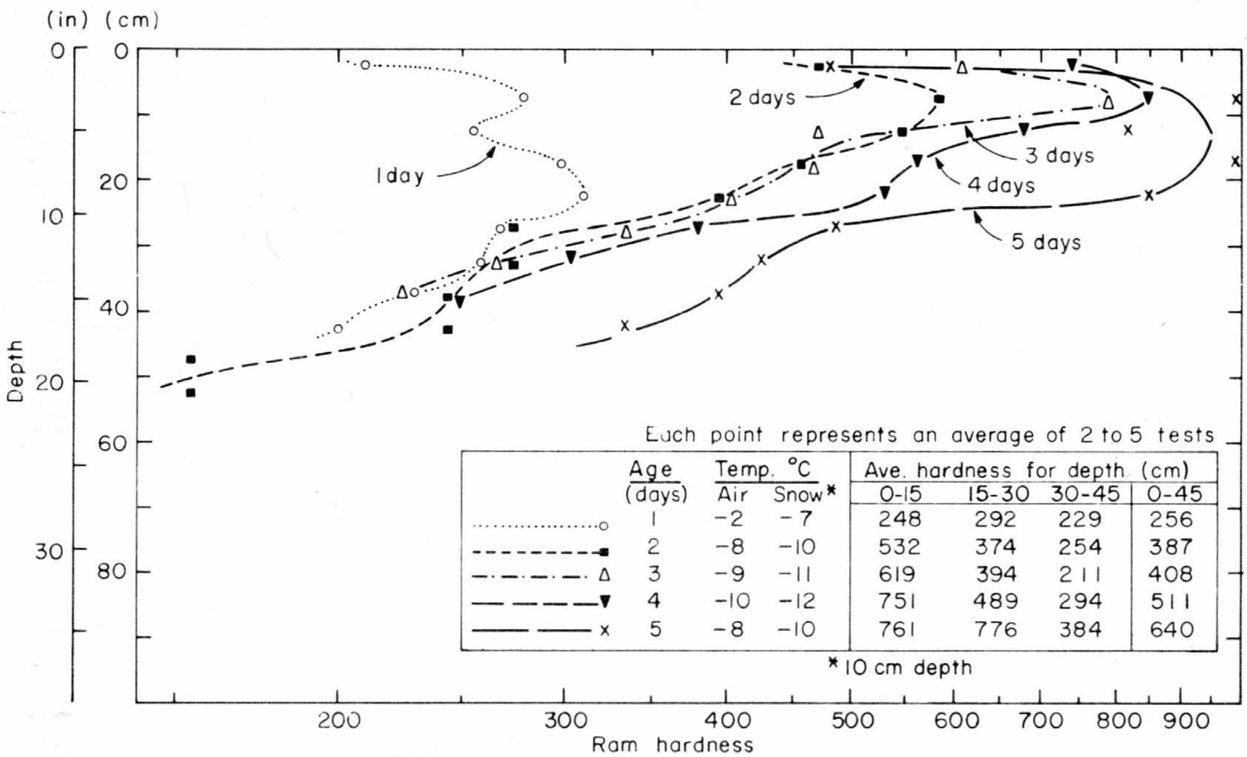
The age hardening process is very sensitive to temperature (Gow and Ramseier, 1963; Ramseier and Sander, 1965). The rate of initial age hardening increases with an increase in temperature, up to 0C. Except during the early stages of age hardening, the strength of snow decreases with an increase in temperature. That is, at -2C, for example, snow will age harden at a higher rate, complete its effective age hardening process in a shorter period of time, but reach a lower apparent ultimate strength than snow which is hardening at -10C.

Moser (1964) and Page (1964) have stated that age hardening is delayed at temperatures above 25F. According to theory and available field data, indications are that the age hardening process is not arrested until a snow temperature of 0C is reached. The governing temperature is the snow temperature. Occasionally solar radiation during a period when the air temperature approaches 0C can cause the snow temperature to reach 0C, thus temporarily arresting the age hardening process.

The ram hardness profiles of the Peter processed cross-wind runway section for the period from 1 through 5 days are shown in Figure 9.

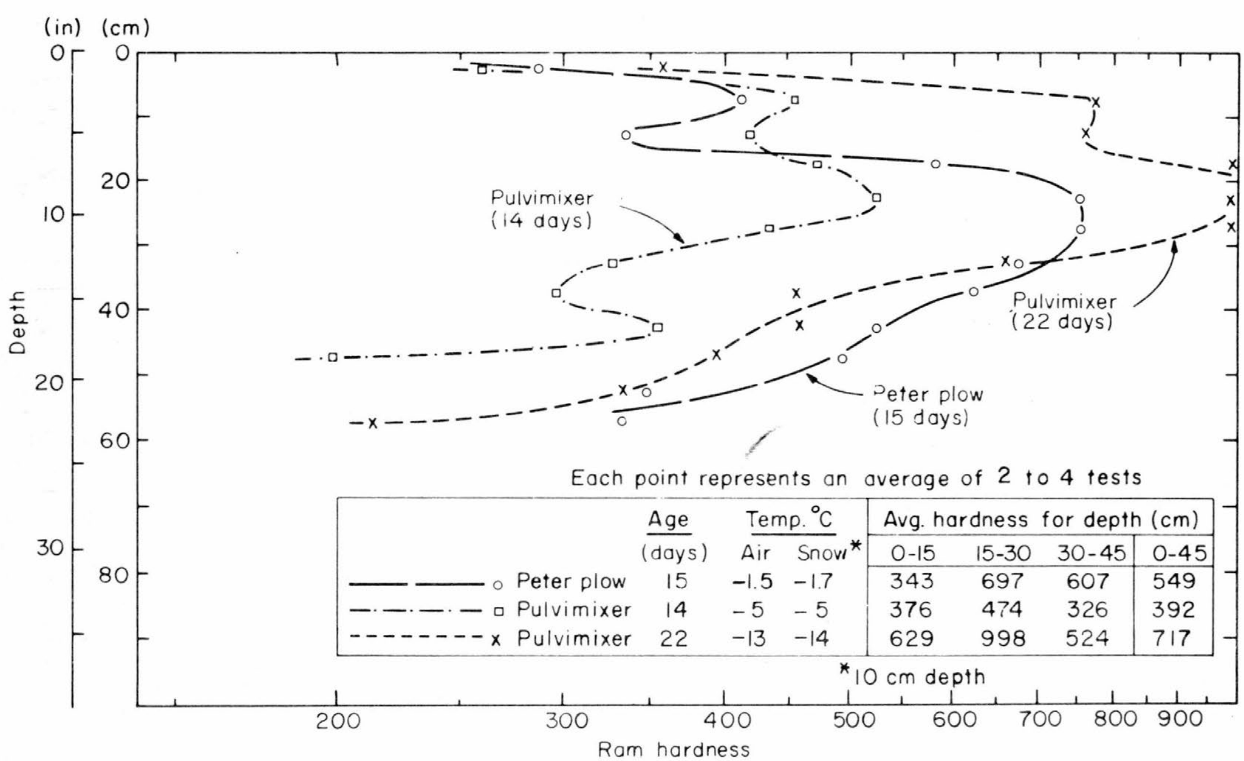
After 5 days of hardening, the area from which the hardness data were obtained was subjected to bulldozer traffic during leveling of the adjacent, newly processed area. This very probably resulted in some strength loss to a depth of 10 or 20 cm, due to breaking of bonds between the snow particles. Ram hardness data were not obtained during this period.

After 12 days of age hardening, the air temperatures (see App. C) rose to above 0C for periods of several hours during the day. This condition persisted for 2 or 3 days. On the 15th day, ram hardness tests were performed. The results showed that the snow had softened considerably to a depth of approximately 20 cm (Fig. 10). The snow temperature at 10 cm was -1.7C.



Age (days)	Temp. °C Air	Temp. °C Snow*	Ave. hardness for depth (cm) 0-15	15-30	30-45	0-45
1	-2	-7	248	292	229	256
2	-8	-10	532	374	254	387
3	-9	-11	619	394	211	408
4	-10	-12	751	489	294	511
5	-8	-10	761	776	384	640

Figure 9. Ram hardness profiles of compacted Peter snow.



	Age (days)	Temp. °C Air	Temp. °C Snow*	Avg. hardness for depth (cm) 0-15	15-30	30-45	0-45
Peter plow	15	-1.5	-1.7	343	697	607	549
Pulvimixer	14	-5	-5	376	474	326	392
Pulvimixer	22	-13	-14	629	998	524	717

Figure 10. Ram hardness profiles of compacted Peter and pulvimixer snows.

Ram hardness data after 14 days of hardening were also obtained on the pulvimixer section (Fig. 10), which was processed a day after the Peter section. There the effect of the above freezing temperature period is also apparent. The snow surface would be harder if above freezing temperatures did not occur during the age hardening process.

The effectiveness of the LGP D-8 compaction on the resulting ram hardness is apparent in the Peter snow hardness profile in Figure 10, extending to at least a 60-cm depth.

On the 16th day a 1500 ft long section of the runway, including the Peter plow processed area, was lost due to ice breakout.

Ram hardness data on the pulvimixer snow were again obtained on the 22nd day (Fig. 10).

The ram hardness as a function of time is shown in Figure 11. For simplicity of representation, the snow pavement is divided into 15-cm thickness increments and their respective average hardness data shown.

The rate of age hardening of the Peter snow up to 5 days is roughly comparable, although somewhat slower, with the rates observed in Greenland under similar temperature conditions.

The decrease in hardness at the 0 to 15-cm depth, due to the period of above freezing air temperatures, possibly combined with the effects of solar radiation, prior to the 15th day, is again obvious. The snow at the 30 to 45-cm depth, insulated by the snow above it, has continued to harden at a normal rate during the warm period.

The hardness data for the pulvimixer snow at 14 and 22 days are also shown.

The age hardening of the uncompacted Peter snow is shown in Figure 12. Because no data were obtained during the warm period, the loss of strength during that time cannot be detected. (This would be at 17 to 20 days of age hardening, since this test section was constructed 5 days earlier than the respective cross-wind runway section.) The hardness after 28 days indicates that probably most of the strength lost during the warm period was regained during the freezing period that followed.

Flexural, unconfined compressive strength, and traffic tests. The flexural strength tests on the Peter and pulvimixer processed cross-wind runway sections were performed after 2 weeks of age hardening. The method used is described below with the discussion on ice strength. The results are shown in Figure 13.

The flexural strength data were obtained at the same time the ram hardness tests were performed, hence the temperature conditions were the same.

As a result of the depth of processing and the compaction with a LGP D-8, the Peter snow strength profile of the cross-wind runway was quite uniform to a depth of 60 cm. In the pulvimixer snow there was a noticeable decrease in strength below a 20-cm depth. The thickness of the top layer in this area was 35 cm. The bottom layer of the pulvimixer snow extended from 35 to 70 cm.

The flexural snow strength profiles of the NCEL runway (at station 67+00) and the runway section processed during the 1963-64 season (at the end of the present NCEL runway) are also shown in Figure 13. At this particular location (Sta. 67+00), the NCEL runway exhibits a considerable decrease in strength below the 15-cm depth. This weak layer is also indicated by the unconfined compressive strength profile (Fig. 14). The increase in strength at approximately 40 cm represents the runway during the previous (1963-64) season.

It appears that, when a new layer of snow is processed on top of an existing snow surface, proper bonding of the snow does not occur above the interface of the two layers. An extremely weak layer at a 20 or 30-cm depth in a snow runway

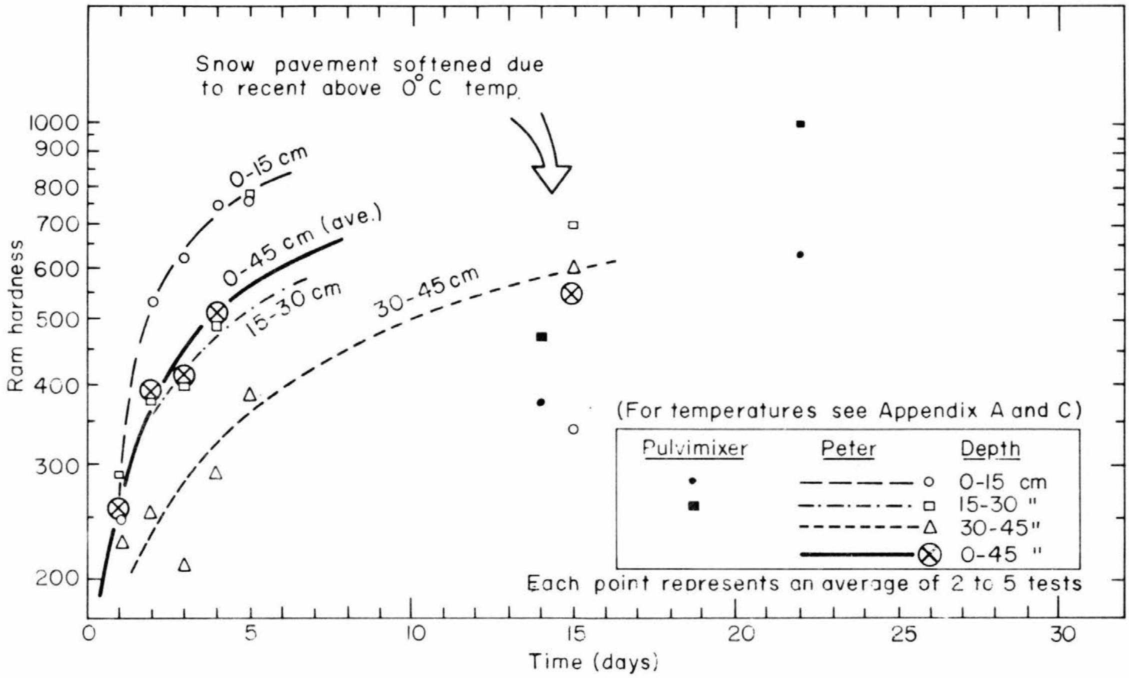


Figure 11. Age hardening of processed, compacted snow.

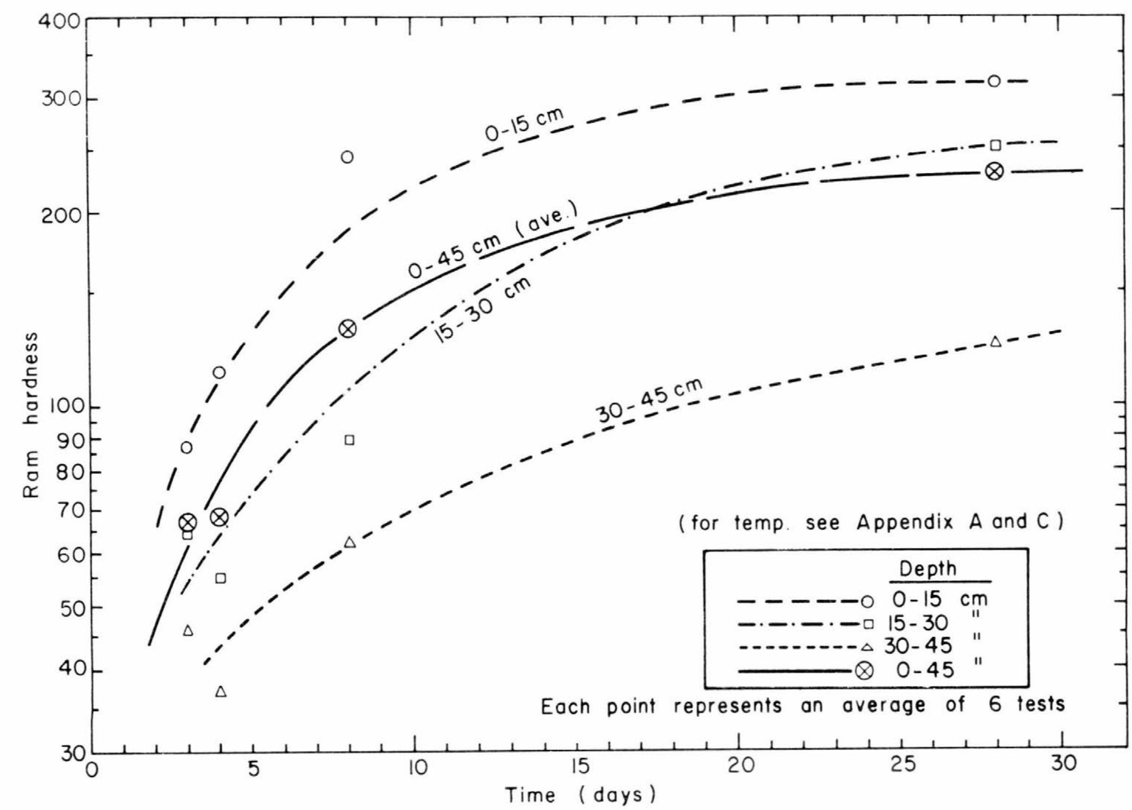


Figure 12. Age hardening of uncompacted Peter snow.

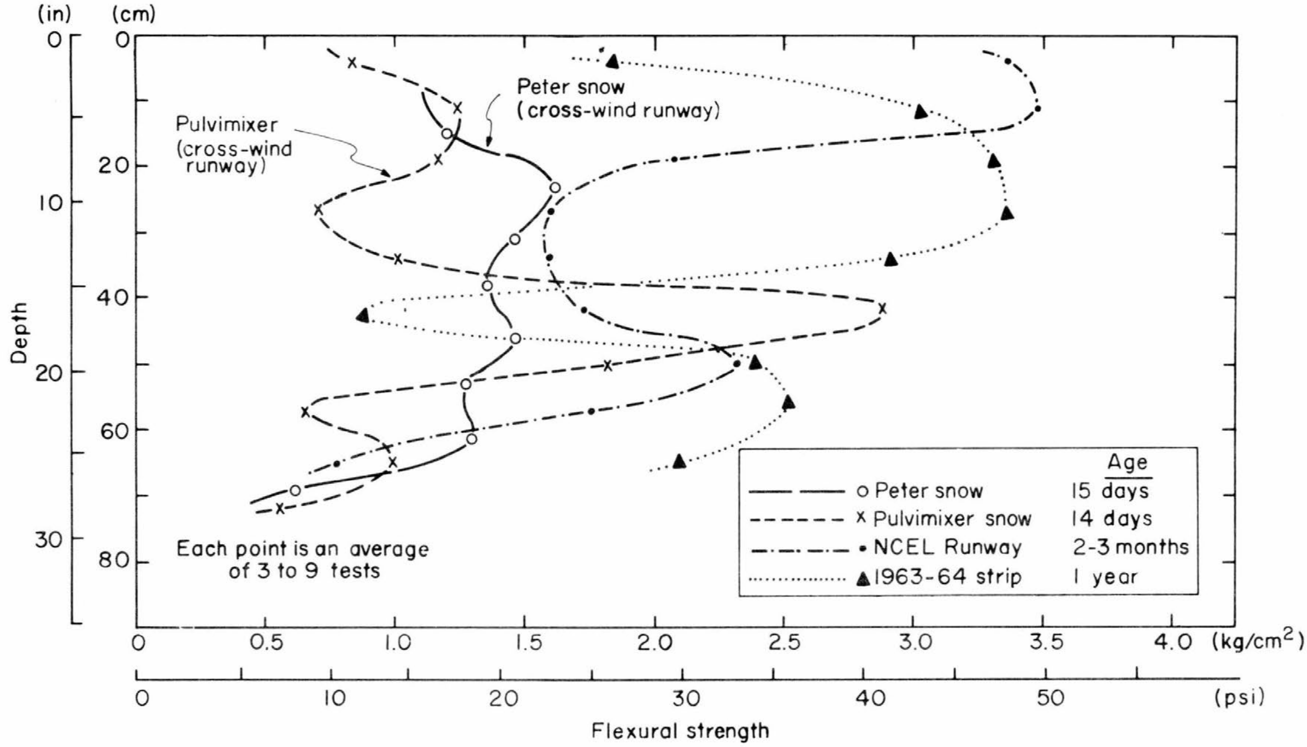


Figure 13. Flexural strength profiles of processed snow.

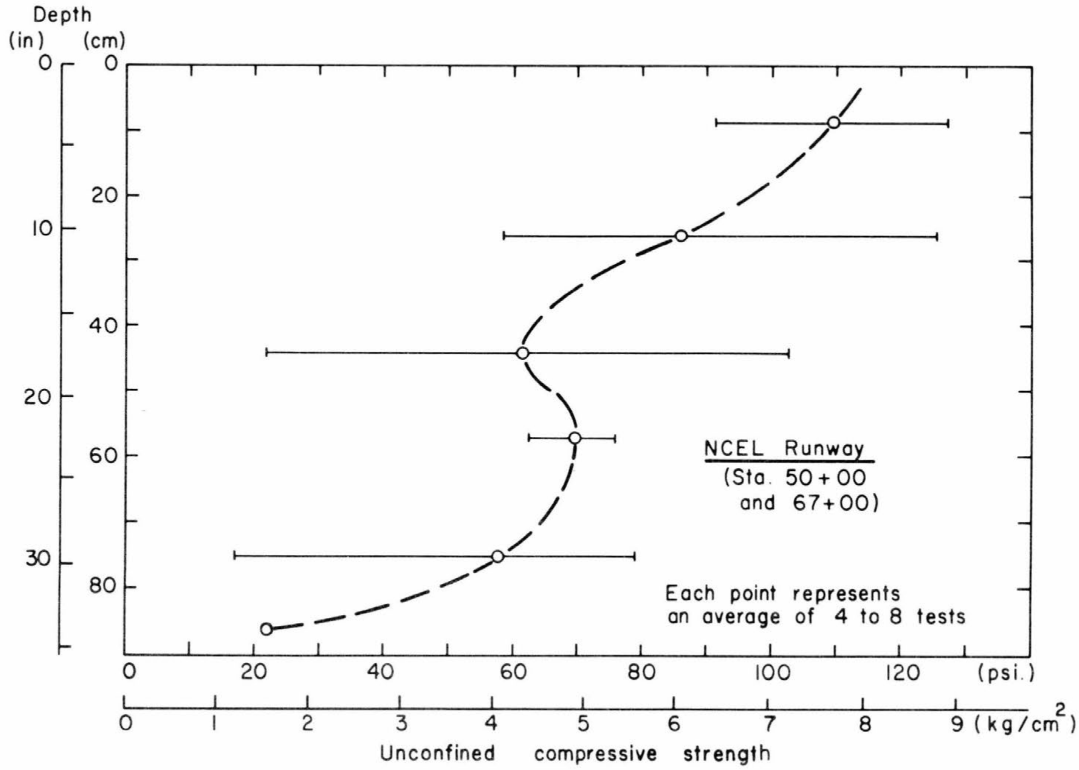


Figure 14. Unconfined compressive strength profile of pulvimixer snow.

pavement could conceivably cause a pavement failure under loads which produce sufficiently high stresses at this depth (Nevel, 1963; Wuori, 1962a).

This condition may have been, in some cases, the cause for the failures on the NCEL runway during C-130E aircraft traffic tests (gross weight 125,00 lb; tire inflation pressure 85 psi) on 24 January 1965.

This weak layer is also noticed in the strength profile of the area processed with the pulvimixer during 1963-64, in this case at a depth of 40 to 45 cm (see Fig. 13). The strength for the 0 to 10-cm depth is lower than that of the present NCEL runway. The 15 to 40-cm depth, however, is stronger than the corresponding depth in the present NCEL runway.

The presence of the weak layer at the interface of the two processed layers and the insufficient thickness of the top layer are, perhaps, the significant deficiencies of the pulvimixer processing method. Improved compaction methods, such as using a LGP D-8 as a compactor, may remedy these deficiencies to some extent. Increasing the depth of processing would certainly be advantageous.

This condition occurs also in Peter snow and would be more noticeable if processing were performed in thinner layers. Since Peter plow processing is effective to a depth of 80 cm or more, a weak layer at this depth is not nearly as dangerous as at 20 or 30 cm.

In other areas on the NCEL runway during the 24 January tests, inspection of the vertical face of the failure rut revealed very granular, chunky snow below a 20-cm depth. This snow appeared to be unprocessed, indicating insufficient depth of processing (a processing "holiday"). This condition appeared to be responsible for more than half of the failures during the aircraft traffic tests.

The air temperature during these tests was -7C. It is probable that during lower temperatures fewer failures would have occurred.

On 14 February 1965 the C-130E aircraft traffic tests (gross weight 135,000 lb; tire inflation pressure 95 psi) were repeated on the NCEL runway. The failure areas from the previous tests had been repaired. The air temperature during these tests was considerably lower, -18 to -23C. The maximum wheel penetration did not exceed 4 or 5 cm, and this was observed in only a few isolated areas. No actual surface failures were observed.

The unconfined compressive strength tests on the cross-wind runway were planned to be performed sometime between 2 and 3 weeks of age hardening. Because of the ice breakout, this was not possible.

South Pole snow. The snow properties at the South Pole have been described by Gow and Ramseier (1963). However, some additional data were obtained during this study.

The particle size distribution of the natural snow at South Pole is shown in Figure 15. The distribution is narrow, 84% of the particles being in the 0.4 to 0.8 mm range. Processing of this type of snow would increase somewhat the amount of fine particles, but the lack of coarser particles could not be easily remedied. Near 0C temperatures, a high rate of age hardening could be expected, but the ultimate strength achieved would be quite low. However, since processing would probably occur at -35C or below, the rate of age hardening would be very low (Gow and Ramseier, 1963). It would probably be difficult to obtain a snow pavement capable of supporting heavy wheeled aircraft.

The operation of the processing equipment at these temperatures would itself present a problem.

The density profiles of the natural snow and the runway at the South Pole station are shown in Figure 16.

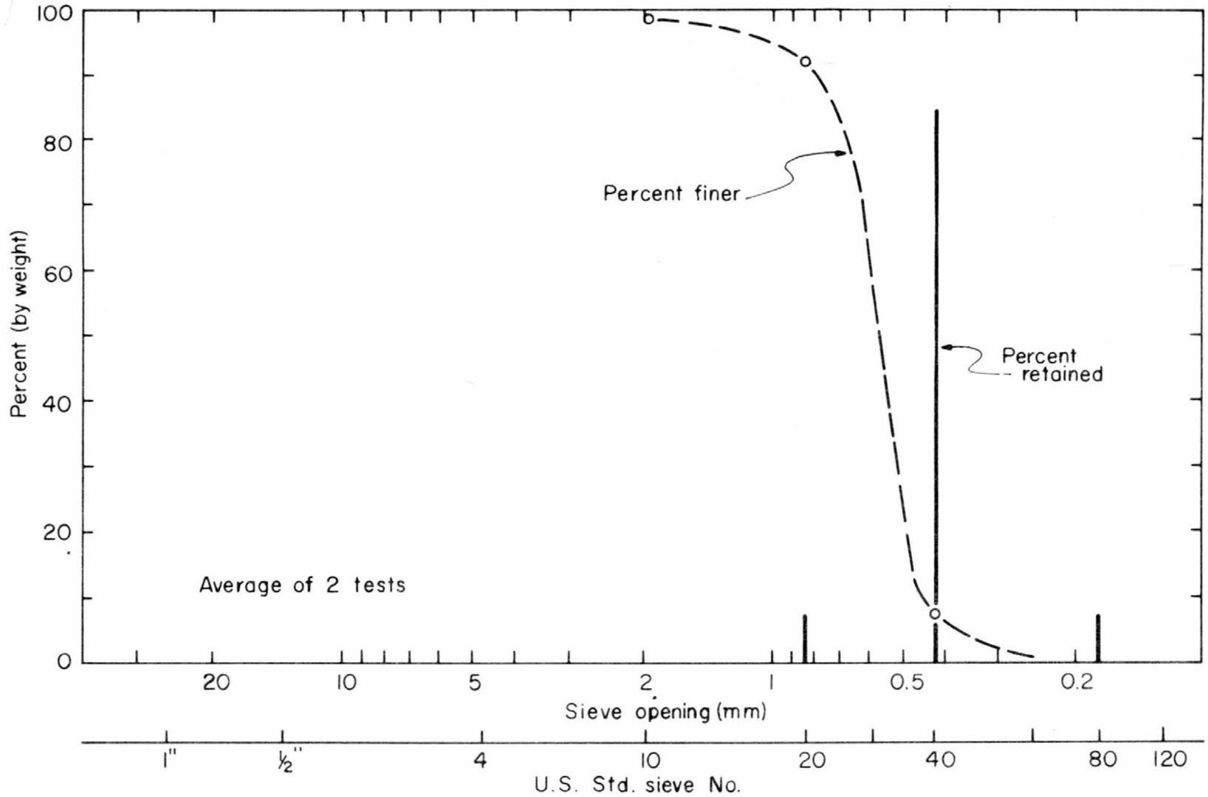


Figure 15. Particle size distribution of South Pole snow.

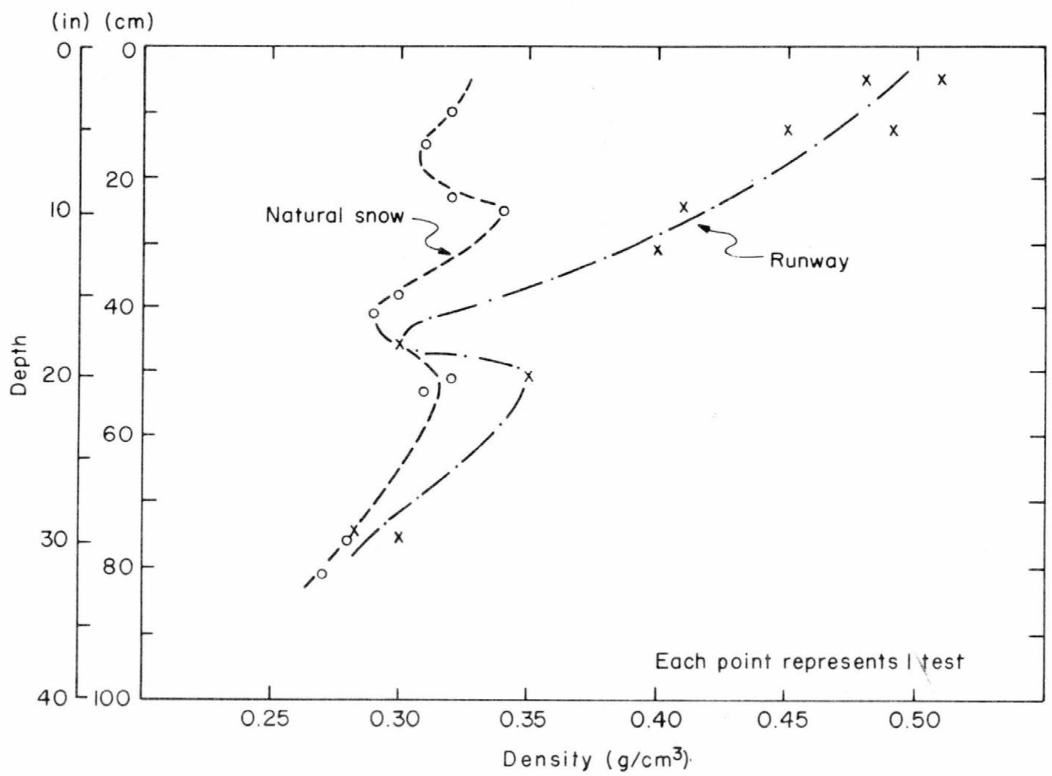


Figure 16. Density profiles of South Pole snow.

Preliminary criteria for support of aircraft on processed snow runways

From available data obtained mostly in Greenland and at the Keweenaw Field Station, Houghton, Michigan, a correlation between the wheel load supporting capacity and some of the mechanical properties, in particular the ram hardness of the snow pavement, has been developed. This is shown as a nomogram in Figure 17.

The wheel load condition has been defined by three parameters: the average contact pressure of the tire, the wheel load, and the number of repetitive wheel load applications (or wheel coverages) within a short period of time (less than 1 hour). The average contact pressure is estimated by dividing the wheel load by the tire contact area (Wuori, 1962b). This may not necessarily represent the maximum contact pressure produced.

The required snow strength is indicated in terms of ram hardness for a depth equal to the equivalent circular contact area radius ("r") of the aircraft tire. (For example, the tire contact area of a C-121C aircraft at a gross load of 130,000 lb and a tire inflation pressure of 120 psi is 245 in^2. The radius of a circular area of 245 $in.^2$ is 8.8 in. or 22 cm. The ram hardness, read from the nomogram, is therefore the hardness required for a depth of 0 to 22 cm.)

The original correlation was obtained between the load supporting capacity and ram hardness. The corresponding unconfined compressive strength, shown on the nomogram, has been estimated from a previously established strength vs ram hardness correlation (Abele, 1963) and is only an approximate indication of the strength required.

The required ram hardness values for a depth "r" for four selected aircraft are shown on the nomogram (Fig. 17). The aircraft specifications data used are shown in Table I.

Table I. Aircraft specifications
(from Portland Cement Assoc., 1955, 1960).

Aircraft type	Gross wt (lb)	Wheel load (lb)	Tire area ($in.^2$)	Tire pressure (psi)	Avg contact pressure (psi)	"r" (in.)	"r" (cm)
C-47	25,200	11,800	238	45	50	8.7	22
C-130E	135,000	28,500	360 (est.)	95	80 (est.)	10.7	27
C-121C	130,000	31,000	245	120	127	8.8	22
KC-135	250,000	33,500	250	134	134	8.9	23

Since the C-130 and the KC-135 have tandem wheels, the "two wheel coverages" condition is used. The effect of dual wheels on a snow pavement has not yet been conclusively determined and is not considered in this nomogram.

It should be noted that the nomogram has been developed from an empirical and not a theoretical approach. Extrapolation for wheel load conditions indicating ram hardness below 200 and above 1000 may not be reliable. For vehicle wheel load conditions, such as a 5-ton truck, an empirical criterion has been developed for various sizes of tires (Abele, 1965).

It should also be noted that the nomogram does not apply to wheel load conditions which would cause the line between the "average contact pressure" and "wheel load" scales (Fig. 17) to cross the shaded area.

The required ram hardness profile to a depth of 80 cm has been computed using Boussinesq equations, which are based on an elastic, isotropic, homogeneous

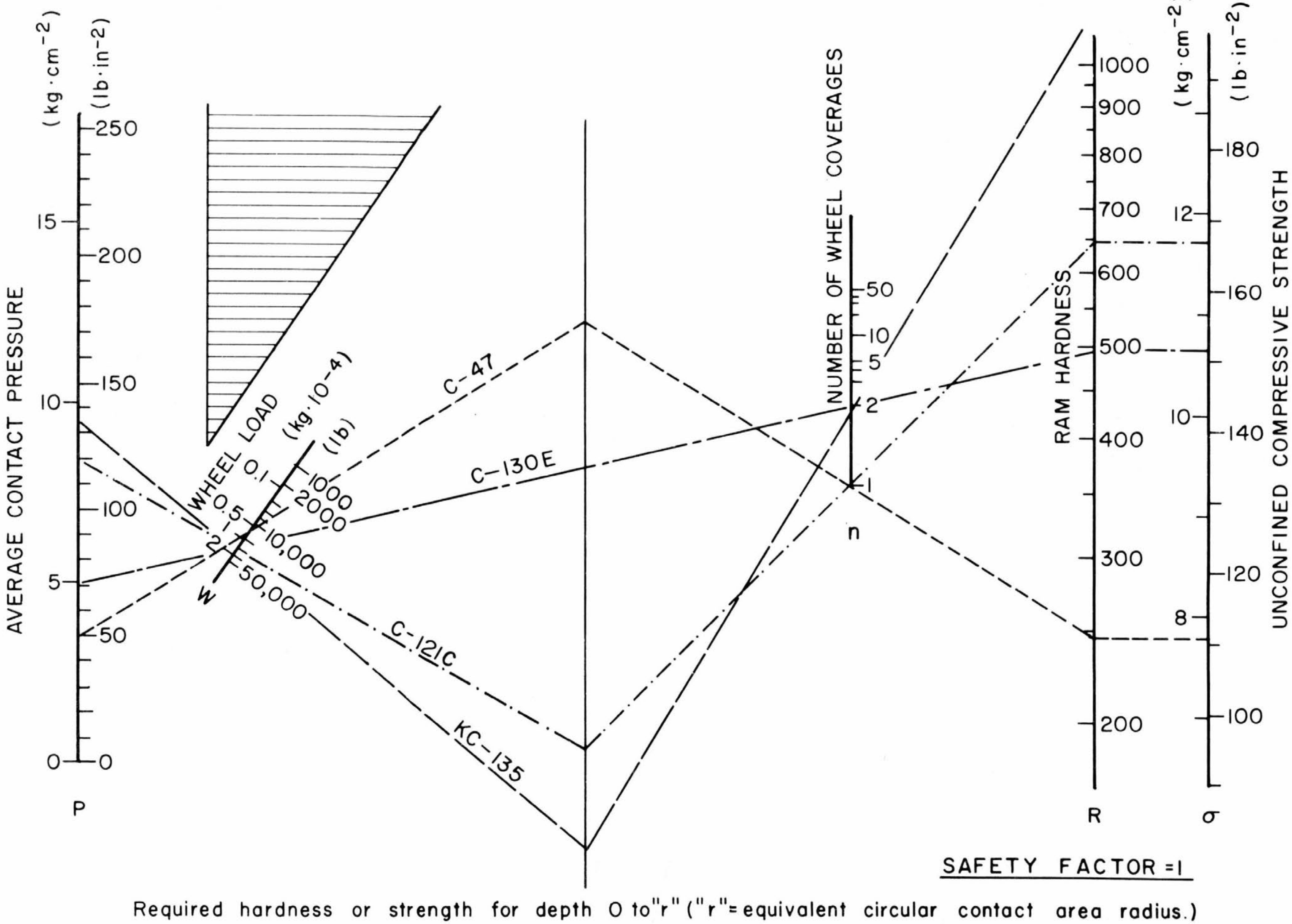


Figure 17. Required surface hardness (or strength) of a snow pavement for various wheel load conditions.

mass. Snow does not satisfy these characteristics, but previous studies (Wuori, 1962a) indicate that the stress distribution in a high-density, processed snow approximates the Boussinesq distribution.

The computed required hardness (or strength) profiles (safety factor = 1) for the four selected aircraft are shown in Figure 18.

The preliminary criteria so far appear to agree with aircraft traffic results (ACFEL, 1954; Bender, 1957; Moser, 1963; Page, 1964). Further refinements are, nevertheless, to be expected.

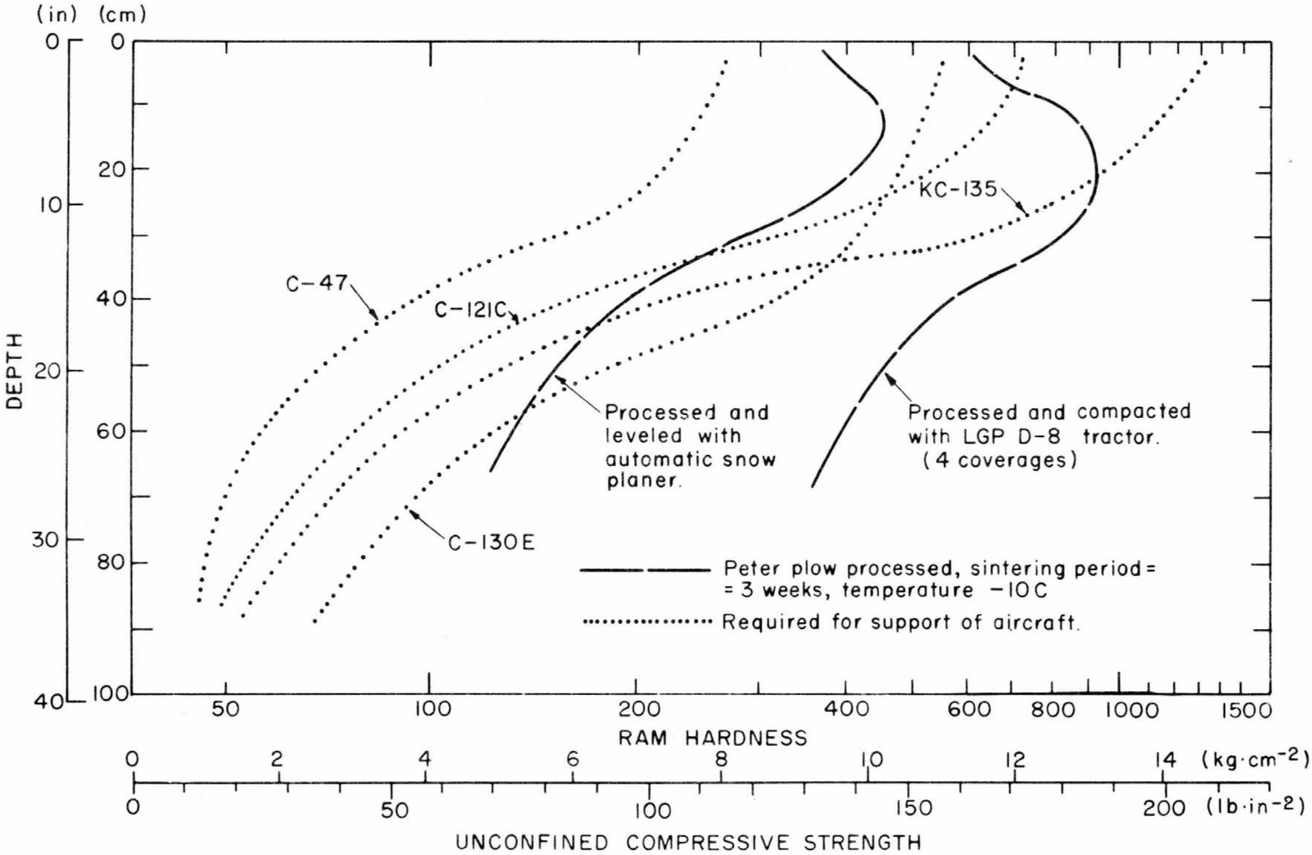


Figure 18. Required hardness (or strength) profiles of a snow pavement for various aircraft.

STUDY OF ICE PROPERTIES

Outline of study

The joint USA CRREL-NCEL ice project for "Operation Deepfreeze 65" originally called for the two organizations to test the ability of their ice chippers to level the ice hummocks that exist in the McMurdo-Williams Field Road. Unfortunately, no traxcavators were available, so the ice study was restricted to small-scale strength tests on the annual sea ice.

USA CRREL performed dynamic tests to determine Young's modulus and static tests to determine the flexural and ring tensile strength of the ice. NCEL conducted ring tensile and shear strength tests. The test procedure and results of the USA CRREL tests are reported here.

The ice strength test results were related to the brine volume, which is a function of the salinity and temperature of the ice.

Dynamic tests

Procedure. A soniscope, an instrument developed for finding voids or measuring the deterioration of concrete, was used to find Young's modulus of the ice. This instrument measures the group velocity of the longitudinal waves passing through the ice (Leslie and Cheesman, 1949).

The ice samples used for the determination of Young's modulus and flexural strength were harvested on the annual sea ice near Scott Base, McMurdo, Antarctica. The samples were mainly in the shape of a simple beam, but a few were 3 in. diam cores obtained with a standard 3-in. ice coring auger.

The beams were obtained by removing blocks of ice and cutting them into horizontal beams (5.0 x 5.0 x 50 cm). The position of each beam within the ice sheet was recorded.

The soniscope equipment consists of the control unit and a transmitting and receiving transducer. The transducers are made of piezoelectric ceramic crystals mounted in a metal housing and covered with a hard rubber diaphragm. The transducers had a resonance frequency of 70 KC. To determine the velocity through an ice specimen, the transmitting transducer is pressed against one end of the specimen and the receiving transducer is pressed against the other end. The control unit generates electrical pulses which are transformed into mechanical waves picked up by the receiving transducer. The time required for the wave to travel through the ice is measured electronically in the control unit. The velocity of the dilatational wave is related to Young's modulus, E, by

$$V^2 = \frac{E}{\rho} \frac{1-\mu}{(1+\mu)(1-2\mu)} \tag{1}$$

for an infinite medium and

$$V^2 = \frac{E}{\rho} \tag{1a}$$

for long samples where V is the pulse velocity, E is Young's modulus of elasticity, ρ is the density of the material, and μ is Poisson's ratio. Equation 1a was used for the tests reported here.

The density was obtained by weighing samples with a Metrogram balance and determining the volume from dimension measurements made with vernier calipers. Salinity of the melted ice samples was found with a conductivity meter. The ice temperature was obtained by drilling a hole into the ice sample just large enough for a calibrated mercury thermometer.

Results. Figure 19 is a plot of Young's modulus (E) versus the measured density ρ. The plot shows considerable scatter but does indicate that there is a correlation between E and ρ, E increasing with an increase in density. A least squares fit of the points gave a straight line equation of

$$E = (-20.82 + 32.62\rho) \times 10^{10} \tag{2}$$

where E is in dynes/cm^2 and ρ is in grams/cm^3. A correlation coefficient of 0.62 for the data gives an indication that eq 1 fits the data reasonably well.

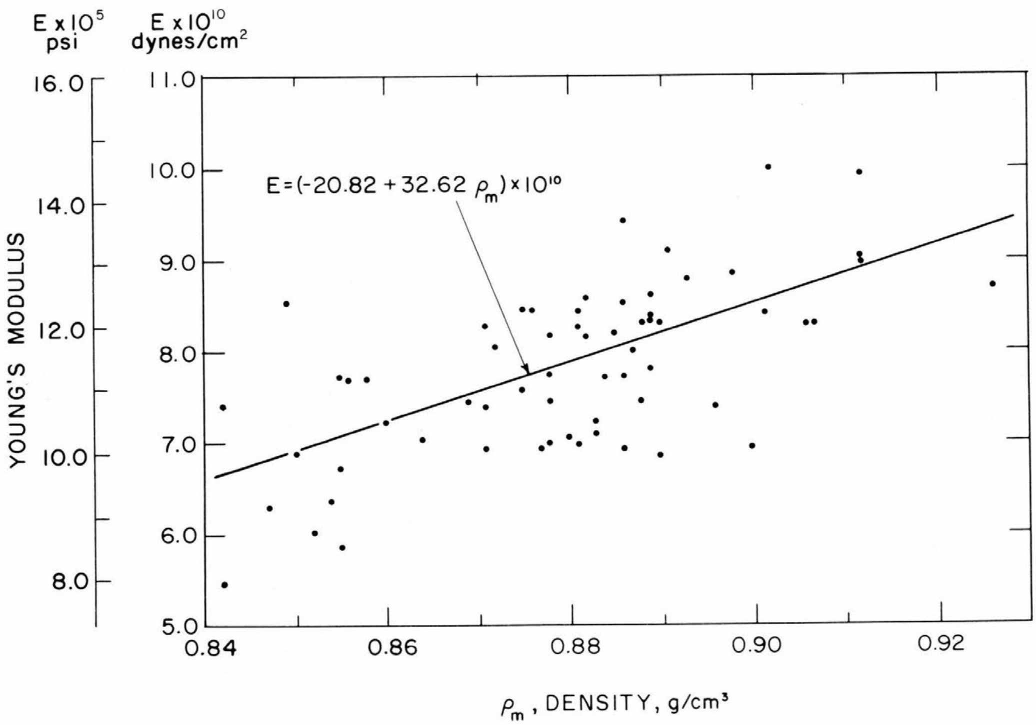


Figure 19. Young's modulus of annual sea ice vs density.

The data are in agreement with the available data from snow studies of Greenland and the Ross Ice Shelf which show that Young's modulus for snow is also dependent on the snow density (Smith, 1965; Bentley et al., 1957; Ramseier, 1963) and that the value of E decreases as the density of the snow decreases.

Sea ice strength is related to the brine volume. The brine volume is that volume of ice which contains liquid brine; it is related to the salinity and temperature. A number of investigators (Pounder and Langleben, 1964; Pounder and Stalinsky, 1960; Brown, 1963) have shown that E is also related to the volume of brine. This paper reveals a similar relationship but other values.

Brine volume for the dynamic samples was derived from the test salinity and temperature of the sample and its relative value taken from Assur's (1960) brine volume table. The samples were stored at -8C for from 2 to 11 days.

A total of 65 dynamic tests were performed. The individual test values were then randomly grouped into 13 groups of 5 tests each. Figure 20 A is a plot of the average value of E versus the average brine volume, ν, of the 13 groups. A least squares analysis of the data gives the equation

$$E = (9.01 - 0.464\,\nu) \times 10^{10} \text{ dynes/cm}^2 \qquad (3)$$

where ν is expressed in percent.

The value for E is lower than previously reported data (Pounder and Langleben, 1964; Pounder and Stalinsky, 1960; Brown, 1963; Smith, 1965; Roethlisberger, personal communication). Brown used the seismic method while the others used a method similar to that reported here. The low values are a result of brine drainage. As the brine drains from the ice it is replaced by air.

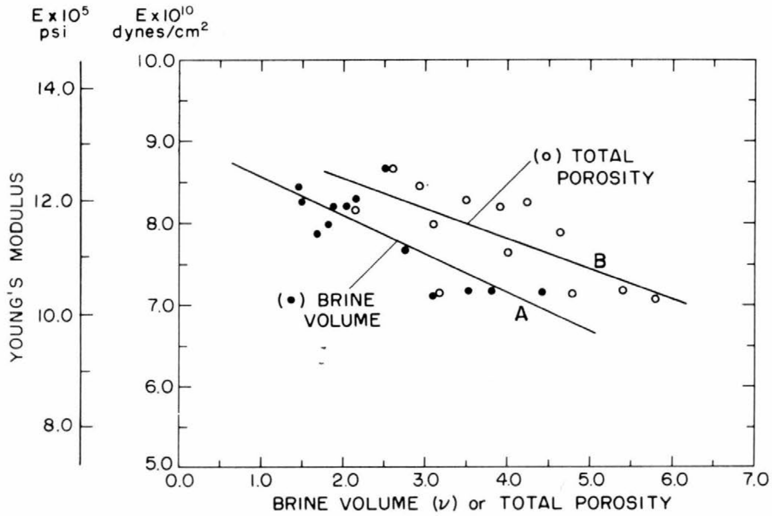


Figure 20. Young's modulus of annual sea ice versus brine volume and porosity. Line A represents E = $(9.01 - 0.464\,\nu) \times 10^{10}$ dynes/cm^2 and line B, E = $(9.24 - 0.361\,\nu') \times 10^{10}$ dynes/cm. Line B is the total porosity, air plus brine.

The results of the tests indicate that a considerable porosity exists because of the entrapped air. This is verified by comparing the measured densities with computed densities listed in Table II. The total porosity (Assur, 1966) is given as

$$\nu' = \nu_a + \nu_b = 1 - \rho_m \left[\frac{1}{\rho_i} + S\left(\sum \frac{\nu_s}{\rho_s} - \frac{\gamma_b + \gamma_s}{\rho_i} \right) \right] \qquad (4)$$

where ρ_m is the measured density, S the salinity, ρ_i the density of ice, ρ_b the density of the brine and ρ_s density of the salts. The relative weight of the brine using tables by Assur (1960; Table III) is

$$S(\gamma_b) = \left(\frac{\text{ions} + H_2O}{34.325} \right) \qquad (5)$$

and the weight of salts

$$S(\gamma_s) = \left(\frac{\text{salts}}{34.325} \right) \qquad (6)$$

where 34.325‰ is the salinity of sea water used in the table. The density of the brine ρ_b was taken from Anderson (1961). The densities of the salts, ρ_s, $Na_2SO_4 \cdot 10H_2O$ and $CaCO_3 \cdot 6H_2O$ were taken from Handbook of Chemistry and Physics (1961), and the density of fresh ice from Bader (1964).

Table II. Summary of grouped data.

Group	Density (measured) (g/cm³) ρ_m	Density (computed) (g/cm³) ρ_t	Young's modulus $E \times 10^{-10}$ (dynes/cm²)	Brine volume (%)	Total porosity (%)
1	.892	.927	8.64	2.54	2.55
2	.878	.924	7.67	2.75	4.00
3	.863	.923	7.09	3.11	5.77
4	.884	.924	7.15	3.81	3.44
5	.867	.924	7.17	4.43	5.40
6	.872	.924	7.15	3.51	4.77
7	.888	.925	8.27	2.15	3.48
8	.873	.923	7.86	1.69	4.68
9	.897	.924	8.16	1.87	2.14
10	.887	.925	7.99	1.81	3.07
11	.879	.925	8.19	2.02	3.90
12	.875	.924	8.23	1.50	4.24
13	.888	.924	8.44	1.44	2.91

Figure 20 B is a plot of Young's modulus, E, versus the ν', the total porosity. A least squares fit yielded

$$E = (9.24 - 0.361\ \nu') \times 10^{10}\ \text{dynes/cm}^2 \qquad (7)$$

where ν' is in %. A correlation coefficient of 0.86 indicates that eq 8 fits the data reasonably well. A much better correlation was obtained with eq 8 than with eq 2.

At -8.2C, $Na_2SO_4 \cdot 10H_2O$ begins to precipitate (Assur, 1958). When this happens, the strength of sea ice will increase. The data reported here (Appendix B) show that at -8.2C and below E will also increase. The average E value for ice above -8.2C was 6.88×10^{10}, compared with 8.31×10^{10} for ice below -8.2C. The available information is not sufficient to indicate an effect of solid salt inclusion. The standard deviation for E of the warmer ice was 0.41 dynes/cm² and for the colder ice 0.49 dynes/cm².

Static tests

Flexural strength. The flexural strength was determined from center-loaded simple beams (7.6 x 7.6 x 40.8 cm or 3.0 x 3.0 x 16.1 in.). The beams were harvested and prepared in the same way as the beams used for the dynamic tests. The method of loading was either a simple beam breaker device or a power-operated testing machine.

The beam breaker was a simple frame device with a lever arm attached so that when the lever arm was raised, a load was applied at the center of the beam. The applied load was measured with a spring scale. The flexural strength was the computed maximum tensile stress assuming elastic conditions to rupture.

The testing machine was similar to a standard unconfined compression testing machine. The applied load indicator of the machine did not function properly at lower temperatures; therefore, the applied load was measured with a load cell.

Table III summarizes the flexural strength tests according to layers. Figure 21 gives a plot of the average flexural strength of the layers versus the brine volume of the layer. The brine volume was determined from the profile salinity and test temperature. A straight line fit of the data gave the equation

$$\sigma = 8.13 - 3.07\,\nu^{\frac{1}{2}} \tag{8}$$

which has a correlation coefficient of 0.124 and where $\nu^{\frac{1}{2}}$ is relative amount of brine.

Ring tensile strength. The ring tests are the most commonly used field strength tests for ice. The procedure is described in detail by Ripperger, Davids (1947), Butkovich (1958) and Assur (1958). The samples were harvested with a 3 in. diam coring auger. The sample had an approximate length of 7.6 cm with a $\frac{1}{2}$-in. hole drilled coaxially through the center. The samples were ruptured by a compressive load applied at right angles to the axis of the specimen. The rupture load was measured with a proving ring.

The ring tests were performed on the annual ice, harvested at the same location as the ice used for beam tests. This was done so that a comparison of the two tests could be made. Figure 21 gives a plot of both test results. (The results of the individual ring tests are reported in USA CRREL Technical Report 157 by Hendrickson and Rowland.) An equation for the straight line for the ring tests yielded:

$$\sigma = 21.69 - 31.70\,\nu^{\frac{1}{2}} \tag{9}$$

which had a correlation coefficient of 0.349.

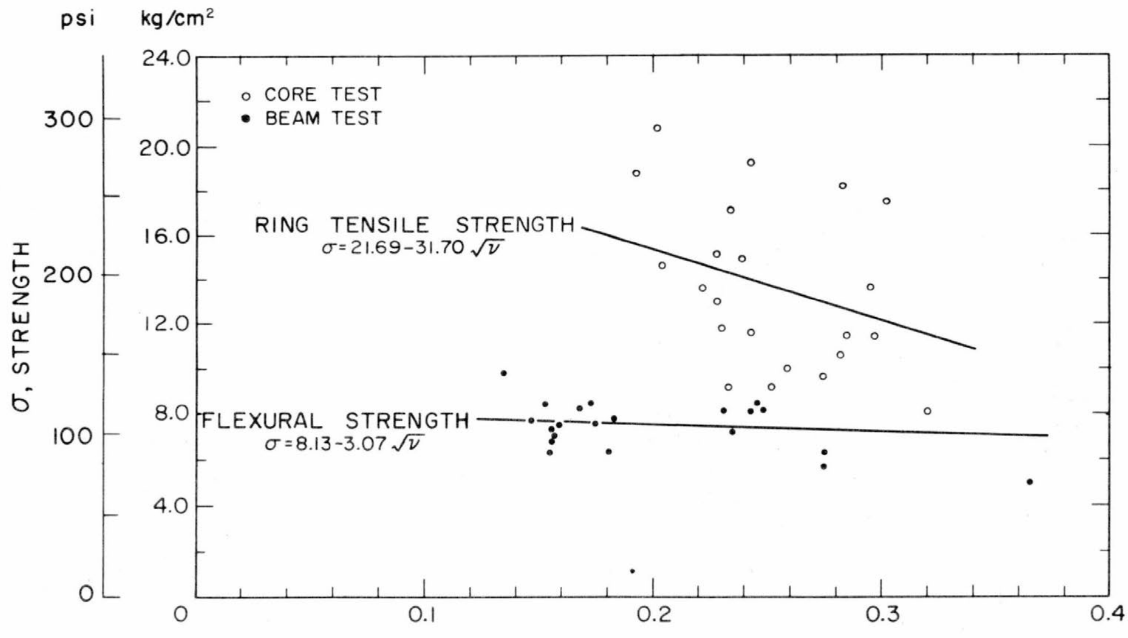


Figure 21. Ring tensile strength and flexural strength versus the square root of the relative amount of brine. Tests conducted on annual sea ice of similar characteristics.

Table III. Summary of beam tests.

Layer	No. of tests	Avg depth to center of sample (cm)	Max stress				Temp (°C)	Salinity test (‰)	Salinity profile (‰)	Brine volume $\nu^{\frac{1}{2}}$*
			Max	Min (kg/cm²)	Avg	Avg (psi)				
30 January 1965										
7	4	59.3	9.68	5.17	8.18	116.3	12.1	3.5	4.6	.148
8	4	67.0	9.42	4.20	7.46	106.1	11.3	2.5	5.0	.159
4 February 1965										
1	5	3.8	12.4	7.88	9.79	139.2	13.0	1.3	4.0	.135
2	4	11.4	11.0	7.80	9.81	139.5	12.5	2.9	4.8	.150
3	5	19.0	11.1	8.61	10.2	145.1	12.8	3.1	5.0	.152
4	5	26.6	8.67	8.03	8.43	119.9	12.2	2.8	4.9	.153
5	5	34.2	8.26	6.80	7.50	106.7	12.6	2.4	5.3	.157
6	5	41.8	8.22	5.41	6.97	99.1	12.0	3.9	5.1	.157
7	5	49.4	9.95	7.52	8.77	124.7	12.6	3.4	4.8	.150
8	3	57.0	8.84	6.52	7.68	109.2	12.4	3.7	4.6	.147
9	5	64.6	10.0	6.49	7.95	113.1	11.9	3.3	5.1	.157
10	5	72.2	6.86	2.88	5.03	71.5	12.1	3.8	4.7	.150
11	4	80.8	10.9	3.45	7.37	104.8	11.3	4.2	4.8	.156
12	4	88.4	10.3	2.58	6.55	93.2	12.0	3.6	5.1	.157
13	4	96.0	7.71	6.48	7.09	100.8	12.6	4.0	5.1	.154
14	4	103.6	6.93	5.45	6.32	89.9	12.7	4.0	5.2	.155
15	5	111.2	8.62	3.72	5.98	85.0	13.0	3.5	5.6	.160
16	5	118.8	11.4	4.73	6.80	96.7	13.2	3.5	5.4	.156
17	5	126.4	8.76	5.13	6.95	98.8	13.1	3.6	5.4	.157
18	5	134.0	8.18	5.14	6.54	93.0	12.7	3.3	5.8	.164
19	5	141.6	12.0	5.35	8.21	116.8	13.7	3.5	6.4	.168
20	4	149.2	7.17	4.46	6.02	85.6	11.7	4.8	6.4	.177
11 February 1965										
1	5	4.6	10.5	4.53	8.15	115.9	3.9	1.5	4.2	.231
2	5	13.1	14.3	5.78	10.8	153.6	4.0	3.0	4.9	.248
3	5	20.8	11.5	10.7	10.9	155.0	3.2	2.9	5.0	.274
4	5	28.4	10.7	6.82	8.19	116.5	4.0	2.2	4.9	.248
5	4	36.1	6.79	5.20	6.13	87.2	3.3	3.2	5.3	.280
6	5	43.8	10.7	6.17	8.13	115.6	4.2	3.1	5.0	.243
7	5	51.5	10.3	7.17	8.29	117.9	3.8	3.1	4.7	.247
8	5	59.1	9.14	6.92	8.01	113.9	4.7	2.7	4.6	.223
9	5	66.8	8.80	5.94	7.18	102.1	4.6	2.9	5.0	.235
10	5	74.9	8.89	4.11	6.59	93.7	4.9	3.6	4.7	.221
11	3	83.3	6.20	3.83	4.95	70.4	1.8	1.9	4.9	.365
12	5	91.1	8.81	5.90	7.05	100.3	2.4	2.5	5.1	.323
13	4	98.6	8.62	5.03	7.38	105.0	3.9	2.3	5.1	.254
14	4	106.3	11.9	6.39	8.54	121.5	4.6	3.5	5.5	.246
15	3	113.9	10.4	7.89	9.02	128.3	4.2	4.1	5.6	.259
16	4	121.6	7.64	4.69	5.68	80.8	3.5	1.9	5.4	.275
17	4	129.4	7.84	5.61	6.34	90.2	4.2	2.1	5.6	.257
18	4	136.7	6.98	5.56	6.29	89.5	4.5	2.5	6.2	.264
19	4	144.2	7.51	4.15	6.28	89.3	4.2	2.7	6.4	.275
14 February 1965										
1	4	7.3	9.88	6.53	7.62	108.4	8.5	2.3	4.4	.167
2	4	14.8	11.9	6.36	8.49	120.8	9.0	3.3	5.0	.173
3	5	22.4	9.16	6.82	8.23	117.0	8.4	3.5	5.0	.179
4	5	30.1	8.42	4.38	6.04	85.9	8.5	3.4	4.9	.176
5	5	37.8	8.57	6.44	7.83	111.4	8.5	4.9	5.3	.183
6	5	45.2	7.31	5.08	6.39	90.9	8.4	3.8	5.0	.179
7	4	52.8	9.03	5.29	7.55	107.4	8.2	3.4	4.7	.175
8	4	60.5	9.54	5.91	8.11	115.3	8.1	3.3	4.9	.180
9	4	68.0	9.25	5.05	6.39	90.9	8.0	3.5	4.9	.181

*$\nu^{\frac{1}{2}}$ was determined from the profile salinity.

Equation 10 compares favorably with the pack ice data collected by Assur and Frankenstein in 1958 (unpublished) but the limited amount of these data, of course, does not allow for further conclusions.

As expected, the ring tests yielded higher strength values than the flexural tests, the average value being 13.8 kg/cm^2, compared with 7.5 kg/cm^2 from the flexural tests. Some of the difference in the strength values may be explained by the size effect, that is, a smaller volume will produce higher strength values (Butkovich, 1959).

CONCLUSIONS

The Peter plow processing method appears to be superior to the pulvimixer method as far as the effective depth of processing and the resulting mechanical properties of the processed snow are concerned. The pulvimixer method results in a processed layer that may not be sufficiently thick for heavy aircraft loads. A weak layer frequently is developed at the interface of the snow layers. The Peter plow method, however, appears to be more difficult operationally.

The LGP D-8 tractor compaction method appears to be highly effective for extent and depth of compaction. It is comparable to the roller method from an operational standpoint.

The automatic snow finegrader did not perform efficiently, perhaps because of a hydraulic malfunction, and a realistic comparison between this machine and a land planer could not be made. Previous experience has indicated that the automatic finegrader is superior to any other leveling device as a runway surface finishing tool. On a very soft or rough surface, however, it is not very efficient. The automatic finegrader leveling method is more difficult than the land planer method. A high drawbar pull is required for towing this machine and a skilled operator is required.

Snow runways capable of supporting a C-130 aircraft on wheels can be constructed by either the Peter plow or pulvimixer processing method, if a high degree of quality control is maintained. During processing, and the first few weeks of age hardening, favorable temperature conditions (-15 to -1C) are necessary. The runway would be reliable only during comparatively low temperatures (-15C and below) for C-130 aircraft traffic on wheels. The runway could not be expected to be operational within the desired degree of safety during temperatures above -10C.

The feasibility of supporting a C-121 on wheels on this type of a runway is marginal, unless low temperatures (below -15C) exist for several days prior to, and during, the C-121 wheeled traffic. Some type of runway surface strengthening seems to be necessary. A landing mat or additives may be considered. A surface layer of ice, several inches thick, may be preferable. The C-121 requires a stronger surface (to a depth of 30 cm) than the C-130 aircraft (Fig. 18). The required strength for the depth below 10 cm can be obtained with the Peter plow or pulvimixer processing methods. The top 10 cm of snow, however, would probably require processing with heat or water or some other strengthening method, particularly for temperatures above -15C. Extensive compaction with equipment producing high pressures on the snow surface may be sufficient, but the required quality control may be difficult to attain.

The occurrence of above freezing temperatures at McMurdo during the Antarctic summer months (December through February) is the most serious and detrimental factor as far as dependability of a reliable snow runway is concerned.

Young's modulus, as reported here, increases as the ice density increases and decreases with a decrease in density. The data also show that Young's modulus is related to the ice temperature, the colder ice resulting in a higher Young's modulus value.

The results of the ice tests indicate that the annual sea ice at McMurdo, Antarctica, has similar strength characteristics as sea ice of the Arctic for any given salinity and temperature. This means then that the bearing capacity tables obtained from Arctic test data may be used for operational uses in the Antarctic.

The authors have been informed that an annual sea ice runway may be in operation during "Operation Deepfreeze 66." This runway would be used until mid-December, after which all air operations would be conducted with ski-equipped aircraft. The skiway will be located on the ice shelf near the NCEL compacted runway. If the annual ice runway proves successful, flights can be made to McMurdo during the Antarctic winter with aircraft similar to the C-135 jet transport.

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APPENDIX A. SNOW PROPERTIES

Grain size distribution

Location		Williams Field, Cross-wind runway					South Pole*	
Type of snow		Peter plow processed			Pulvimixer processed		Natural	
							40cm depth	18cm depth
Date		1 Feb 65	1 Feb 65	1 Feb 65	3 Feb 65	3 Feb 65	8 Feb 65	8 Feb 65
Snow temp, °C		-7	-7	-7	-8	-8	-10	-10
Air temp, °C		-7	-7	-7	-7	-6.5	-7	-7
Sieve no.	Sieve size				% passing			
½"	12.7 mm	100.0	100.0	100.0	95.0	89.3	100.0	100.0
4	4.76 mm	93.3	98.4	97.6	83.6	78.4	100.0	100.0
10	2.00 mm	85.2	91.2	91.7	76.1	70.4	98.6	98.7
20	0.84 mm	56.0	51.2	52.2	47.8	43.2	93.9	90.1
40	0.42 mm	8.6	5.6	8.5	10.9	4.6	9.5	6.1
80	0.177 mm	0.15	0.1	0.15	0.05	0	0.05	0.05
200	0.074 mm	0	0	0	0	0	0	0

*Sieve analyses on snow samples obtained at South Pole were performed at McMurdo 8 hours later. Original snow temp -31C.

Sample size: 200 g, sieved for 2 minutes with a manually operated shaker.

Density

Location	Williams Field			NCEL Camp		
Type of snow	Natural			Natural		
Date	27 Jan 65			6 Feb 65		
	Depth (cm)	Density (g/cm³)	Temp (°C)	Depth (cm)	Density (g/cm³)	Temp (°C)
	4	.49	-6	3	.42	-8
	25	.41	-7	20	.45	-9
	35	.49	-8	35	.40	-9.5
	46	.42	-8	50	.37	-10
	61	.40	-8	75	.43	-10.5
				100	.41	-10.5

Location	Williams Field, cross-wind runway						South Pole Station			
Type of snow	Peter processed, uncompacted		Peter processed, compacted		Pulvimixer processed, compacted		Natural		Compacted (runway)	
Date	4 Feb 65		3 Feb 65		3 Feb 65		8 Feb 65		8 Feb 65	
Air temp, °C	-9		-2		-2		-29		-29	
	Depth (cm)	Density (g/cm³)	Depth (cm)	Density (g/cm³)	Depth (cm)	Density (g/cm³)	Depth (cm)	Density (g/cm³)	Depth (cm)	Density (g/cm³)
	5	.57	11	.62	10	.59	10	.32	5	.51
	20	.56	40	.63	20	.62	15	.31	5	.48
	35	.55	65	.60	30	.60	23	.32	13	.45
							25	.34	13	.49
							38	.30	25	.41
							41	.29	31	.40
							51	.32	46	.30
							53	.31	51	.35
							76	.28	76	.28
							81	.27	76	.30

Ram hardness

Location	Williams Field, cross-wind runway							
Type of snow	Peter plow (processed and compacted)						Pulvimixer	
Age hardening	1 day	2 days	3 days	4 days	5 days	15 days	14 days	22 days
Air temp, °C	-2	-8	-9	-10	-8	-1.5	-5	-13
Snow surface temp, °C	-7	-10	-11	-12	-10	-1.7	-5	-14
Depth (cm)	Average hardness*							
0 - 5	210	470	602	735	470	286	258	357
5 - 10	279	583	786	840	~1000	410	453	775
10 - 15	255	544	469	679	814	334	417	754
15 - 20	298	454	454	559	~1000	584	469	994
20 - 25	310	394	394	529	844	754	522	~1000
25 - 30	267	274	334	379	484	754	432	~1000
30 - 35	259	274	264	304	424	674	327	664
35 - 40	229	244	224	244	394	624	297	454
40 - 45	200	244	144	334	334	524	354	454
45 - 50		154				494	199	394
50 - 55		154				349		334
55 - 60		214				334		214
Average (0-45 cm)	256	387	408	511	640	549	392	717

*Average of 2 to 5 tests.

Ram hardness

Location	Williams Field							
Type of snow	Peter plow processed, uncompacted							
Age hardening	3 days		4 days		8 days		28 days	
Date	30 Jan 65		31 Jan 65		4 Feb 65		24 Feb 65	
Air temp, °C	-3		-2		-10		-13	
Snow surface temp, °C	-6		-8		-10		-14	
Depth (cm)	Avg*	Range	Avg*	Range	Avg*	Range	Avg*	Range
0 - 5	143	132-188	207	132-200	405	188-584	385	300-470
5 - 10	67	26-122	77	45-102	205	122-333	327	179-583
10 - 15	52	28- 88	54	40- 64	122	64-220	232	160-424
15 - 20	60	28- 88	62	28- 88	102	40-184	264	160-424
20 - 25	64	40-100	52	28- 64	86	40-124	246	112-364
25 - 30	68	28-124	50	40- 64	80	40-148	242	88-352
30 - 35	50	28-100	40	28- 52	76	40-172	172	76-280
35 - 40	42	28- 64	42	28- 52	54	40- 64	116	76-196
40 - 45	45	28- 64	29	8- 40	57	40- 76	88	28-160
Average (0-45 cm)	66		68		132		230	

*Average of 6 tests.

Flexural strength

Location	Williams Field, cross-wind runway													
Type of snow	Peter plow processed, compacted							Pulvimixer processed, compacted						
Age hardening	15 days							14 days						
Date	16 Feb 65							16 Feb 65						
Air temp, °C	-1.5							-5						
		No.	Strength						No.	Strength				
	Depth (cm)	of tests	Min	Max (kg/cm²)	Avg	Avg (psi)	Temp (°C)	Depth (cm)	of tests	Min	Max (kg/cm²)	Avg	Avg (psi)	Temp (°C)
	15	3	1.12	1.30	1.20	17.1	-8.0	4	4	0.68	1.09	0.83	11.8	-7.5
	23	4	1.27	1.96	1.62	23.1	-8.2	11	4	0.72	1.58	1.24	17.7	-7.7
	31	4	1.24	1.58	1.46	20.8	-8.1	19	4	1.07	1.36	1.17	16.7	-8.0
	38	4	1.30	1.45	1.36	19.4	-8.3	27	4	0.46	1.01	0.70	10.0	-8.2
	46	4	1.35	1.67	1.47	20.9	-8.5	34	4	0.73	1.33	1.02	14.5	-8.5
	53	4	1.15	1.43	1.28	18.2	-8.5	42	4	2.78	3.01	2.90	41.3	-8.6
	61	4	1.16	1.38	1.30	18.5	-8.8	50	4	1.59	2.07	1.83	26.1	-8.8
	69	3	0.51	0.71	0.62	8.8	-9.0	57	4	0.53	0.78	0.65	9.2	-8.9
								65	4	0.85	1.19	1.01	14.4	-9.0
								72	4	0.48	0.65	0.56	8.0	-9.2

Specimen size: Length = 50 to 60 cm
Width = 7 to 8 cm
Height = 6.5 to 9 cm

Note: depth denotes the center of sample.

Flexural strength

Location	NCEL Runway, Sta. 67+00							1963-64 Runway (NCEL)						
Type of snow	Pulvimixer processed, compacted							Pulvimixer processed, compacted						
Age hardening	2 - 3 months							1 year						
Date	1 Feb 65							1 Feb 65						
Air temp, °C	-6.5							-6.5						
		No.	Strength						No.	Strength				
	Depth (cm)	of tests	Min	Max (kg/cm²)	Avg	Avg (psi)	Temp (°C)	Depth (cm)	of tests	Min	Max (kg/cm²)	Avg	Avg (psi)	Temp (°C)
	4	6	2.03	4.20	3.37	48.0	-7.7	4	4	0.17	2.04	1.83	26.1	-6.4
	11	9	2.95	4.67	3.48	49.5	-8.3	11	4	2.43	3.70	3.03	43.1	-6.7
	19	9	0.98	3.98	2.08	29.6	-8.0	19	4	3.02	3.52	3.30	47.0	-6.3
	27	4	1.38	1.80	1.60	22.8	-8.7	27	4	2.57	4.13	3.37	48.0	-6.1
	34	4	1.35	1.89	1.60	22.8	-8.4	34	4	2.01	3.41	2.92	41.6	-6.2
	42	4	1.28	2.29	1.72	24.5	-8.5	42	4	0.47	1.16	0.88	12.5	-5.8
	50	4	1.75	3.00	2.33	33.2	-8.4	50	4	1.99	2.73	2.39	34.0	-5.5
	57	4	1.27	2.01	1.76	25.1	-8.3	57	3	2.15	2.71	2.51	35.7	-5.3
	65	3	0.70	0.85	0.78	11.1	-8.8	65	4	1.79	2.63	2.10	29.9	-5.3

Specimen size: Length = 50 to 60 cm
Width = 7 to 8 cm
Height = 6.5 to 9 cm

Note: depth denotes the center of sample.

Unconfined Compressive Strength

Location	NCEL Runway							
Type of snow	Pulvimixer processed, compacted							
	Sta. 67+00				Sta. 50+00			
Age hardening	2 - 3 months				2 - 3 months			
Date	6 Feb 65				18 Feb 65			
Air temp, °C	-3				-5.5			
	Depth (cm)	Temp (°C)	Strength (kg/cm²)	Strength (psi)	Depth (cm)	Strength (kg/cm²)	Strength (psi)	Density (g/cm³)
	7	-3.1	8.10	115.2	8	8.86	126.0	.60
	8	-	7.22	102.7	10	7.50	106.7	.58
	10	-	6.35	90.4	10	7.80	111.0	.59
	25	-	8.70	123.8	22	4.03	57.4	.59
	26	-3.5	5.12	72.8	25	5.38	76.6	.57
	29	-4.8	7.18	102.3	27	5.50	78.2	.56
	37	-4.0	4.10	58.3	41	4.38	62.4	.54
	40	-	1.43	20.5	42	2.84	40.4	.55
	43	-5.2	7.18	102.3	46	5.70	81.8	.55
	50	-	6.18	88.0	50	2.57	36.6	.55
	54	-4.5	4.33	61.6	55	5.19	73.9	.54
	57	-5.0	5.27	75.0	61	4.48	63.8	.55
	77	-4.8	4.26	60.6	71	4.92	68.5	.54
	78	-3.7	5.50	78.2	71	3.44	49.0	.55
	85	-	1.46	20.8	72	4.89	69.6	.55
					77	1.12	15.9	.50

Specimen size: Length = 12.7 to 22.6 cm
Diameter = 7.5 to 7.6 cm

Rate of deformation: 2 in./min

Note: depth denotes the center of sample.

Dynamic measurements

Young's modulus measurements were obtained from samples from the NCEL (1964) runway. The method and procedure used to measure Young's modulus is explained under the discussion on snow studies.

The correlation between density and Young's modulus for the small range of densities used agreed very well with data by others (see Fig. A1).

The mean of Young's modulus values was 2.3×10^{10} dynes/cm² for processed snow with an average density of 0.56 g/cm³ at a temperature of -4C.

Unconfined compressive strength tests were performed on the samples used for Young's modulus measurements. Previous data from Greenland indicate a definite relationship between unconfined compressive strength and the dynamic Young's modulus. However, because of the limited amount of data from this study, the correlation was not evident here.

Young's Modulus

Sample	Sample length (cm)	Density ρ (g/cm³)	Young's modulus E (dynes/cm²)	Unconfined compressive strength* (kg/cm²)
1	14.3		2.00×10^{10}	4.03
2	12.7	.54	1.70	5.19
3	14.0	.58	2.08	7.50
4	18.6	.55	2.02	2.84
5	31.5	.53	1.83	
6	16.4	.55		4.48
7	14.9	.50		1.12
8	13.4	.59	2.65	7.80
9	15.3	.57	2.46	5.38
10	21.3	.55	2.30	5.70
11	22.6	.55	2.35	4.89
12	13.8	.60	3.29	8.86
13	26.7	.55	2.31	
14	19.0	.54		4.38
15	23.4	.55	2.23	
16	19.6	.54	2.22	4.92
17	22.2	.56	2.63	5.50
18	43.2	.55	2.44	
19	21.2	.55	2.13	2.57
20	21.6	.55	2.07	3.44

*Rate of deformation = 5 cm/min
Age of samples = 1 year in field
Temp = -4C

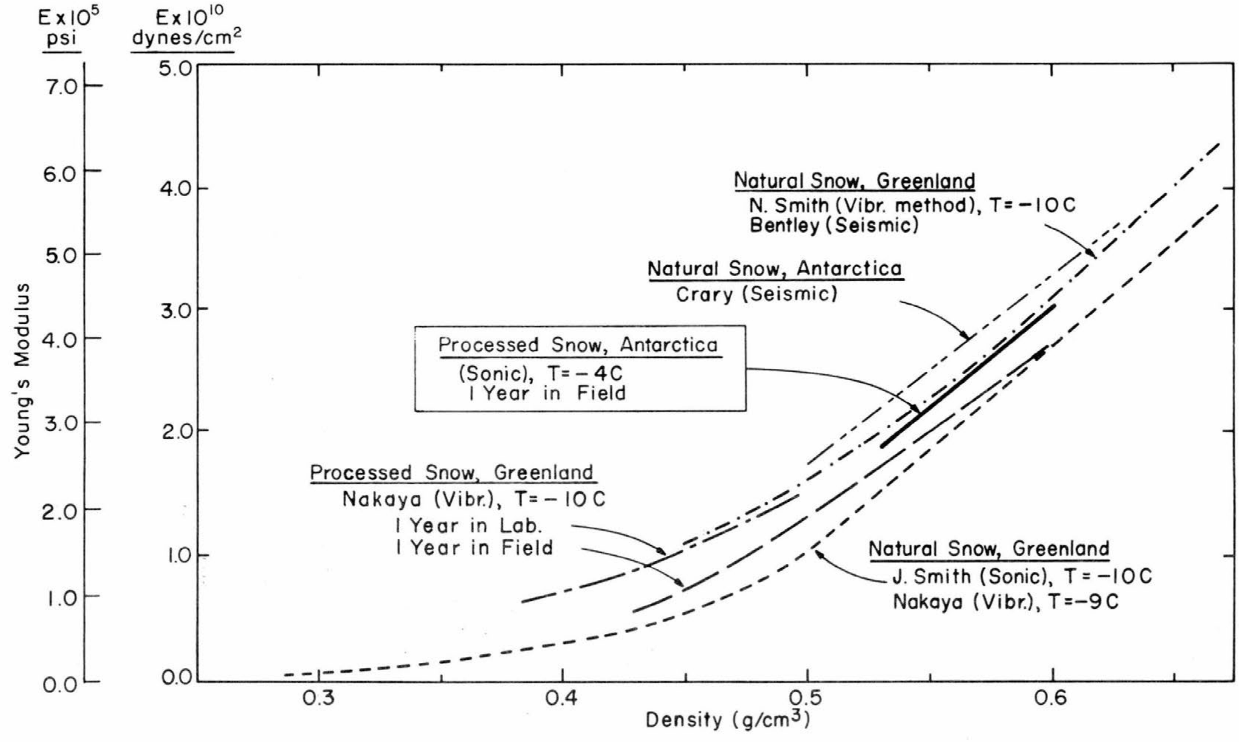


Figure A1. Young's modulus of snow vs density.

APPENDIX B. ICE DATA

Number	Depth to center of sample (cm)	Length* (cm)	Density (meas) (g/cm³) ρ_m	Density (comp) (g/cm³) ρ_t	Young's modulus E x 10^{-10} (dynes/cm²)	Brine volume, $\nu^\dagger$ (%)	Porosity, ν' (%)	Salinity (test) (‰)	Temperature (-°C)	Flexural strength Kg/cm²	psi
					30 January 1965						
1	7.0	58.15	.882	.923	8.17	1.74	3.64	2.7	8.3	10.7	152.1
2	14.5	34.42	.887	.926	8.02	2.37	3.08	3.9	8.9		
3	22.2	57.98	.881	.925	8.44	2.26	3.75	3.5	8.3	9.70	138.0
4	44.2	57.12	.855	.925	7.73	2.24	6.59	3.5	8.4	7.47	106.2
5	51.8	57.08	.888	.926	8.34	2.44	2.98	3.9	8.6	7.58	107.8
6	59.3	59.08	.875	.925	8.47	2.24	4.40	3.5	8.4		
7	67.0	56.75	.885	.924	8.22	2.00	3.31	3.1	8.4		
					4 February 1965						
8	3.8	53.25	.842	.921	7.43	0.59	7.93	1.3	13.0	9.13	129.8
9	11.4	51.50	.889	.924	8.41	1.36	2.80	2.9	12.5	7.80	110.9
10	19.0	52.08	.889	.924	8.37	1.43	2.80	3.1	12.8	10.4	147.9
11	26.6	52.55	.878	.924	7.97	1.33	4.01	2.8	12.2	8.39	119.3
12	34.2	53.70	.872	.923	8.06	1.12	4.66	2.4	12.6	7.02	99.8
13	41.8	53.81	.871	.926	8.29	1.88	4.78	3.9	12.0	7.68	109.2
14	49.4	55.26	.914	.925	8.80	1.58	0.07	3.4	12.6	8.91	126.7
15	57.0	35.24	.887	.925	8.99	1.74	3.02	3.7	12.4	6.52	92.7
16	64.6	54.78	.882	.925	8.59	1.60	3.58	3.3	11.9	7.00	99.6
17	72.2	54.70	.878	.926	8.18	1.82	4.01	3.8	12.1	6.86	97.6
18	80.8	46.48	.886	.926	8.53	2.12	3.15	4.2	11.3	3.45	49.1
19	88.4	45.66	.884	.925	7.72	1.74	3.36	3.6	12.0	2.58	36.7
20	96.0	45.91	.898	.926	8.87	1.86	1.82	4.0	12.6	7.71	109.6
21	103.6	46.86	.902	.926	8.43	1.85	1.38	4.0	12.7	6.67	94.9
22	111.2	46.20	.889	.925	7.82	1.60	2.80	3.5	13.0	3.72	52.9
23	118.8	46.20	.880	.925	7.08	1.58	3.78	3.5	13.2	4.73	67.3
24	126.4	46.46	.907	.925	8.32	1.63	0.83	3.6	13.1	5.95	84.6
25	134.0	46.65	.883	.925	7.24	1.53	3.46	3.3	12.7	5.68	80.8
26	141.6	46.89	.878	.925	6.99	1.54	3.99	3.5	13.7	12.0	170.7
27	149.2	40.44	.906	.927	8.35	2.36	0.96	4.8	11.7	6.54	93.0
					10 February 1965						
28	4.6	41.25	.890	.921	6.86	1.90	2.83	1.5	3.9	10.5	149.3
29	13.1	46.20	.881	.924	6.99	3.76	3.82	3.0	4.0	12.3	174.9
30	20.8	49.05	.886	.924	7.72	4.35	3.28	2.9	3.2	10.9	155.0
31	28.4	45.52	.860	.922	7.24	2.76	6.11	2.2	4.0	10.7	152.2
32	36.1	47.38	.869	.925	7.46	4.74	5.14	3.2	3.3	5.81	82.6
33	43.8	46.00	.855	.924	6.72	3.66	6.65	3.1	4.2	9.10	129.4
34	51.5	47.95	.875	.924	7.58	4.03	4.48	3.1	3.8	8.03	114.2
35	59.1	45.42	.871	.923	7.40	2.92	4.90	2.7	4.7	7.62	108.4
36	66.8	56.80	.877	.923	6.94	3.19	4.24	2.9	4.6	7.42	105.5
37	74.9	51.12	.883	.925	7.11	3.74	3.58	3.6	4.9	4.11	58.4
38	83.3	34.70	.864	.924	7.05	5.17	5.70	1.9	1.8	4.82	68.6
39	91.1	41.85	.854	.924	6.37	5.12	6.79	2.5	2.4	7.71	109.6
40	98.6	44.90	.871	.922	6.94	2.92	4.91	2.3	3.9	5.03	71.5
41	106.3	46.05	.888	.925	7.45	3.85	3.04	3.5	4.6	6.39	90.9
42	113.9	40.90	.886	.926	6.94	4.90	3.27	4.1	4.2	10.4	147.9
43	121.6	45.08	.842	.922	5.46	2.66	8.08	1.9	3.5	5.50	78.2
44	129.4	45.30	.847	.922	6.29	2.48	7.52	2.1	4.2	5.61	79.8
45	136.7	46.28	.855	.923	5.86	2.80	3.37	2.5	4.5	6.11	86.9
46	144.2	46.05	.852	.923	6.03	3.19	6.98	2.7	4.2	4.15	59.0

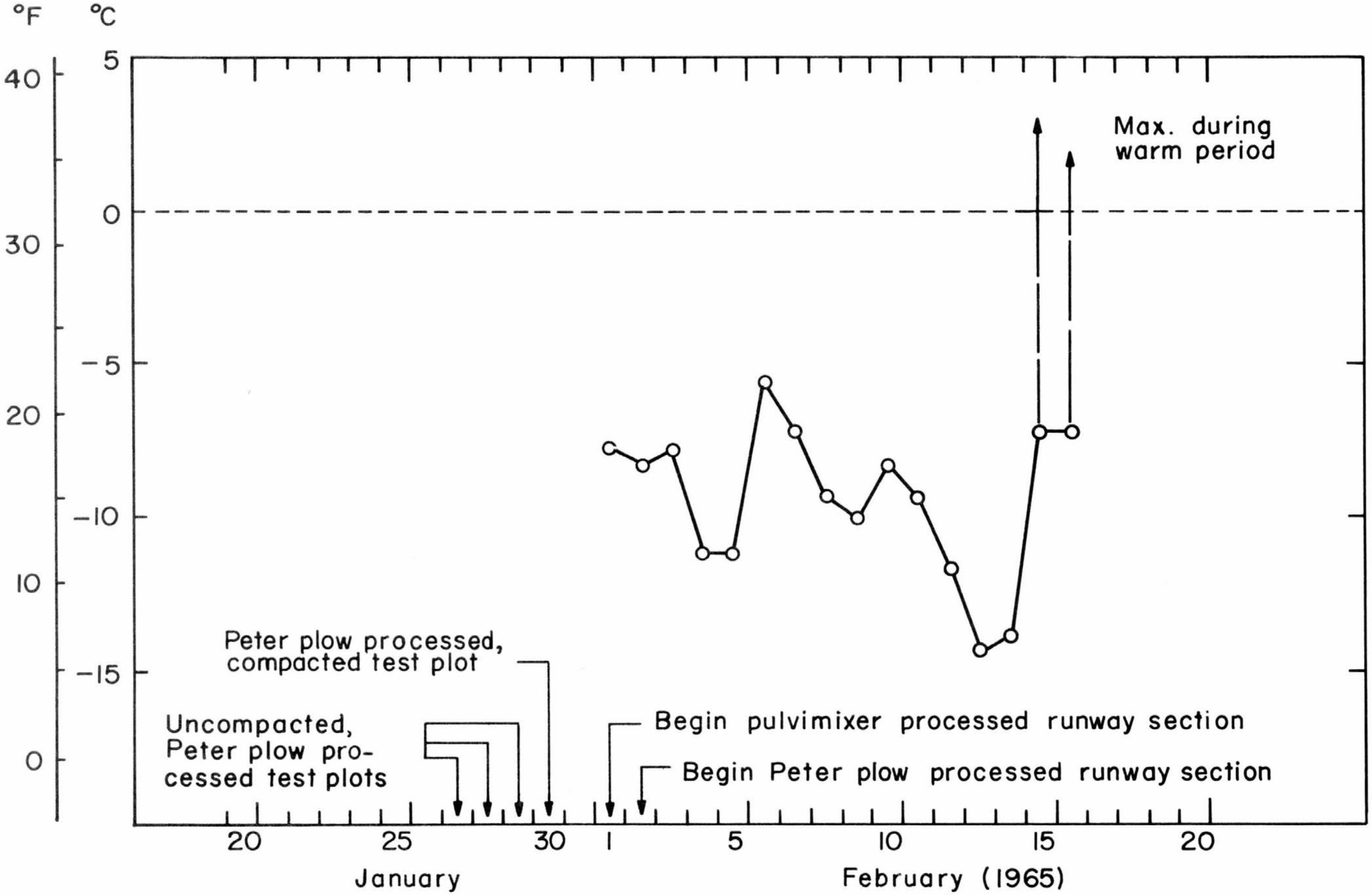
*Beams measured approximately 5.0 x 5.0 cm in cross section.
†Brine volume was determined from the test salinity.

APPENDIX B

Number	Depth to center of sample (cm)	Length* (cm)	Density (meas) (g/cm^3) ρ_m	Density (comp) (g/cm^3) ρ_t	Young's modulus E x 10^{-10} (dynes/cm^2)	Brine volume, ν† (%)	Porosity, ν' (%)	Salinity (test) (‰)	Temperature (-°C)	Flexural strength Kg/cm^2	Flexural strength psi
					11 February 1965						
47	39.5	45.00	.912	.924	9.06	2.97	4.12	3.0	5.2		
48	86.6	35.38	.878	.925	7.76	3.69	4.12	3.8	5.2		
49	128.5	32.30	.858	.924	7.60	3.43	6.31	3.5	5.2		
50	166.1	28.91	.890	.924	8.32	3.27	2.81	3.3	5.2		
51	192.6	13.92	.896	.925	7.40	3.60	2.16	3.6	5.1		
					13 February 1965						
52	7.3	45.65	.856	.923	7.70	1.45	6.48	2.3	8.5	9.88	140.5
53	7.3	23.50	.850	.921	6.89	1.06	7.14	1.6	8.1		
54	14.8	49.10	.849	.925	8.57	1.99	7.23	3.3	9.0	11.9	169.2
55	14.8	26.38	.927	.925	8.72	2.13	-	3.3	8.3		
56	22.4	49.25	.893	.925	8.81	2.24	2.44	3.5	8.4	9.16	130.3
57	30.1	41.98	.900	.925	6.96	2.15	1.67	3.4	8.5	8.42	119.8
58	37.8	43.30	.902	.928	10.04	3.10	1.45	4.9	8.5	8.57	121.9
59	45.2	46.55	.876	.926	8.46	2.43	4.29	3.8	8.4	7.17	102.0
60	52.8	48.52	.889	.924	8.63	2.22	2.88	3.4	8.2	5.29	75.2
61	52.8	24.48	.891	.924	9.12	2.48	2.66	3.8	8.2		
62	60.5	47.60	.891	.923	9.14	2.18	2.66	3.3	8.1	9.24	131.4
63	60.5	23.30	.912	.924	8.96	2.07	3.61	3.2	8.3		
64	68.0	46.95	.881	.924	8.26	2.33	3.75	3.5	8.0	9.25	131.6
65	68.0	23.52	.886	.925	9.45	2.23	3.20	3.5	8.4		

Tests 47-51 are 3 in. diam cores.

*Beams measured approximately 5.0 x 5.0 cm in cross section.
†Brine volume was determined from the test salinity.



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13. ABSTRACT

Dynamic tests were performed to determine the Young's modulus of sea ice, derived from longitudinal wave velocities measured with a soniscope. Static tests consisted of standard ring tensile strength and simple beam or flexural strength tests. The strength data were plotted on a base of the brine volume for each test. The test results indicate that the annual sea ice at McMurdo Sound is capable of supporting cargo type aircraft. Snow runways capable of supporting a C-130 aircraft on wheels and providing marginal support to a C-121 can be constructed either with the Peter plow or with the pulvimixer. However, the runway would be reliable only during comparatively low temperatures (< -15C). Peter snow miller processing and bulldozer compaction methods appear to be feasible for effective depth processing and compaction of high strength snow pavements. The criteria for support of various types of aircraft on a snow runway are presented.

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