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Technical Report 42

JULY, 1956

Testing of a Compacted Snow Runway (U)

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Downgraded at 3 year intervals;
Declassified after 12 years.

SNOW, ICE AND PERMAFROST
RESEARCH ESTABLISHMENT
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Technical Report 42

JULY, 1956

Testing of a Compacted Snow Runway (U)

by James A. Bender

Declassified *UUC*, by authority
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PREFACE

This report describes the methods and techniques used in testing a snow runway built on deep snow on the Greenland Ice Cap during the summer of 1955. The runway was built by members of the 1st Engineer Arctic Task Force, commanded by Lt. Col. Elmer P. Clark and under the immediate supervision of Capt. John Napier, with Mr. Paul Beigheder of the Engineer Research and Development Laboratories, Corps of Engineers, as project engineer. Mr. James A. Bender, Chief of the Snow and Ice Basic Research Branch, Snow Ice and Permafrost Research Establishment, was responsible for the testing of the strip, aided by members of the 1st Engineer Arctic Task Force, especially Pfc Frank Royse. The information regarding the landings of the C-124 was obtained from Lt. W. H. McTigue, who was an official observer of the 1st EATF.

Ms. received 4 June, 1956

Department of the Army Project No. 8-66-02-004

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SUMMARY

A snow runway was built on deep snow on the Greenland Ice Cap and tested during the summer of 1955. The strip was constructed by members of the 1st Engineer Arctic Task Force using modified pulvimixers with heat. Testing included Rammsonde measurements, and snow temperature observations on the strip; undisturbed cores were taken and tested for density, structure, unconfined compressive strength, unconfined shear strength, and stress/strain relations. Large-scale testing was done with a Bros rubber-tired roller, and C-47, C-54 and C-124 type aircraft. A formulation between the ram hardness values and the unconfined compressive strength is developed, and the Rammsonde is suggested as a simple instrument for determining the bearing capacity of a snow. Formulas are given for the increase in strength of snow with decreasing temperature and also for the amount of age-hardening with time.

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TESTING OF A COMPACTED SNOW RUNWAY (U)

INTRODUCTION

The processing of the snow for the runway, by modified pulvimixers using heat, was started on 6 July and completely finished by 1 September. Successful landings on the 200 x 10,000 ft strip were made by C-47, C-54, and C-124 type aircraft. The conclusion that the strip could support these aircraft and the decision to land the planes were based on the laboratory testing.

This report describes the methods and techniques used in testing a snow runway built on deep snow, and gives suggested requirements of a snow runway to support various type aircraft. It is not intended as a report on the operational aspects of making such a runway, nor as a critique on the techniques used. Also, it should be realized that this represents the beginning of a long-range program and that additional theoretical work and field work are still necessary.

TEST PROCEDURE

The testing procedure may be divided into three methods: (a) simple in-place testing, (b) the taking of undisturbed samples and testing them in a laboratory, and (c) large-scale testing. Procedures (a) and (b) require only two men and simple testing equipment. It is desirable that procedure (a) perhaps supplemented by (b) give sufficient information to predict the results of large-scale tests and the capabilities of a snow runway.

Simple in-place testing

A large number of ram hardness readings were made systematically on the strip several times during the test period. The Rammsonde (see discussion by R. Haefeli, in Bader *et al*, 1939, Ch. II) is a simple instrument which requires only one man to operate and another to take readings (see Fig. 1), and one profile was obtained in about 5 minutes. Several pits were dug in the runway and the temperature-depth profile obtained using Weston dial thermometers. Daily air temperatures (Fig. 2) during the period were obtained from the Air Force.

Laboratory testing

A laboratory was made by the simple expedient of digging a 6 x 8 x 8-ft deep hole in the snow and covering it with a few 2 x 6-in boards and a tarpaulin. The roof was soon covered by a foot of drifted snow. This provided an ample working space protected from the elements and at a temperature of about -10°C (14°F). Undisturbed specimens for testing were obtained from the strip with the SIPRE modified auger (Fig. 3). Vertical cores 3 in. (7.6 cm) in diameter and up to 34 in. (86 cm) long were obtained. The procedure used was to take several cores, noting the position on the strip for each one, place them individually in cardboard tubes, and transport them to the snow laboratory. Here, each core was visually inspected and the depth of each layer and its structure noted. The core was then cut into sections with a simple miter box and saw. Cuts were made at layer boundaries, with a maximum length of 10 in. (25 cm) the largest size useable in the specially designed press (Fig. 4). The exact diameter, length, and

Figure 1. Rammsonde operated by one man.

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Figure 2. Daily air temperature.

Figure 3. SIPRE modified 3-in auger.

weight of each cut portion were measured in order to obtain the density with depth. Whenever possible, the ultimate unconfined compressive strength and stress-strain relationship were obtained, with the rate of loading and temperature noted.

In addition to the vertical sampling, four pits were dug and horizontal core samples taken for shear measurements. The depth, structure, density, and ultimate shear strength (zero lateral pressure) of each specimen were obtained, with the rate of loading and temperature noted.

Large-scale testing

A four-wheeled rubber-tired Bros roller (Fig. 5) was pulled over the entire strip, first empty, and then with increasing load up to 13,000 lb per wheel with approximately 100 psi tire pressure. The areas where breakthrough occurred were noted and studied. Readings were taken with a rod and transit to determine whether or not there was any deflection of the strip (due to plate action) when the tractor and roller passed by.

The final testing was the successful landings and take-offs of C-47, C-54, and C-124 type aircraft (Figs. 6, 7, and 8).

TEST RESULTS

The processing of the snow is summarized in Table I. All sampling was done three or more days after processing. The division of the strip into sections is shown in Figure 9.

Laboratory tests

Density. The densities with depth and position on the strip are shown in Figure 10. It was noted that the processing caused a hard top layer of high density and strength; below it, the density decreased from that of the top layer to that of the virgin snow. The hard uppermost layer was caused by disaggregating action of the pulvimixer and the heating of the snow with the resultant free moisture and their freezing. The second layer's increased density is partly due to the pulvimixer action and partly to compaction by a loaded skid which followed. The densities (specific gravities) are considered to be accurate to 0.01. It may also be noted that the depth

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of the processed layer varies considerably which is due to the inherent variation in pulvimixer action. The method of processing used in Section I, with the rotors running backwards, gave much deeper penetration.

The average density and depth of the top layer by sections are shown in Table II.

Table I. Processing of Air Strip

Section	Processing	Date Completed
I	6 passes pulvimixer wo/heat (rotors turning backwards)	15 July
	3 passes pulvimixer w/heat	20 July
II	3 passes pulvimixer wo/heat	12 July
	3 passes pulvimixer w/heat	20 July
III	3 passes pulvimixer w/heat	27 July
	Reprocessed using 3 passes pulvimixer w/heat	24 Aug
IV	3 passes pulvimixer w/heat	26 July
	Reprocessed using 3 passes pulvimixer w/heat	4 Aug
V	3 passes pulvimixer w/heat	11 Aug
	Reprocessed using 3 passes pulvimixer w/heat	22 Aug
	Old processed snow removed, virgin snow brought in and processed with 3 passes of pulvimixer w/heat	1 Sept
VI	3 passes pulvimixer w/heat	10 Aug

Table II. Average Density of Processed Layer

Section	Average Density (g/cm ³)	Average Depth of Processed Layer	
		(cm)	(in.)
I	.60	49	19
II	.57	23	9
III	.60	38	15
IV	.55	28	11
V	.58	39	15
V*	.59	43	18
VI	.56	26	10

The virgin snow was generally about 76 cm (30 in.) below the top of the processed layer and had a density of about 0.42. The density of the snow between the processed and virgin layer decreased with depth. The density and temperature profile of the snow before processing are shown in Figure 11.

* On virgin snow that was hauled in and processed.

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Figure 4. Press for testing strength of snow samples.

Figure 5. Bros rubber-tired roller.

Figure 6. Ski-wheeled C-47 airplane on strip.

Figure 7. C-54 airplane on strip.

Figure 8. C-124 airplane on strip.

Figure 9. Division of processing of the strip into sections.

Figure 10a. Variation of density with depth and position.
(See Fig. 9 for positions on strip.)

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Figure 10b. Variation of density with depth and position.
(See Fig. 9 for positions on strip.)

TESTING OF A COMPACTED SNOW RUNWAY

Figure 11. Density and temperature profile of snow before processing.

Figure 12. Compressive strength vs. depth, sections I and II.

Figure 13. Compressive strength vs. depth, Section III.

Figure 14. Compressive strength vs. depth, Section IV.

Figure 15. Compressive strength vs. depth, Section V.

Figure 16. Compressive strength vs. depth, Section VI.

Figure 17. Type of break of specimen under compression.
 a) Collapse at interface of hard and soft layers. b) Failure at base. c) Collapse. d) Bending. e) Shear. f) Shear. g) Axial break.

Compressive strength. The ultimate unconfined compressive strength of the vertical cores (Fig. 12-16) was determined with the mechanically loaded press (Fig. 4). The cores were allowed to come to the temperature of the testing laboratory; the average rate of loading was about 8.8 kg/sec (19 lb/sec). There was no deliberate attempt to vary the temperature or the rate of loading, but rather to keep them about the same, noting the value of each. The strength values were all corrected to -10°C in the manner shown in the appendix.

The specimen would break in various ways as shown in Figure 17. Care was taken in cutting core specimens to exclude more than one stratum of snow, as a break similar to the one shown in Figure 17a would result. The second specimen (17b) shows a break at the base which was caused either by an uneven base, or by an inherent weakness in the snow near the base. Almost all of the virgin snow and the lower-density processed snow samples broke by a collapse of the snow structure in a horizontal plane, as shown in Figure 17c. A large deformation accompanied the collapse. If the loading continued, the pressure would again build up and cause another collapse. In a few cases on processed snow, where the two bases were not parallel, eccentric loading developed, causing the bending shown in Figure 17d. Most of the strong specimens of processed snow failed in shear. Two such cases are shown in 17e and 17f and another case, not shown, of cone failure also occurred. Breaking along the axis of loading (Fig. 17g) happened only rarely.

The average compressive strength values are given in Table III. Since only a very small number of compressive tests were run on samples from Sections I and II, these values are not included. Also only a few tests were run on Section V (Fig. 15) after the old snow had been reprocessed, but this was because of the difficulty of obtaining samples that did not crumble.

Stress/strain ratio. The press was so designed that the amount of deformation of the sample as well as the load could be read. Four typical stress-strain curves are shown in Figure 18. The variation of the linear portion of the stress-strain ratios with depth for Sections IV and VI are shown in figures 19 and 20. The length of the lines indicates the length of the specimen and its position. The averages are shown in Table IV.

Figure 18. Stress-strain curves for four typical specimens.

Table III. Average Compressive Strengths

Depth (cm) (in.)	Section III		Section IV		Section V				Section VI	
	(kg/cm²) (psi)		(kg/cm²) (psi)		1st testing*		2nd testing**		(kg/cm²) (psi)	
0-15 0-6	8.4	124	11.5	169	5.1	75	7.5	110	10.7	157
15-45 6-18	5.5	81	5.7	84	2.0	29	4.8	71	3.7	54
45-75 18-30	0.8	12	0.7	10	0.8	12	1.6	24	0.6	9

* Old snow reprocessed for the second time.

** Processed virgin snow hauled in.

Figure 19. Stress/strain ratio with depth, Section IV.

Figure 20. Stress/strain ratio with depth, Section VI.

Table IV. Average Values of Stress/Strain

Section IV		Section V	
Depth (cm)	$E \times 10^8$ (dynes/cm ²)	Depth (cm)	$E \times 10^8$ (dynes/cm ²)
0-15	6.10	0-20	6.60
15-33	5.60	20-35	4.80
33-70	4.50	35-70	3.10

Table V. Average Shear Strength

Section	Depth (cm)	Depth (in.)	Density (g/cm ³)	Shear Strength (kg/cm ²)	Shear Strength (psi)
I	17	7	.61	4.2	62
I	43	17	.57	3.1	46
I	87	35	.53	3.3	49
II	10	4	.57	4.0	59
II	32	13	.50	3.8	56
III	22	9	.57	2.3	34
III	48	19	.50	2.5	37
IV	20	8	.54	4.9	72
IV	48	19	.48	2.0	29

In SIPRE Report 4 (1951) the values of Young's moduli for ice are given as 1 to 5×10^{10} dynes/cm² for static tests and about 10×10^{10} for dynamic tests. Dynamic tests by Yamaji and Kuroiwa (1954) on 0.54 density snow showed values of about 6×10^9 dynes/cm². Landauer (1955) calculated from relaxation data a value of 1.6×10^9 dynes/cm² for a snow of 0.42 density.

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It was to be expected that the values obtained from the strip testing would be smaller than those obtained by dynamic means, especially since we have a visco-elastic porous material. There is certainly some question as to whether values obtained from the stress-strain curves on a material like snow may properly be called Young's moduli.

Shear strength. The shear strength of the snow at zero lateral pressure was determined also with the press. The rates of loading and temperatures were about the same as for the determination of the compressive strength. The average of ten shear values for each layer is shown in Table V.

In-place tests

Ram hardness readings were taken at various times on the strip near the places where cores were obtained. The hardness readings for Sections I and II (Figs. 21 and 22) each represent the average of 6 determinations; the ones for Section III and V (Figs. 23 and 25) each represent the average of 4 determinations; and the ones for Sections IV and VI (Figs. 24 and 26) are each the average of 12 determinations.

It may be noted on all of the graphs that the 0-10 cm (0-4 in.) readings are considerably lower than the 10-15 cm (4-6 in.) readings, all in the same hard upper layer. This difference may be explained when it is realized that the Rammsonde is a cone penetrometer and the initial readings will be low until the full diameter of the cone is in the snow. The averaged readings from 0-10 cm are plotted against the averaged reading from 10-15 cm in Figure 27. In Figures 28-33, showing the average ram number of each layer, the values for 0-10 cm were replaced by the values of the 10-15 cm readings. The slope of the straight line in Figure 27 is $\frac{1}{3}$, and since in many cases the surface layer is too shallow to permit readings from 10-15 cm, it is recommended that the 0-10 cm Rammsonde readings be multiplied by 3 to give more realistic values.

There is a considerable time lag before the ambient temperature changes the snow temperature below the surface. There is also a decrease in amplitude of temperature variation with depth. As the actual temperature of the snow affects its strength (this is explained quantitatively in the appendix), pits in the strip were dug and the temperature with depth obtained at various times.

Figure 21. Ram hardness vs. depth, Section I.

Figure 22. Ram hardness vs. depth, Section II.

Figure 23. Ram hardness vs. depth, Section III.

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Figure 24. Ram hardness vs. depth, Section IV.

Figure 25. Ram hardness vs. depth, Section V.

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Figure 26. Ram hardness vs. depth, Section VI.

Figure 27. Ram hardness from 0-10 cm depth vs. 10-15 cm depth.

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Figure 28. Average ram hardness by layer, Section I.

Figure 29. Average ram hardness by layer, Section II.

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Figure 30. Average ram hardness by layer, Section III.

Figure 31. Average ram hardness by layer, Section IV.

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Figure 32. Average ram hardness by layer, Section V.

Figure 33. Average ram hardness by layer, Section VI.

Large-scale testing

Large-scale testing of the strip was started 15 August, by pulling the four-wheeled rubber-tired Bros roller over the strip and increasing the total load to 42,000 lb, with the tire pressure at approximately 100 psi.

The strip failed very noticeably in Sections III and V. Section V became so bad that it was necessary to doublehead tractors to pull the roller out (Fig. 34). These two sections were then reprocessed.

On 27 August, the strip was tested by a ski-wheeled C-47 airplane. The plane first landed on skis nearby, taxied over to the strip, and took off empty using less than 2500 ft of runway (Sections I and II). The plane then landed on wheels on Section I and II, taxied past Section III and into Section IV (about 3500 ft), turned around and parked at about the 1500 ft mark. A 3500-lb load was put on; the plane taxied the entire length of the strip and took off.

Inspection of the strip showed that Sections III and V were definitely rutted, and the pilot had to work the motors quite hard to get through Section V. A sketch of breakthroughs in sections III and V is shown in Figure 35. It is very important to note that in no case was there failure by a punching of the top layer into the layer below. Because of the breakthroughs in Section V, the snow was removed, virgin snow was hauled in and received three passes of the pulvimixer with heat.

A C-54 type aircraft tested the strip on 10 September. It landed, taxied, and took off several times. The average roll on landing was about 3000 ft, take-off empty required about 2200 ft, and take-off with a 5000 lb load required about 2600 ft. The pilots said that there were no unusual problems in the landings and take-offs.

In several places, the C-54 plane broke through newly deposited and rolled snow to the top of the harder processed layer. However, in Section III, there were two minor failures in the processed layer, similar to that shown in Figure 35 (top). The depth of cohesionless snow in the breaks was less than 7 cm (3 in.) and 5 cm (2 in.).

On 25 September, a C-124 type aircraft made two landings on the strip. Additional landings were made on 26, 27, and 28 September. There was rutting of the rolled newly deposited snow, but not enough to hinder operations. On the last two landings of the C-124, failures were noted in Section III. In the extreme case, failure consisted of complete disaggregation down to 45 cm (18 in.) depth, which included 20 cm (8 in.) of new rolled snow and 25 cm (10 in.) of the processed layer. The snow under the breakthrough was still very hard. Loads up to 20,000 lb were carried. Empty aircraft required 4,000 -4,500 ft for take-off. Table VI lists the landings on the strip:

Table VI. Landings on the strip

Type of Aircraft	Number of Landings
C-47	12
C-54	6
C-124	9

Deflection Readings: Attempts were made to observe any deflections on the strip due to plate action, using a rod and transit that were available. The transit was set up and leveled about 100 ft from the rod resting on the snow. The "cat" operator drove the D-8 tractor and the Bros roller (42,000 lb), mounted on a skid, as close as possible to the rod and past it. Readings were taken before, at time of passage, and after they had passed by. Although the rod was near the edge of both the D-8 and the skid, it was still about 10 ft from their center line. The readings are given in Table VII. In no case did the observed deflection return to a zero reading. The size of the deflections are of the same order as the accuracy of the readings. It may therefore be considered that, if there are deflections, they are very small.

Figure 34. Tractors pulling Bros roller out of breakthrough.

Figure 35. Sketch of manner of surface failure.

Figure 36. Difference in homogeneity of samples from sections III and IV.

Figure 37. Large iced snow clumps from Section III.

Table VII. Deflection Readings

Date	Section	Deflection (in.)
16 August	VI	1/100
16 August	VI	0
16 August	IV	1/200
16 August	IV	0
17 August	IV	0
17 August	IV	0
17 August	VI	1/200

DISCUSSION OF RESULTS

It is apparent from the figures that the pulvimixer and the techniques of using it have not been developed to a point where a fairly homogeneous processed layer may be expected. It may also be noted that the density of the snow alone is not sufficient to indicate the bearing capacity. The extreme cases were Sections III and V, which had relatively high densities but low strengths. This was mainly because the snow had been processed and subjected to heat so many times that icy clumps were formed and good cohesion could not develop between them. Figure 36 shows the readily distinguishable differences between samples taken from Section III (first and third from left) and samples of a homogeneous snow from Section IV. Figure 37 shows the actual size of a few of the larger clumps taken from Section III.

Figures 38-41 show a composite of the average density, compressive strength, and ram values by layer for Sections III, IV, V, and VI. The ram hardness is for the same day that the density and strength values were obtained.

Figure 42 shows a plot of the ram hardness versus the compressive strength - with each point representing a large number of tests. The straight line $\underline{R}$ computed by means of least squares is:

$$R = 57 + 26\sigma \quad (1)$$

or, in terms of compressive strength:

$$\sigma = 0.04 R - 2.2, \quad (2)$$

if σ is in kg/cm^2 .

If σ is in terms of psi, then:

$$\sigma = 0.57 R - 32.5. \quad (3)$$

For a ram hardness value of 57 or less there is no compressive strength. This is to be expected, as an entirely cohesionless material would give a Rammsonde reading and the strength values given here are for the unconfined case.

Test results published by the Directorate of Engineer Development (1953) on a shallow snow runway underlain by frozen ground indicate that an average ram hardness reading ($\underline{R}$) of 250 or over would support aircraft with pressures up to 65 psi. The Air Proving Ground Command (1954) tested a large number of aircraft including fighter planes having tire pressures up to 180 psi, although it is difficult to analyze their results because their runway was so shallow and contained up to 10% foreign material. A section of the runway with a ram hardness of over 500 supported a F84F fighter (150 psi) but a section with a reading below 250 $\underline{R}$ failed. Tests in Greenland by the U. S. Naval Civil Engineering Research and Evaluation Laboratory (Moser, 1954) indicated that a 16-in. processed layer with a 259 $\underline{R}$ reading floating on virgin snow of 44 $\underline{R}$, would not support a C-47 (60 psi) but a

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similar mat of 520 R would support the C-47. Some of the Greenland 1955 test results are shown in Tables VIII and IX.

Table VIII. Average Ram Hardness Values of Processed Layer

Section	R	Date Taken	C-47 Landings	27 August
I	765	22 August	Supported	
II	1226	22 August	Supported	
III	366	27 August	Failed in places	
IV	500	22 August	Supported	
V	174	25 August	Failed badly	
VI	916	22 August	Supported	

Table IX. Average Ram Hardness Values of Processed Layer

Section	R	Date Taken	Landings	
			C-54 10 September	C-124 28 September
I	1212	4 September	Supported	Supported
II	1469	4 September	Supported	Supported
III	604	5 September	Minor Failure	Minor Failure
IV	1261	5 September	Supported	Supported
V	627	5 September	Supported	Not tested
VI	946	5 September	Supported	Not tested

From Table VIII, it may be noted that sections with an average R of 500 or more supported a C-47, an average of 174 definitely would not, while Section III failed in places. A closer examination of the individual readings in this section disclosed that there was a Rammsonde reading of only 246 at the actual place of failure.

It appears from Table IX that a section with a R-number of over 627 will support a C-54. Again examination shows that the individual reading at the place of break-through in Section III was an average of only 190 R for the top 15 cm. It is much more difficult to ascertain the requirements of the C-124 because of the time differences between the ram hardness readings and the C-124 tests. However, an approximation would be that the same readings would apply for the C-124 as for the C-54 if the processed layer was thick enough.

A plot of known ram hardness values for a processed surface that supported or failed under various tire pressures is shown in Figure 43. The straight line (also shown on Figure 42 as R') may be expressed by the following empirical equations:

$$\sigma(\text{psi}) = \frac{R}{2} - 80 \quad (4)$$

or

$$\sigma(\text{kg/cm}^2) = \frac{R}{30} - 5. \quad (5)$$

It should be realized that the values of compressive strength are for the unconfined case, while tires on a runway represent a confined case. Since the confined strengths are higher than the unconfined strengths, this represents a safety factor.

The making of a snow runway differs in many respects from making an earth runway. The Corps of Engineers can build a ground strip to support a bomber of

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Figure 38. Average density, compressive strength, and ram hardness by layer, Section III.

Figure 39. Average density, compressive strength, and ram hardness by layer, Section IV.

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Figure 40. Average density, compressive strength, and ram hardness by layer, Section V.

Figure 41. Average density, compressive strength, and ram hardness by layer, Section VI.

Figure 42. Ram hardness versus compressive strength.
 $R = 57.2 + 25.8\sigma$; $R' = 157.2 + 32.2\sigma$.

over 350,000 lb, or a fighter with tire pressures of 200 psi, and has done considerable work in determining the requirements for the best and most economically constructed strip for the operation required. On a high polar glacier, however, the subgrade, the base, and the wearing surface must all be made from snow. Furthermore, with the present techniques of making a snow runway, it is necessary to use the maximum ability because even this is just barely satisfactory.

It is important for people familiar with the CBR and its successful application to field runway construction to appreciate the differences, namely:

- (a) There is no choice of material or degree of processing in a snow runway.
- (b) The CBR curves presently available are not adequate for determining the bearing capacity of a snow runway once it is made, because of the differences in the material (plasticity, temperature effects, age hardening, etc.).

Some of the problems of a snow runway are clarified when the maximum vertical stress curves with depth are examined for various aircraft, as shown in Figure 44. These stresses were computed by approximating the tires as representing uniform circular loads and using the Boussinesq equation. It may be noted that, for the cargo

Figure 43. Ram hardness vs. support of failure of aircraft.

planes, a strong mat about 10 in. (25 cm) thick is required on top and, except for the C-124, the stress decreases very rapidly from 10 in. on. It is necessary to have sufficient thickness of the processed layer so that the stress at the virgin snow layer will be less than its strength. It may also be noted that if a 5-in. (12½-cm) layer of snow-ice or equivalent could be put on top of the pulvimixed surface, it would support small high-pressure tires (fighters and bombers).

For operational purposes, it is suggested that the Rammsonde be used as a simple test instrument. With Equations 4, 5 and Figure 44, showing the stress with depth curves, a strip may be easily tested with a Rammsonde to see if it is sufficiently strong to support a given aircraft.

CONCLUSIONS

The pulvimixer is at present the only piece of equipment in supply which, with modifications, can produce a processed snow runway. It is at best a marginal piece of military equipment, whose success is weather dependent. It is doubtful whether the 1955 Greenland strip would have been able to support aircraft if completed earlier and tested in July. There was a drop of over 19°F between the average July and September temperatures. This corresponds to an increase in strength of over 12% (see Appendix A). In 1954 there was a difference in average temperature of over 34°F between these two months, which corresponds to an increase in strength of 27%. These temperature figures are of course for the Site 2 locality. If you go another 100 miles westward from Site 2 toward Thule, the mean annual temperature increases about 12°F.

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Figure 44. Stress distribution with depth of various aircraft.

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The strip would be improved by processing the entire length of the strip in one pass instead of by sections as was done in the 1955 summer season. Since it is desirable to have several passes in one lane, the processing should be done by a train of pulvimixers with a minimum amount of time between multiple passes on a given lane and turnarounds only at the end.

It is desirable to have as finely disaggregated snow as possible, in order to achieve maximum strength. Not much can be done with the present pulvimixer in this respect. The Engineer Research and Development Laboratories' T-4 snow packer and also the Peter snow plow tested by SIPRE have a milling type of action (high-speed rotating drum) and produce a much finer snow, and consequently should be able to make a stronger air strip. The possibility of putting on a hard surface layer of snow-ice should also be investigated. This could support planes with a high tire pressure and also would give a safety factor for the present strip, which is quite temperature-dependent.

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APPENDIX A.
Effects of Temperature and Age-hardening on
the Strength of Snow

Temperature effect

Quantitative data on the effect of temperature on the strength of snow is limited, although there is general agreement that "the colder the snow is, the stronger it is".

Bucher (1948) performed a series of experiments to determine the effect of grain size, density, and temperature on the tensile strength of low-density snows. Fuchs (1946) obtained a series of shear strength vs. temperature curves for screened snows of high densities. The Russians also have a curve on hardness vs. temperature (Buvert, 1951) with hardness measured by a surface cone penetrometer. Butkovich (1954) in his work on snow-ice found the crushing strength to have a temperature dependence similar to that obtained by Fuchs.

Almost all of the above data may be represented by the equation

$$\log \frac{S_2}{S_1} = 0.16 \log \frac{T_2}{T_1} \quad (A1)$$

where S_1 is the strength at T_1 centigrade and S_2 is the strength at $T_2^\circ\text{C}$. It is easier to use this in a graph form as shown in Figure A1 by a series of parallel lines.

Example: If the strength at -5°C (23°F) was 3.6, what is the strength at -30°C (-22°F). Draw a line parallel to those shown and passing through 3.6 at -5°C . The answer then is 4.8 at -30°C , in this case a $\frac{1}{3}$ increase in strength. Or, if a slide rule is handy: $\log S_2 - \log 3.6 = 0.16 \log \frac{30}{5}$.

It was also pointed out by Bucher that the strength of a fine-grained snow is much more temperature-dependent than that of a coarse-grained snow. This is shown in Figure A2.

Age-hardening

A number of people (Bader et al., 1939; Taylor, 1953; Kragelski and Shakhov, 1945; De Quervain, 1945; Shakhov, 1948) have suggested reasons for a given snow becoming harder with time, and the phenomenon has been observed by many people in the field. Nevertheless, there is very little quantitative information on the rate of age-hardening with time and as a function of temperature.

Although the term "hardness" or "hardening" is usually thought of in terms of resistance or increase of resistance to penetration, in snow it has come to indicate the corresponding increase in strength as well.

The author performed a series of investigations in the SIPRE laboratory using the work required to disaggregate a unit volume of snow as a measure of age hardening. A typical curve for a screened snow compacted to a density of 0.60 and allowed to harden at a temperature of -5°C (22°F) is shown in Figure A3. Fuchs (1942) also ran a series of tests on screened snow, but used a direct shear test to measure the hardening. His curves are similar to the one shown in Figure A3, but he found a maximum increase in hardness at -4°C (25°F). Fuchs also noted that fine-grained snow became harder than coarse-grained snow. The ratio of increase, i.e., strength at time of compaction/strength several days later, is shown in Figure A4, which represents the average of the SIPRE laboratory tests. It should be noted that the case where the snow originally was wet is not considered. A good rule of thumb is to allow at least 3 days of hardening at moderate temperatures and about 4 to 5 days at low temperatures before strength tests or heavy traffic tests.

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Figure A1. Strength vs. temperature plot on a log-log scale.

Figure A2. Temperature effect on tensile strength of various grained snow.
(From Bucher, 1948)

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A3

Figure A3. Work required to disaggregate snow vs. days of age-hardening.

Figure A4. Ratio of strength increase vs. days of age-hardening.

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B1

APPENDIX B.
Preliminary Instructions for Determining whether a Specific
Aircraft can Land Safely on a Given Compacted Airstrip

The following instructions are based on the contents of this report. Until more data become available, the following criteria may be used.

Take a large number of ram hardness readings (a minimum of 20) on the entire strip. No testing should be done until 3 to 5 days after final processing, to allow the strip to age harden. If there are areas of discolored snow, these should receive extra testing, as they are likely to be weak. The following table lists the minimum ram hardness numbers at different depths acceptable for landing certain aircraft. Do not take the average of the ram readings, but only consider the lowest values.

This table is based on Figure 44 (stress distribution with depth of various aircraft) and Equation 4, relating ram values to compressive strength.

REQUIRED RAM HARDNESS VALUES WITH DEPTH

Depth (cm)	F-94A	C-54	C-119	C-124	C-47
0-10*	170	108	100	100	94
10-15	430	310	284	290	272
15-20	300	296	274	288	264
20-25	260	280	260	280	256
25-30	220	252	240	270	240
30-35	210	234	226	264	224
35-40	196	224	212	252	210
40-45	190	214	208	236	200
45-50	184	210	200	230	296
50-55	180	206	190	224	290
55-60	176	200	186	216	186
60-65	174	196	182	212	184
65-70	160	180	170	200	172

* Required hardness readings in the surface layer (0-19 cm) are only $\frac{1}{3}$ of the true value, due to the cone effect.

Extra hardness in the upper 50 cm can make up for lesser hardness at greater depth, but quantitative recommendations on this matter can not yet be made.

The hardness of snow varies with temperature. A runway which was tested at low temperatures and found satisfactory should be retested if the temperature rises significantly, since it will have weakened. On the other hand, a runway tested at relatively high temperatures and found to be too weak may strengthen sufficiently for landings when the weather turns colder.

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