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SNOW COMPACTION—INVESTIGATION OF METAMORPHISM OF SNOW

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SNOW COMPACTION—INVESTIGATION OF METAMORPHISM OF SNOW

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by

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ABSTRACT

Although processing and compacting increase the density and bearing capacity of surface snow for use as roads and trails, these processes have not been able to achieve the degree of densification that occurs naturally as snow slowly metamorphoses to glacier ice. A study was made at the Naval Civil Engineering Laboratory of the processes and influences of the major mechanisms that control snow metamorphism—grain size, pressure, temperature and solar radiation—in order to provide a basis for developing better techniques for higher strength snow pavements. It was concluded that maximum snow strengths are achieved at or near a critical density of 60 gm/cm^3, followed by bond growth, or age hardening, at temperatures between -12°C and -7°C. In addition, as distribution of applied loads with depth is essential to the development of operational criteria for such pavements, it is recommended that research be conducted to develop this knowledge.

CONTENTS

INTRODUCTION

Perennial snow covers much of Antarctica, Greenland, and some of the Arctic. Annual snow covers the rest of the polar regions 6 to 10 months each year. Utilization of snow for runways, roads, and trails has developed as the polar regions have become more populated. Compaction and processing techniques are used to increase the density and bearing capacity of surface snow for these purposes. Even so, the treated surface does not achieve the degree of densification that occurs naturally as snow slowly metamorphoses to glacier ice—a process that is influenced by the chemical and physical properties of snow.

Laboratory tests and analysis of field data were made to determine the effect of the major mechanisms controlling snow metamorphism—grain size, pressure, temperature, and solar radiation—to provide a basis for developing better techniques for improved military operations in snow. The results are summarized in this technical report.

This research relates to the technological capabilities outlined in the Navy Technological Forecast: Section 536-31, "Polar Horizontal Construction."[*]

BACKGROUND

Polar glaciers are monomineralic rock formations which grade from sedimentary unconsolidated snow at the surface to metamorphic glacier ice at depth (Flint, 1957; Winchell and Winchell, 1951). The metamorphism of snow to ice is a progressive phenomenon that can be divided into different phases according to its physical and mechanical properties.

The density of natural snow increases with depth and, at the same time, the permeability decreases (Figure 1). As the depth of burial increases, the air trapped within the snow at deposition becomes isolated into small

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[*] Technological Forecast 536-31, Polar Horizontal Construction in Chief of Naval Development. Navy Technological Forecast (U), pt. 2. Functional area 500 (Technological Support). Appendix F. Washington, D. C., October 1968 SECRET NOFORN updated October 1969.

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bubbles. Gow (1968) measured the occurrence of zero permeability, or pore close-off, at a density of 0.828 gm/cm³, which is defined as the point at which snow becomes bubbly glacier ice. In a deep core from Greenland, Langway (1967) measured the load at this density as 4,800 gm/cm² and concluded that all increase in density above zero permeability is a result of plastic compression of the ice and a reduction in void volume. For purposes of this discussion, only the properties of snow at a density less than 0.828 gm/cm³ will be considered.
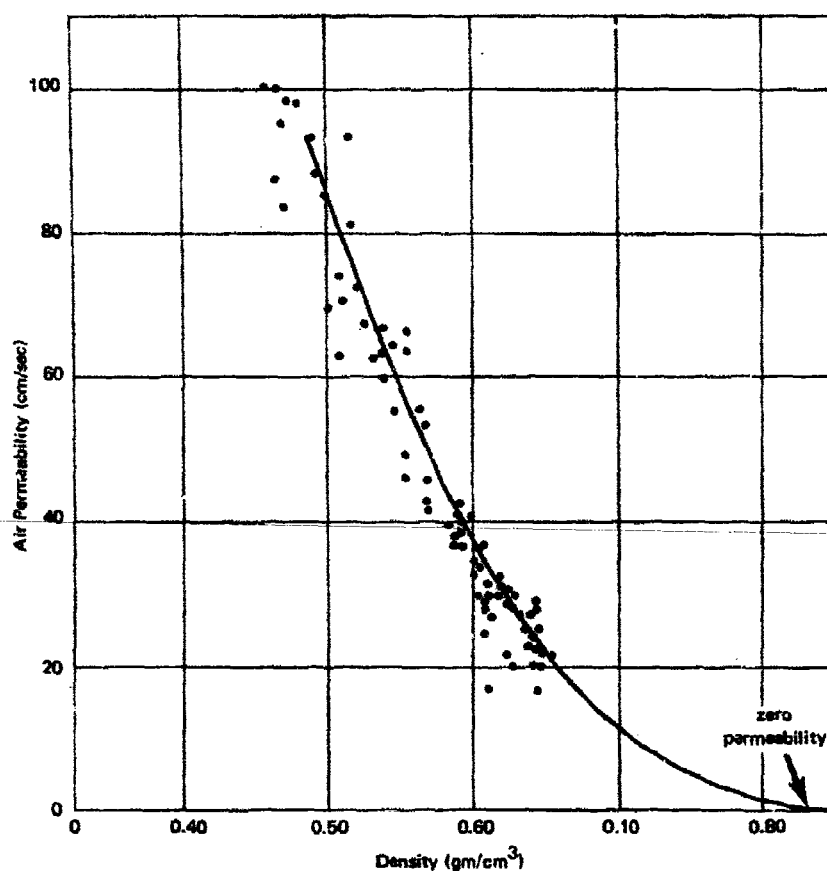

Figure 1. Decrease in air permeability of snow with increase in density (after Rameier, 1966).

Changes in the physical properties of natural snow take place by the transport of material (H_2O) by evaporation–condensation, surface diffusion, volume diffusion, and viscous or plastic flow (Kingery, 1960a). In experiments with ice spheres, Kingery (1960b) determined that the decrease in surface energy, which is high where the particles are fine, is initially the major source of energy for transport of material, particularly where no volume change occurs.

The energy state of a particle is dependent on the surface area so that, for a given weight of snow, the finer the particles or the more irregular the surface, the greater the energy available. An irregular particle of ice tends to evaporate at highly curved points and deposit in less curved areas, resulting in rounding of the particles. Since the energy increases with the surface area, a decrease in the diameter of the particle to one-tenth its original size increases the total surface area by 10.

Kingery (1960a) calculated that the decrease in free energy on the consolidation of 1-mm particles to dense, large-grained ice was only 1.41×10^{-4} cal/gm, which is small compared to the heat of fusion (80 cal/gm); Yosida (1958) considered it to be so small as to be insignificant as a cause of rounding. However, when calculated as the free energy potential of surface tension (Kingery, 1960a), it is equivalent to the positive hydrostatic pressure of 7 cm of overlying snow at a density of 0.5 gm/cm^3 (3,600 dynes/cm^2). Although this probably accounts for long-term grain growth, Yosida (1961) concluded that the rapid grain growth near the snow surface is due to a temperature gradient, which promotes vapor transfer and grain growth.

Volume change, or shrinkage, occurs when the centers of the particles move closer together, increasing the density (Kingery, 1960a). Since initial changes in the natural snow cover include an increase in density, viscous flow and volume diffusion are probably the most prominent effects. Where no volume change occurs, Kingery (1960b) concluded that surface diffusion was the primary process. The rate of material transfer determined experimentally as measured by neck-growth rate showed a large temperature dependence and a very high value for the surface diffusion coefficient. Kingery suggests that this could be accounted for by a high surface mobility of molecules on the particle surface. This would provide a layer of high atomic mobility as required by the proponents of a liquid-like surface layer. However, at near melting temperatures (Nakaya and Matsumoto, 1954), surface and volume diffusion may be as much as 10^4 times slower than evaporation–condensation.

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FACTORS INFLUENCING METAMORPHISM

The major mechanisms, which contribute to the natural metamorphism of snow into ice, are grain size, temperature, solar radiation, and pressure.

Grain Size

The effect of grain size, which generally increases with time, varies depending on the property being measured. When comparing the effect of grain size on the change in density with load from laboratory tests (see the Appendix) as shown in Figure 2, it appears that at lighter long-term loads (<9 kg/cm^2), the larger grain size densified at a faster rate, and at greater long-term loads (>9 kg/cm^2), the smaller grain size densified faster. This indicates that packing is probably more important in increasing density of fine grained snow, whereas recrystallization is more important with the larger grained snow.

In tests of the effect of crystal size on strength, Gold (1956) found a decrease in hardness with an increase in crystal size, although he did not define what he meant by crystal size. Jellinek (1957) measured the effect of particle size, as determined by sieving, and found that the compressive strength increased with an increase in particle size. This disagreement can probably be explained by the fact that Gold and Jellinek measured two different parameters—hardness by penetration of a plate into the snow, and unconfined compressive strength, respectively. In the hardness tests, the snow with smaller particles would be denser and harder to compress because the smaller particles have closer packing; Gold demonstrated that shear did not occur along the edge of the plate. During the unconfined compressive strength tests, failure probably occurred at the smaller sizes along grain boundaries which are weaker than grains, but as the grain size became larger, failure was forced through the stronger grain.

In nature the mean crystal size increases nearly linearly with depth, age, and density (Langway, 1967; Gow, 1968) except in the first centimeter where the size increases very rapidly (Stephenson, 1967). The crystal size at a given density varies with average temperature; at pore close-off density it is projected to have a 0.5-mm diameter at the South Pole, whereas at Byrd it has a 0.95-mm diameter. Gow (1968) attributes this to the difference in rate of densification, which he suggests depends on the rate of accumulation (that is, load) and mean annual temperature. Gow (1961) cites experimental evidence confirming that the rate of crystal growth varied by approximately two orders of magnitude between -60°C and -15°C.
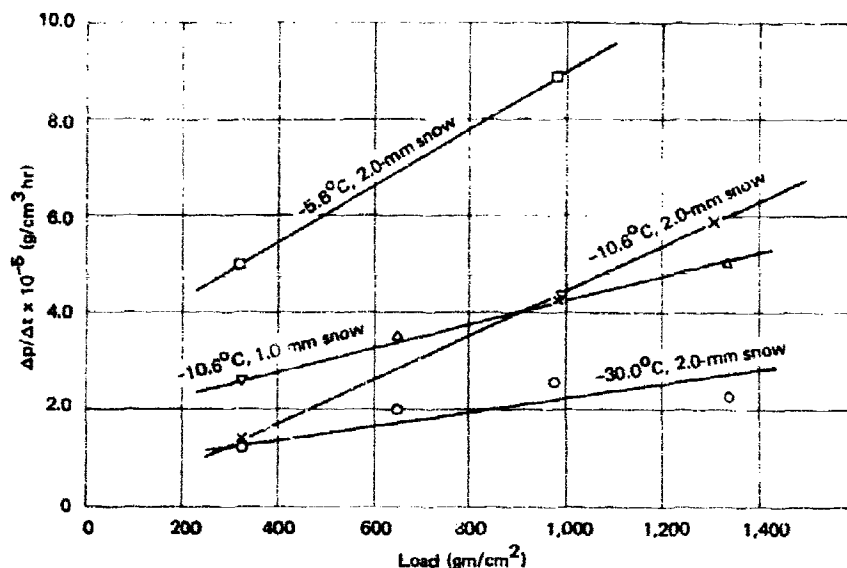
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Figure 2. Change in density per unit time versus load.

Temperature and Solar Radiation

Temperature is probably the greatest influence on metamorphism, progressing more rapidly as the snow temperature approaches the melting point. As a measure of this, cylinders of compacted snow were subjected to different amounts of solar radiation at air temperature of $-9.4°C$ and $-15°C$ to determine the effect of solar radiation on metamorphism as measured by density and strength. The test methods and sample preparation are discussed in the Appendix.

Exposure of the specimens to solar radiation had little effect on density at either temperature, as shown in Figure 3. At $-9.4°C$, however, solar radiation in excess of 0.81 $cal/cm^2/min$ melted the specimens.

Solar radiation had considerable effect on unconfined compressive strength. At a low solar radiation a gradual increase in strength for the first 7 days was followed by a very rapid rise the last 4 days (Figure 4). At $-15°C$, the higher solar radiations resulted in a rapid increase in strength throughout the test period. There was little difference in strength between the two high radiation exposures.

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Figure 3. Density of snow cylinders at different solar radiation exposures.
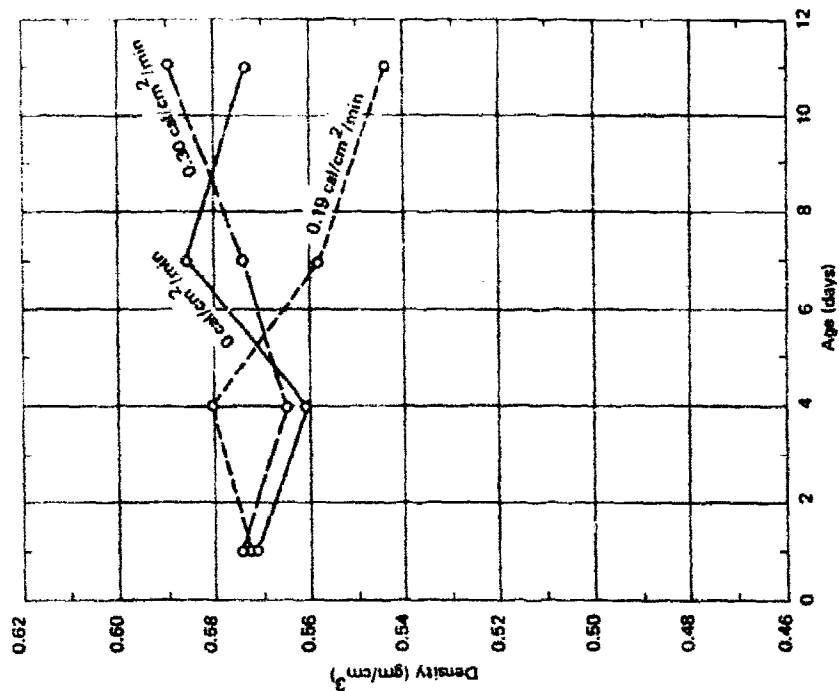
(a) At −15°C air temperature.

(b) At −9°C air temperature.

(a) At −15°C air temperature.
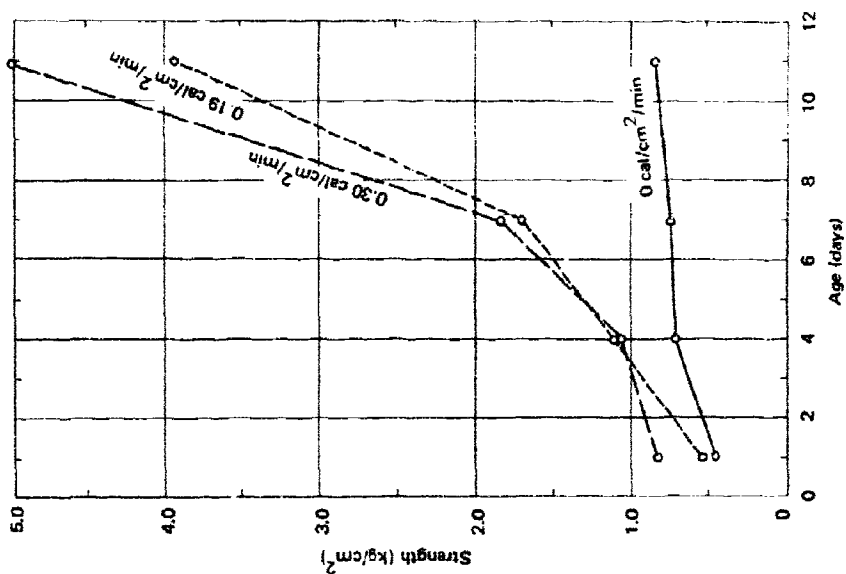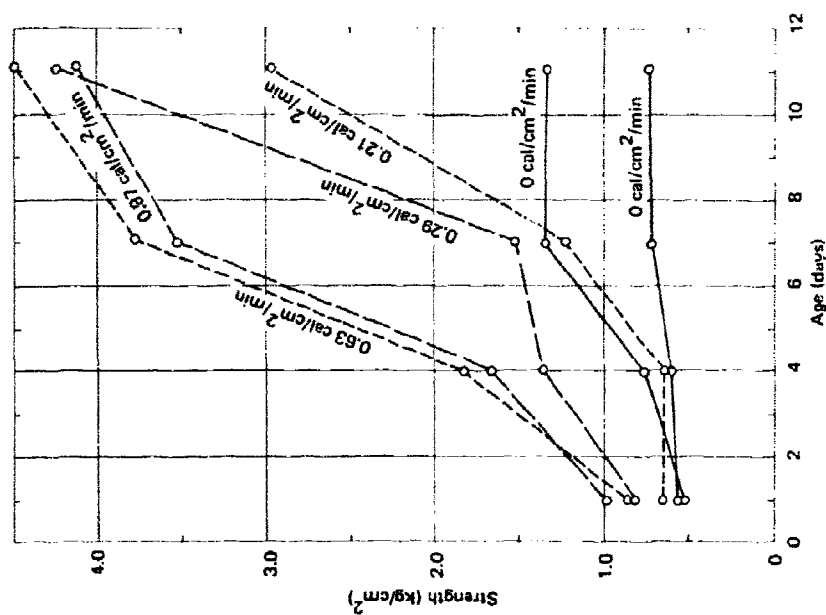
(b) At −9.4°C air temperature.

Figure 4. Unconfined compressive strength of snow cylinders at different solar radiation exposures.

Field tests have shown that if the snow remains at the warm temperature after the ultimate strength for that temperature has been achieved, then the strength begins to drop off. Figure 5 shows the rapid decrease in average shear strength with an increase in temperature above -9.4°C without the influence of solar radiation. This is also illustrated in Figure 6 which shows that the bearing strength of a compacted snow layer decreased to 2/3 the maximum value attained as the air temperature remained at -5°C. These results, however, are also influenced by solar radiation which increased along with the average air temperature.

Figure 7 illustrates the influence of solar radiation on snow temperature. These snow samples were kept in a cold chamber maintained at either -9.4°C or -15°C; each sample was subjected to a different amount of simulated solar radiation for a 2-week period. The temperature of the snow, as measured 3/4 inch below the surface with a thermocouple, increased with increasing solar radiation. At a radiation of 0.6 Langleys/min, which is about equal to the December radiation in Figure 6 averaged per minute, the surface snow temperature at an air temperature of -15°C would be -9.4°C, and at an air temperature of -9.4°C, the snow temperature would be -3.3°C.

The percent of incoming solar radiation absorbed by the snow depends on its albedo, or ability to reflect radiation. Albedo is generally highest, although rarely more than 0.90, in new snow and at low temperatures and is lower, nearer 0.55, at warm temperatures and in old snow (Hoeck, 1958). Since the absorption of solar radiation decreases parabolically with depth (Figure 8), its influence on the temperature of the snow must decrease similarly.
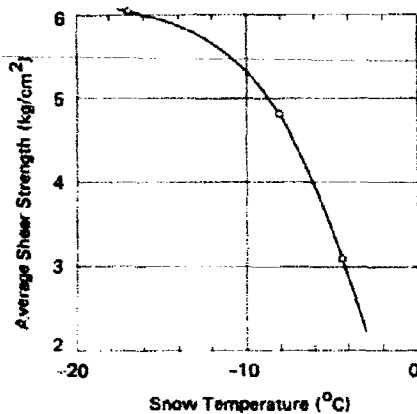
Figure 5. Strength versus temperature for compacted snow (after Sherwood and Moser, 1967).

Benson (1962) pointed out that the natural snow depth—density curves differ in different snow facies,[*] which are differentiated by average temperature; therefore, temperature must be an influencing factor. Benson has plotted critical density versus critical temperature (Figure 9) based on his field data and from this developed the following equation:

$$\rho_c = \rho_{cl} + (\rho_{co} - \rho_{cl}) e^{S T_c}$$

* Layers of snow, each with different physical characteristics.

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where ρ_c = critical density

ρ_{ci} = minimum critical density, 0.50 gm/cm^3

ρ_{co} = maximum critical density, 0.73 gm/cm^3

S   = a constant, 0.07 C^{-1}

T_c = critical temperature

Ramseier (1966) and Langway (1967) attributed this critical density change to closer packing of the grains; at a lower density, the snow is mainly compacted by the overlying snow with little deformation occurring in individual grains. As higher densities are achieved, an additional increase in density can be achieved only by deformation and rearrangement of grains.

The rate of increase in density of snow with overlying load (Figure 10) varies, depending on climatic factors. The difference in rate can probably be attributed to the difference in mean annual temperature, which is generally the snow temperature from 10 meters to pore close-off. This would also explain the increase in the rate of densification below 40 meters at Little America, since the snow there begins to warm below that depth.

Pressure

The density of natural snow increases gradually with time and depth (Figure 2) at a given temperature due to mainly the pressure exerted by the constantly increasing thickness of overlying snow. Laboratory tests were conducted with snow cylinders under different loads to determine the effect of pressure on density with time at a constant temperature. The test methods and sample preparation are described in the Appendix. The density increase was very rapid the first 10 hours, the rate of increase decreasing until it was fairly even after 100 hours. The change in density per unit time ($\Delta\rho/\Delta t$) is plotted versus load in Figure 2. This indicates that the increase in density is greater as the temperature and load increase, with the rate of change increasing more rapidly as the temperature approaches 0°C.

A noticeable change in slope of the density—depth curves from natural snow occurs between 10 and 12 meters at a density between 0.51 and 0.68 gm/cm^3. On the density—load curves (Figure 10), this change in slope, which is a decrease in the rate of densification, occurs rather uniformly at a load of 500 gm/cm^2 where the density varies between 0.50 and 0.60 gm/cm^3, depending on temperature. This critical density represents the limit beyond which grain packing is no longer effective. It corresponds to close random packing of particles (porosity of 36% to 37%) except at temperatures near 0°C
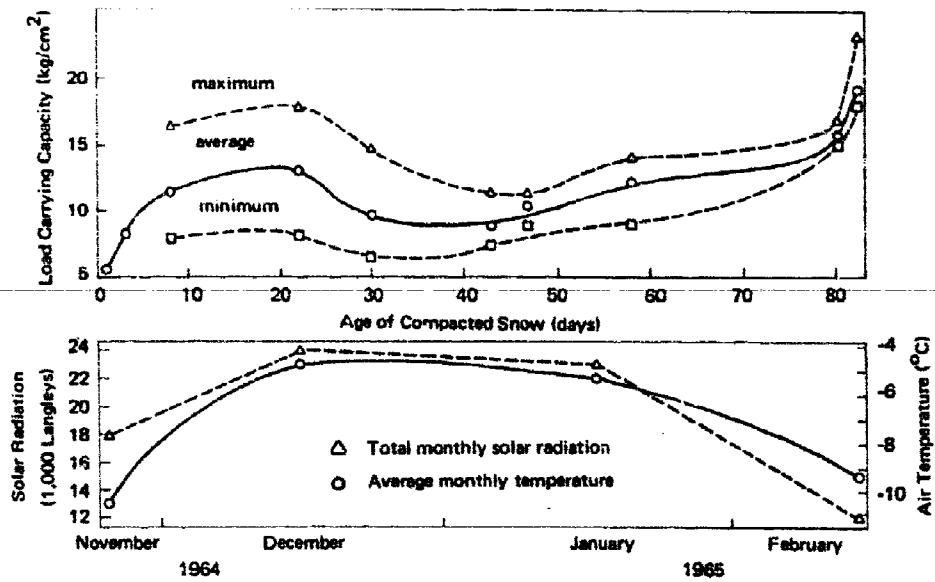
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Figure 6. Load carrying capacity in the DF-65 compacted snow layer on the 10-70 test area as determined by confined shear (after Moser and Sherwood, 1966).
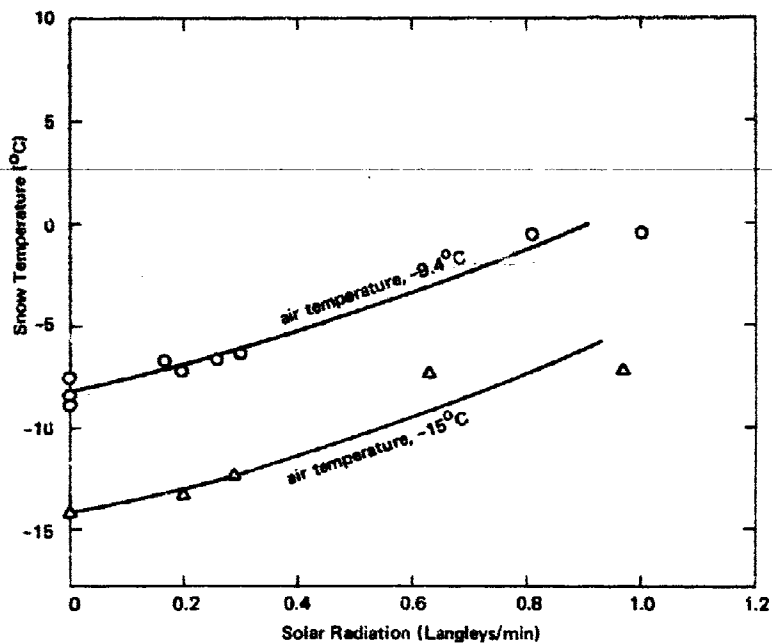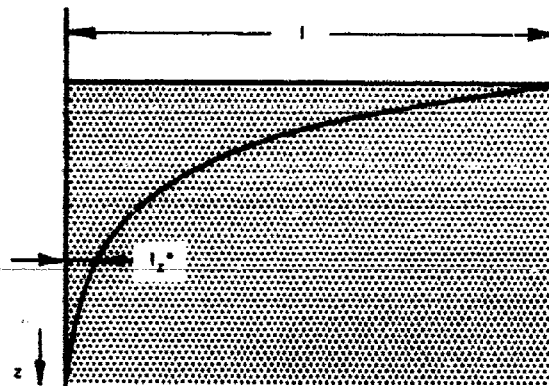
Figure 7. Influence of solar radiation on snow temperature.

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$^*I_z$ = radiation at depth z = $I e^{-kz}$

where I = $S \sin h + D - R$

 k = absorption coefficient of snow for short-wave radiation

 z = limiting layer of the snow column

$S \sin h$ = vertical component of solar radiation (S = total radiation, h = sun's height)

 D = diffuse sky radiation

 R = radiation reflected by the snow

Figure 8. Absorption of short-wave radiation in the snow cover (after Hoeck, 1958).

(Figure 9). This is also the maximum density that can be achieved by processing and compaction of snow without adding water. Densification beyond this density occurs only by changing the size and shape of the grains as they grow or shrink to relieve stress. Free water in the snow assists closer packing by filling interstices and lubricating grains. This increases the rate of densification by packing and results in a higher critical density (Anderson and Benson, 1963). As temperatures increase, the water vapor increases, thus enhancing the free-water content of the snow. Critical density, because it reflects a structural change, also indicates a change in other physical properties. This can be seen in the plot of unconfined compressive strength versus density (Figure 11).

APPLICATIONS

As metamorphism of the snow progresses the bearing capacity of the snow increases. After the surface snow has been mechanically processed and compacted, bonds of ice grow between grains of snow, a process that is
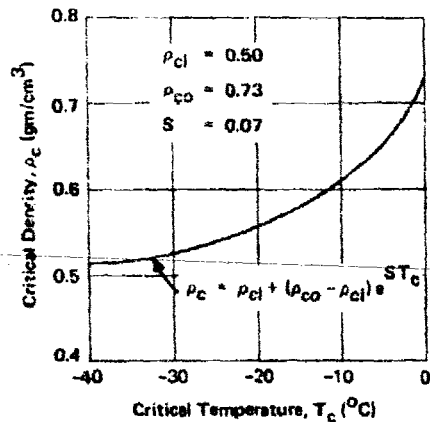
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Figure 9. Critical density versus critical temperature (from Benson, 1962).

$$\rho_c = \rho_{cl} + (\rho_{co} - \rho_{cl})\, e^{ST_c}$$

$\rho_{cl} = 0.50$

$\rho_{co} = 0.73$

$S = 0.07$

Critical Density, ρ_c (gm/cm³)

Critical Temperature, T_c (°C)

generally called age hardening, or sintering. During age hardening, the density remains constant, but the strength and hardness of the snow pavement increase. The rate of age hardening, strength, and hardness, however, are greater with a higher initial density (Abele, 1963).

Consequently, maximum initial densification is desired for surface snow pavements. This can best be achieved by pulverizing the snow as fine as possible, or at least within a wide size range, and then compacting to the critical density, about 0.6 gm/cm³, depending on the temperature (Figure 9). Vibratory compaction at a frequency above 1,400 cpm has been shown to increase density even more than compression. Vibration can work only if done shortly after pulverizing, however, before bond growth has progressed very far. Although a density greater than the critical density can be achieved with the addition of water, such an increase is not necessary, for beyond the critical density bond growth determines the ultimate strength. Because bond growth depends on the movement of water molecules, it can be speeded up with warmer temperatures, but too high a temperature can cause excess melting. At near melting temperatures an excess of moisture may be produced, yielding ice grains, or corn snow, that has few or no bonds. This is particularly true during high solar radiation, which may increase the surface temperature by 5.5°C. In addition, bond strength decreases with an increase in temperature; therefore, warm temperatures after much of the bond growth has occurred is detrimental. According to field data, the greatest increase in strength occurs within the first 3 weeks (Figure 12), although strength increases at a diminishing rate for over a year. Consequently, warm temperatures are needed only during the first 3 weeks, at most.

Observations on the failure of a compacted snow pavement have shown that a punching failure, or wheel breakthrough, directly under the wheel was the principal type of failure (Coffin, 1966). It was also observed that only the snow directly under the wheel was displaced in the failure area, regardless of the length of the failure. The snow was generally sheared around the perimeter of the wheel contact area, and the snow under the wheel was disaggregated

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and either compressed under the wheel or displaced from the wheel track.
Static load tests (Wuori, 1962) have shown similar results in that the defor-
mation of the snow is limited to a width and depth 1-1/2 times the tire
diameter.
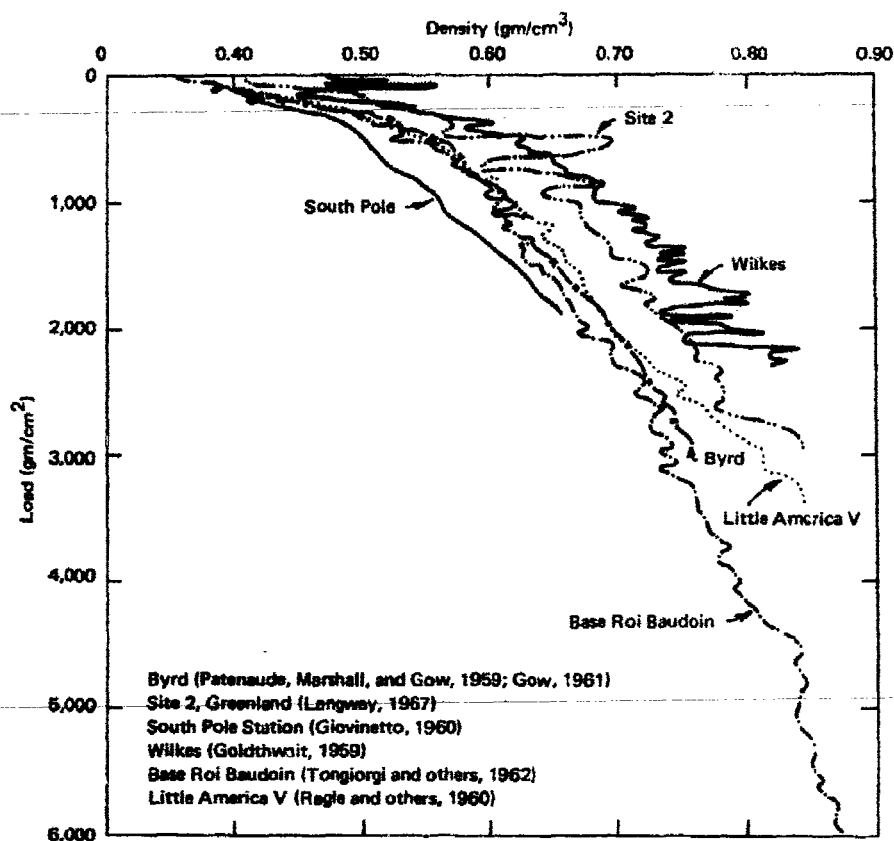
Station	Location	Average Temperature (°C)	Average Net Accumulation (yr)	Elevation (m)
Byrd	80°S 120°W	−28.0	15 gm/cm²	1,500
Site 2, Greenland	77°N 56°W	−23.3	41 gm/cm²	2,100
South Pole Station	90°S	−51.0	6.6 gm/cm²	2,800
Wiikes	66°30'S 112°15'E	−19.0	13.3 gm/cm²	1,140
Base Roi Baudoin	70°26'S 24°19'E	−16.0	38.3 gm/cm²	38
Little America V	78°11'S 152°10'W	−23.0	21.5 gm/cm²	44

Figure 10. Increase in snow density with increase in load at different sites.
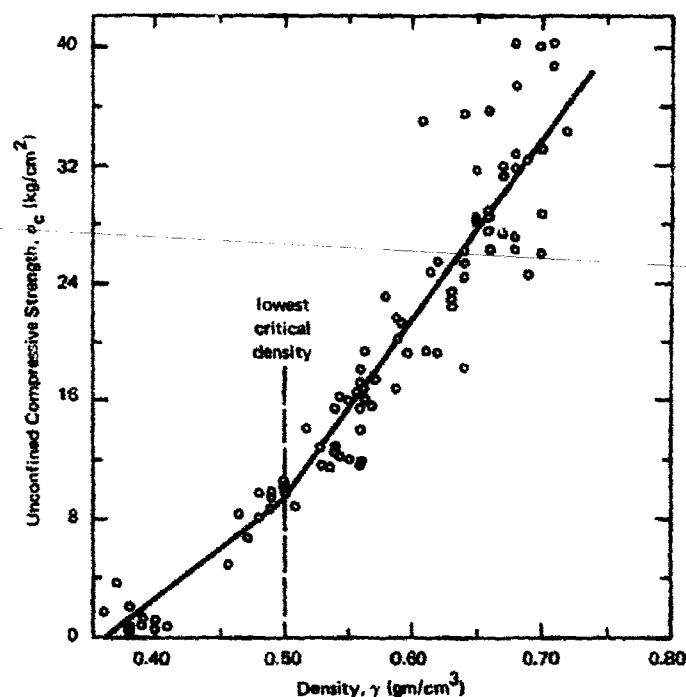
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Figure 11. Unconfined compressive strength versus density above and below
the critical density (after Kovacs, 1967).

Because failure of a compacted snow pavement apparently occurs
by shearing, NCEL developed a confined shear test apparatus. Results of
tests with this apparatus have been used to determine the load carrying
capacity of compacted snow pavements. Initially, however, most measure-
ments were made with a CRREL-developed rammsonde rod or by unconfined
compression; these have been correlated together by Abele (1968) and with
the NCEL shear test results by Coffin (1966), Moser and Stehle (1964) and
by Abele (1968) in Figure 13. Because of the wide variation in the correla-
tion of shear strength and unconfined compressive strength as compared to
the close correlation of rammsonde rod readings and shear strength, Abele
(1968) questions the validity of this relationship; Wuori (1962) also states
that the unconfined compression test is not reliable for evaluating the wheel
supporting capacity of a snow pavement. In addition, unconfined compressive
failure does not generally occur in nature.

It was found from field tests on confined shear strength that the load
carrying capacity of compacted snow ranged from 24% to 27% of the total
resistance to confined shear, which is determined by summing the individual

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shear strengths for each inch of thickness (Moser and Sherwood, 1967). This did not determine how the load was distributed at depth, although the load distribution at depth has been approximated using Boussinesq equations as in Figure 14 (Abele, Ramseier, and Wuori, 1968). Because no data were available to verify this, NCEL initiated laboratory tests to determine stress within a snow pavement using soil-type gages.

Results of initial tests at low pressures (0.4 kg/cm^2 or less) show a more elongated pressure bulb (Figure 15) than that with the Boussinesq equations, and the 0.1q-to-0.6q isopressure lines (q = total load) are very nearly equally spaced at depth. The percent of total load between 0.1q and 0.6q versus depth determined from Figures 14 and 15 is shown in Figure 16; the decrease in load with depth is nearly linear from the NCEL test data but not from calculations using Boussinesq equations (Abele, Ramseier, and Wuori, 1968). This may be due in part to the large difference in total load used in the two methods.
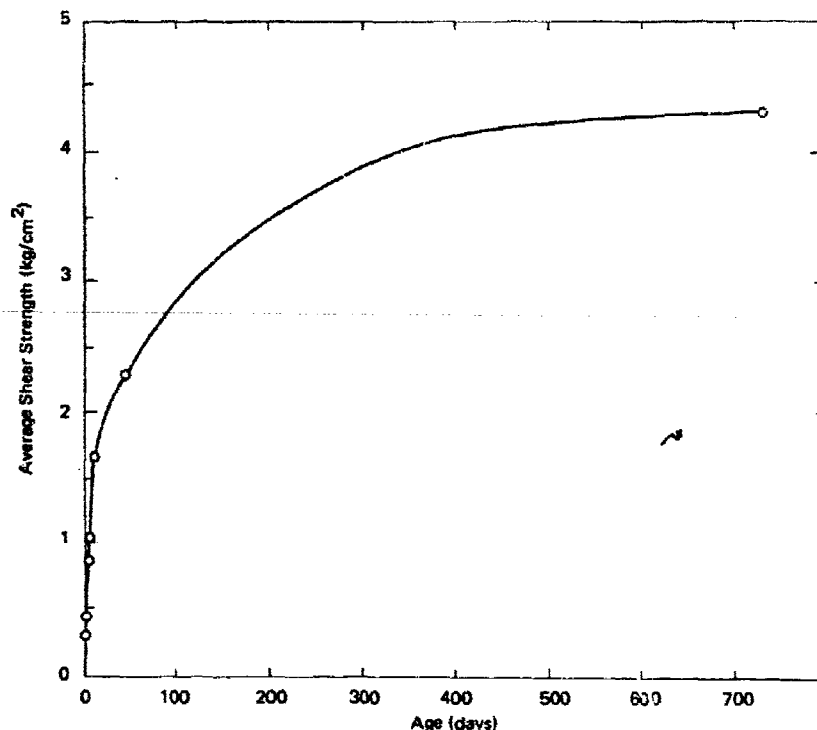
Figure 12. Increase in average shear strength with time (after Moser and Stehle, 1964).

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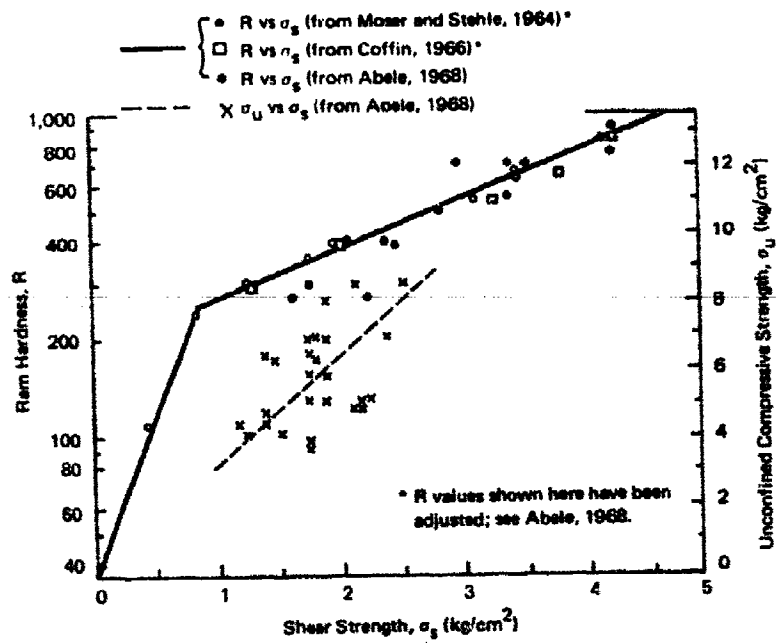
Figure 13. Relation of shear strength to ram hardness and unconfined compressive strength (after Abele, 1968).
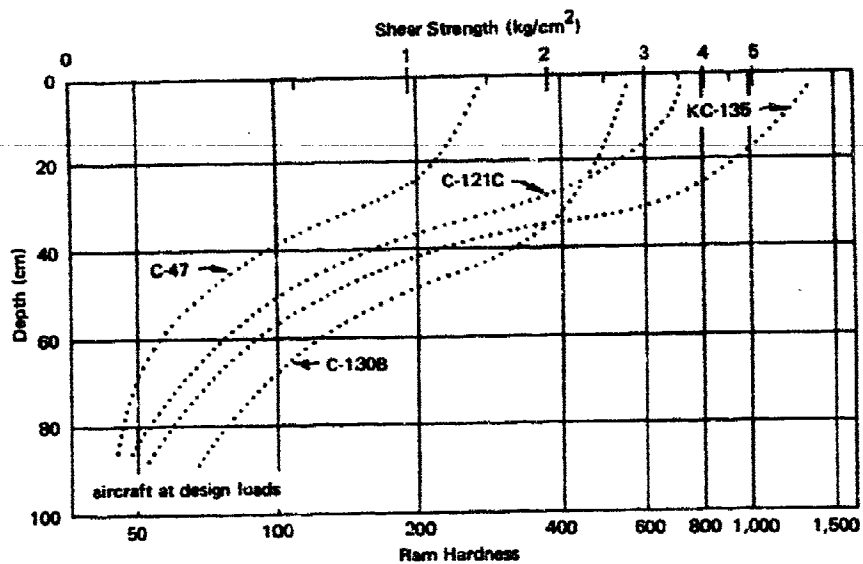
Figure 14. Required hardness or strength profiles of snow pavement for various aircraft based on Boussinesq equations (after Abele, Ramseier, and Wuori, 1968).

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centerline

radius of load

Distance From Center of Load (cm)

0   10   20   30

0.6q

0.5q

0.4q   0.3q

0.2q

0.1q

Depth (cm)

0

10

20

30

40
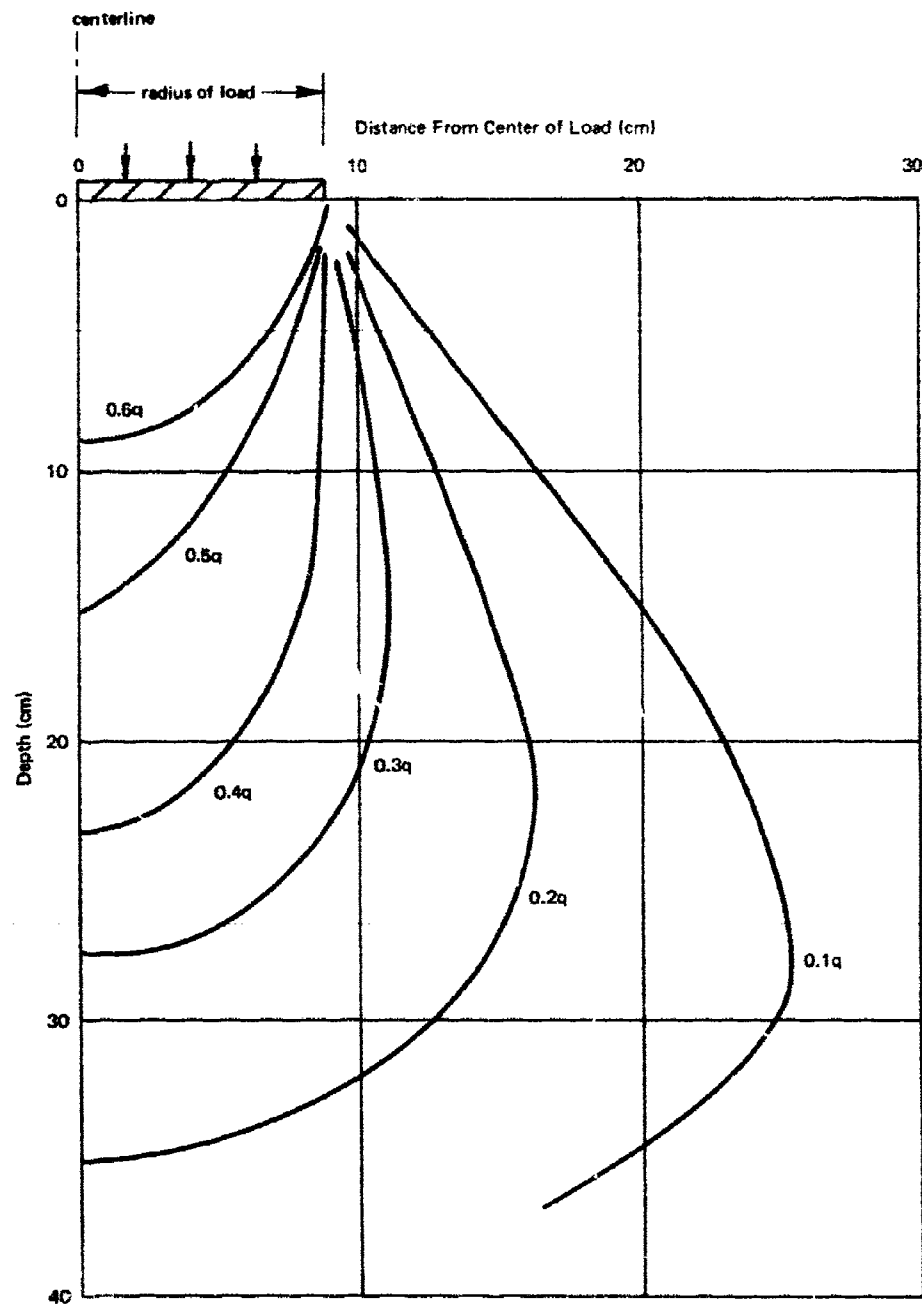
Figure 15. Cross-sectional distribution of static load, q, at depth; distribution is assumed symmetrical about the centerline.

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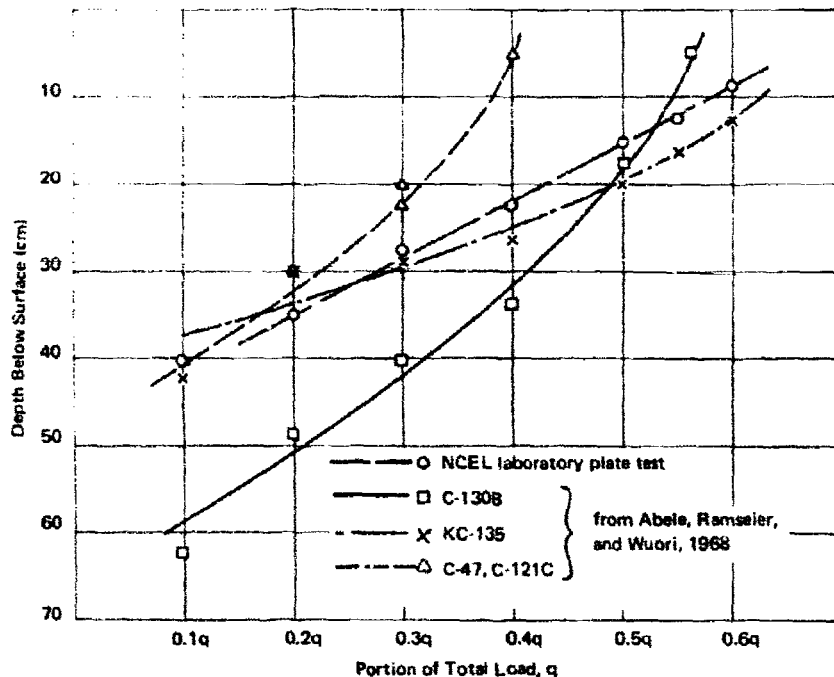
Figure 16. Theoretical and actual load distribution at depth.

CONCLUSIONS

1. Grain size, pressure, temperature, and solar radiation are the major mechanisms in the metamorphism of snow that control the mechanical development of surface-snow pavements for improved military operations on snow; pressure and grain size are the most important in attaining the critical density required for such pavements, while temperature and solar radiation have the most influence on bond growth.

2. Maximum strength in surface-snow pavements accomplished by accelerated metamorphism develops at or near a critical density of 0.60 gm/cm^3, which is best achieved with fine-grained, well-packed snow.

3. Maximum bond-growth rate of age-hardening in surface-snow pavements is achieved at snow temperatures between -12°C and -7°C; lower temperatures retard this growth rate, and higher temperatures or high solar radiation absorption generally results in a decrease in bond-growth rate.

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4. Distribution curves for various applied loads with depth in surface-snow pavements of varying temperature is needed for developing operational criteria for such pavements.

RECOMMENDATIONS

1. Current snow paving techniques and equipment should be improved or developed, as required, that are capable of producing average pavement densities at or near the critical density of 0.60 gm/cm^3.

2. For maximum strength, snow pavements should be scheduled for construction, when feasible, during that season of the year when the average snow temperatures range between -12°C and -7°C for several weeks followed by decreasing air temperatures; at McMurdo Station, Antarctica, for example, this period falls between mid-December and mid-January.

3. Laboratory and field research should be conducted to determine the load distribution curves for varying loads and temperatures in snow pavements to develop operational criteria for such pavements.

Appendix

EQUIPMENT AND PROCEDURES FOR TESTING

PRESSURE TESTS

Snow was disaggregated at the test temperature or colder through a sieve with either a 2.0-mm or 1.0-mm opening directly into a 7.6-mm-diameter, hollow, open-end metal cylinder on a metal plate. When the snow was 15 to 17 cm deep, the cylinder was transferred to a totally enclosed box in which the air temperature remained within $\pm0.2^{\circ}C$ and the temperature of the snow fluctuated even less. A solid metal cylinder that fit snugly without binding was then placed inside the hollow cylinder on top of the snow and weights were applied (Figure 4) to obtain the desired force. A dial indicator, reading to 0.0025 cm, was placed so as to indicate the amount of vertical shortening; no horizontal movement could occur because the snow was confined laterally by the cylinder. Manual readings of the dial indicator were taken hourly the first 8 hours and at least twice a day thereafter.

The snow was made in a $-32^{\circ}C$ cold chamber using a commercial snow gun. A sieve analysis was made of snow screened in a manner similar to that placed in the cylinders. Although these tests were run using laboratory-made snow, the results of size-distribution analyses indicate that at $-31^{\circ}C$ the size distribution was nearly identical with Mellor's (1963) from Greenland.

The cylinders after sieving through the 2.0-mm screen were tested at $-5.6^{\circ}C$, $-10.6^{\circ}C$, and $-30^{\circ}C$ with loads of 0.32, 0.65, 0.99, and 1.34 kg/cm^2; when screened through the 1.0-mm sieve, they were tested at $-10.6^{\circ}C$ with loads of 0.33, 0.65, 0.98, and 1.31 kg/cm^2. For these tests, it was assumed that the load was transmitted vertically through the snow with a negligible amount transmitted laterally.

SOLAR RADIATION TESTS

Snow was disaggregated at the test temperature through a sieve with a 1.68-mm opening. Snow cylinders were molded in 7.5-cm-diameter, 15-cm-long, split-type concrete casting molds. A constant amount of disaggregated snow was added to the mold and hand tamped in place with a 7.5-cm-diameter rod using the same method each time; each increment was about 2.5 cm. The snow cylinder was permitted to set until it was firm enough to remove from the casting mold without crumbling, about 1/2 hour. The cylinders were

arranged beneath 250-watt infrared lamps so as to obtain the desired exposure to simulate solar radiation. Thirteen samples were used of each radiation and temperature. One was used to record snow temperature from a thermocouple embedded about 2.5 cm from the top, and three each were removed after 1, 4, 7, and 11 days of exposure, measured for density, and tested for unconfined compressive strength; shear tests would have been preferable but, since the diameter of the samples changed due to sublimation, they would not fit in the shear cylinders. Average radiations for each test temperature are shown in Figure 7; radiation was measured before and after testing at five or more locations.

Initially, both 7.5- and 15-cm-long specimens were tested to determine what effect size had on the results. It was determined that the variability of results was considerably reduced using the 15-cm specimens or a length-to-diameter ratio of 2 to 1; consequently, all results discussed pertain to the 15-cm-long specimens.

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Naval Civil Engineering Laboratory
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TR-706   25 p. illus   December 1970   Unclassified

1. Metamorphism of snow   1. Z-R011-01-01-118

Although processing and compacting increase the density and bearing capacity of
surface snow for use as roads and trails, these processes have not been able to achieve the
degree of densification that occurs naturally as snow slowly metamorphoses to glacier ice.
A study was made at the Naval Civil Engineering Laboratory of the processes and influences
of the major mechanisms that control snow metamorphism—grain size, pressure, temperature
and solar radiation—in order to provide a basis for developing better techniques for higher
strength snow pavements. It was concluded that maximum snow strengths are achieved at
or near a critical density of 60 gm/cm^3, followed by bond growth, or age hardening, at
temperatures between -12°C and -7°C. In addition, as distribution of applied loads with
depth is essential to the development of operational criteria for such pavements, it is recom-
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13. ABSTRACT

Although processing and compacting increase the density and bearing capacity of surface snow for use as roads and trails, these processes have not been able to achieve the degree of densification that occurs naturally as snow slowly metamorphoses to glacier ice. A study was made at the Naval Civil Engineering Laboratory of the processes and influences of the major mechanisms that control snow metamorphism—grain size, pressure, temperature and solar radiation—in order to provide a basis for developing better techniques for higher strength snow pavements. It was concluded that maximum snow strengths are achieved at or near a critical density of .60 gm/cm^3, followed by bond growth, or age hardening, at temperatures between $-12^\circ C$ and $-7^\circ C$. In addition, as distribution of applied loads with depth is essential to the development of operational criteria for such pavements, it is recommended that research be conducted to develop this knowledge.

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Permeability						
Density						
Snow compaction						
Runways						
Roadways						