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Processing snow for high strength roads and runways

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Abstract

Using a variety of conventional snow processing equipment in deep snow fields in West Yellowstone, Montana, we studied snow processing techniques having the potential for producing high-strength snow roads and runways. The test location and timing were selected to obtain snow properties and winter ambient temperatures as dry and cold as possible, in a convenient location, to simulate conditions in polar regions. Four separate test sites, each with a different treatment, were established using the snow processing equipment. Observations were made for 12 weeks after construction to monitor the snow's hardness (strength) and its temperature distribution. Plane sections were taken at each site on a weekly basis to allow comparison of bond density and strength. We also used image analysis to find which critical microstructural properties correlate best with compressive strength changes. Temperature data were also correlated with strength changes. Test results indicate that a powered tiller with a relatively dense tooth population provided the highest strength snow. This snow was strong enough to easily support contact loads greater than 700 kPa, which could allow the use of conventional aircraft and wheeled vehicles in areas of deep snow.

Keywords: Snow compaction; Snow strength; Snow road tests; Snow sections; Snow tillage

1. Introduction

Although snow roads and runways have been constructed for hundreds of years, common practice today yields roads suitable only for vehicles with ground pressures less than approximately 100 kPa. This is the result of an inability to attain high enough snow strengths with past and current snow processing techniques, and the use of equipment that primarily focused on snow compaction. Thus, the vast majority of vehicles operating on snow have to be specially modified to reduce their ground pressure. For aircraft this means using skis. Besides being expensive to equip aircraft with skis, other cost disadvantages are often associated with operation of these specialized vehicles (e.g. the payload of a C-130 with skis is reduced by 3600 kg from the airplane's greater empty weight, less efficient aerodynamics, and the higher motion resistance of sliding skis compared to a rolling wheel). The same case can

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be made when it is necessary to build or modify surface vehicles for low ground pressure. The ability to construct a functional processed-snow runway, capable of supporting fully loaded heavy wheeled aircraft could be very advantageous. For example, there are plans to rebuild the aging Amundsen–Scott South Pole Station, which will require the delivery of as much as 8.2 million kilograms of materials. Additionally, current annual fuel requirements are 757 000 liters. Since oversnow transportation and a route from the coast to the South Pole has not been explored, delivery is now accomplished with ski-equipped aircraft operating from McMurdo Station, 1300 km away on the Ross Sea. A processed snow runway capable of supporting conventional wheeled aircraft would provide significant increases in payload per flight, access to a more diverse fleet of aircraft, and thus significant cost savings. A similar argument can be made for surface vehicles where processed snow roads of sufficient strength to support typical wheeled vehicles can also have a significant impact.

For a snow road or runway to be feasible, a method for processing snow is needed such that the resulting snow "pavement" attains a strength that can support tire pressures in the range of 690 kPa. Most cargo-carrying vehicles can easily be equipped to operate with tire pressures at or below 690 kPa and the C-130 Hercules tire pressure normally ranges from 550 to 690 kPa. Ideally, a snow strength that could support 1380 kPa would be desirable, since that would allow the operation of essentially any conventional surface vehicle or cargo aircraft.

Acceptable snow roads and runways have been constructed in the past (Abele, 1990; Averianov et al., 1985), but the focus of producing a high strength snow pavement has typically been only through compaction methods. Binders, such as sawdust, have also been added to snow and have improved initial snow strength under certain conditions (Lee et al., 1989; Barber et al., 1989). However, they ultimately produced a lower strength material due to significant snowpack warming caused by the sawdust absorbing incoming solar radiation.

A variety of devices are now in use to alter or control snow properties. Currently marketed snow processing equipment is primarily machinery that was originally devised for either agricultural applications (e.g., disks, tillers, and harrows) or for snow management on highways (e.g., blades and blowers). Originally, ski areas adapted these devices for snow quality improvement during drought periods and to provide an improved and more durable snow surface throughout the ski season.

The goal in processing snow to increase its strength is to minimize the grain sizes, ensure a well-graded snow (include a range of grain sizes), and minimize the pore space. Two components of snow strength can be considered: cohesion and internal friction. The cohesive strength of snow having a density less than 500 kg/m^3 is governed by bonding or "neck growth" that results from the combined processes of pressure sintering, diffusion of vapor, volume diffusion and grain boundary diffusion (Brown and Edens, 1991). Ambient and snowpack temperatures, together with the temperature gradient, affect the cohesive strength of snow. In the presence of large temperature gradients (and hence concentration gradients), bonds can be destroyed as sublimation removes mass from the smallest grains with the highest curvature including their bond areas and vapor diffusion transports and redeposits the vapor, forming a number of larger, and possibly faceted or partially faceted crystals with reduced intergranular bonding. Additionally, the snow structure itself can inhibit or encourage the formation of temperature gradients. Obviously, a snowpack with no temperature gradient cannot be continually achieved in the field.

Maximizing the internal friction of snow is accomplished by maximizing interparticle contacts. Both the internal friction and cohesive strength are dependent on gradation, minimal pore space, and grain size and shape. To maximize strength gains, it is also necessary to control ambient temperature conditions. Although maintenance of a constant ambient temperature cannot be achieved in the field, methods of producing consistent, small grain sizes in sufficient quantities for road and runway construction are available. Combined with an understanding of the relationship between strength change and temperature fluctuation, it should be possible to construct high strength snow pavements.

The objective of this project was to use currently available snow processing technology to build a series of test snow pavements. Snow properties were to be quantitatively analyzed to ascertain an optimum method for making an evenly graded snow capable of yielding a robust snow road or runway in cold regions. Typical field measurement techniques were employed in conjunction with the use of image analysis to examine the snow's microstructure. Measurements were taken weekly, with density, strength, and observed physical characteristics logged at the site. In addition, cores were taken weekly and transported to a laboratory. There, plane sections were prepared for several horizons in the snowpack and image analyses were performed. This paper discusses the construction techniques used to create the processed snow test sites, and the results of strength measurements and image analyses. Ultimately, an efficient method for building a robust high-strength snow pavement is proposed.

2. Test site construction

Tests were performed in West Yellowstone, Montana, at an airport that is closed to air traffic during the winter. This site was chosen because statistical winter data indicated that the snow properties and winter ambient temperatures were comparable to summertime conditions in a polar region. Tests were performed under very cold, dry conditions because these represent a difficult situation for producing strong snow.

Logan Manufacturing Company (LMC) provided several types of machinery for snow processing. The primary piece of equipment was an LMC 3700C grooming vehicle equipped with a 12-way snow blade. Snow processing implements, all used as attachments to the 3700C, included a powered rotary tiller with an "Eastern" tooth population, a powered rotary tiller with a "Western" tooth population, and a power harrow (overlapping tine groups rotate about a vertical axis yielding an "eggbeater" action). Table 1 lists details on each implement. Two experienced LMC equipment operators were responsible for test site construction. Four separate sites (plots) were established using the equipment.

Snow was preprocessed using a small rotary snowblower (Gebrueder Holder GmbH model C6000 turbo). The plot sites were stripped down to the pavement with the blower. The natural (original) snowpack was approximately 60 cm of low density, unbonded (new) snow. Additional snow was plowed to the vicinity of the plot sites with the LMC 3700C and preprocessed with the rotary blower. The preprocessed snow was then blown into three piles, approximately 20–25 m long. These piles were then levelled with the 3700C and allowed to sit undisturbed overnight. The sides of the plots were shored up with bulkheads of unprocessed snow using the 3700C. Finally, most of the preprocessed snow was graded back from the four plots, and the snow then was blown back onto the plots in layers. Each layer of snow was reprocessed with the desired implement (referred to as Eastern tiller for the powered tiller with the relatively dense tooth population, Western tiller and power harrow) specifically designated for that plot. One plot was not reprocessed with an implement; it served as a control.

Following processing with the implement, the snow was smoothed with a pressure bar mounted behind the 3700C. The bar applied a downpressure of 18.83–20.55 kPa with a bearing surface of 7664.5 cm^2. No further compaction was performed. The average maximum plot depth was 90 cm with approximate widths of 6 m and lengths of 20–25 m. Construction was begun shortly before midnight on 15 December 1992 and all four plots had been completed approximately 16 hours later, including the time needed to change implements on the 3700C. The plots were then marked with stakes and chalk so

Table 1
Parameters for LMC snow processing implements

Implement	RPM	Horizontal tooth spacing (cm)	Tooth type	Tooth population	Weight (N)
Eastern tiller	1356	7	7.6-cm battle ax	172	8000
Western tiller	1248	4.3	7.0-cm battle ax	118	6670
Power harrow	620	33	28-cm U-blades [a]	10	12450

[a] 6.4 cm overlap on blades.

that the original surface was easily identifiable for plowing and testing. Plot surfaces were plowed immediately following any new snow deposition throughout the test period.

3. Testing methods and results

Snow density, hardness, grain size, and sorting were monitored for each test site over the course of the 12-week period between 18 December 1992 and 9 March 1993. Snow samples were also taken weekly, using an ice coring tool, to supply plane sections for image analysis. Plane section samples, taken from three different horizons within the snow pavement, were prepared with traditional techniques (Good, 1986) by saturating the snow with liquid dimethylpthalate tinted with the dye oil N blue. The samples were then cooled to allow the dimethylpthalate to freeze. Smooth, prepared plane sections were digitized for analysis with a frame grabber interfaced to a computer.

Thermocouple strings were installed in each test site with sensors located at 10-cm intervals extending from the surface to a depth of 80 cm. Snowpack temperatures were monitored with Campbell Scientific CR10 data loggers. The data loggers maintained a 60-second sampling rate, and half-hour averages were stored for later analysis.

In an engineering approach for the prediction of the mechanical behavior of granular materials, it is useful to determine what physical characteristics might serve as indices. Two commonly used indices for granular materials (e.g., soils) are particle size and sorting. If a granular material is primarily composed of particles of a single size, it will contain an insufficient amount of fines to fill the void space between the larger particles. An open porous structure will result, regardless of the degree of compaction. By contrast, a well-graded material contains a range of grain sizes that allow it to be compacted to a high density and give rise to numerous grain contacts points, providing increased internal friction.

Making precise determinations of the diameters of all individual snow particles in a sample is seldom practical; therefore, size fractionation (separation of a sample into particle size groups or fractions) is commonly employed. We used U.S. Standard soil sieves to analyze the snow for grain size and sorting characteristics. The gradation curves from the four snow types, taken immediately after final processing, are shown in Fig. 1. A gentle, even slope indicates good gradation and a steep or broken slope indicates poor gradation.

From the gradation curves, the plot processed with the Eastern tiller seems to be the most evenly graded, although it is not ideal. The most poorly graded snow results from processing with the rotary blower alone. However, differences among the four curves are slight. Some improvement in particle size gradation might be made by further processing with any of the implements, but each of these curves (Fig. 1) indicate a lack of fines. (Possibly we did not capture all of the fines due to melting that may have occurred during agitation of the sieves.) It is also noteworthy that the Eastern tiller snow exhibits the smallest 50% grain size (i.e., the grain size for which half of the snow mass has larger diameter grains and half has smaller grains). Particle sizes in all of the processed snows ranged from 4.75 to 0.25 mm. By comparison, an "ideal" gradation for highway subgrade soils includes particle sizes ranging from 5.00 to 0.003 mm (Peck et al., 1974).

The processed snow was tested weekly for hardness (strength) using a U.S. Army Engineer Waterways Experiment Station (WES) cone penetrometer equipped with a 1.29-cm^2-diameter cone and a proving ring for recording displacements from applied load. Snow strength was calculated from the load vs. displacement curve provided by the manufacturer. In many instances the snow in the Eastern tiller plot was impenetrable with the cone penetrometer. The proving ring was limited to a displacement less than 0.25 cm, which corresponded to a strength of 5862 kPa. Fig. 2 show the bearing strength envelopes for each test plot for the upper 12.5 cm of snow. All four snow types exhibited a marked increase in compressive strength during the first week after construction. Fluctuations in strength were seen during the next 11 weeks.

Generally, the strength decreases noted in Fig. 2 correlate strongly with lower ambient temperatures. Since the lower boundary temperature (asphalt) remained relatively constant and warm throughout the test period, a drop in ambient temperature induced an increase in temperature gradient through the snowpack. Similarly, increases in ambient temperature (decreases in temperature gradient) reflected increases in strength. Deterioration of snow strength under a strong temperature gradient is a well documented phenomenon in a natural snowpack (Brown and Edens, 1991; Colbeck, 1982). Thermal and concentration diffusion occurs when a temperature gradient is present. Under a gradient, mass is removed from areas of higher vapor pressure by sublimation, and redeposited in areas of lower vapor pressure. The net vapor flux is in the direction of decreasing temperature, typically toward the snow/air interface. Bonds can be destroyed as sublimation removes mass from the smallest grains with the highest curvature including their bond areas, and vapor diffusion transports and redeposits the vapor, forming a number of larger, and possibly faceted or partially faceted crystals with reduced intergranular bonding. The

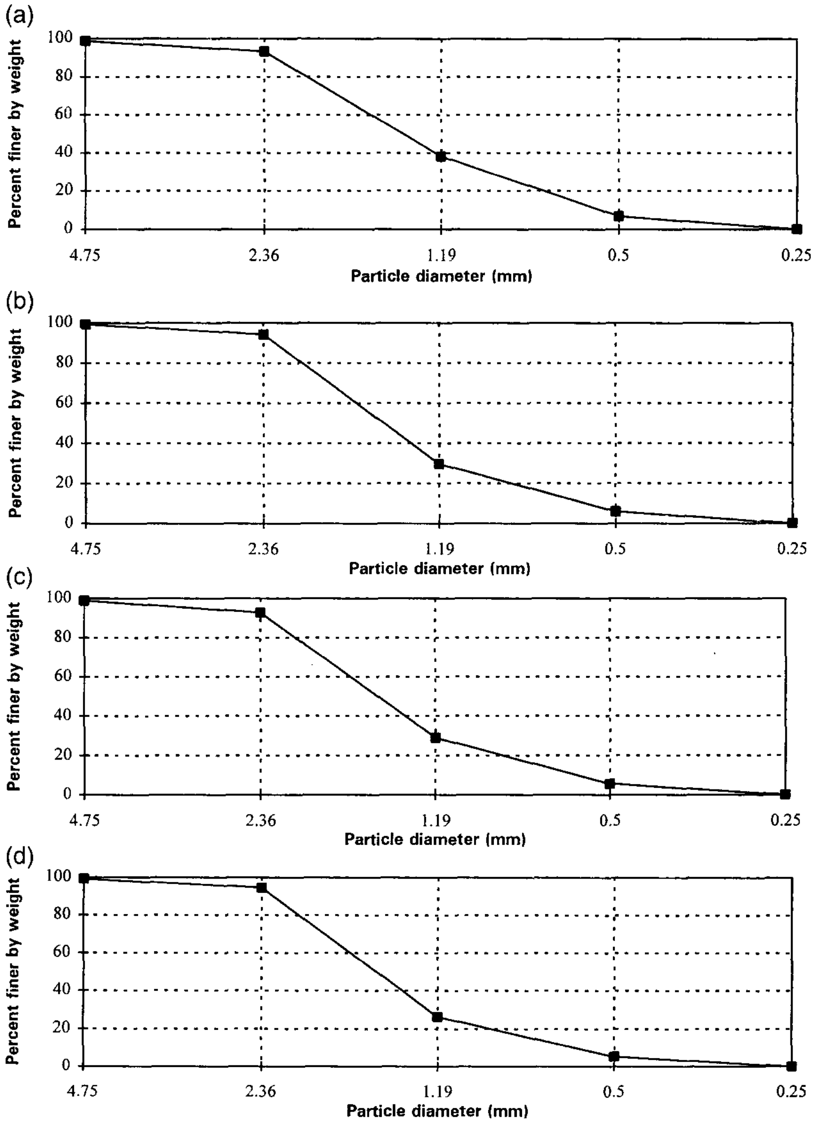


Fig. 1. Initial gradation curves for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d) test plots. Fines have probably melted during agitation.

construction of these sites on an asphalt surface was considered to be a "worst-case scenario". Adjacent to the plots, the asphalt was initially fully exposed to insolation, and later was covered with a shallow, low-density snow cover (less than 30 cm maximum). This lower boundary condition of a fully exposed or sparsely covered black surface was thought to allow for the development of the largest possible temperature gradients within the test plots, and hence the most rapid deterioration of the processed snow within the test plots. As the focus of this preliminary study was to investigate the plausibility of constructing a functional processed-snow runway, capable of supporting fully loaded heavy wheeled aircraft in the vicinity of the Amundsen–Scott South Pole Station, the actual lower boundary condition would be a high density, "infinite" depth snowcover at a relatively cold, stable temperature (Brandt and Warren, 1993). For any application, the temperature distribution within the pavement and the lower boundary would require close observation.

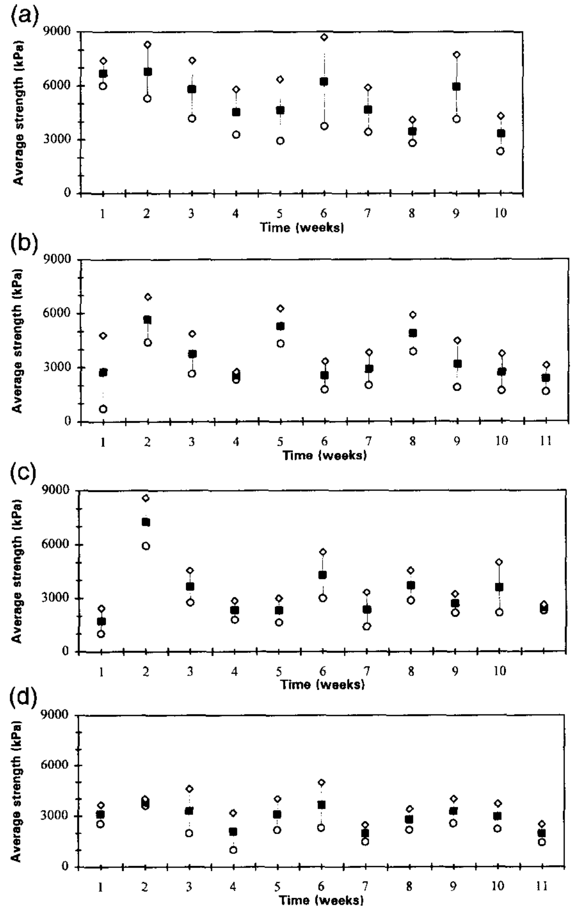


Fig. 2. Bearing strength envelopes for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d) test plots through time.

Fig. 3 shows the half-hour average temperatures recorded in the plots, near the snow surface and at a 10-cm depth. A period of low temperatures and moderate temperature gradients persist from about weeks 2.5 through 4. This matches well with the steady loss in strength seen in Fig. 2 over the same time period. From just prior to week 4 until week 5.5, there is an ambient warming trend (decreasing temperature gradient in the snow). In response, snow strength shows a strong recovery between weeks 4 and 6. In some cases, snow strength returns to values near the maximum initial level attained during week 2. A second interval of cold weather progressed from week 5.5 to just past week 7. Again, snow strength showed a corresponding relapse during this time period.

A distinct warming–cooling cycle occurs between just after week 7 to week 9. This is followed immediately by a rapid jump in temperature of about 5°C. During the cycle from week 7 + until week 9, snow strength in the power harrow and Western tiller sites closely mimics the temperature profile, as expected. The other sites show a mixed response during this period.

From just after the week 9 point onward, all of the plots show a strength loss. A period of stable temperatures occurs from just past week 9 until week 10; then temperatures drop slightly for half of a week before they begin to rise steadily until week 12 when monitoring ended. It is not clear why snow strength in the plots drops during this period, when we might expect it to increase. However, it may be that the changes in temperature are too rapid and erratic for us to see corresponding strength changes with our once per week strength sampling rate. Possibly the air temperature had also finally reached a high enough level that the snow could no longer sustain a high strength, regardless of the temperature gradient and number of bonds.

The Eastern tiller site demonstrated the highest strength values over the course of these tests. The minimum strength seen here was three times higher

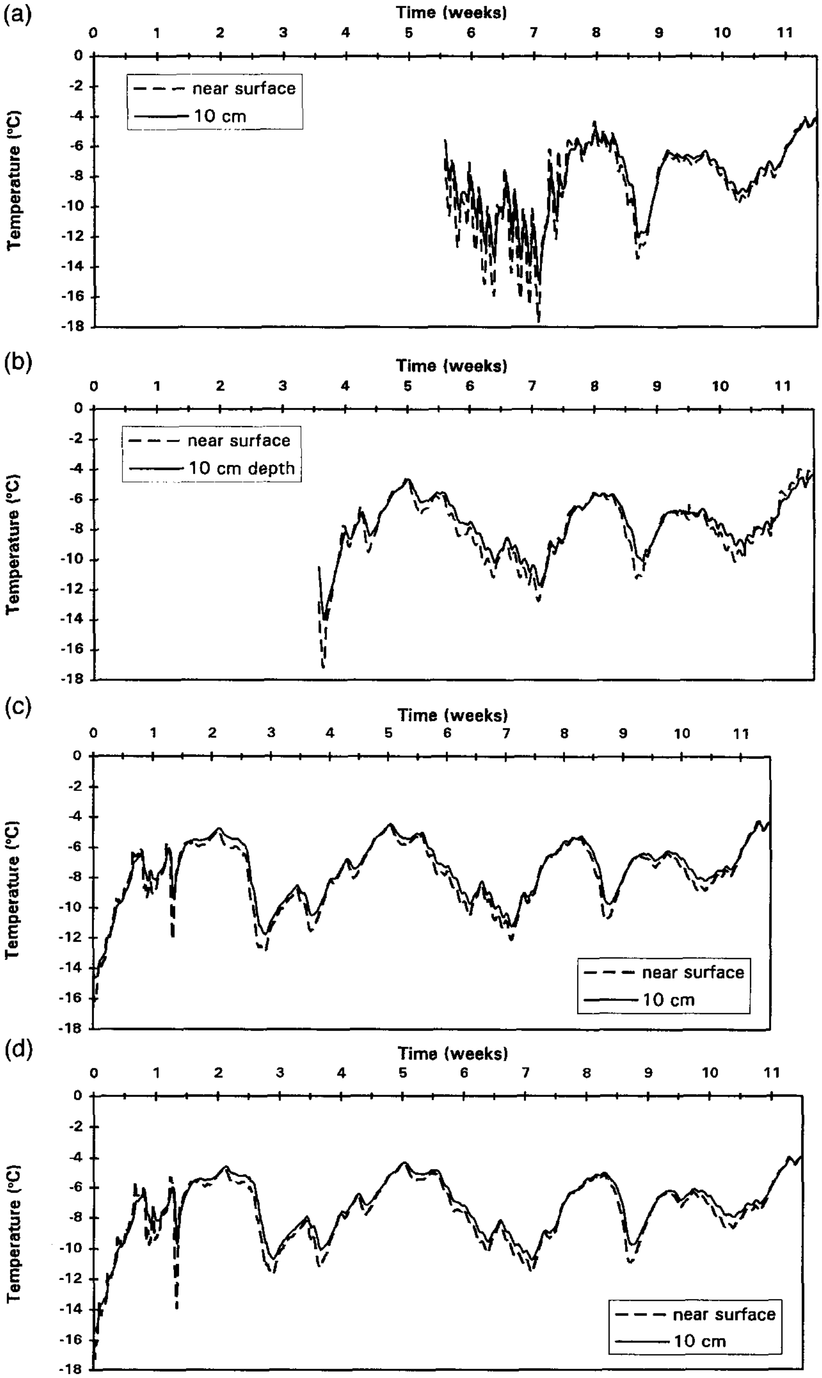


Fig. 3. Temperature distribution in the upper horizon (top 10 cm) in the Eastern tiller (a) (installed during week 5), Western tiller (b) (installed during week 3), power harrow (c) and rotary blower (d) test plots. Temperatures were sampled at a rate of 60 seconds and averaged every half hour.

than the minimum value found in the other three sites. However, the Eastern tiller site (along with the rotary blower site) also displayed the greatest variability. Strength values in the Western tiller and power harrow sites were much more consistent, though, at times, they were three times lower than the strength found in the Eastern tiller site. The minimum value of bearing strength recorded in the Eastern tiller site, approximately 3000 kPa, would provide a large factor of safety for a 690-kPa tire requirement.

Stereology, the science of quantifying and interpreting data presented in two-dimensional images, is a potentially useful tool for analyzing any type of granular solid for which a planar section can be generated and viewed. The basic premise is that statistical methods can be used to yield estimates of system properties, assuming isotropy. Analysis of plane sections allows many different particles and their interactions with surrounding particles to be observed. Techniques developed in the statistical analysis of metals (Miles and Davies, 1976; Davies and Lundlin, 1979; Davies, 1979; Rhines, 1980; Miles, 1985) can be directly applied to snow. Many authors have taken this step and have applied image analysis techniques in determining macroscopic snow properties (Gubler, 1978; Dozier and Davis, 1986; Good, 1986; Hansen and Brown, 1986). We think the most fruitful use of image analysis on snow is in the study of the relationship between snow strength and such factors as temperature gradient, grain size, and intergranular bond characteristics.

We attempted to use image analysis on weekly plane sections from the test plots to identify any critical microstructural properties of the snow that appeared to contribute to compressive strength increases or decreases. It was hoped that the image analyses would provide accurate information on density and surface/volume ratio, in addition to the ability to estimate bonding (cohesion) in snow.

Two obvious and unresolved limitations to current image analysis routines exist: (1) the ability to estimate three-dimensional parameters from two-dimensional images and (2) the primitive or missing algorithms for dealing with nonconvex, unconnected particles. For example, current techniques apparently can not tell whether two adjacent particles in a planar image are distinct, or rather are connected above or below the image plane. There is a recurring question as to whether or not bonds between grains can be differentiated from the grains themselves. Though some current software uses a form of algorithm to estimate the number of bonds, the issue of accuracy is still open to debate since no such algorithms have been validated.

For our study, the algorithms of the image analysis software that are of primary importance are point density and intercept density. These two quantities form the independent properties from which many other quantities related to snow microstructure and metamorphism can be calculated.

Point density P_p is reported as a dimensionless quantity: the ratio of white pixels to total pixels. Because isotropy is assumed, the average point density for several random samples can be integrated over a volume to yield a volumetric density from a two-dimensional image. Intercept density N_L represents the ratio of snow to pore space and is measured by drawing random, straight lines through the image and counting the number of intersections with surface boundaries. Intercept density has the units of mm^{-1}. From these three parameters other strength indicators are calculated (Dozier and Davis, 1986):

Specific surface density per unit volume	$S_v = 2N_L$	[mm^{-1}]
Volumetric density of snow	$\rho_s = \rho_i P_p$	[kg/m^3]
Volume to surface ratio	$V_s = P_p/(2N_L)$	[mm^{-1}]
Mean intercept length	$L_3 = 2P_p/N_L$	[mm]

Surface density per unit volume S_v should decrease if a temperature gradient is present and the desirable structure is deteriorating into a collection of faceted, unbonded crystals. Larger, facetted crystals grow at the expense of particles with a high surface to volume ratio. The rate of deterioration is a function of the magnitude of the local temperature gradient and the initial density and gradation of the snowpack. The product of P_p with the volumetric density of ice ρ_i (assumed to be 916 kg/m^3) yields a volumetric density ρ_s for snow. Volume/surface ratio V_s is the product of the volumetric density and the inverse of S_v. This quantity can also be used to observe the growth of the grains over time. Mean intercept length L_3 is the average length of a test line that falls within the white pixels. L_3 is a measure of the snow grain and pore space distribution. As both the mean intercept length and the volume/surface ratio depend on the values of surface density per unit volume and volumetric density, examining these two independent quantities in addition to the bond density should be sufficient.

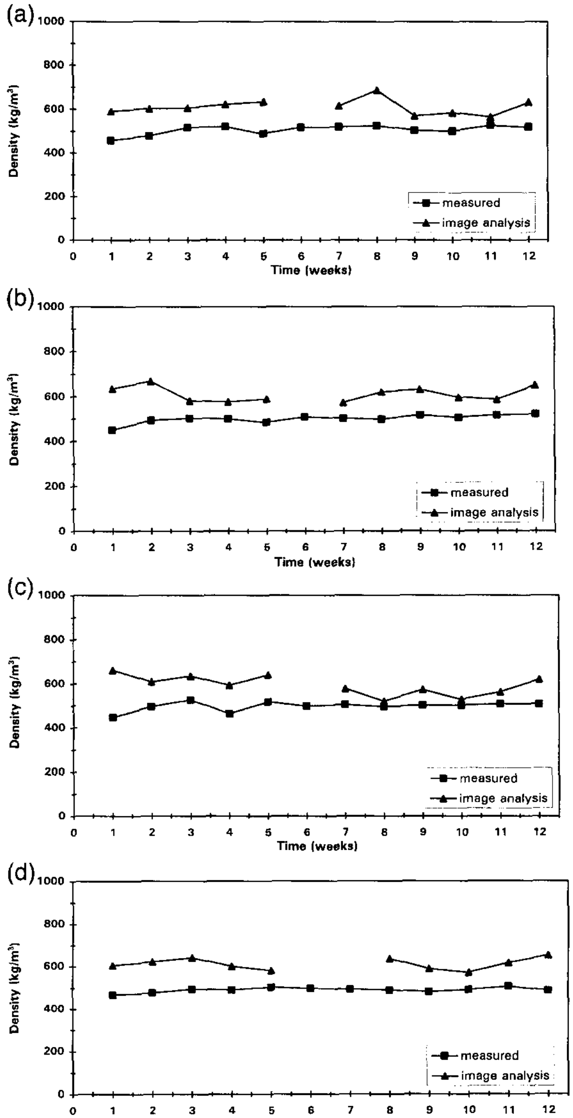


Fig. 4. Comparison of field measured volumetric densities to calculated volumetric densities from the image analyses for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d).

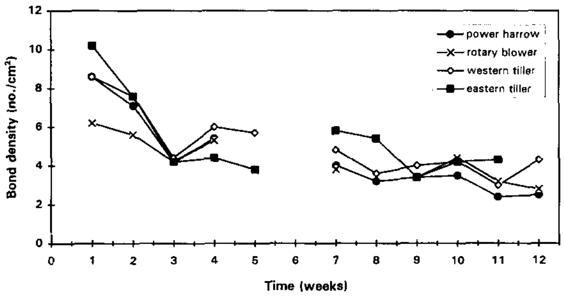


Fig. 5. Comparison of two-dimensional bond number density through time for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d) test plots.

Processing of the images was completed for the samples taken from the upper horizon (top 12.5 cm) in each test site. Image preprocessing was accomplished using the National Institute of Health (NIH) public domain software called IMAGE, version 1.41. Analyses on the preprocessed images were performed using the Image Processing Workbench (IPW).

Volumetric density is a commonly used index property of granular materials. Density can be used as an index of compressibility, since a material with a large void volume is much more compressible than one with minimal interparticle spaces. Density determination through stereology was compared with manual density measurements taken on-site (Fig. 4). It is not surprising that some disagreement between the two techniques is seen. Inaccuracies in the manual density measurements were most likely caused by the difficulty in obtaining a consistent sample size from the hard, dense snow. The density predictions from the image analyses contain errors caused by the extrapolation of a volumetric property from a surface image. For an isotropic material, errors should not occur by this extrapolation. The density measurements provided by image analysis appear to provide a better correlation with the measured bearing strength. However, densities acquired from image analyses are typically higher than expected and may result from poor sample preparation (Gubler, 1978).

The two-dimensional bond number density is a measure of the connectedness of the snow grains. Neither software program (IMAGE or IPW) was

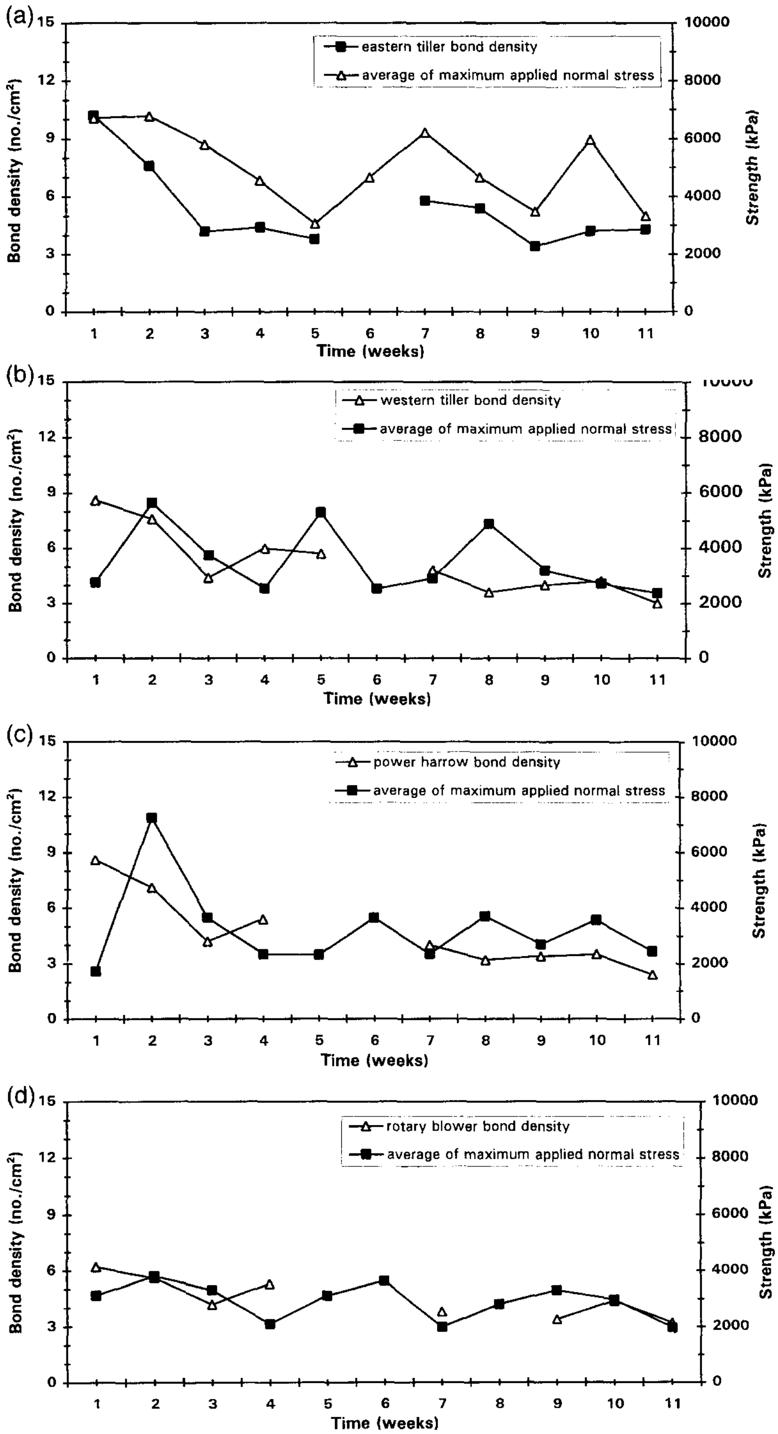


Fig. 6. Comparison of measured strength to bond density for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d) test plots through time.

able to calculate two-dimensional bond number density. However, two-dimensional bond number density should be directly related to the intercept density as intercepts are measured by drawing random, straight lines through the image and counting the number of intersections with surface boundaries. The two-dimensional bond number densities were obtained by examining the images and manually counting the number of obvious bonds in the entire sample and dividing by the total surface area of the image. Bond counts were performed independently by three of us; there was very little difference among the number of bonds counted. A comparison of the two-dimensional bond number densities from the four sites is shown in Fig. 5. For the majority of the test period, the two-dimensional bond number density counts indicated that the Eastern tiller site had the greatest bond number density. This suggests that the Eastern tiller processes snow in a manner that encourages bond development. Over the first 9 weeks of the test period, the rotary blower site showed the lowest bond development. Both of these bond number density observations seem to correlate with the strength measurements.

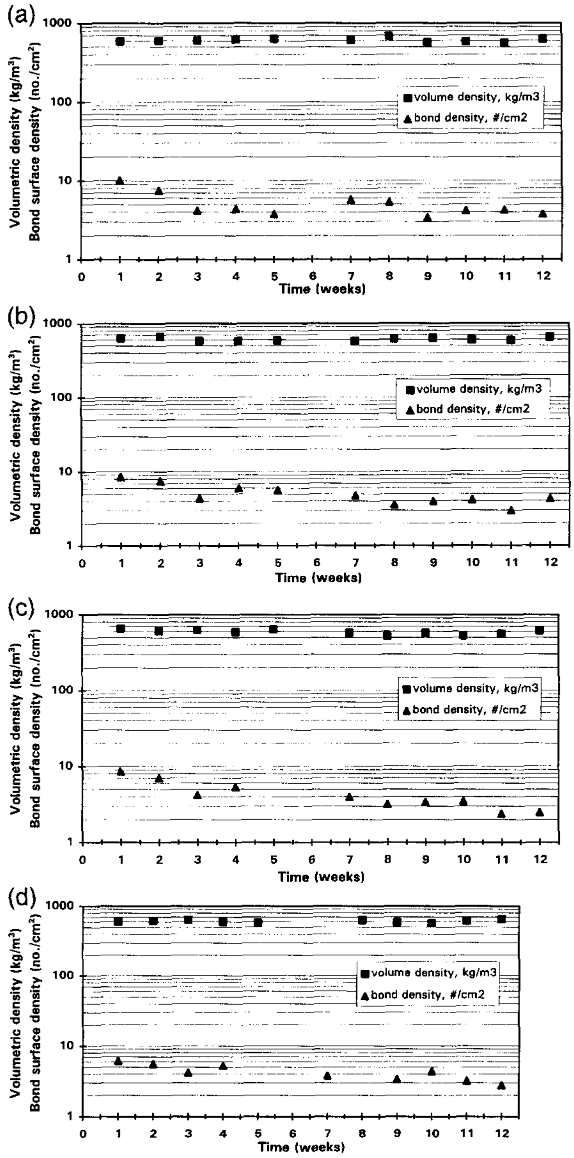


Fig. 7. Comparison of bond density to volumetric density through time for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d) test plots.

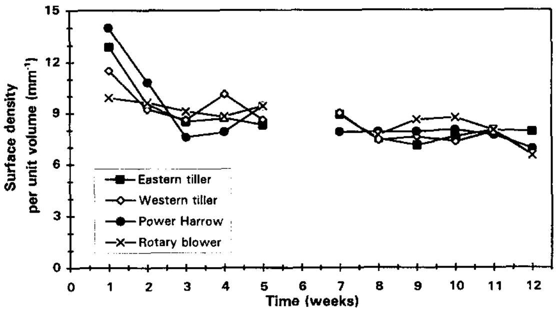


Fig. 8. Analytically determined surface densities through time for the Eastern tiller (a), Western tiller (b), power harrow (c) and rotary blower (d) test plots.

Fig. 6 compares, through time, the measured strengths calculated from the penetrometer readings and from stereologic bond number density values for each test plot. The results indicate a very good correlation between strength and bond count fluctuations. However, the bond number density differences (Fig. 5) do not correlate with the measured strength variations. This suggests that two-dimensional bond number density may be a good indicator of how the cohesive strength of a given snow is changing as the result of environmental influences, but that it cannot be used to quantitatively estimate compressive snow strength.

A comparison of two-dimensional bond number density to volumetric density from the image analyses results is depicted in Fig. 7. In some cases,

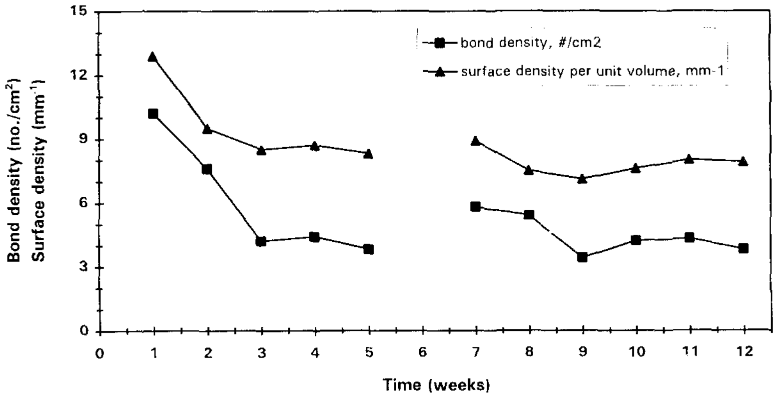
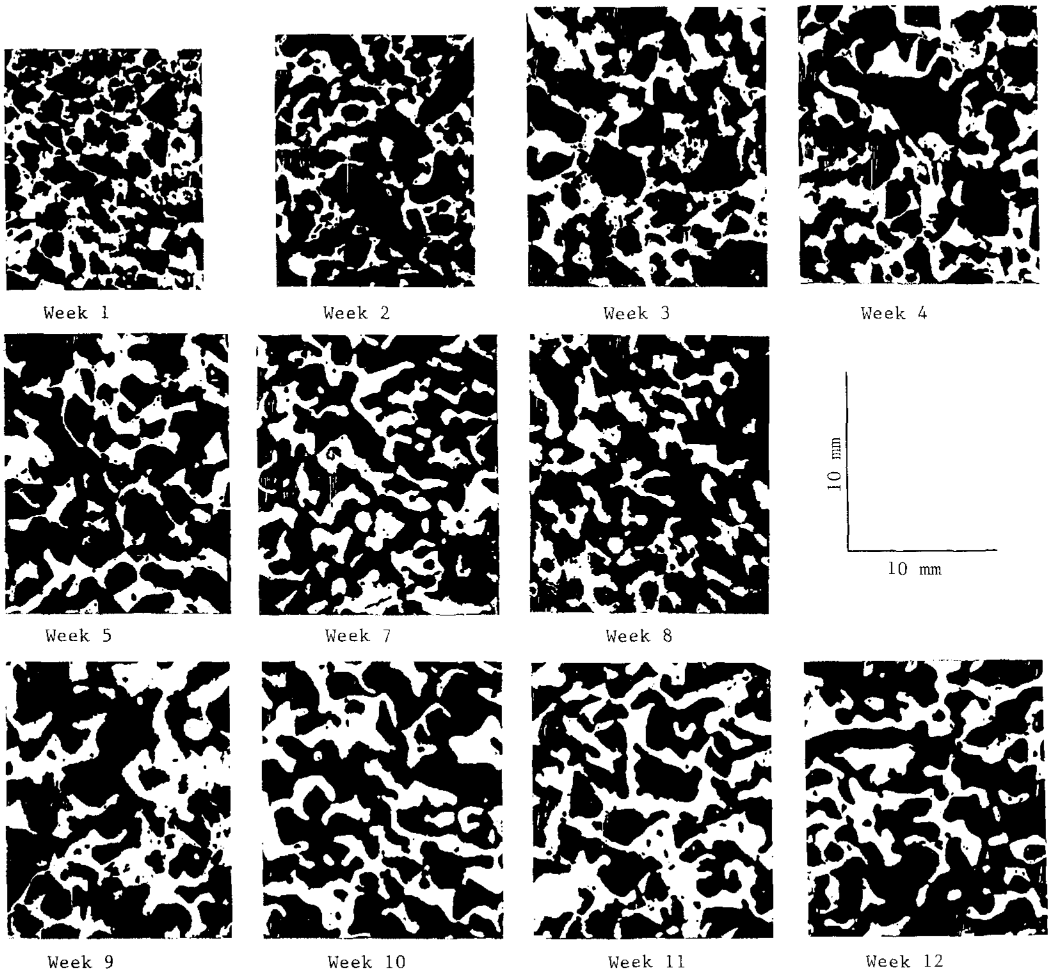


Fig. 9. Comparison of bond density to surface density through time for the Eastern tiller site.


Week 1 Week 2 Week 3 Week 4

Week 5 Week 7 Week 8

Week 9 Week 10 Week 11 Week 12

Fig. 10. Series of digitized plane section images from the Eastern tiller plot, upper horizon (upper 12.5 cm). Images are from weeks 1 through 12; no sample was taken during week 6.

increases in volumetric density are linked to decreases in bond number density. Thus, no strong correlation between these two quantities is evident, although volumetric density should reflect changes in surface density. Also, two-dimensional bond number density depends on the statistical probability that a grain and the grain bond is transected by an observation plane. As an index property, volumetric density probably reflects the internal friction of the snow. Certainly, bond number density indicates the value of cohesion. Upon application of an external load, loss of cohesion or bond breakage would need to occur prior to the load being supported through interparticle contact. Conceptually, this can be compared to plotting strength test results on a standard Mohr's circle; the cohesive shear strength reflects the minimum applied normal stress in a failure envelope.

Surface density per unit volume should reflect changes in the thermal environment in the snowpack, and hence, a change from well-bonded, equi-temperature snow to snow that has undergone temperature gradient metamorphism to some degree. Fig. 8 shows the analytical results of S_v calculations for the four test plots. The changes in surface density reflect the changes in bond density in Fig. 5. In order to better illustrate this, Fig. 9 depicts both the bond density and surface density through time for the Eastern tiller plot alone.

The foregoing analysis indicates that stereological calculations can provide some insight into the expected level of the cohesive strength of snow and snow response to environmental influences. Simple visual examination of the snow's microstructure from the digitized images can provide limited information on the expected macroscopic behavior. A series of images from the Eastern tiller plot is shown in Fig. 10. Transition from a desirable system of well-rounded grains with bonds to faceted crystals is not apparent, although the periods of time during which the snow was subjected to a temperature gradient are substantiated by slight changes in grain structure. A uniform, high density snow should inhibit vapor transport within the snow and the digitized images tend to support this.

4. Conclusions and recommendations

On the basis of on our test results, producing a well-graded, small-grained, firmly compacted section of snow is expedient to generating a robust snow pavement. However, ambient temperatures, and more importantly, temperature gradients through the snowpack, will control the day-to-day strength of a processed snowpack. Of the tools used in our study, a power rotary tiller (Fig. 11) with an Eastern tooth population, provided the most evenly graded and strongest snow. This snow maintained a strength between 3000 and 7000 kPa throughout the course of our 12-week study. This strength is more than suitable for the support of heavy wheeled vehicles and aircraft which typically would not require more than 1000 kPa strength.

Compressive snow strength is principally a function of intergranular bonds and particle-to-particle

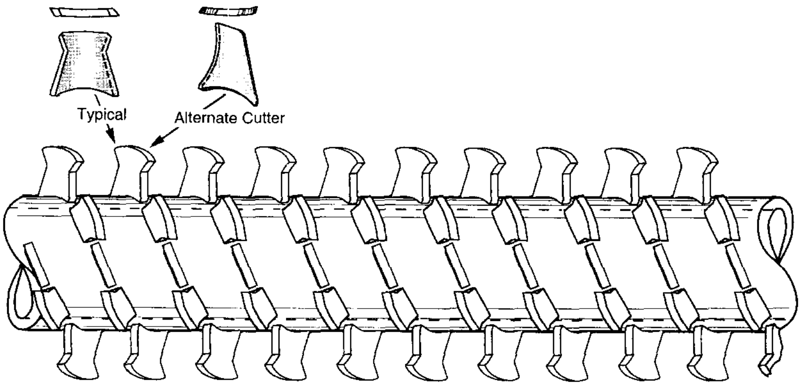


Fig. 11. Typical section of rotating drum from a power tiller.

contacts. As the number and size of bonds increases, so does cohesive strength. Thus, construction techniques should aim to produce small snow grains with a range of diameters to allow close packing. The snow needs to be compacted in such a way as to maximize intergranular contact, both for encouraging bond development and to help distribute load. In our study, initial snow densities could have been further increased by processing the snow several times with an implement, followed by the application of a higher compaction effort during construction. Generally, the snow pavement area needs to have lateral support during compaction to prohibit spreading of the snow mass along its edges. Overprocessing should be avoided to prohibit contamination of the snow by hydraulic fluids, motor oil, and exhaust fumes. These precipitate a condition of low cohesion, contaminated snow, a disaggregate of grains that are unable to bond due to the presence of hydrocarbons.

The technique we describe for construction of a snow pavement maximizes only the potential for a strong snow mass. Our tests showed that strength changed significantly as a function of temperature gradient through the snowpack. Increasing ambient temperatures gave rise to decreasing temperature gradients through the pack and a corresponding increase in strength. Likewise, strength fell as ambient temperature decreased. A slight lag time may be present for strength response, but our sampling frequency was not adequate to make this determination for certain. The strong dependence on temperature makes it important to monitor the temperature distribution in a snow pavement. The effect of short-term temperature gradients was seen as beneficial in this study, but enduring gradients should be accompanied by diligent retesting of the compressive strength of the snow.

Simple field tests can be used to measure index properties and to obtain a sufficient amount of information to assess snow strength. Fractionation of the snow into particle size ranges and graphing of an initial gradation curve is a simple technique to provide a priori an estimate of the compressibility of the granulate. Volumetric density also indicates the compressibility of a granulate based on the available pore space and hence interparticle contacts available for bonding and particle-to-particle support. A penetrometer can be used to provide instant point source strength in the field as well. However, prior to opening a road or runway for operation, it would be prudent to perform compression tests on snow samples. Small, portable load frames are available for this purpose. Compressive strength tests will yield a better indication of the factor of safety for vehicle and flight operations on a snow pavement. Penetrometer measurements are only index measurements related to compressive snow strength (Abele, 1990) and cannot simulate the pressure distribution due to a wheel load. As the static wheel load is the worst case load (see, for example, O'Massey, 1978, Blaisdell and Lang, 1994 or Lang and Blaisdell, 1996), no attempt was made to analyze the transient loading of a moving wheel. Similarly, it is assumed that any pavement constructed of a granular material, such as a soil roadbed, would require some surface maintenance depending on the frequency of traffic.

Image analysis, although of scientific interest, does not yet appear to be a reliable or efficient tool in predicting the quantitative strength characteristics of snow in a timely fashion. The immediate drawbacks include:

1. A great deal of time is required to sample and construct plane sections for analysis. It is important that the technician is well trained in preparing the samples for digitization or an unusable image will result.

2. Digitizing, preprocessing and processing an image is too time consuming for the amount of information that results from the analysis packages now available. Image analysis software currently requires a workstation environment and is not yet user friendly, making it unsuitable for field work in remote areas where computer access is limited. If images are digitized and preprocessed on a personal computer, they must usually be transferred to a workstation or mainframe environment for processing. The results of the analyses must finally be transferred to a spreadsheet environment for statistical and graphical analysis, which, in our case, had to be retyped into the PC environment.

3. Although image analyses did provide some of the information that we required (i.e., the bond density in the form of a surface density), this measurement would be available from a simple compression test since bond density is a measure of the cohesion in snow (Lang and Harrison, 1995).

The result of this preliminary research is an improved understanding of the factors that are required in constructing a functional, compacted snow pavement capable of supporting heavy vehicles including wheeled aircraft. Even at our current level of understanding, the compressive snow strengths obtained in this study were more than four times the required strength for fully loaded C-130 wheeled aircraft. The results of this study can be applied in the building of good quality, robust snow roads for recreation, construction, exploration, and military use in snow-covered regions.

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