Processing a high strength snow for South Pole compacted snow runway: Test results from Winter 1992-1993

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Abstract

Field studies were required in order to identify the optimum snow processing technique that will produce a compact and bonded snow suitable for the construction of high strength snow roads and runways. Improving the strength of the snow runway at Amundsen-Scott South Pole Station, Antarctica would be required if the United States Antarctic Program (USAP) considers wheeled aircraft as a possible delivery system. The types of conventional snow processing equipment that produces the highest snow strength were quantitatively verified using image analysis techniques and other on-site testing methods. Tests were performed in West Yellowstone MT where the snow properties and winter ambient temperatures are as analogous as possible to those at South Pole during the austral summer and in other Arctic and Antarctic regions. Four separate sites were established using Logan Manufacturing Company (LMC) equipment and the test plots were observed for 12 weeks. The processed snow was tested for hardness (strength) using a soil penetrometer, and strength values were correlated to bond density. The temperature distributions in the processed snow were monitored using a thermocouple stack and CR10 datalogger and are correlated to strength increases or decreases. Plane sections of the different plots were taken on a weekly basis and image analyses were performed in order to determine the critical microstructural properties of the snow that contribute to compressive strength increases or decreases as image analysis provides information on volumetric density, surface density per unit volume, etc., and the ability to estimate bonding in snow. Manual volumetric density measurements were also made and are compared to the stereological results. Test results indicate that a powered tiller with a relatively dense tooth population provided the highest strength snow.

Introduction

Although snow runways have been constructed since the advent of World War II, they have principally been suitable only for aircraft equipped with skis due to limitations on the maximum possible snow strength attainable with past and current snow processing techniques. Ski equipped aircraft are severely limited in number and dependence on these imposes limitations on the air delivery systems in Arctic and Antarctic regions. The construction of a functional, compacted snow runway, capable of supporting fully loaded wheeled aircraft (C-130 or C-141), may be required in the vicinity of the South Pole as air delivery is currently under consideration as a possible material delivery system. A snow runway that is capable of supporting wheeled aircraft with a large factor of safety would have a significant impact on the improvement of payload capabilities, as the rolling friction of tires is considerably less than the sliding friction of a large surface area ski, which in turn decreases the required power for take-off velocity. Increasing the payload of aircraft results in significant reductions in transportation costs, as demonstrated by the development of the Pegasus glacial ice runway on the Ross Ice Shelf near McMurdo Station, Antarctica (Blaisdell and Lang, 1994). It is therefore important to identify the optimum method for processing snow such that the resulting compacted snow has attained the maximum compressive strength possible, with the goal of supporting a tire pressure range of 85 psi (Hercules C-130) to 110 psi (Starlifter C-141).

The ideal method for increasing the strength of processed snow would be to minimize the grain sizes, insure an evenly graded snow, and minimize the pore space. Methods of producing small grain sizes in sufficient quantities for runway construction are available. Current available snow processing equipment includes types of equipment originally devised for agricultural applications (e.g., power disc, rototiller, power harrow) and equipment intended for snow removal from highways (e.g., the rotary snowblower). Ski areas have adopted the use of modified agricultural equipment for road making and snow quality improvement during drought periods. Viable snow roads and runways have been constructed (Abele, 1990; Aver'yanov, et al., 1985) but the focus of producing a high strength snow pavement has typically been compaction methods. Binders, such as sawdust, have been added to snow and have improved initial snow strength under certain conditions but ultimately produced a lower strength surface as the surface will deteriorate more rapidly as the sawdust will absorb more of the incoming solar radiation (Lee, et al., 1989; Barber, et al., 1989) and cause melting.

The ambient and snowpack temperatures and temperature gradient will affect the cohesive strength of snow. The cohesive strength dictated by the degree of 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). In the presence of large temperature gradients (and hence concentration gradients), bonds can be destroyed as vapor diffusion removes mass from the bond areas and redeposits the vapor formimg faceted crystals. Additionally, the snow structure itself can inhibit or encourage the propagation of temperature gradients. Obviously, a snowpack with no temperature gradient cannot be continually achieved in the field.

The objective of this project was to use currently available technology to build a series of model test plots and quantitatively analyze snow properties through time, in order to establish an optimized method of processing an evenly graded snow suitable for building robust snow roads and runways in cold regions. Typical field measurement techniques were employed in conjunction with the use of image analysis to examine the snow microstructure.

Image analysis is the science of quantifying and interpreting the data presented in images. It utilizes statistical methods, random sampling of basic parameters, and a variety of algorithms to determine specific attributes. Image analysis techniques have become increasingly more sophisticated and complex in order to meet the demands of modern imaging. The basic premise, however, remains the same, i.e., statistical methods yield estimates of system properties. Many different disciplines use image analysis to study systems by examining their constituent parts. From this, generalizations can be made about the systems as a whole. Image analysis is used in the study of metals to learn about grain size, bonding, densities, sintering, and behavior under applied loads or displacements (Miles and Davies, 1976; Davies and Lundlin, 1979; Davies, 1979; Miles, 1985). The statistical analysis of metals can provide a good correlation to snow and many authors have applied image analysis techniques in determining macroscopic snow properties (Gubler, 1978; Dozier and Davis, 1986; Good, 1986; Hansen and Brown, 1986). Image analysis can be used to study the relationship between snow strength and factors such as temperature gradient, grain size, and bond density. Snow and metals have many things in common: both are made up of small irregularly shaped grains which interact in a variety of ways, both experience sintering, and they each have definite macroscopic properties despite the infinite number of shapes that constitute their microstructure. One of the things that allows image analysis to be a useful tool for analyzing granular solids is that planar sections can be viewed and analyzed, allowing individual particles and their interactions with surrounding particles to be observed. This allows grains and bonds to be viewed together and their interactions documented over time and different temperature ranges.

Once the test plots were established, both field measurements and plane sections for image analysis were taken on a weekly basis. This paper addresses the construction techniques and test results, and then proposes an optimum method for snow road and runway construction and testing based on these results.

Test plot construction

Tests were performed in West Yellowstone MT where the snow properties, altitude and winter ambient temperatures are as analogous as possible to those at the South Pole (and other polar regions) during the austral summer. The test site was the West Yellowstone airport that is closed to air traffic during the winter.

Logan Manufacturing Company (LMC) provided various types of equipment for snow processing to test. Dedicated equipment included a 3700C grooming vehicle equipped with a 12 way blade, two powered tillers with different tooth populations and shapes and a power harrow (see Table 1 for details on implements). Two experienced LMC equipment operators were responsible for the plot construction. Four separate sites (plots) were established using the LMC 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. 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 3 piles, approximately 20-25 m long. These piles were then leveled with the 3700C and allowed to sit undisturbed overnight. The sides of the plots were bulkheaded with unprocessed snow using the 3700C. Finally, most of the preprocessed snow was graded back off of the four plots and the snow was blown back onto the plot in layers. Each layer of snow was then 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 as a control. Downpressure was applied with the 3700C pressure bar that applied a downpressure of 18.83-20.55 kPa (2.73-2.98 psi) with a bearing surface of 7664.5 cm^2 (1188 square inches). 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 time for all 4 plots was approximately 16 hours, which included changing the implements on the 3700C. The plots were then marked with stakes and chalk so that the original surface was easily identifiable for plowing and testing.

Table 1. Parameters for LMC snow processing implements

Implement	**RPM**	**horizontal tooth spacing (in)**	**tooth type**	**tooth population**	**weight (lb)**
Eastern tiller	1356	2.75	3" long battle ax	172	1800
Western tiller	1248	1.71	2.75" long	118	1500
power harrow	620	13.0	11" long U shape blades*	10	2800

*2.5" overlap on blades

Testing methods and results

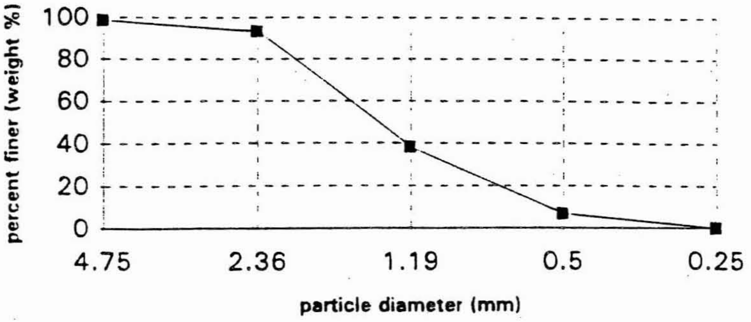
The initial snow surface was tested for grain size and sorting using U.S. Standard soil sieves, density and hardness. Samples were taken for plane sections using an ice coring tool and plane sections were taken from three different horizons. Plane section samples were prepared with dimethylpthalate and a frame grabber was used to digitize the images. Testing and sampling were repeated on a weekly basis for a period of 12 weeks. Thermocouples were installed in each plot at 10 cm intervals extending from the surface to a depth of 80 cm. Snowpack and ambient temperatures were then monitored with

Campbell Scientific CR10 dataloggers with a 60 second sampling rate and half hour averaging.

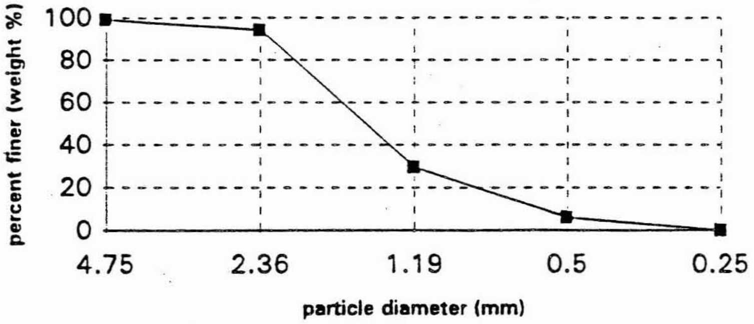
One of the first steps in an engineering approach to the prediction of the behavior for a granular material is to learn what physical characteristics might be used as indices. Two commonly used indices for granular materials such as soils are particle size and sorting. As it would seldom be practical to make precise determinations of the diameters of individual snow particles, fractionation (separation of a sample into fractions of particle sizes) was employed using U.S. Series Sieves. The initial gradation curves from the four snow types are shown in Figure 1. A gentle, even slope indicates good gradation and a steep or broken slope indicates poor gradation. If a granulate 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 compaction. The initial gradation curve from the plot that was processed with the Eastern tiller is the most even although not ideal. The most poorly graded snow results from processing with the rotary blower alone. Some improvement is made by reprocessing with any of the implements, but all curves indicate a lack of fines. Melting of fines could have occurred during agitation of the sieves. It is also noteworthy that the Eastern tiller snow exhibits the smallest 50% grain size. Particle sizes in all of the processed snows range from 4.75 mm to 0.25 mm. Ideally graded soil is defined with particle sizes ranging from 5.00 mm to 0.003 mm.

Snow was tested weekly for hardness (strength) using a U.S. Army Corps of Engineers Waterways Experiment Station (WES) cone penetrometer equipped with a 1.29 cm^2 (0.20 in^2) cone and a proving ring which records a displacement due to the applied load of the user. 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. The proving ring accuracy is limited to a displacement less than 0.25 cm (0.10 in) which corresponds to a strength of 5862 kPa (850 psi). Figure 3 shows the bearing strength envelopes for the plots in the upper 12.5 cm of snow. All four snow types exhibited a marked increase in compressive strength during the first week after construction, followed by a series of fluctuations during the next 10 weeks. The strength decreases correlate strongly with decreasing ambient temperature and increasing temperature gradients in the plots. Similarly, increases in temperature and decreases in temperature gradients are reflected as increases in strength. Deterioration of snow strength under an imposed temperature gradient is a well document phenomenon in natural snowpacks (see, for example, Brown and Edens, 1991). Thermal and concentration diffusion occurs when a temperature gradient is present. Mass is removed from areas of higher vapor pressure, and redeposited in areas of lower vapor pressure. The net vapor flux is in the direction of decreasing temperature, typically the snow-air interface. Also, higher vapor pressures are located at concave surfaces that correspond to bond or neck regions in the snow microstructure. Mass is removed from the bond areas and redeposited, forming faceted crystals. Figure 3 shows the half hour average

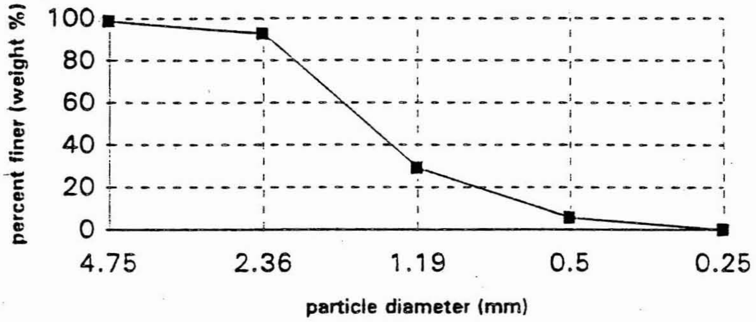
initial gradation curve for the Eastern Tiller processed snow



initial gradation curve for the Western TIller processed snow



initial gradation curve for the Power Harrow processed snow



initial gradation curve for the Rotary Blower processed snow

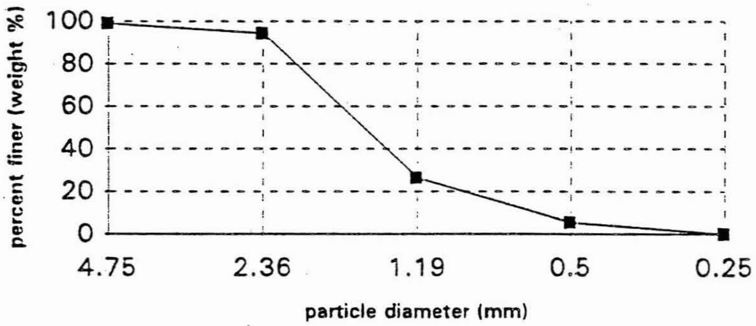


Figure 1. Initial gradation curves for the four test plots. Fines have probably been melted during agitation.

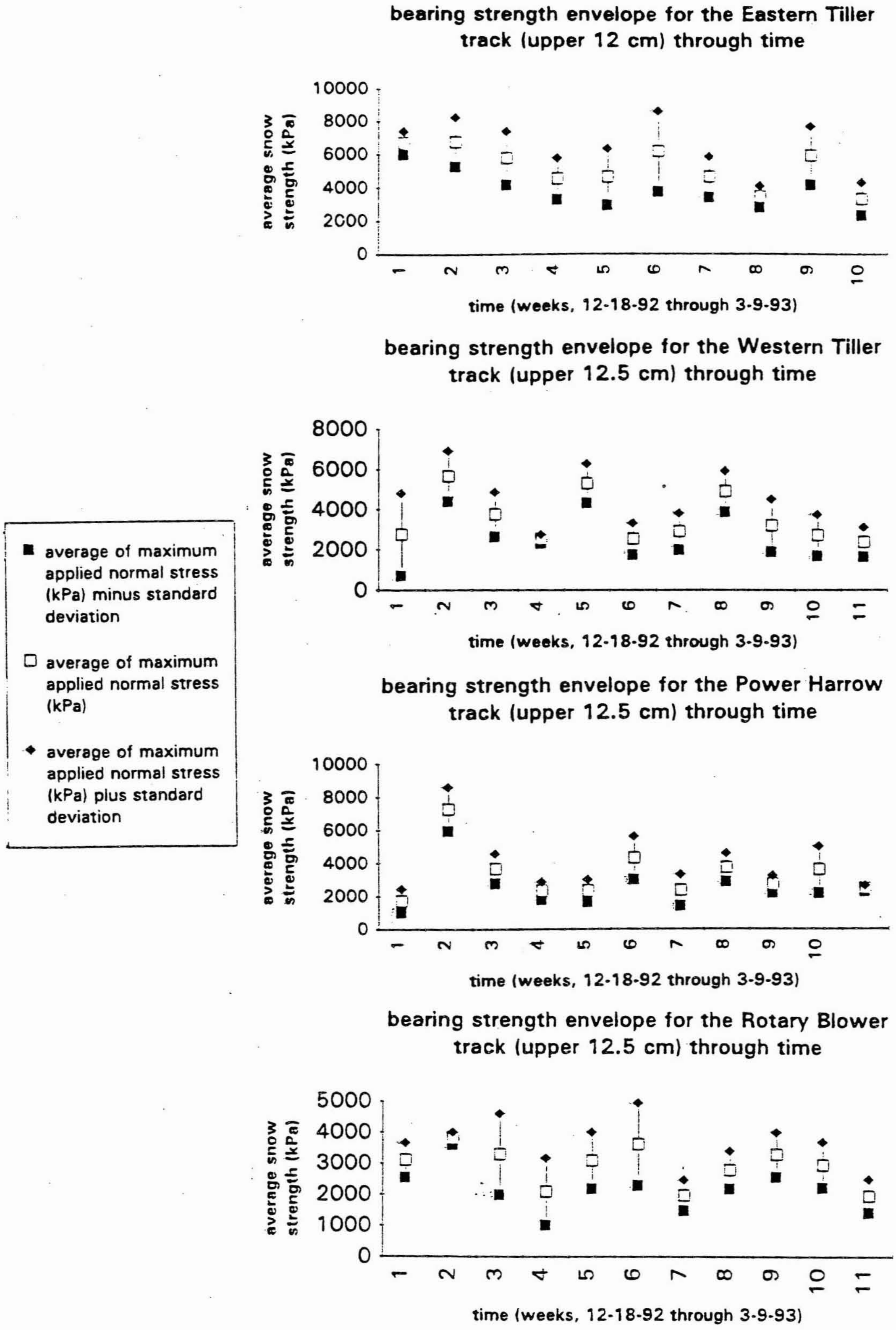


Figure 2. Bearing strength envelopes for the four test plots through time.

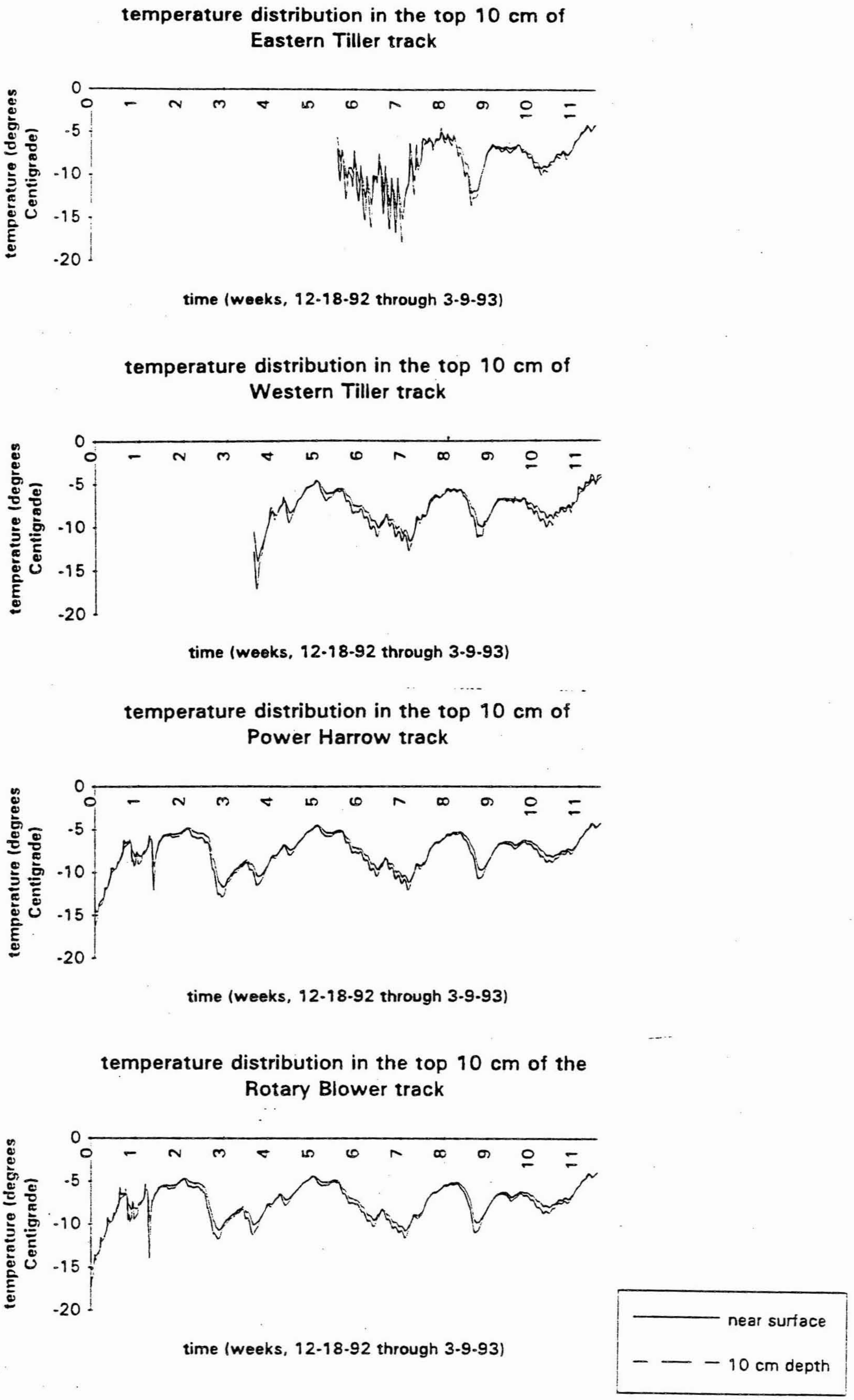


Figure 3. Temperature distribution in the upper horizon (top ten centimeters) in the four test plots. Temperatures were sampled at at rate of 60 seconds and averaged every half hour.

temperatures recorded in the plots near the surface and at the 10 cm depth. A temperature gradient is established in the snow after one week of testing and endures for approximately ten days. As the temperatures increase and the gradient decreases over the next period of time the snow strength seems to return to values near the maximum initial values. Another interval of cold weather follows with a corresponding relapse in strength followed by a return to a warmer pattern and higher strengths. The Eastern tiller demonstrates the highest values in compressive strength with the minimum value being three times higher than the minimum value in the other three plots. However the Eastern plot also displays as much variability as the Rotary blower plot. Strength values in the Western tiller and Power Harrow plots are much more consistent but in some cases three times lower than the Eastern plot. The minimum value of bearing strength recorded in the Eastern tiller, approximately 3000 kPa (435 psi), would provide a large factor of safety for a 100 psi tire requirement.

Plane sections of the different plots were also taken on a weekly basis and image analyses were performed in order to determine the critical microstructural properties of the snow that contribute to compressive strength increases or decreases. It was hoped that the image analyses would provide accurate information on density, surface to volume ratio, etc., and the ability to estimate bonding in snow. These different quantities can be used to determine which properties predict most accurately the strength of a given material, in this case snow.

There are two current limitations to image analysis: 1) the estimation of three-dimensional parameters from two-dimensional images and 2) the development of algorithms for non-convex unconnected particles. For example, are two particles connected above or below the image plane? An optimum technique for estimating three-dimensional attributes from two-dimensional surfaces and attaching regular geometry to irregular systems are currently unresolved topics. There is a recurring question, for example, as to whether or not bonds between grains can be differentiated from the grains themselves. Though some current software does apply an algorithm to estimate the number of bonds, the issue of accuracy is still open to debate.

The strategy is to use image analysis software to obtain three basic and four derived parameters, then use these to form a picture of the snow's microstructure. A primary assumption in image analysis is that the snow images represent isotropic cross-sections of the larger snowmass and that the cross-sectional properties may be extrapolated to the rest of the snow. Isotropy is an adequate approximation for processed snow. The results from the image analysis software that are of primary importance are point density and intercept density. These two quantities form the basis (i.e., are the independent properties) from which many other important quantities related to snow microstructure and metamorphism can be calculated.

Point density, P_p, represents the total number of white pixels in a binary image, and 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. Point density is a dimensionless quantity and is a ratio of (white) pixels to total pixels. The product of P_p with the volumetric density of ice yields a volumetric density for snow. Intercept density, N_L, represents the ratio of snow to pore space and is measured by drawing random test 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 can be calculated:

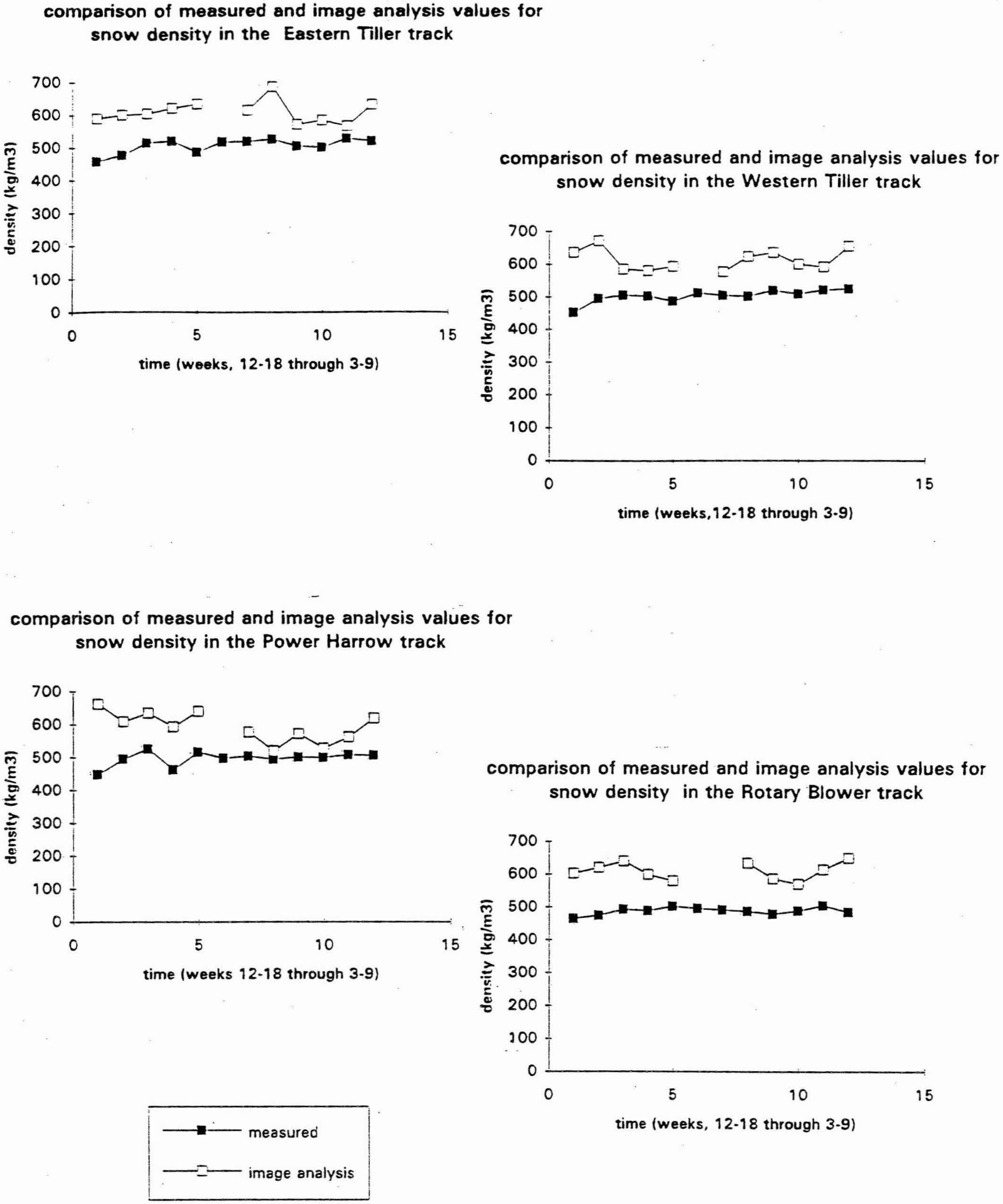
surface density per unit volume $S_v = 2N_L\ [=]\ mm^{-1}$
volumetric density $\rho_s = \rho_i P_p [=]\ kg/m^3$
volume to surface ratio $V_s = P_p / (2N_L)\ [=]\ mm$
mean intercept length $L_3 = 2P_p / N_L\ [=]\ mm$

(Dozier, et al., 1986). Surface density per unit volume (S_v) should increase if the snow structure is thermally equilibrated, i.e., well-rounded grains and bonds are developing. If a temperature gradient is present and the desirable structure is deteriorating into the faceted, unbonded crystals, S_v should decrease. Volume to 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 to surface ratio are dependent on the values of surface density per unit volume and volumetric density, it should be sufficient to examine these two independent quantities in addition to the bond density.

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

Volumetric density is an index property of granular materials. Density is an index of compressibility, as a material with a large magnitude of void volume is much more compressible than a material with minimum interparticle voids. Manual density measurements were made and compared to the stereological results. The results are depicted in Figure 4. Errors in the manual density measurements can be attributed to the difficulty in obtaining a consistent sample size from the hard, dense snow. The density predictions from the analyses contain error due to the extrapolation of a volumetric property from a surface image. Most likely, the actual value for density lies in between the two values. The density measurements provided by image analysis appears to provide a better correlation with the measured bearing strength.

Bond density is a measure of the connectedness of the snow grains. Neither software program was able to calculate bond density. However, bond density should be directly related to the intercept density. Bond surface densities were obtained by



comparison of measured and image analysis values for snow density in the Eastern Tiller track

comparison of measured and image analysis values for snow density in the Western Tiller track

comparison of measured and image analysis values for snow density in the Power Harrow track

comparison of measured and image analysis values for snow density in the Rotary Blower track

Figure 4. Comparison of field measured volumetric densities to calculated volumetric density from the image analyses.

examining the images and manually counting the number of bonds in the entire sample and dividing by the total surface area of the image. Bond counts were performed and agreed upon by three of the authors. A comparison of the bond densities from the four plots is shown in Figure 5. The bond density counts again indicate that the Eastern tiller was able to manufacture the most suitable snow for bonding ability and hence highest bearing strength. Figure 6 compares the measured strengths calculated from the penetrometer readings and bond density through time for each test plot. The results indicate a very good correlation between strength and bond count fluctuations. On comparing bond density to volumetric density from the image analyses in Figure 7 one observes that in some cases, increases in volumetric density correspond to decreases in bond density, such that no strong correlation between these two quantities is evident, although volumetric density should reflect changes in surface density. As an index property, it is likely that volumetric density reflects the internal friction of the snow and certainly bond density indicates the value of cohesion. Upon application of an external load, loss of cohesion or bond breakage would occur prior to the load being supported by interparticle contact. If plotted 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, equitemperature snow to snow that has undergone temperature gradient metamorphism to some degree. Figure 8 shows the analytical results of S_V for the four test plots. The changes in surface density reflect the changes in bond density in Figure 5. In order to better illustrate this, Figure 9 depicts both the bond density and surface density through time for the Eastern tiller plot.

Simply examining the snow microstructure from the digitized images does provide information on the expected macroscopic behavior. A series of images from the Eastern tiller plot is shown in Figure 10. Transition from a desirable system of well-rounded grains with bonds to faceted crystals is not apparent to any degree, although the periods of time during which the snow was subjected to a temperature gradient are substantiated by slight changes in grain structure. Pore space seems to elongate in the vertical direction, but bonds and grain structure are not significantly deteriorating. A uniform, high density snow should inhibit vapor transport within the snow and the digitized images tend to support this.

Conclusions and recommendations

Based on the test results, a powered tiller with an "Eastern", or relatively dense tooth population provides the most evenly graded and strongest snow. The Eastern tiller also performs at the greatest (angular) velocity. Initial snow densities could be further increased by processing the snow more than once with the implement and the application

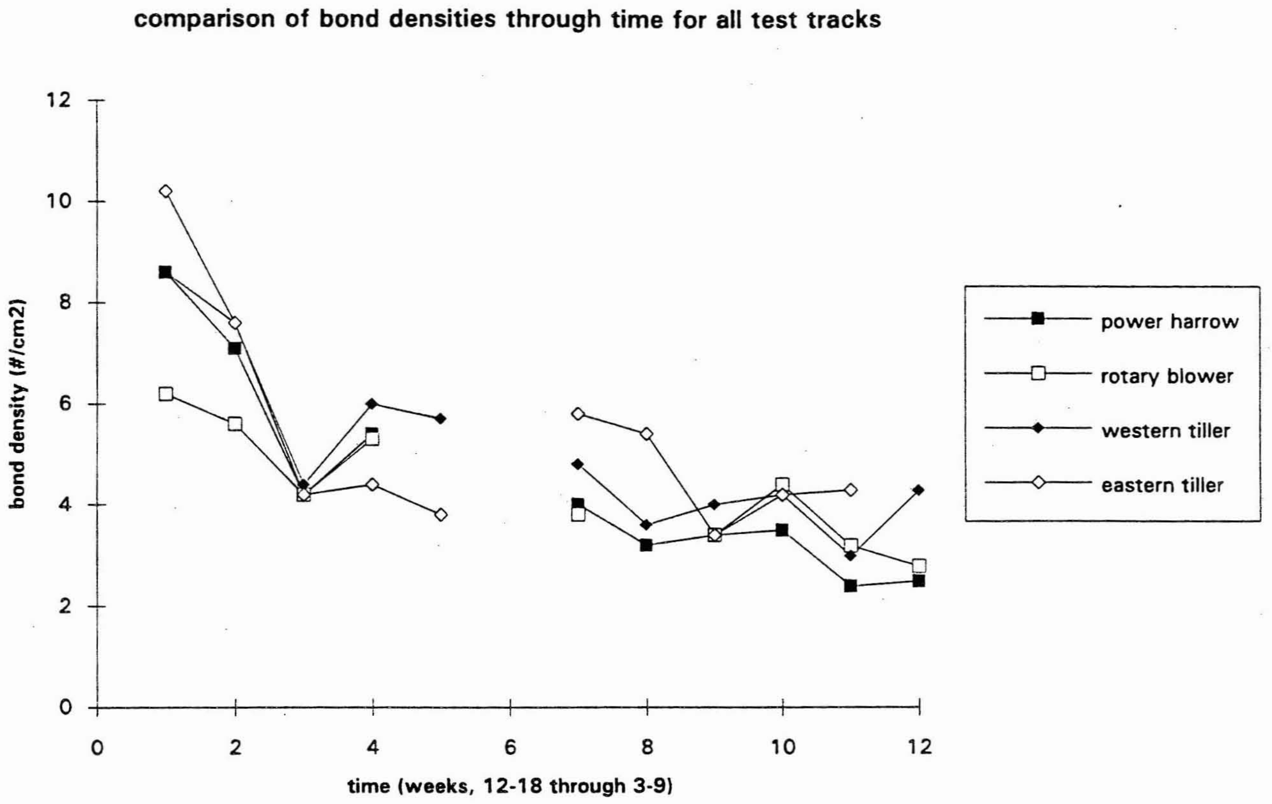
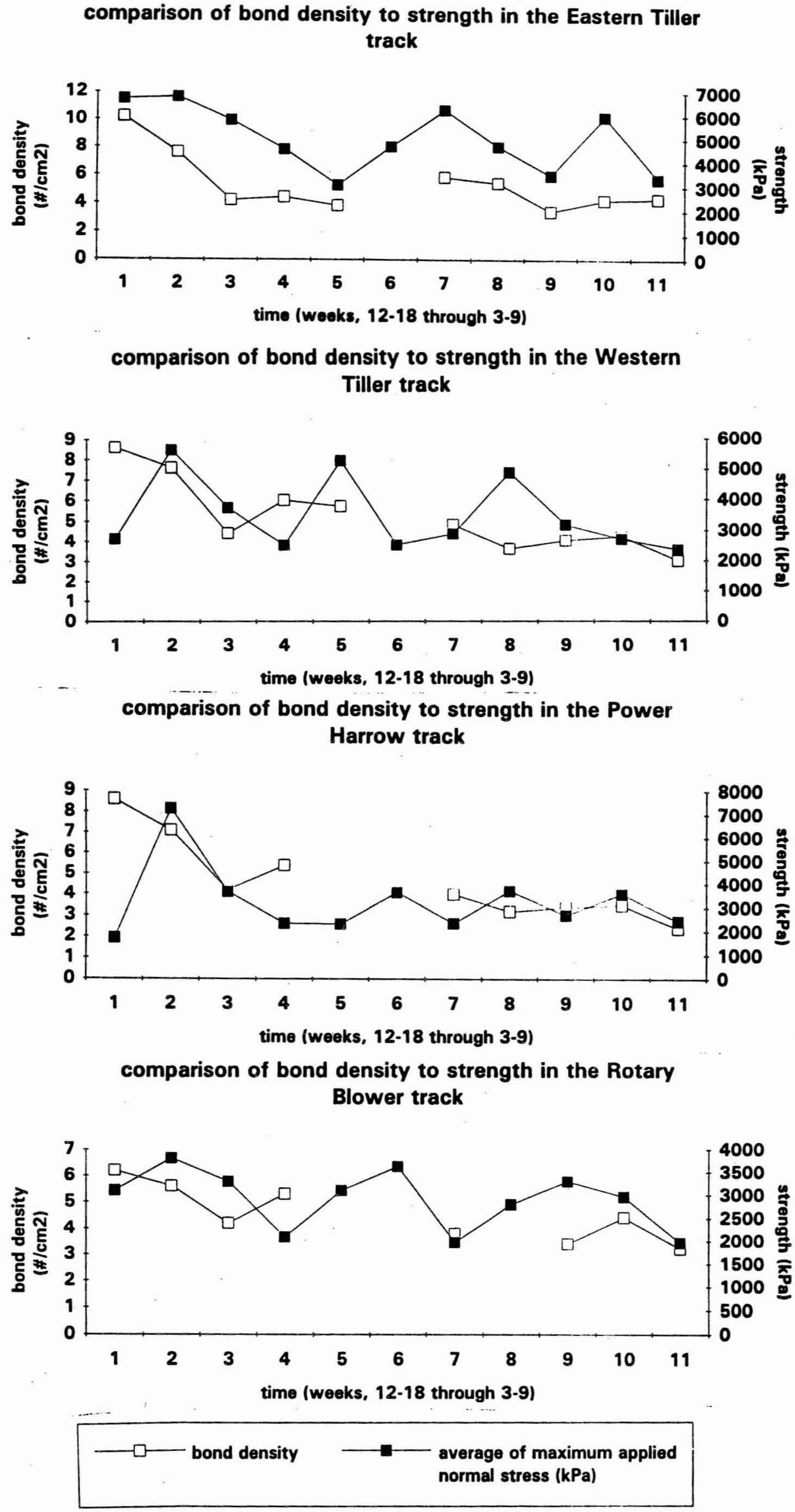


Figure 5. Comparison of bond density through time for all test plots

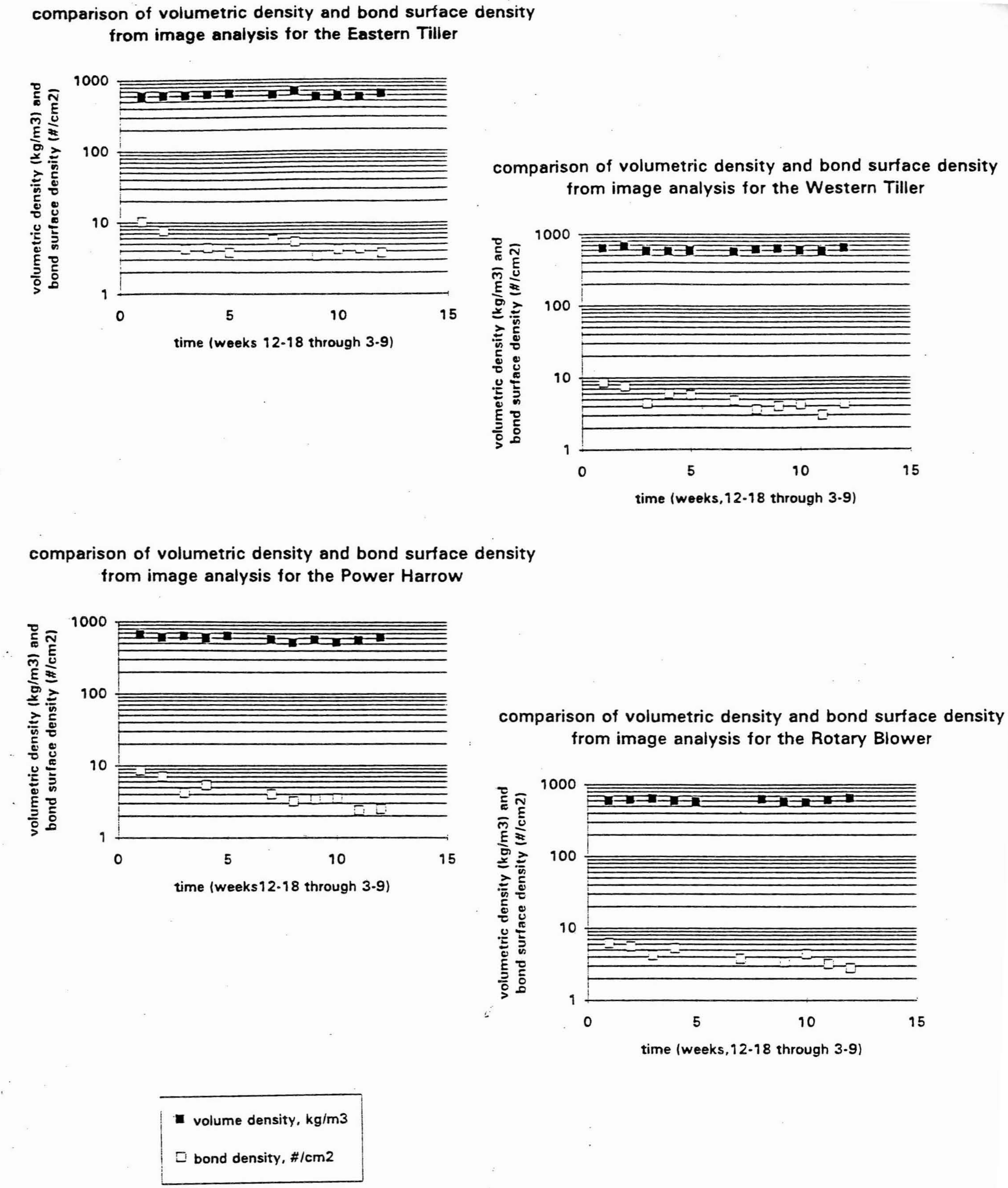

comparison of bond density to strength in the Eastern Tiller track

comparison of bond density to strength in the Western Tiller track

comparison of bond density to strength in the Power Harrow track

comparison of bond density to strength in the Rotary Blower track

Figure 6. Comparison of measured strength to bond density through time for all test plots.



comparison of volumetric density and bond surface density from image analysis for the Eastern Tiller

comparison of volumetric density and bond surface density from image analysis for the Western Tiller

comparison of volumetric density and bond surface density from image analysis for the Power Harrow

comparison of volumetric density and bond surface density from image analysis for the Rotary Blower

Figure 7. Comparison of bond density to volumetric density through time for all test plots.

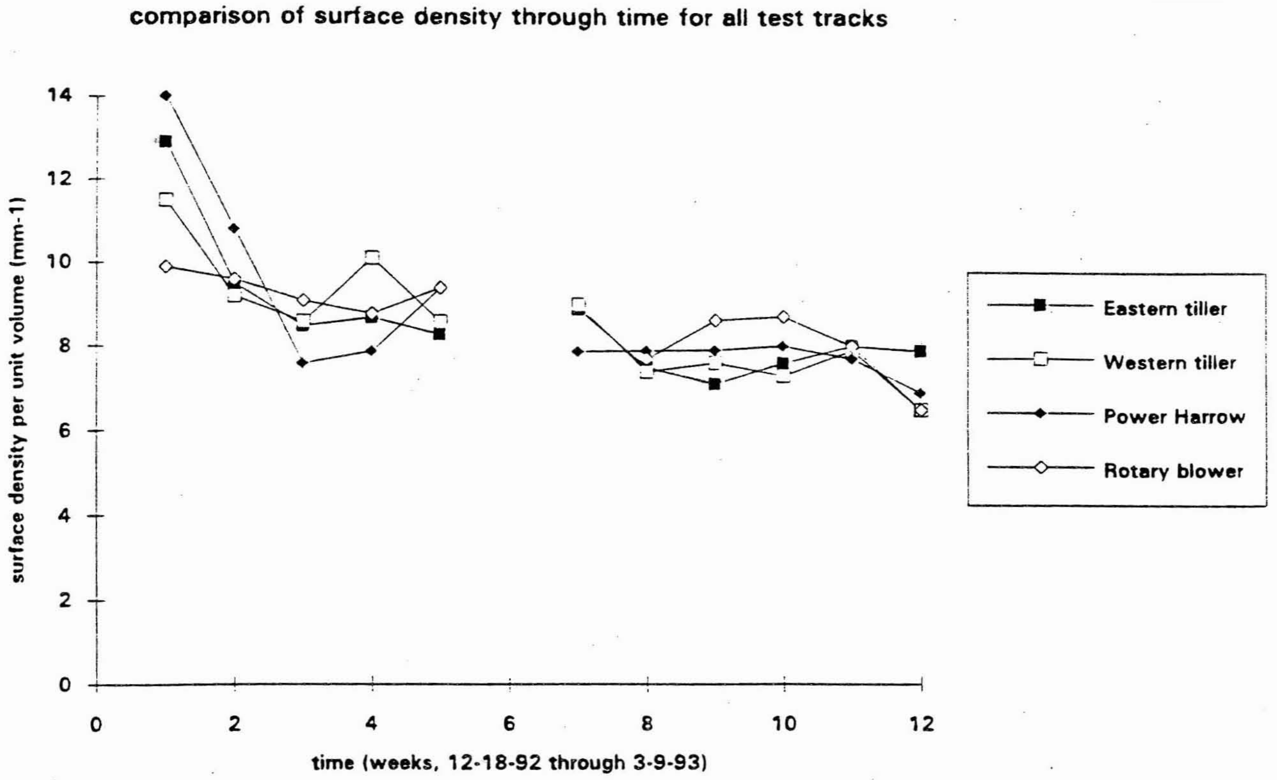


Figure 8. Image analyses results of surface density, S_V, through time for all test plots.

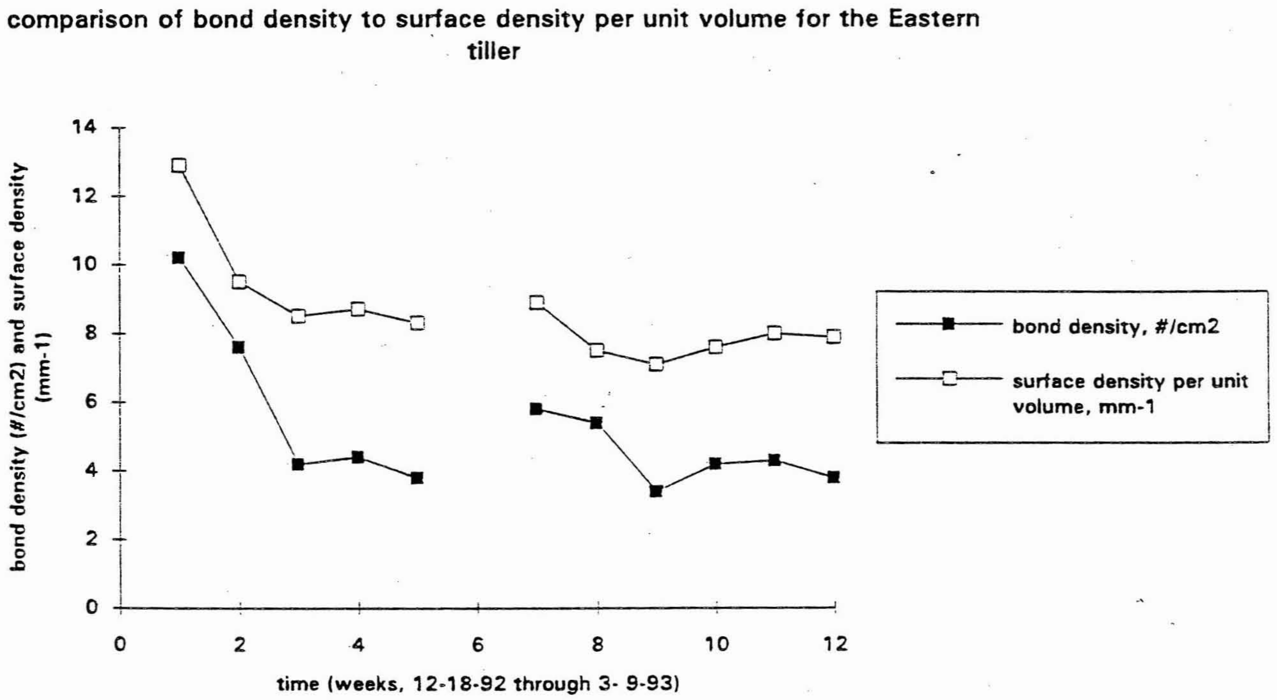


Figure 9. Comparison of bond density to surface density through time

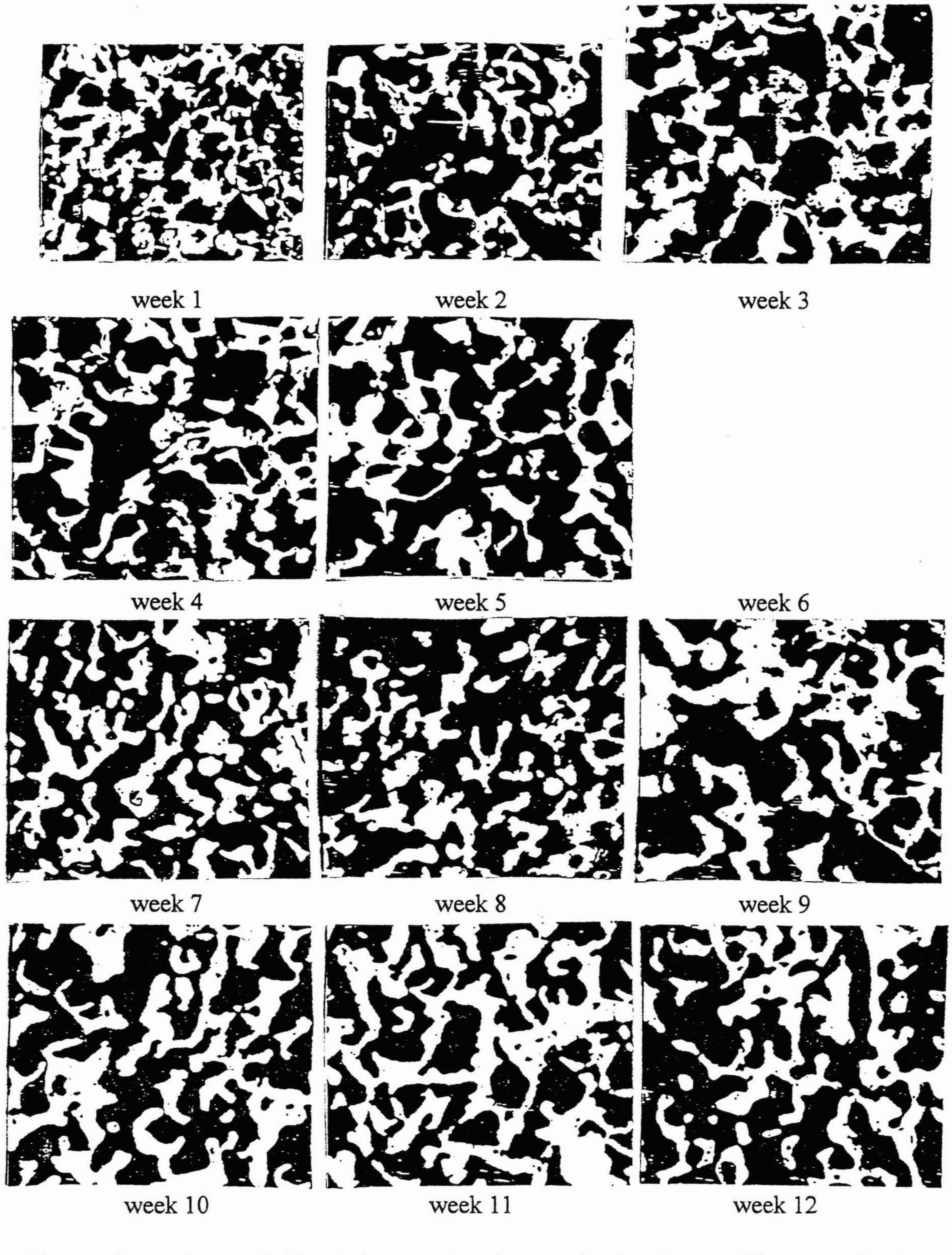


Figure 10. Series of digitized plane section images for the Eastern tiller upper horizon (upper 12.5 cm). Horizontal scale is 1.25cm = 1mm, vertical scale is reduced by 83.7%. Some images have been cropped.

of a higher downpressure during construction, as long as the plot is laterally supported to disallow spreading of the snowmass. Overprocessing is to be avoided as contamination of the snow by hydraulic fluids and motor oil could occur. This would result in a condition known as "swim snow", a disaggregate snow that is unable to bond due to the presence of hydrocarbons.

It is possible to perform simple field tests and obtain a sufficient amount of information on snow strength based on index properties. Fractionation of the snow and the construction of initial gradation curve is a simple technique employed by construction engineers on subgrade soils. It provides an estimate on the compressibility of the granulate a priori. 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. The use of a penetrometer also provides instant strength information in the field. However, prior to opening a road or runway for operation, it would be advised to perform compression tests on snow samples. Small, portable load frames are available for this purpose. Compressive strength tests would yield a better indication on the factor of safety for flight operations on a runway or for moving heavy equipment on a road..

Image analysis, although of scientific interest, does not yet appear to be a useful tool in predicting the strength characteristics of snow in a timely fashion that would be requisite for an engineering application such as snow road and runway construction. The immediate drawbacks are:

1) An inordinate amount of time is required to sample and construct the plane sections. It is important that the technician is well-trained in preparing the samples for digitization or an unusable image will result.

2) Digitizing, preprocessing, processing and postprocessing an image is too time consuming for the amount of information that results from the analyses. The image analysis software requires a workstation environment and is not very user-friendly, which makes it unsuitable for field work in remote areas where computer access is limited. If the image is digitized and preprocessed on a PC, the image must be transferred to a workstation or mainframe environment for processing. The results of the analyses must then again be transferred to a spread sheet environment for statistical and graphical analysis, and in our case, had to be retyped into the PC environment.

3) Although the image analyses did provide 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 as bond density is a measure of the cohesion in snow (see Lang and Harrison, 1994).

It is important to monitor the temperature distribution in the snow road or runway as temperature gradients do accomplish a deterioration in the surface bearing strength.

An enduring temperature gradient should be accompanied by diligent retesting of the compressive strength of the snow.

The immediate application of the results of this research is improved methodology in constructing a functional, compacted snow runways capable of supporting fully loaded wheeled aircraft. Air delivery by wheeled aircraft is the most logical choice for a material delivery system at the South Pole as compressive snow strengths more than four times the required strength can be achieved with snow processing techniques. The results of this study should also aid in the construction of good quality, robust snow roads for ski areas, construction and military use in Alaska and other northern and polar regions.

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References

ABELE, G., 1990 Snow roads and runways. *U.S. Army CRREL Monograph*, no.90-3, 100 p.

AVER'YANOV, V.G., ET AL., 1985 Construction of snow airstrips for wheeled aircraft in the Antarctic. *Polar Geog. And Geol.*, Vol. 9, pp.37-44.

BARBER, M.J., LEE, S.M., AND BROWN, R.L., 1989 Binders for snow roads and runways in Antarctica, *J. of Cold Regions Eng.*, vol.3, pp.84-96.

BROWN, R.L. AND EDENS, M.Q. 1991 On the relationship between neck length and bond radius during compression of snow. *J. Glac.*, Vol. 37(26) pp 203-208.

DAVIES, D.L., AND LUNDLIN, C.D., 1979 Area fraction analysis of multiphase metal systems using a digital segmentation technique. *Microstructural Sci.*, Vol. 7, pp 433-436.

DAVIES, D.L., 1979 Digital analysis of oriented structures using the method of the gradient rose. *Microstructural Sci.*, Vol. 7, pp 437-444.

DOZIER, J. AND DAVIS, R.E., 1986 On the objective analysis of snow microstructure. *IAHS Pub. no.162*, pp 49-57.

GOOD, W. , 1986 Thin sections, serial cuts and 3-D analysis of snow. *IAHS Pub. no.162*, pp 35-48.

GUBLER, H. 1978. Determination of the mean number of bonds per snow grain and of the dependence of the tensile strength of snow on stereological parameters. *J. of Glaciol.*, Vol. 20(83) pp 329-341.

HANSEN, A.C. AND BROWN, R.L. 1986 The granular structure of snow: an internal state variable approach. *J. Glaciol.*, Vol. 32(112). pp 434-439.

LANG, R.M. AND HARRISON, W.L. 1994 Triaxial tests on dry, naturally occurring snow. *Cold Regions Sci. and Tech.*, (in press)

MILES, R.E., AND DAVIES, P., 1976 Precise and general conditions for the validity of a comprehensive set of stereological fundamental formulae. *J. of Microscopy*, Vol.107, pp 211-226.

MILES, R.E., 1985 A comprehensive set of stereological formulae for embedded aggregates of not-necessarily-convex particles. *J. of Microscopy*, Vol.138, pp 115-125.

RHINES, F.N., 1980 Use of the global and topological parameters in microstructure-property correlation. *Microstructural Sci.,* Vol. 8, pp 123-139.

YONG, R.N., AND FUKUE, M. 1977 Performance of snow in confined compression. *J. Terramechanics*, 14(2), 59-82.