SNOW ROAD CONSTRUCTION

A THESIS
SUBMITTED TO THE
FACULTY OF GRADUATE STUDIES
UNIVERSITY OF MANITOBA
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE MASTER OF SCIENCE IN CIVIL ENGINEERING

by

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Winnipeg, Manitoba
December 1976

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A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

This study investigates the application of snow in the construction of snow roads and the suitability of the snow road as a transportation facility. The snow properties are reviewed and the current status of snow road technology is identified. In the field studies, where variations in snow road construction procedures are evaluated, a conventional snow blower is utilized as a snow processing implement. The results indicate that an equidimensional particle size is produced with no significant change occuring in either the particle size or distribution with repeated processing. The results further identify the operational difficulties in handling blower-processed snow during snow road construction. Increasing the snow road density by introduction of free moisture into the pore spaces, through surface heat application, is also investigated. For this purpose a prototype wood-fired heater is utilized. The test results give promising indication that this method of surface heat application, in combination with heavy compaction, could have considerable practical merit. The snow road strength is indicated in terms of snow 'hardness' determined by the Rammsonde cone penetrometer. The conventional Rammsonde hardness equation is re-evaluated and the hardness index is correlated to snow temperature.

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation and gratitude to Dr. K.M. Adam for his guidance and assistance in the preparation of this thesis and for his generous and unstinting help during all phases of the degree program. Sincere appreciation is also extended to the members of the thesis examination committee, Dr. J. Graham and Dr. G.E. Laliberte, for their invaluable suggestions.

I give full acknowledgement of my indebtedness to the University of Manitoba Maintenance Department for making available, on a rental basis, the necessary equipment and personnel, and to the National Research Council of Canada who provided financial support for the project. I also gratefully acknowledge the personal sources of assistance which during the course of the degree program included: a University of Manitoba Graduate Research Assistantship, a University of Manitoba Graduate Fellowship, and a National Research Council Post-graduate Scholarship.

To Ms. Janet Gourlay, I extend my warmest thanks for doing a fine job in typing this manuscript and for offering timely editorial advice.

Finally, I wish to express my deepest gratitude to my parents for instilling in me the value of education that has guided my endeavours.

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LIST OF SYMBOLS

Symbol		Dimensions†
A	Empirical constant in strain-rate equation	none
a	Subscript indicating "air"	none
a	Subscript indicating "apparent"	none
a	Empirical constant in equation for hydraulic conductivity	none
b	Empirical constant in creep-rate equation	none
b	Subscript indicating "bubbling"	none
C	Hydraulic conductivity	L/t
C	Specific heat capacity	H/MT
C	Vapour concentration	M/L^3
C	Volumetric heat capacity	H/L^3T
C	Correction factor for effective conductivity	none
c	Subscript indicating "critical saturation"	none
c	Coefficient of cohesion	F/L^2
c	Subscript indicating "capillary"	none
D	Diffusivity	L^2/T
d	Grain diameter	L
E	Young's Modulus	F/L^2
e	Subscript indicating "effective"	none
e	Coefficient of restitution	none
e	Efficiency	none
g	Gravitational acceleration	L/t^2
H	Vertical distance	L
i	A counting integer	none

LIST OF SYMBOLS (cont'd)

Symbol		Dimensions†
i	Subscript indicating "ice"	none
K	Thermal conductivity	H/LTt
k	Permeability	L^2
k	A measure of confidence in units of "number of standard deviations"	
L	Latent heat of fusion	H/M
L	Characteristic length	L
l	Subscript indicating "liquid"	none
m	Mass	M
N	Empirical constant in equation for hydraulic conductivity	none
n	A counting integer	none
o	Subscript indicating "saturated"	none
P	Pressure	F/L^2
p	Subscript indicating "constant pressure"	none
Q	Weight of cone penetrometer	F
q	Intensity of evaporation or condensation	M/L^3t
q	Heat flux	H/L^2t
R	Rammsonde hardness number	F
r	Correlation coefficient	none
r	Subscript indicating "relative permeability"	none
r	Subscript indicating "residual"	none
S	Saturation	none
S	Penetration	L
s	Subscript indicating "solid"	none

LIST OF SYMBOLS (cont'd)

Symbol		Dimensions†
s	Subscript indicating "snow"	none
s	Specific surface	L^2/L^3
s	Shear strength	F/L^2
T	Temperature	T
T	Detector resolution time	t
t	Time	t
V	Velocity	L/t
W	Weight	F
w	Subscript indicating "wetting phase"	none
x	Cone penetration	L
x	Spatial coordinate	L
z	Spatial coordinate	L
α	Thermal diffusivity	L^2/t
γ	Weight density	F/L^3
Δ	Denotes a difference	none
ε	Exponent in relative permeability equation	none
$\dot{\varepsilon}$	Strain-rate	t^{-1}
θ	Volumetric water content	L^3/L^3
λ	Pore-size distribution index; $-d(\log S_e)/d(\log P_c)$	none
μ	Dynamic viscosity	Ft/L^2
ν	Poisson's ratio	L/L
ρ	Mass density	M/L^3
Σ	Summation	none

LIST OF SYMBOLS (cont'd)

Symbol		Dimensions†
σ	Stress	F/L^2
ϕ	Porosity	none
ϕ	Angle of shearing resistance	none
∇	Gradient operator	$1/L$
div	Divergence operator	$1/L$
*	Superscript indicating resultant of surface and body forces	none

† Fundamental dimensions:
force ....F
heat ....H
length L
mass ....M
temperature ....T
time ....t

CHAPTER I

INTRODUCTION

With increasing oil and gas exploration and the subsequent interest generated by this activity in Canada's North, the potential damage resulting from the movement of goods and machines becomes increasingly important. In particular, consideration of a Northern pipeline development has brought to the forefront a recognition of many multi-disciplinary problems.

The studies by Adam [1,2] point out the applicability of snow roads and ice-capped snow roads in the transportation of men and materials during winter pipeline construction. The studies also indicate that while the idea of compacting snow as a means of improving oversnow trafficability is extremely old, the procedure for constructing snow pavements capable of carrying heavy wheeled traffic, is not well established. This is partly due to the fact that in the past no apparent standard for the identification and treatment of the snow properties has been followed and that the existing information, though extensive, is widely dispersed.

In Chapter II and III of this study, pertinent facts are "pooled" to form a single comprehensive review. The review includes discussion of the porous characteristics and the thermodynamic and mechanical behaviour of snow. A procedural guide for the field identification of the index properties is also presented. Chapter III is a summary of the snow road construction experience where construction equipment, procedures and results are discussed.

Previous studies indicate that snow compaction alone will not produce the strength required of snow roads subjected to intensive wheeled traffic. Disaggregation, milling and mixing of the snow (prior to final grading and compaction), to produce a more non-uniform particle-size distribution becomes necessary. For this purpose, modified agricultural earth tillers and special pulvimixers have been used, but with varied success. In this study, the conventional snow blower is evaluated as a snow processing implement and the significance of multiple processing is determined.

The ice-capped snow road is a processed and compacted snowbed with water applied to the surface to increase the road density and strength. Although this class of winter road offers some significant advantages, its use may be seriously limited in permafrost regions where the large quantities of fresh water required may not be available. The feasibility of utilizing a portable wood-fired surface heater to produce the free water is investigated as an alternative to the direct water application method. The wood burner would have the dual advantage of utilizing right-of-way slash material as fuel , and at the same time provide a facility for the disposal of the waste material.

CHAPTER II

SNOW AS A MATERIAL

Snow is a porous medium composed of ice crystals and/or aggregates of ice grains. The pore spaces contain air, and water vapour and,in the case of "wet" snow, liquid water as well. Thus the snow pack forms a heterogeneous system which exhibits a complex and continuous interaction between the phases.

In this chapter, the properties of snow and the processes that occur due to the thermodynamic instability of snow are reviewed. The review cites pertinent theory and includes qualitative explanation of governing principles and terminology.

A. SNOW METAMORPHISM

Destructive Metamorphism

After the deposition of fresh snow, very local transformations, called destructive or isothermal metamorphism, are first observed. During this process the sharp points of the branches of individual snow flakes become blunt. This is achieved partly by evaporation due to the higher vapour pressures associated with small radii of curvature, and partly by the migration of molecules in the quasi-liquid surface layer (Bader [6]). The crystals become rounded and the larger spheres then grow at the expense of the smaller ones exclusively by vapour transfer. After a few days, crystal shape is almost completely lost. Each grain is a single crystal ranging from 0.5 to 1 mm in size with only one or two small crystallographic faces. The grains are weakly bonded and the density of this finegrained snow usually ranges from 0.15 to 0.25 gm/cm^3.

Constructive Metamorphism

Following the original deposition of snow, a temperature gradient through the snow cover develops (colder at the top than at the bottom), and constructive or gradient metamorphism sets in. Constructive metamorphism involves heat and mass transfer and is characterized by growth of selected crystals; decrease of crystal number per unit bulk volume; and development of crystallographic faces, edges and vertices (de Quervain [18]). In dry snow, the mass transfer occurs primarily over the vapour phase by diffusion and,owing to the temperature gradient, is accelerated by convective air flow in the pore spaces.

At low snow densities (below 0.3 gm/cm^3), constructive metamorphism is very rapid and results in production of a distinctive snow type known as "depth hoar". Here grain size is between 2 and 8 mm and single crystals as large as 15 mm have been observed (Bader [2]). Depth hoar exhibits very poor bonding, and has a high viscosity. It is the major cause of avalanching and is most difficult to compact to a hard snow pavement.

Melt Metamorphism

Melt metamorphism characterizes the changes produced in snow by the presence of liquid water. As the weather becomes warmer, and the snow becomes moist, temperature gradients and their effect vanish (Yen [44]). Crystallographic elements also quickly vanish due to the high surface tension of the water film covering all the grains. Thus crystals become rounded and clusters of grains coalesce to form larger polycrystalline grains. As meltwater percolates through the snow, crystals grow to a maximum size of about 3 mm and composite grains to about 15 mm. The bonding between the grains is very weak and within a few days, the well known "rotten" snow of the thaw season is produced. Upon refreezing however, the wet snow aquires a high strength due to the growth in bond area.

Due to the inhomogeniety of the snow pack, the percolating meltwater is not equally distributed in all the layers. Some layers retain very little water while others absorb water almost to saturation which convert to dense ice lenses on refreezing.

Pressure Metamorphism

Pressure metamorphism characterizes the densification of dry nevé (granulated snow accumulated and subsequently compacted to glacier ice). This process is very slow and may take several decades to change snow of density 0.45 gm/cm^3 to ice of density 0.83 gm/cm^3. (At the density of 0.83 gm/cm^3, air permeability decreases to zero and the snow changes to ice by definition. Pure ice has a density of 0.917 gm/cm^3). During this period of slow change, grain and grain-bond growth by vapour or surface migration appears to be of secondary importance (Bader [6]). The densification is apparently dominated by processes of mechanical deformation under pressure.

At the surface of the snow pack, hard crusts generally form.

Bader [6] attributes crust formation to: refreezing of surface layers previously wetted by thaw, rainfall or wet fog fall-out, surface condensation from moist air, wind packing, and vapour migration from lower snow layers.

B. SNOW AS A POROUS MEDIUM

The parameters predominantly used to describe porous media systems are porosity, the pore-size distribution, and the relationships between capillary pressure and the permeability and saturation of the fluid phases. In treating snow systems (wet or dry), complications arise due to the inherent thermodynamic instability of snow. As evidenced earlier in the discussion of snow metamorphism the physical properties of snow are very strongly time and temperature dependent. Phase equilibrium and thermal complications prevent extensive experimental analysis of the parameters.

Porosity

Porosity is the ratio of volume of voids to the snow bulk volume. It is calculated from the measured snow density using the following relationship;

$$\phi = \frac{\rho_i - \rho_s}{\rho_i} = \frac{0.917 - \rho_s}{0.917} = 1 - 1.090\ \rho_s \qquad (2.1)$$

where

ϕ = porosity (sometimes called "absolute" porosity),

ρ_i = density of pure ice = 0.917 gm/cm^3,

ρ_s = density of snow, gm/cm^3.

The term "absolute" porosity is used when dealing with high-density snow (above 0.7 gm/cm^3) and is distinguished from "relative porosity" which refers to the volume of communicating pores only. Apparently at densities greater than 0.7 gm/cm^3, the volume of the isolated pores becomes significant. The relative and absolute porosities are approximately equal for low and medium density snow. No measurement of relative porosity of high-density snow was found in the review of pertinent literature.

Pore-Size Distribution

The hydraulic behaviour of a porous medium is affected by the porosity and the distribution of pore-sizes from point to point in the pore space. The pore-size distribution index, λ, is derived from a log-log plot of effective saturation S_e, versus capillary pressure head expressed as $P_c/\rho g$, (Laliberte [25]). The negative slope of the straight line portion of the curve represents the pore-size distribution index, λ. Qualitatively, the larger the index the more uniform is the pore-size distribution. Capillary pressure for the air-water system is defined as the pressure difference across the interface of the two immiscible fluids, given as

$$P_c = P_a - P_w \tag{2.2}$$

where

P_c = capillary pressure, dynes/cm^2, and

P_a, P_w = pressure of the air and water phases respectively, dynes/cm^2.

Effective saturation, S_e, is defined by;

$$S_e = \frac{S - S_r}{1 - S_r} \tag{2.3}$$

where

S = saturation, (volume of water expressed as a decimal fraction of the volume of voids), and

S_r = residual saturation, (saturation corresponding to a capillary pressure at which the saturation decreases very little with large increases in capillary pressure).

Friesen [22] obtained values of λ ranging from 6.2 to 9.9 for snow densities between 0.40 and 0.48 gm/cm^3. Colbeck (noted by Adam and Wilson [3]) obtained $\lambda = 4.9$ for snow densities of 0.55 and 0.59 gm/cm^3. Laliberte [25] indicates a pore-size distribution index of 7.3 for glass beads (uniform pore size) and 3.7 for a fine sand.

Bubbling Pressure

The bubbling pressure head, $P_b/\rho g$, is defined as the intercept of the straight line in the log-log plot of S_e versus $P_c/\rho g$, (Laliberte [25]). The bubbling pressure is a function of the largest continuous pores of the porous medium and is normally very close to the minimum capillary pressure head where the nonwetting fluid permeability can be measured during drainage. The lower the bubbling pressure, the larger are the continuous pores in the porous medium.

Colbeck (noted by Adam and Wilson [3]) obtained a bubbling pressure head of 5 cm for a snow-kerosene system and 3.7 cm for a snow-water system. Friesen [22] estimated a bubbling pressure head of 8 cm and 9 cm for snow densities of 0.48 gm/cm^3 and 0.40 gm/cm^3 respectively, in snow-soltrol C[*] systems.

Saturated Permeability and Conductivity

Fluid permeability is one of the basic quantities that describe the physical properties of a porous medium . Saturated "permeability" is distinguished from saturated "conductivity" the former being a quantity dependent on the porous matrix and the latter being a quantity dependent on the porous matrix and the fluid.

The relationship between volume flux and conductivity (for stable porous materials fully saturated with one liquid at a constant temperature) was discovered experimentally by D'Arcy. A popular form of the Darcy equation for one-dimensional flow is:

$$q = -C \frac{\Delta\left(\frac{p^*}{\rho g}\right)}{L} \tag{2.4}$$

where

C = conductivity, cm/sec ,

p^* = piezometric potential, dynes/cm^2 (represents the resultant of the normal surface and body forces per unit volume acting on a volume element in a fluid of uniform density and has dimensions of energy per unit volume),

ρg = specific weight, dynes/cm^3,

$\frac{p^*}{\rho g}$ = piezometric head, cm ,

L = length over which the incremental change in piezometric head occurs in the direction of flow, cm , and

---

[*] Soltrol C is a light hydrocarbon oil.

q = volume flux, cm/sec (the component of the volume of discharge per unit time per unit of bulk area in the direction L).

The Darcy equation re-written in terms of permeability becomes

$$q = -\frac{K\ \Delta p^*}{\mu\ L} \qquad (2.5)$$

where

μ = dynamic viscosity of the fluid, $\frac{\text{dyne-sec}}{\text{cm}^2}$, and

K = permeability, cm^2.

The coefficients C and K are related by

$$C = K\,\frac{\rho g}{\mu}. \qquad (2.6)$$

Calculations of permeability and conductivity based on structural parameters have been proposed by various authors. The Kozeny-Carman equation (Laliberte [25]) approximates the saturated permeability of a porous medium with uniform pore size and low eccentricity:

$$K_{ow} = \frac{\phi^3}{5s^2} \qquad (2.7)$$

where

K_{ow} = saturated permeability, cm^2 (permeability of the wetting phase at saturation $S = 1$),

ϕ = porosity, dimensionless, and

s = specific surface, cm^2/cm^3, (ratio of the surface area of solid pore boundaries to the bulk volume of the medium).

The equation yields poor approximations, however, for media exhibiting secondary porosity. Although snow usually possesses a small range of pore size, it exhibits some secondary porosity or structure.

Shimizu (Colbeck [11]) related the saturated permeability of snow to grain size and density by:

$$K_{ow} = 7.7 \times 10^{-4} d^2 \exp(-7.8 \times 10^{-3} \rho_s) \qquad (2.8)$$

where

d = grain diameter, cm , and

ρ_s = snow density, gm/cm^3 .

Kuriowa (Colbeck [10]) expresses the permeability of snow as a function of porosity:

$$K_{ow} = 1.17 \times 10^{-9} \exp(15.9\phi) \text{ cm}^2 \qquad (2.9)$$

For a snow-kerosene system, Kuriowa [24] relates saturated conductivity to porosity as follows:

$$C_{ow} = \frac{a \phi N}{N-\phi} \qquad (2.10)$$

where

C_{ow} = saturated conductivity cm/sec , and

a,N = emperical constants dependent on snow structure.

For snow-water systems, Moskalev (noted by de Quervain [18]) expresses saturated conductivity as a function of both porosity and grain size by the relationship: