The Compaction of Wet Snow on Highways

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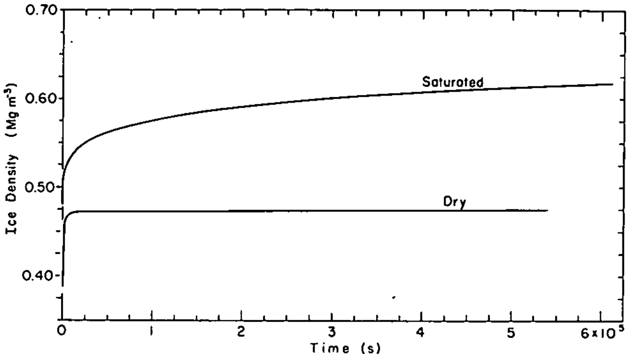
The compressibility of wet snow decreases with decreasing liquid water content but increases with decreasing salinity. Also, the tendency for snow splashing on highways increases with increasing liquid water content and increases with decreasing salinity. These opposite effects are complicated by the fact that liquid water content and salinity are not necessarily independent. The amount of liquid present can be controlled somewhat by the road grade and salinity is generally determined by how much salt is applied to the road surface. For different situations it may be desirable to regulate salt applications in order to achieve a maximum amount of splashing with a minimum of compaction of wet snow into ice. Here we provide a qualitative review of wet snow and suggest how an understanding of wet snow's behavior on a road surface might increase our ability to deal with snow removal problems.

Snow fall on highways has some very expensive consequences for our society. The most obvious costs include the direct costs of snow removal, snow related accidents, and chemically caused deterioration of vehicles, roads and bridges. The indirect costs of reduced mobility and chemical contamination of water supplies and roadside vegetation are also large. The advantages of de-icing chemicals (usually salt) are well known by virtually everyone using the highways in the temperate zones but the problems caused by salt are equally well known. The alternatives to the use of salt (reduced mobility and increased risk) are unacceptable, hence much research is being done in order to find ways to optimize the use of salt. The effects which liquid water and salt have on the mechanical properties of snow must be well understood in order to realize the best possible methods for removing snow from highways.

Hydrologists are quite familiar with the rapid changes which occur in snow upon the first introduction of liquid water (1). There are also marked variations in the properties of wet snow (ie, snow containing some liquid water) depending on the liquid water content (percent liquid by volume), salt content, grain size, density, and the history of these parameters. These parameters must be carefully specified to predict the exact behavior of the snow. Although it is well known that wet snow is more easily compacted than dry snow (see Figure 1) very little quantitative information about the properties of wet snow has been developed. Our purpose here is to provide a qualitative description of wet snow, review what is known about its mechanical behavior (especially the compaction of wet snow under an applied load), and suggest how this might increase our understanding of wet snow's behavior on a road surface.

Figure 1. Measured density (ice only) versus time for wet and dry snows (-2°C) compacted by a stress of 4790 Pa (0.69 psi).



General Description of Wet Snow

Snow is a complicated material because of the variety of forms it can take and because it is a thermodynamically unstable material which undergoes rapid changes when stressed, subjected to a temperature gradient, or wetted. The application of stress or formation of water are particularly important here because snow on highways is compressed by traffic and wetted by rain, melting and/or salting. The importance of melting is enhanced on highways because the snow cover is kept relatively thin thus allowing solar radiation absorption on a dark road surface which may cause melting even at subfreezing air temperatures. Also, salting is an important consideration here because cold, dry snow can be wetted by the application of salt; thus salting alone can change the character of the snow from dry to wet. As shown on Figure 1, the compressibility of wet snow is very much greater than that of dry snow, hence wetting by the application of salt can have the drawback of greatly increasing the rate at which the snow can be compacted into ice.

With the first introduction of liquid, snow undergoes rapid changes, especially grain rounding, grain growth, and densification. The distribution of grain sizes in wet snow has been measured (2) and thermodynamic relationships which describe the equilibrium conditions among the three phases of water have been derived (3). In the case of liquid soaked snow as is often found in the snow just over a road surface, the pore space is mostly filled with liquid and the ice particles tend to round off very quickly. In this state there is very little bonding between the ice particles hence very little resistance to discrete particle motion. If any adhesion does exist at the grain boundaries between particles, it tends to disappear when the grain boundaries are stressed or exposed to solar radiation. Thus the ice particles tend to behave individually without forming strong structural bonds with their neighbors. The destruction of the inter-particle adhesion partly accounts for the densification which occurs when snow is wetted for the first time.

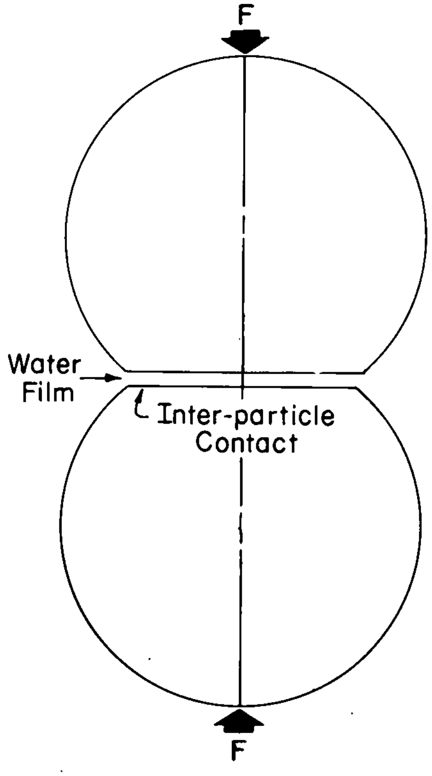
Freely draining snow normally contains a very small amount of liquid water which is almost entirely confined in liquid menisci between the ice grains. When these liquid menisci are present the spherical particles are thermodynamically unstable hence grain growth and grain rounding do not occur so intensely at low liquid contents. The presence of the liquid meniscus assures some adhesion between the ice particles because the liquid pressure is less than that of either the air or ice particles (i.e., the liquid exhibits a "tension"). Accordingly, wet snow has a higher inter-particle strength at low liquid contents thus unsaturated snow is relatively strong as compared with well soaked snow.

Meltwater moves freely downward in wet snow until a relatively impermeable boundary (such as a road surface) is encountered (1). At that boundary a soaked layer is formed whose thickness is determined by the rate of melting and/or rain, slope of the road surface, and permeability of the soaked snow. The thickness of the layer of snow which is soaked by water is important because the soaked snow behaves quite differently than the unsaturated snow. We quantify these differences later but here we note that the thickness of the soaked layer is less for less intense melting and/or rain, for steeper or well drained surfaces, and for lower density snow. Note that we can increase melting by salting and affect the surface drainage by small adjustments in the surface slope but the density of the soaked snow is determined by the complicated interaction of its history of liquid content, salinity, and the loads applied by the passing traffic. In order to understand the compaction of wet snow on highways, the theory and observation of the compression of wet snow is reviewed.

Snow Compression Model

When confined and stressed, wet snow compacts very quickly up to a density about 0.5 Mg/m^3 where the particles are packed in a fairly efficient manner. Further densification requires the particles to change shape in order to accommodate the same number of particles in a smaller volume. Wet snow is nearly unique in that pressure melting is the dominant mechanism responsible for the deformation of particles at their stressed contacts (4). Pressure melting occurs at the stressed particle contacts (see Figure 2) because the ice-liquid temperature is depressed by 0.0074°C per 10^5Pa (14.5 psi) stress between the particles. The depressed temperature at the contact causes heat flow from the stress-free surfaces where refreezing occurs. The meltwater being discharged from between the particles causes a separation of about $2x10^{-5}$ mm (4) thus ensuring that little inter-particle adhesion will develop at least as long as a load is applied. Each particle tends to conserve its mass by refreezing an equal mass of water on its stress-free surfaces as it melts on its stressed surfaces.

Figure 2. Two particles pushed together melt at their mutual contact thus allowing the particles to change shape to accommodate a closer packing.

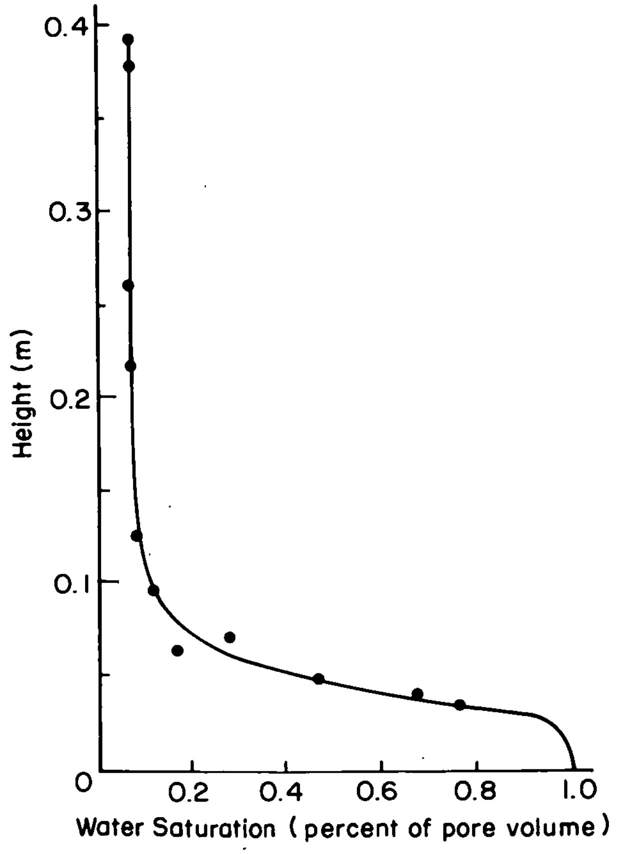


The rate of pressure melting and rate of densification have very complicated dependence on the density, particle size, applied load, salt content, and liquid water content. The density increase with time can be computed when the necessary parameters are specified (4) but these computations involve a complicated number of feedback loops involving heat flow, fluid flow, salt and dissolved air flow, and changes in geometry. Without describing the details of the model, we turn to the discussion of the significance of the results of the model runs, associated laboratory tests, and other concepts about the physical properties of wet snow.

Application to Snow on Roads

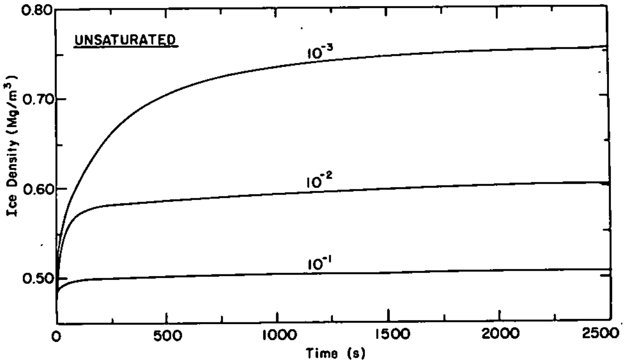
During rainstorms or periods of melting, some water must be "ponded" on the road surface thus soaking at least some of the snow. The fraction of the snow which is soaked depends on the ability of the water to drain away (rain and melt rates, surface slope and snow density) and, of course, on the depth of snow on the road. In cases where the depth of the snow is greater than the depth of the soaked layer, a typical water retention curve would look like that shown in Figure 3. The sharp transition from saturated to unsaturated snow is typical of porous materials with large grains. A measure of the large pores of snow is provided by the "bubbling pressure" test. In this test, the height to which water in a sample of snow can be raised above a water surface without draining is measured. Typical values for a small sample of snow are 3 to 4 cm of rise above the water surface (5). Of course the height of water ponded on a road surface may be different depending on the drainage of the surface.

Figure 3. Typical water retention curve for a snow sample whose bottom touches a water surface (taken from 3).



The significance of the profile of liquid water content contained in the snow overlying a road surface becomes obvious when we consider the different responses that soaked and unsaturated snows have to vehicle traffic. As stated earlier, there is very little bonding strength between the particles in soaked snow hence well soaked snow tends to splash rather than compress when loaded suddenly by a vehicle tire. Splashing is common and very desirable compared to the compression of snow into ice under the weight of the vehicle tires. Since splashing has a minimal effect on traction as opposed to the compression of wet snow which greatly decreases traction, we should understand this phenomenon as well as possible. When a road surface is drained and a large fraction of the snow is unsaturated, the inter-particle strength due to the liquid meniscus and ice-to-ice adhesion is sufficient to prevent or at least minimize splashing. In this case the snow is compressed under the vehicle loads and our model (4) of the compaction of wet snow can be used to compute the compaction for various loads, salinities, and liquid contents. For a stress of 2x10^{5}Pa (29 psi) on a highly unsaturated snow, the compaction is shown as a function of time for various sodium chloride contents on Figure 4. At very low salinities the snow compacts rapidly to densities approaching that of pore close-off where snow becomes, by definition, ice. The compaction is most rapid when the stress is first applied and proceeds at an ever decreasing rate. After being stressed for 500 seconds, the snow reaches an ice density (neglecting the liquid mass) of more than 0.70 Mg/m^{3} and thus would have the same coefficient of friction with rubber as wet ice.

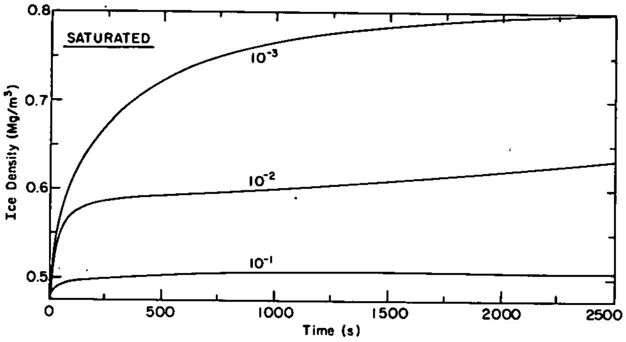
Figure 4. Computed density (ice only) as a function of time for various salinities (g-mol NaCl per kg of solution times ions per molecule). The snow is highly unsaturated and compressed in confinement under a constant stress of 2x10^{5} Pa (29 psi).



At lower salinities the compaction is little different from that shown for the 10^{-3} concentration because of the action of electrostatic forces between the ice particles (4). However, Figure 4 shows that the rate of compaction decreases rapidly with increasing salinity. As observed by Yarkin et al (6), snow is much harder and more resistant to compaction when more ionic impurities are present. The salinity of the wet snow on highways is highly variable but considering typical application rates of salt and typical tire pressures, the results shown on Figure 4 should be representative of the compaction of unsaturated snow on highways. The wide range of compaction rates shown on Figure 4 suggests another benefit of salt, a large reduction in the rate of compaction of wet snow into ice due to the passage of vehicles. This action greatly increases the time available for snow removal before vehicles compact the snow into ice. However, it should also be noted that the presence of the salt increases the inter-particle adhesion thereby decreasing the chances that splashing will occur.

In soaked snow the inter-particle strength tends to be very low hence splashing is more likely than compression to ice. However, in some situations, well soaked snow can be compressed under vehicle tires. These situations might include a snow cover which is soaked at the road surface but highly unsaturated just above the road surface. In this case the overlying snow may have sufficient strength to confine the soaked snow and prevent splashing. In another situation, the snow may have just become soaked in which case the particles could not have had time to lose their bonding strength and splashing may be prevented or reduced. In Figure 5 we show how saturated snow compresses under a stress of $2x10^5$Pa (29 psi); salinity is shown as a parameter.

Figure 5. Computed density (ice only) as a function of time for various salinities. The snow is soaked and compressed in confinement by a constant stress of $2x10^5$ Pa (29 psi).



The rate of compaction is somewhat greater when the snow is saturated as shown by the experiments of Tusima (7) and explained by the physical model used here (4). Figures 4 and 5 show the difference between the unsaturated and saturated snow. These results also show that the salinity effect may be more important than the liquid water content. At low salinities ($\leq 10^{-3}$ g-moles NaCl per liter times ions per molecule which is equivalent to 4.81 lb salt per lane mile on 0.5 in. water in the snow), compaction occurs quickly for both saturated and unsaturated wet snow. At a salinity of 0.01 which would be typical if all of the salt applied on a road surface were dissolved uniformly throughout the liquid, the rate of compaction is greatly reduced for both saturation regimes. In fact, at salinities of 10^{-2} or greater, it seems unlikely that really high density snow could ever be achieved by vehicle compaction.

Summary

Much attention is being given to improved methods of snow removal from highways. The properties of wet snow are discussed here to help provide an understanding of the material being removed. Snow is either dry (no liquid present), unsaturated (low liquid content) or well soaked (nearly 100 percent of the pore volume filled with liquid). Dry snow compresses very slowly but wet snow can be compressed to ice quite quickly. The rate of compression depends on the liquid content, load and salinity. Well drained road surfaces retain less liquid hence the snow does not compress so easily (an advantage) but at the same time the snow will not splash so easily (a big disadvantage). The introduction of salt further complicates this situation because salt reduces the rate of compaction of snow into ice but salt also increases the inter-particle strength and thus decreases the tendency for splashing to occur. Of course a dry snow can be wetted by the application of salt hence these two parameters, liquid water content and salinity, are not necessarily independent.

The advantage of salt cited most frequently is its ability to keep snow from bonding to the road surface but its use introduces complicated physiochemical responses which should be investigated in more detail and included in our thinking about the best ways to remove snow from highways.

Acknowledgments

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References

1. Colbeck, S.C. The Physical Aspects of Water Flow through Snow. Advances in Hydroscience. In press.
2. Wakahama, G. The Metamorphism of Wet Snow. General Assembly of Bern. IUGG/IAHS General Assembly, Sept-Oct 1967, pp. 370-79.
3. Colbeck, S.C. Theory of Metamorphism of Wet Snow. U.S. Army Cold Regions Research and Engineering Laboratory. Research Report 313, 1973, 13 pp.
4. Colbeck, S.C. The Compression of Wet Snow. U.S. Army Cold Regions Research and Engineering Laboratory.
5. Wankiewicz, A. Water Pressure in Ripe Snowpack. Water Resources Research. In Press.
6. Yarkin, I.G., I.A. Tyutyunov and A.V. Sadovskii. Physiochemical Method of Strengthening Snow. Osnovaniya Fundamenty i Mekhanika Gruntov, no. 4, 1972, pp 21-22.
7. Tusima, K. Tests of Repeated Loadings on Snow. Low Temperature Science, Ser. A31, 1973, pp. 57-68.