The influence of aqueous solution on compacted snow: A field investigation

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Abstract:

Slippery road surfaces are a threat to traffic safety especially in winter where snow falling on roads forms a hard crust which is extremely difficult to remove. In order to prevent this hard crust formation, salt is applied to roads. However, high salt amounts are harmful to the environment and expensive. Therefore the optimization of salt applications become a priority for transportation agencies.

This study evaluates the effects of NaCl aqueous solution on compacted snow through a field investigation. A test car was driven on snow mixed with different amounts of aqueous NaCl solution (from 0 wt.% to 40 wt.%); this experimental run was then repeated approximately 20 times. A scraping test was also performed in order to evaluate the compacted salted snow's strength. Findings of this study are: an aqueous solution content of 10 wt.% keeps snow loose and easily removable from road traffic, while an aqueous solution of 5 wt.% weakens the snow substantially, allowing the snow mixture to be more easily plowed.

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Introduction:

In cold regions, slippery road surface conditions pose a threat to traffic safety. For example, drivers rely on high tractive forces between their vehicles' tires and the road surface, and a maximum level of friction is achieved when the tire rubber is able to make direct contact with the asperities on the road surface. The presence of snow or ice between tire rubber and asperities interferes with this physical contact, thereby lowering the level of friction created by it. Therefore, in order to ensure acceptable levels of friction both during and after a snowfall, many road administrations use a strategy that aims to regain a bare road surface quickly (within hours) after a snowfall(PIARC, 2015). This type of strategy has been variously called an anti-icing strategy (Ketcham et al., 1996), bare pavement strategy (Shi and Fu, 2018) or black road strategy (PIARC, 2015). Typically, an anti-/de-icing chemical is applied either before or at an early stage of the snowfall, followed by mechanical removal using snow plows. For instance, in Norway alone, more than 200,000 metric cubic tons of sodium chloride are used each winter during snowfalls (Vaa, 2005). However, high levels of salt applications are environmentally unfriendly, pollute water (Shi et al., 2013) (Fay and Shi, 2012)(Blomqvist, 1998) and are expensive (Hanbali, 1994). Therefore, the optimization of salt applications has become an intensive priority for municipalities as well as governmental agencies.

Transportation agencies have tried to come up with guidelines, e.g. (Salt Institute, 2016), attempting to identify the best winter maintenance practices (Theses, 2015). Others have presented their guidelines based on field investigations (Raukola et al.,, 1993) (Lysbakken, 2013)(Ikiz and Galip, 2016), attempting to correlate laboratory tests with field tests (Muthumani et al., 2014). Still other agencies have optimized road salting by using Road Weather Information Systems (Kramberger and Žerovnik, 2008). As road weather models are improving and knowledge of salt's longevity on road surfaces is increasing, one possible avenue for further optimization is to predict when and how many chemicals should be applied during snowstorms. However, this approach requires accurate weather predictions, a detailed understanding of how salt affects snow and defined criteria with respect to the minimum amount of chemicals needed.

Snow compaction mainly happens when the air temperature fluctuates around 0°C (Ketcham et al., 1996). When approaching melting point, ice particles slowly begin to melt, forming in turn a liquid layer which, upon making contact with the solid ice particle, freezes, forming a solid bond with existing solid ice particles (Szabo and Schneebeli, 2007) and adhering strongly to other surfaces (Makkonen, 2012). The purpose of salting has traditionally been viewed as a measure used to weaken the bond between pavement and snow (Ketcham et al., 1996; Minsk, 1998; Penn and Meyerson, 1992)*;* thus salt, or any other de-icer, has typically been applied either prior to or during the first minutes of a snowfall. Several studies on how salt affects the mechanical properties of snow (Wåhlin et al., 2016; Wåhlin and Klein-Paste, 2015, 2014) have provided us with the belief that the entire snow layer, and not only the snow-road interface, is affected by salt. When snow starts to fall on a salted road, the snowflakes start to melt, and the pavement becomes wet from the resulting meltwater. The salt becomes diluted, and this melting process may continue until the melting capacity of the de-icier is reached (Nilssen, 2017). The pavement is now covered with diluted solution, the concentration of which being equal to the equilibrium concentration given by the phase diagram of the particular de-icer in use. As it continues to snow, crystals start to accumulate on the road and co-exist with the diluted de-icer solution, which prevents any bonds between the crystals being formed (Wåhlin et al., 2014)*,* thereby weakening the snow. Therefore, salting prior to snowfall may be considered an “anti-compaction” measure. The notion that anti-/de-icing chemicals create a solution diluted until it has reached its equilibrium concentration at the prevailing temperature suggests that a certain amount of solution is needed in order to weaken the snow sufficiently.

To our knowledge, (Schaerer, 1970) was the first to suggest this criterion based on solution content, his recommendation being to salt until the solution content was at least 30 wt.% so that the snow would either become soft enough to be squeezed off of roads from the effects of traffic or able to be easily removed by snow removal vehicles. Nevertheless, various parameters, such as air and asphalt temperature, chemical snow mixture density, traffic load, type of tire with relative inflation pressure, were not considered in (Schaerer, 1970)’s investigation, making it difficult to interpret his results. Through their laboratory experiments (Giudici et al., 2017) suggest that the solution content can be substantially lowered (to about 10 wt.%) and still provide satisfactory anti-compaction effect; however, this assertion needs to be tested through field studies using different temperatures for verification under realistic conditions.

Based on a completed field study, this paper aims to define the minimum amount of salt that is needed in order to weaken snow enough to allow mechanical removal and provide sufficient friction by re-exposing the underlying asphalt aggregates to tires. The study was performed in a “worst-case” scenario, when the air temperature was either approaching or above zero. To the best of our knowledge, this is the first study of anti-compaction at melting temperatures. Finally, we discuss the results’ implications for future salt optimization efforts.

Methods:

A field study was conducted where a car drove multiple times over snow samples containing various amounts of diluted solution. The snow samples were placed on either wet or dry pavements, the air and pavement temperatures being close to 0°C. The tracks were visually inspected and photographed after five and 20 vehicle passes, respectively. Finally, the strength of the remaining snow in the track was assessed by performing a scraping test with a metal blade.

Test site and test conditions

The field tests were conducted at the Winter Maintenance Research Lab of the Norwegian University of Science and Technology between February 2018 and March 2018. The tests were performed using a Mercedes Benz Vito equipped with 4 studded Nokian Hakkapellitta 7 SUV 215/65R16. The shore hardness lay within a range between 62 and 70 (ASTM, 2012). The inflated tire pressure was 200 kPa. Prior to each testing day, the pavement was rinsed off with water in order to remove any salt residuals. The pavement was dried by using a flame torch in order to avoid any sort of ice formation and left overnight to cool down to ambient temperature. The test site was in a parking lot located close by the Winter Maintenance Research Lab facility. The building provided shade from the sun during a large part of the day, and while the test site was covered by an overhanging roof, the other building sections were exposed to the outside air.

Salted snow sample preparation

After a snowfall, loose dendritic snow (about 120 kg) lying near the test site was first collected and then stored in a cold room at -20°C. Before each test, about 10 kg of the stored snow was transferred to the test site and allowed to heat up to about -2°C. Once the snow had reached this temperature, it was mixed with a sodium chloride solution of 3.33 wt.%, which has a freezing point of -2°C (Haynes, 2014). When using this NaCl concentration and setting a temperature of -2°C, no ice particle melting or freezing occurs. The NaCl solution was prepared by dissolving NaCl into distilled water. The snow and solution were then placed inside a plastic bucket and mixed by intense, manual shaking for two minutes.

The solution content varied between 0 and 40 wt.%, as calculated in equation 1:

$$SC[\%] = \frac{m_{sol}}{m_{sol} + m_{snow}} * 100 \tag{1}$$

where m_{sol} represents the mass of the NaCl solution, and m_{snow} represents the mass of the snow.

The salted snow mixture was placed into a wooden frame of 30x30x3 cm^3 that was placed on the asphalt pavement. The snow filled the wooden frame without being compacted. Increasing the solution content inside the snow increased its initial mass and density. The density was measured for each snow sample, and the average and standard deviations are shown in Table 1. The wooden frame was removed before testing, leaving 3 cm square snow height samples.

Table 1. Average density and standard deviation of snow samples.

Solution Content (wt.%)	ρ average [g/cm^3]	Standard Deviation [g/cm^3]
0%	0.29	0.069
5%	0.34	0.056
10%	0.37	0.036
20%	0.46	0.089
40%	0.61	0.166

Experimental procedure

The five snow samples containing diverse solutions were placed on the asphalt. Two samples were placed in front of both front tires having a distance of 90 cm (1.5 times the tire circumference), while the fifth sample was placed 9 meters further away. This spacing was chosen to prevent/minimize salt contamination spreading from one sample to another. The sample density and temperatures were recorded before the car was driven in a straight line at a speed of approximately 20 km/h. To avoid cross-contamination between samples, the test car was driven in only one direction from dry snow (SC=0 wt.%) to the sample containing SC=40 wt.%. Both the front and rear tires drove on the samples during each pass. Figure 1 shows the placement of the samples prior to testing.

Figure 1. Placement of snow sample (marked in red) prior to testing.

Under the effect of the rolling tires, the snow samples were first compressed, compacted and/or squeezed out from their original positions. The snow samples were visually inspected and photographed after 5 and 20 vehicle passes in order to observe the salted snow's ability to flow

(Giudici et al., 2018) and to determine whether or not any asphalt asperities were visible on the snow surface.

Based on the amount of bare asphalt asperities exposed to air, the snow samples were classified as shown in Table 2:

Table 2. Pavement classification.

Asphalt classification	
1	No pavement asperities visible
2	Partial asperities visible
3	Full asperities visible

Scraping Test

A scraping test was performed after the car had been driven 20 times over the snow samples. The aim of this test was to simulate the mechanical removal of a snowplow. A stainless steel blade was scraped multiple times over the snow samples, and a video was recorded for each scraping action. Based on both the video and observations made after the scraping test, the pavement was reclassified in the same categories.

Results:

Both the unpredictability of weather conditions and using a test area that is open to other traffic make outdoor tests a challenge. Nevertheless, a total of 6 successful tests were performed under the desired testing conditions of asphalt and temperatures during the winter of 2018. Table 3 shows the different test conditions.

Table 3. Study cases with relative testing properties.

Case	Date (dd/mm)	Asphalt Condition	Air Temperature (°C)	Pavement temperature (°C)
1	08/02	Dry	0	0
2	13/02	Wet	0	+1.7
3	13/03	Wet	+1.6	+1.5
4	15/03	Dry	-2.0	-2.2
5	20/03	Wet	+2.0	+2.4
6	27/03	Dry	+1.8	+1.5

The first row in Figure 2 shows the compressed and compacted snow after five passes for different SC, and the second row shows the compressed and compacted snow after 20 passes by the test car. Regarding SC 0 wt.% and 5 wt.%, in both rows of Figure 2, the snow was compacted. Regarding SC 10 wt.%, 20 wt.%, and 40 wt.%, it is possible to observe a higher flowability, meaning that the snow was pushed aside by the tire having a higher SC. This is particularly true with respect to SC 40 wt.%, where the snow totally splashed out of the testing area, allowing the tire to make contact with the asphalt.

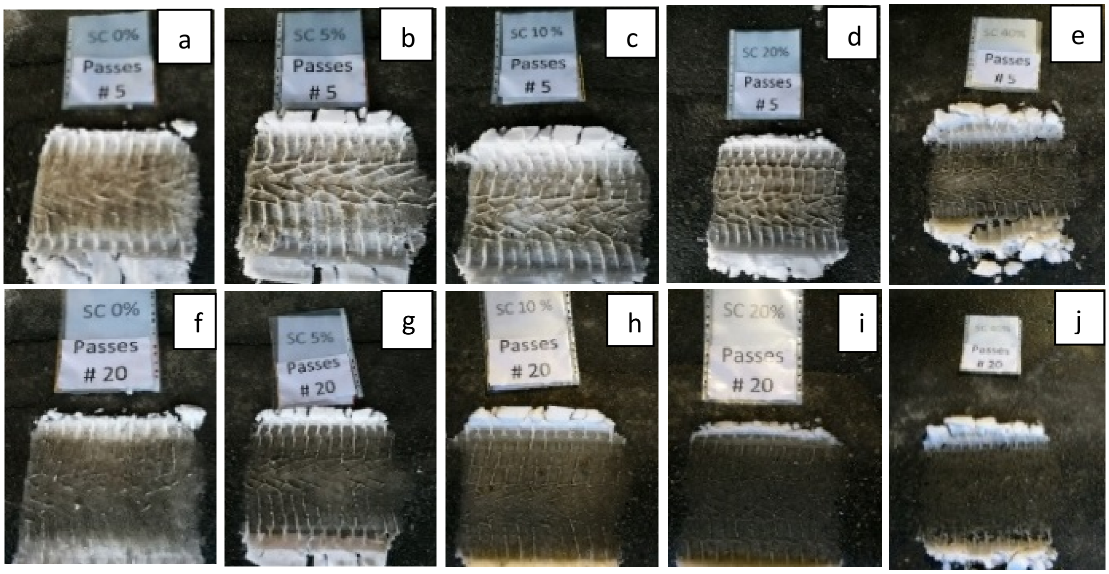

Figure 2. Snow samples containing various solutions after five and 20 vehicle passes on case 1, a) SC=0 wt.% after 5 passes; b) SC=5 wt.% after 5 passes; c) SC=10 wt.% after 5 passes; d) SC=20 wt.% after 5 passes; e) SC=40 wt.% after 5 passes; f) SC=0 wt.% after 20 passes; g) SC=5 wt.% after 20 passes; h) SC=10 wt.% after 20 passes; i) SC=20 wt.% after 20 passes; j) SC=40 wt.% after 20 passes.

Figure 3 shows the effect of the scraping action on the snow. The blade applied a sheer force at the interface between the compacted salted snow and the asphalt. The snow typically detached in irregular flakes at SC 0 and 5 wt.%. A clear difference was experienced during the scraping test depending on the amount of SC in the snow. Approximately the same force was applied using the blade to all the compacted salted snow samples. The more that SC was increased, the easier the snow detached from the pavement surface. Compacted dry snow, SC= 0 wt.%, was very hard; as a result, it was barely affected by the scraping. Salted snow having SC= 5 wt.% was weaker compared to the dry compacted snow, allowing the blade to remove it from the pavement. Salted snow having SC= 10 wt.% was a soft material, not detaching in flakes but behaving rather more like a powder, and it was therefore easily removable. When testing snow at SC=20 wt.%, the compacted snow was slushy and extremely weak. At SC=40 wt.% there was no compacted snow left on the pavement due it being squeezed out from under the tire already after 5 – 10 passes by the test vehicle.

Figure 3. Showing snow with solution contents of 0,5 and 10 wt.% respectively after a scraping test. The snow, for 0 and 5 wt.% solution contents detached from the pavement in flakes, as can be seen in image 3 a) and b).

After 5- 10- 20 passes and the scraping test, all photos were manually classified according to the three categories defined in Table 2. Figure 4 shows both the asphalt visibility and snow compaction as functions of solution content and mechanical action. More specifically, the dots represent our classified observations after 5, 10, 20 passes of the test car and scraping test. The crosses show the data set provided by (Schaerer, 1970).

The data provided by (Schaerer, 1970) classify the snow into the categories of compact snow, loose snow and removed snow as functions of the number of car passings: less than 5, between 5- 10 and between 10- 15 passes. In order to make a comparison between the two data sets, we decided to structure our classification of pavement surface to (Schaerer, 1970) snow classification as follows:

- no asperity visibility corresponds to compacted snow from (Schaerer, 1970),
- partial asperity visibility corresponds to loose snow from (Schaerer, 1970),
- full asperity visibility corresponds to removed snow from (Schaerer, 1970).

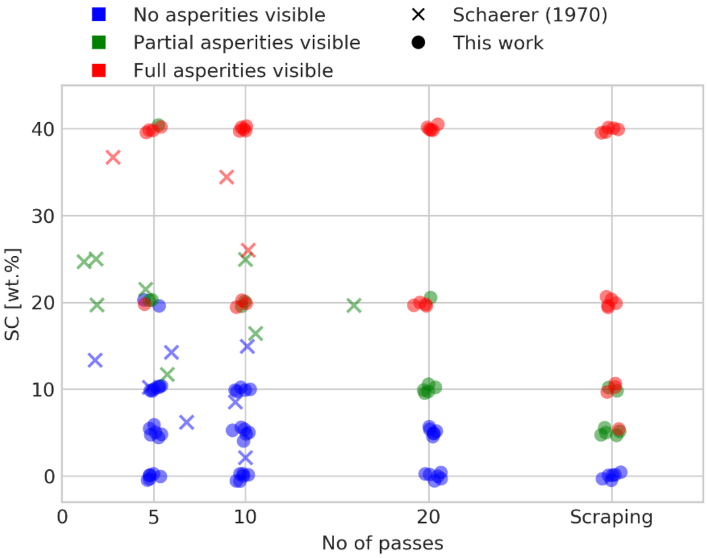

Figure 4. Salted snow compaction/asphalt visibility as function of solution content; regarding visibility, data was moved in both x and y directions.

Looking at Figure 4, it is possible to observe that the data presented in this study are in accordance to Schaerer's data, precisely it is possible to observe the following:

- Regarding snow with no visible asperities (blue dots), the maximum amount of solution content dependent on the the mechanical action. For example, after only 5 cars, snow containing a solution of up to 10 wt.% covered all asperities; indeed, there was one sample even at 20 wt.%. After 10 cars snow containing a solution of up to 10 wt.% covered all the asperities. After 20 cars snow containing a solution of up to 5 wt.% covered all the asperities, and including the scraping test, only dry snow covered all the asperities.
- Regarding snow having partially visible asperities (green dots), there was a minimum and maximum SC wherever it existed. Just as in the case of snow with no asperities, this number varied in accordance with the mechanical action. At 5 passes the partial visibility is observed in snow containing a solution of up to 40 wt.%. At 10 passes the partial visibility is observed in snow containing a solution of up to 20 wt.%, At 20 passes the partial visibility

is observed in snow containing a solution of up to 10 wt.%, and after the scraping test, the partial visibility is observed in snow containing a SC of 5 wt.%.

- In the case of snow in which asperities were fully visible (red dots), there was a minimum SC at which this occurred. This varied with the mechanical action, as after 5- 10- 20 passes, the full asperities visibility is observed already in snow having an SC of 20 wt.%. After the scraping test, full asperities visibility is observed in snow having an SC of 5 wt.%.

Table 4. Minimum amount of sc for partial/total asphalt asperities visibility for each study case.

Case nr.	Asphalt condition	Vehicle Passes		Scraping Test
		5	20	
		SC % wt.	SC % wt.	SC % wt.
1	Dry	40	10	5
2	Wet	40	20	5
3	Wet	20	10	5
4	Dry	40	20	5
5	Wet	20	20	5
6	Dry	40	10	5

Through examining Figure 4, we can identify the minimum amount of solution content needed to achieve the partial or total visibility of asphalt asperities for all study cases, and these are presented in Table 4. After 5 passes the partial (or total) visibility of the pavement asperities is reached with an SC having a range between 20- 40 wt.%. When increasing the amount of car passes to 20, the same result is attainable by having an SC between 10- 20 wt.%. In all the study cases the scraping test shows the same result, namely an SC of 5 wt.%, which is able to weaken the test snow enough so that it can be easily detached from the pavement. No clear difference was observed between the samples placed on dry asphalt and those placed on wet asphalt.

Discussion:

This study can be considered to be a “worse-case scenario” in terms of snow compaction for two reasons: slow driving speeds and temperatures close to the melting point.

The driving speed determines how quickly the snow will become compressed, and at low speeds there is more time for the snow crystals to re-arrange themselves into a denser configuration (Lee, 2009). The re-arranging process of the compressed salted snow fills the voids of the underlying uncompressed snow layer (Lee, 2009), thereby increasing both the snow density and bonds between the ice crystals (Wåhlin et al., 2016).

Snow compaction is more severe at a temperature close to its melting point (Minsk, 1998), as in these cases a higher densification of the solid ice crystals occurs. Consequently, this contact in enhances stronger bonds (Wåhlin et al., 2016) and facilitates the sintering process, which makes the snow layer compacted and thus stronger (Szabo and Schneebeli, 2007). Therefore, the minimum required solution content may be considered to be a conservative estimate.

The main findings of this study are that, independent of whether the temperature was above or below melting point, snow with a solution content ranging between 20- 40 wt.% is removed from road pavement after only five car passes. Furthermore, the higher the number of cars driving across the snow layer, the lower the amount of aqueous solution required to be poured onto the snow in order to avoid the compaction process. After 20 passes, the required amount of aqueous solution needed for achieving anti-compaction and regaining partial asperity visibility was reduced to 10-

20 wt.%. Therefore, once the car has driven over the compacted salted snow 20 times at SC between 10- 20 wt.%, this snow is removed from the road, leaving behind a partially (or completely) bare road surface. On the other hand, the scraping test shows that when using a solution content of 5 wt.%, the compacted salted snow becomes substantially weakened, making it easy to remove by the blade's mechanical action. The scraper's mechanical action is more likely to be less than that of a snowplow, meaning that when an SC of 5 wt.% is applied to roads, a plow is likely to be able to remove the compacted snow. Therefore, a partially (or totally) bare road surface may be achieved with an SC of 5 wt.% after a combination of 20 car passes and mechanical blade action. Additionally, we anticipated that pre-existing water on the pavement would also enhance the snow's bonding; therefore, while we tested on both dry and wet conditions, we did not achieve any measurable differences using the current set-up. Indeed, the results presented here are in line with those of (Schaerer, 1970).

Norwegian roads are classified into different levels of service according to the Norwegian Public Road Administration classifications. Regarding the two highest levels of service, DkA and DkB (NPRA, 2014), the maximum allowed time for spreading salt and plowing is 2 hours. This means that during a snowfall, salt trucks pass the same spot within a 2-hour period. The bare-pavement recovery time is set to 2 – 4 hours after a snowfall, meaning that pavement asperities need to be visible after this point. Since these service levels are only assigned to roads having an annual average daily traffic (AADT) higher than 1,500 vehicles/day, the choice of car pass numbers performed during this study are conservative with respect to the anticipated traffic flow between the cyclical time of salting and plowing actions. Therefore, a solution salt application rate resulting in a 5 wt.% SC after 2 hours would be sufficient for snowplows to be able to remove the snow. A salt application rate producing at least a 10 wt.% solution content would allow for traffic loads to reach the partial or full asperities exposure interacting with car tires once they drive over the treated pavement surface.

When the air temperature dips below 0°C; for example, if the amount of SC required after 2 hours is known, it is possible to calculate the amount of solid NaCl as a function of the temperature and mm of water equivalency. For instance, if we consider an expected snowfall of 5 cm over a 2 - hour period of time with a temperature of -2°C, and we propose using use NaCl as salt, similar calculations from (Giudici et al., 2017) suggest an application rate of approximately 10 [g] for road square meters in order to achieve the partial (or full) asperities visibility during snowfalls. This application rate falls within the Norwegian Public Road Administration's suggested range, 5 – 20 [g/m^2], of spreading salt during a snowfall (NPRA, 2017). Moreover, it must be noted that in the present study we are only talking about the minimum amount of aqueous solution needed to actively weaken snow on pavement. Consequently, in order to find the optimal application rate of salt on roads, we would also have to take into account the salt loss that occurs during the actual application of the various salt spreading methods.

At temperatures higher than zero degrees, it is not possible to make the same calculations. This is because there is no equilibrium concentration of the NaCl solution at temperatures higher than zero degrees. However, based on the results presented here, it also appears possible to extend our anti-compaction considerations above 0°C; SC= 5 wt.% allows easier mechanical removal of compacted snow, and SC= 10 wt.% makes snow loose enough to be removed by the car traffic, including air temperatures above zero. While previous studies (Giudici et al., 2017) have implied this finding for temperatures below zero, this is, to the best of our knowledge, the first time a minimum solution content has been found for anti-compaction at melting temperatures.

Conclusions:

This study aims to find the minimum amount of salt needed on roads to weaken the snow enough to allow tire rubber-road surface contact. Based on this study, the following conclusions have been made:

- Snow having an SC of 10 wt.% does not compact. This salted snow is weak enough to be easily rinsed off the pavement from the effects of road traffic;
- Snow having an SC of 5 wt.% is able to weaken the salted snow mixture enough to allow the mechanical action necessary to make it detach easily from the pavement

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