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Henri Giudici

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Doctoral thesis

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Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Civil and Environmental
Engineering

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How little is enough to prevent snow compaction?

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Abstract

During snowfalls, snow fallen on roads gets compact by traffic and can form an extremely slippery and dangerous road surface. The objective of winter maintenance operations is to ensure road mobility and traffic safety. Typical winter maintenance operations during snow falls are mechanical removal of snow (snow plowing) and altering the snow by the use of de-icers. The most commonly used de-icer is the sodium chloride (NaCl). The use of NaCl is economically demanding as well as detrimental for water and vegetation lying alongside the road surface. In recent years in Norway, more than 250,000 metric cubic tons of NaCl have been applied on roads during winter time. Therefore, there is a growing desire among road agencies to optimize the use of salt on roads without compromising traffic safety. To accomplish this goal, more knowledge is required on the influence of NaCl on the mechanical properties of snow. The focus of this thesis is on the optimization of salt in order to prevent snow compaction during snowfalls. In order to optimize the amount of NaCl used during snowfalls, the way salt affects snow and tire-pavement interaction must be better understood. More specifically, the minimum amount of salt that is needed to bring snow in a weak, cohesionless state is still to be determined.

To my knowledge, the application of salt is mainly based on the experience of winter maintenance personnel and not scientifically based. Therefore there is a need for more knowledge on salted snow and its behavior during mechanical actions.

With indoor and outdoor studies, this thesis aimed to understand the behavior of salted snow under the effect of tire compression and explored applicability of this knowlegde in realistic conditions.The behavioral understanding of snow mixed with diluted NaCl aqueous solution provided in this thesis are:

- For a given load, the snow containing NaCl solution gets compressed to a higher density, compared to snow without NaCl solution. A solution content of 10 wt.% inside the snow increased the density of the snow crystals with up to 30%, compared to pure snow. Beyond 10 wt.% solution content, the density of the compressed snow does not increase but it flattens out.
- Despite the higher density, the presence of NaCl aqueous solution weaken the compressed snow. An solution content of 5wt.% - 10 wt.% is able to substantially reduce the strength of ice in grain-grain contact, such that snow is easily removed mechanical action.
- During the mechanical compression, the presence of NaCl solution increased significantly the flowability of the snow. With 10 wt.% solution content the amount of snow that was squeezed out of the contact area of a rolling test tire (7.2 km/h) increased by more than 50 %, compared to pure snow. Further increase in solution content (up to 40 wt.%) does only slightly increase the squeeze out.
- The field investigation suggest that a solution content of 5-10 wt.% (diluted) NaCl solution is enough to prevent compacted snow formation. 10 wt.% was enough to get the snow removed by the effect of 20 vehicle passes, whereas 5 w% was enough to remove the snow by a scraping blade. These estimates are considered conservative as they were obtained under conditions of that create most severe snow compaction (slow driving, close to 0°C).
- The minimum amount of salt (in g/m^2) is calculated for a given snow fall, using the criterion of 5 and 10 w% NaCl solution content. To determine an actual application rate, a safety factor remains to be determined to account for salt loss during and after spreading.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of philosophiae doctor (PhD).

The presented work was carried out at the Department of Civil and Environmental Engineering (NTNU) between January 2015 and December 2018 under the supervision of prof. Alex Klein-Paste as main supervisor and dr. Johan Wåhlin as co-supervisor. Together with the research project, duty work was done to support the winter maintenance research center in ongoing industry projects. This research project was funded by the Faculty of Engineering Science of the Norwegian University of Science and Technology (NTNU).

Contents

List of Papers

1) Giudici, H., Wåhlin, J., and Klein-Paste, A. ‘Uniaxial Compression on Salted Snow’ Tire Science and Technology, TSTCA, Vol. 46, No. 1, January–March 2018, pp. 16–26. doi: 10.2346/tire.18.460104
2) Giudici, H., Wåhlin, J., and Klein-Paste, A. “Tire-pavement interaction in contact with presence of salted snow: How an aqueous solution affects the compression, squeeze out and compaction of snow” Journal of Cold Region Engineering (accepted with minor revisions).
3) Giudici, H.., Fenre, M.D.., Klein-Paste, A.., Rekilä, K.P., 2017. A Technical Description of LARS and Lumi: Two Apparatus for Studying Tire-Pavement Interactions. Routes/Roads n. 375, pp. 49-54.
4) Giudici, H., Wåhlin, J., and Klein-Paste, A.. “The influence of aqueous solution on compacted snow: a field investigation” submitted to Journal of Cold Region Engineering (under review).

Chapter 1

Problem outline

Winter maintenance of road infrastructures is a demanding task for road agencies located in cold regions. Cold weather conditions are among the causes of traffic volume variations (Datla and Sharma, 2010; Roh, 2015; Shahdah and Fu, 2010), which in turn inflicts high costs on society and delays to goods transportation. Moreover, icy and snowy road conditions increase fatal accident rates (Hanbali, 1994; Knapp et al., 2000; Sherif, 2005). The current strategy used of closing a road due to snow is economically unsustainable and often unsafe, especially during the road's re-opening where snow has to be accurately removed in order to prevent damage to the road.

The objective of winter maintenance operations is to ensure road mobility and traffic safety. Due to economic and environmental constraints, winter maintenance needs to be performed in an efficient yet environmental friendly manner. There are therefore different amounts of effort put into winter maintenance, typically known as Levels of Service. Higher LoS are assigned to highways or major roads found in large cities. On these particular roads there is high traffic volume, so that road agencies have to guarantee safe travel at any time and under any weather conditions for road users, especially in winter.

Based on what the LoS aims to achieve, there are three winter maintenance strategies. The first one is called *bare road strategy*. This strategy aims to restore clean, bare asphalt as soon as possible during any sort of weather condition, and is the required strategy for highways (Ketcham et al., 1996). It relies on two winter maintenance operations: mechanical snow removal and the spread of de-icers (anti-/de-icing chemicals). The most widely used de-icers for winter operations are sodium chloride (NaCl), magnesium chloride (MgCl), calcium chloride (CaCl), calcium magnesium acetate (CMA) and potassium formate (KCOOH). In addition to these chemicals, there are also additives that might be used (along with the listed chemicals) such as: sugar, syrup and other agricultural bi-products (Ketcham et al., 1996). The application of chemicals on roads is made for three main purposes: preventing the formation of ice on roads (anti-icing), preventing the formation of a compacted snow layer (anti-compaction) and melting the ice (de-icing) (Shi and Fu, 2018). Road agencies in different countries establish how much salt should be spread on roads and how often snow should be mechanically removed.

The second strategy is called *winter road strategy*. This strategy allows a compacted snow and/or ice layer on the road surface. The aim of this strategy is to provide acceptable road driving conditions. It is typically used on roads having a lower LoS, for example secondary roads in urban areas. The typical winter maintenance operations for this winter strategy are: the mechanical compaction of snow and the spreading of either sand or other abrasives as friction enhancements.

The use of NaCl during winter is economically demanding for road agencies (Hanbali, 1994). For example, in recent years in Norway, more than 250,000 metric cubic tons of NaCl have been used during snowfalls on road infrastructures (Wåhlin, 2017). This large amount of salt is detrimental for water and vegetation lying alongside the road surface. It also causes corrosion in road vehicles as well as bicycles. Therefore, there is a growing desire among road agencies to optimize the use of salt on roads without compromising traffic safety. The optimization of salt involves using all three of its purposes: anti-icing, anti-compaction and de-icing. Since the majority of salt doses are spread during snowfalls, the focus of this thesis is on the optimization of salt for anti-compaction purposes. In order to do this, the minimum amount of salt that actively weakens snow, allowing in turn easier plowing, or salty snow, in a cohesionless state on road pavement must be understood.

The prevention of a built-up compacted snow layer, in accordance with the anti-compaction purpose, is an important task, especially during snowfalls. This compacted snow layer is a problem in temperatures fluctuating around the snow's melting point (Ketcham et al., 1996) where snow rapidly turns into ice, which is slippery and difficult to remove. Therefore, either prior to or during a snowfall's first moments, the salting truck spreads salt on roads. Once the salt has lain on the road pavement for a while, it partially melts the snow and creates a mixture of salty aqueous solution and solid snow particles. This mixture of salted snow creates a liquid content inside the snow, thereby making it weaker and more easily removable from the traffic load and/or plowing machine. In Norway, the chemical typically used during winter is Sodium Chloride (NaCl). In order to optimize the amount of NaCl used during snowfalls, the manner in which salt affects snow and tire-pavement interaction must be better understood. To my knowledge, the application of salt is mainly based on the experience of winter maintenance personnel and not scientifically based. While scientific literature exists regarding snow compression and tire pavement interaction on snow, there is a lack of knowledge on salted snow and its behavior during mechanical actions. This means that the use of salt might exceed the required amount, meaning that it might be possible to optimize the amount of salt used on roads during snowfalls.

The motivation behind writing this thesis is to reduce the amount of NaCl used on roads during snowfalls for anti-compaction purposes.

1.1 Research Objectives and methods

Snow is an extremely complex material (Colbeck, 1982) and has a wide range of mechanical properties. The presence of NaCl aqueous solution weakens the strength of the bonds between the ice particles (Wåhlin and Klein-Paste, 2015). Therefore, the weakened salted snow may be easily destroyed under the effect of car traffic or a snow plow. Recommended salt dosages on roads are experience based and not scientifically based. This means that increasing the knowledge on the effect of aqueous NaCl solution on snow might lead to a possible NaCl optimization. The complexity of the topic is tackled with an understanding as to how NaCl affects the mechanical properties of snow during mechanical actions; in these cases, snow compacts and intensifies the creation of a strongly compacted snow layer that is extremely slippery and difficult to remove.

The objective of this thesis is to increase understanding of salted snow's behavior and find out the minimum amount of NaCl aqueous solution that is needed on roads for anti-compaction purposes without compromising traffic safety.

In order to reach this objective, scientific knowledge of how NaCl aqueous solution affects the mechanical properties of snow under mechanical actions must be increased. In order to explore the objective, the following two research questions have been posed:

***RQ 1*:** How does diluted de-icer solution change the behavior of snow under the effect of compression?

RQ 2: What is the minimum amount of de-icer solution needed to sufficiently weaken the snow so that it will not become compacted under the compression of a tire?

The methodology developed in this thesis project is based on two laboratory studies and one field test. The laboratory studies investigate RQ1, and the field study investigates RQ2. The three studies have been published in three different manuscripts. The structure of the thesis as well as the content of each investigation and connection to the research questions are addressed in Figure 1. Additionally, each study listed in Figure 1 has been presented in a paper.

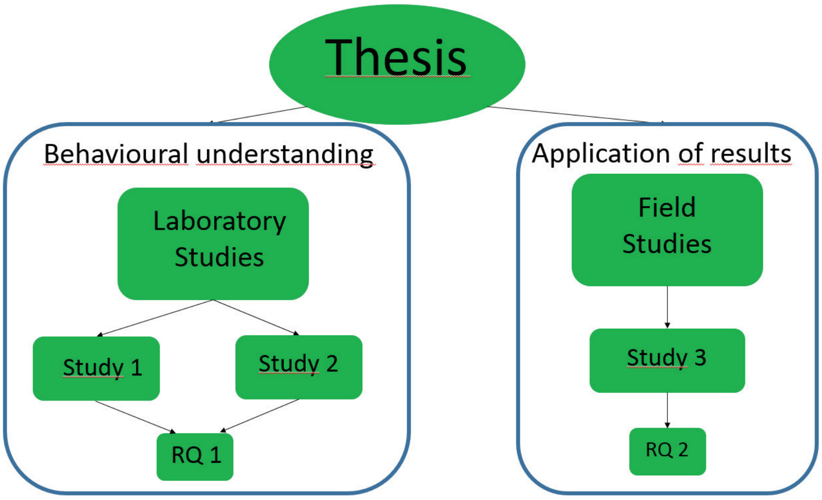


Figure 1 Thesis structure

1.2 Thesis structure

This thesis is divided into six chapters: Chapter 1 is the problem outline. Chapter 2 provides fundamental background information on winter maintenance, the use of NaCl on roads and its effect on snow along with relevant snow properties. Chapter 3 presents the methodology used during the project. Chapter 4 demonstrates the main results. While Chapter 5 contains a discussion of these results. Finally, conclusions and further works appear in Chapter 6. An appendix lists the published studies used throughout the entire PhD project.

1.3 Studies

1.3.1 *Laboratory studies and description of laboratory facilities*

The behavioral understanding of the NaCl aqueous solution mixed with ice particles is explored for two types of mechanical action: uniaxial compression and rolling compression.
The uniaxial compression, also known as the plate indentation test, is a typical and broadly accepted method for understanding how this material behaves under mechanical action once a plate sinks vertically inside the material. The second investigation aims to understand the behavior of the salted snow under the effect of rolling compression performed by a free-rolling pneumatic tire.

Paper 1

This paper presents an experimental investigation where the behavior of laboratory grown snow mixed with NaCl aqueous solution was investigated using a plate indentation test. A plate was used to vertically compress a mixture of snow and different amounts of NaCl aqueous solution. The compression was unconfined; therefore, the snow was able to be pushed aside and compressed under the effect of this mechanical action. The applied pressure on the snow was limited to 2.3 bars, approximately corresponding to the inflation tire pressure produced by a passenger car. The final density and loss of mass of salted snow was examined for different amounts of NaCl aqueous solution and different compression speeds. The results showed that higher amounts of NaCl aqueous solution produced a denser snow that flowed easier. The ability of the snow to compress, compact and flow as a function of the amount of NaCl aqueous solution was presented and discussed.

My contribution to this work was: data collection and analysis in addition to paper writing. Johan Wåhlin helped me with the design of the study, data analysis and paper writing. Alex Klein-Paste helped me with the study's design and commented on the manuscript. This study is published in:

> Giudici, H., Wåhlin, J., and Klein-Paste, A. 'Uniaxial Compression on Salted Snow' Tire Science and Technology, TSTCA, Vol. 46, No. 1, January–March 2018, pp. 16–26. doi: 10.2346/tire.18.460104.

Paper 2

This study was a follow-up to Study 1. In Study 2 the effects of NaCl aqueous solution on the densification, squeeze-out and compaction of snow is investigated after compression by a free-rolling tire. After looking into the densification, squeeze-out and compaction of snow, the manner in which tire pavement interaction is influenced by salt was described. This study used a newly built laboratory where a pneumatic tire could be rolled at high speeds over an asphalt pavement. The details of this laboratory setup is presented in Paper 3. Supported by Study 1, the findings of Study 2 increase knowledge about how the NaCl aqueous solution enhances the weakness of the NaCl solution-ice particle mixture under mechanical action. The main findings of this study are that snow containing aqueous solution compresses to a higher density, and more snow gets squeezed out of the contact region compared to fresh snow. Moreover, the compressed and compacted salted snow gets weaker whenever salt solution is present.

My personal contribution to this work was study design, data collection, data analysis and paper writing. Johan Wåhlin helped me with the study's development and paper writing. Alex Klein-Paste helped me during the results interpretation and manuscript preparation. This study has been submitted for publication

> Giudici H., Wåhlin J., and Klein-Paste A. "Tire-pavement interaction in contact with presence of salted snow: How an aqueous solution affects the compression, squeeze out and compaction of snow" Journal of Cold Region Engineering (accepted with minor revisions)

Paper 3

This paper presents the facilities developed and built for studying the tire-pavement interaction in the presence of snow and de-icers at the Winter Maintenance Research Group of the Norwegian University of Science and Technology. In this publication the Linear Analyser of Road Surface (LARS), a snow machine (Lumi) and a high-speed quality camera are described. The LARS apparatus offer a linear test of a free-rolling tire with a maximum constant speed of 40 km/h. The snow machine Lumi is based on a similar snow machine developed by the WSL Institute for Snow and Avalanche research (SLF) in Switzerland. Along with the facility description, this paper presents preliminary results of their combined use.

Alex Klein-Paste designed and developed the two facilities. Katja-Pauliina Rekila designed the Linear Analyser of the Road Surface. Mathis Dahl Fenre assist the design of LARS and built the snow machine Lumi. Alex Klein-Paste, Katja-Pauliina Rekila and Mathis Dahl Fenre provided comments on the manuscript. My contribution to this work was: final facility testing (in two stages: separate and combined use), development of video analysis, data collection, data analysis and paper writing.

This paper was presented at the XVth International Winter Road Congress, 20-23 February 2018, where it was selected as Best Paper in the category Young Professionals of the Congress and subsequently published in *Routes and Road* magazine.

> Giudici, H.., Fenre, M.D.., Klein-Paste, A.., Rekilä, K.P., 2017. A Technical Description of LARS and Lumi: Two Apparatus for Studying Tire-Pavement Interactions. Routes/Roads n. 375, pp. 49-54.

1.3.2 *Field Study*

Paper 4

This paper refers to Study 3 and extracts the laboratory investigation findings under field conditions. A test car drove multiple times at a constant speed of 20 km/h over snow that had been mixed with the NaCl aqueous solution mixture. The snow samples were photographed after 5, 10 and 20 passes, and a scraping test was performed in order to evaluate the strength of the compacted salted snow. The final study has two main conclusions: an aqueous solution content of 10 wt.% keeps the snow loose and easily removable from road traffic, and an aqueous solution of five wt.% weakens the snow substantially, allowing an easier mechanical removal of the snow mixture. The implications of these main conclusions on winter maintenance operations were presented.

My contribution to this work was: study design, data collection, data analysis and paper writing. Alex Klein-Paste helped me with the study design and paper writing. Johan Wåhlin helped me with the paper writing. This study has been submitted for publication:

> Giudici, H., Wåhlin, J., and Klein-Paste, A."The influence of aqueous solution on compacted snow: a field investigation" submitted to Journal of Cold Region Engineering (under review).

Chapter 2

Introduction

2.1 Winter Maintenance

The term winter maintenance, or snow and ice control, defines the collection of efforts made for keeping roads safe and highly mobile during winter (Klein-Paste and Dalen, 2018). Generally speaking, winter road maintenance is performed by implementing three strategies: bare road, winter road and closed road. The first strategy aims to restore clean pavement conditions as soon as possible, while the second guarantees acceptable driving conditions by allowing a compacted snow layer to remain on the road surface. Another possible strategy during wintertime is to close the road (but only when road users' mobility shifts to other roads).

The very complexity of a road network does not allow performing the same strategic maintenance over the entire road network. Therefore, road authorities have to determine priorities for different roads based on the expected level of service (LoS). Highways and city arteries are classified within the highest LoS due to their daily high traffic volume. Particularly in these cases, road authorities have to guarantee motorists' safe travel on any given day, 24 hours a day, all year around; therefore, the bare road strategy is applied here. For secondary LoS roads having moderate traffic volume and low average speeds, the winter maintenance strategy is applied. Regarding low LoS, including roads with an extremely low traffic volume or those used for seasonal purposes, roads are closed for the entire winter, and road users are obliged to plan their travels using other roads.

The optimal execution of a winter maintenance strategy relies on employing different winter maintenance operations. The most common of these are: mechanical snow removal, applying anti-icing or de-icing chemicals, friction enhancements (i.e. sanding) and monitoring of weather forecast and road surface conditions. Several transportation agencies provide various guidelines (Ketcham et al., 1996; Salt Institute, 2016) whose aims are to improve the winter maintenance practices.

For instance, mechanical snow removal, most commonly snow plowing, is performed according to the bare and winter road strategies on different types of roads. One of the principles suggested by (Minsk, 1998) for efficient snow removal is the principle of *being a bully by hitting the snow when it's down*. Snow must be removed as fast as possible before it becomes unsafe or impractical for road users. Effective snow removal can reduce the accident rates during winter (Salt Institute, 2016). The effectiveness of snow removal relies on the drivers' experience and plowing abilities. Snow removal efficiency is achieved by controlling the plowing parameters, such as the plow's speed or pattern (Klein-Paste and Dalen, 2018). To accomplish optimal snow removal, drivers should be experienced with both the road network and how the plowing action on the different road stretches should be approached. The time interval between the mechanical removal actions along the same stretch of road is called cycle-time. The typical cycle-time for mechanical removal in Norway is 1.5 hours (NPRA, 2014).

Next, friction enhancements consist of spreading sand or other abrasives on roads to improve traction. They are typically used on roads where snow is strongly compacted and are therefore part of the winter road strategy. In Scandinavian countries in particular, these sanding methods perform best at temperatures ranging from -1 °C to -12 °C (Norem, 2009). (Minsk, 1998) suggests three requirements for using abrasive materials for friction enhancements: 1) they should not be soluble, 2) the abrasive should have sharp edges in order to achieve a stronger grip on the compacted snow/ice road surface, 3) the particle sand size should not be lower than the coarse sand in order to avoid contributing to the PM_{10} pollution. There are two spreading methods for sand: dry sanding and warm wet sanding. The first method is relatively inexpensive. Loose, dry sand is spread onto the road, and this method is typicically used in temperatures close to 0 °C. The warm wet sand method consists of mixing the sand with hot water at 95 °C prior to spreading (Vaa, 2004). Using the warm wet sand method, causes the friction gain to last for a longer period of time. This method works well in reliably cold conditions where the temperature is approximately -8 °C (Norem, 2009).

The spreading of anti-icing or de-icing chemicals (referred to hereafter as “de-icers” or “salt”) is performed as part of the bare and winter road strategies. De-icers are used for preventing ice’s bonding to the road surface and melting the already compacted ice (or snow) on roads. In order to reach these goals, different chemicals and agricultural bi-products may be used. De-icers can be divided into chloride and non-chloride based categories. Sodium chloride, NaCl, is the most commonly used de-icer. There are in addition $MgCl_2$, magnesium chloride, and $CaCl_2$ calcium chloride (Ketcham et al., 1996). The most common non-chloride de-icers are: CMA, calcium magnesium acetate, and KCOOH, potassium formate (Minsk, 1998). All these de-icers have different abilities with respect to lowering the freezing point and levels of hygroscopic properties. ABP’s are most often used as additives to de-icers as they are thought to enhance the de-icer’s longevity on the road surface. All the de-icers lower both the freezing point and adhesion process of snow and road pavement. Perhaps most notably, even though de-icers work in the same way, their actual performance varies based on: effective working temperature, required amount, pavement persistency, cost duration, environmental and infrastructure impact. If choosing from among price, snow/ice melting performance, effect on infrastructure and environment, the most important factor is the price (Salt Institute, 2016). Therefore, the NaCl, being as it is the least expensive type of salt, is the one most often used. The focus of this thesis is on NaCl; indeed, no other types of salt have not been taken up for discussion in this dissertation.

There are four main methods of applying de-icers to roads: dry, pre-wetted, slurry and brine. Dry salting is performed by spreading solid salt on road pavement. This process is relatively cheap and works well on wet pavement as well as during precipitation, as it increases adhesion between the salt and road surface. While in the case of dry pavement, the distributed solid particles first bounce on top of and then blow off the road (Lysbakken, 2013, 2011). Therefore, using dry salt is not advisable when the pavement is dry. However, in the presence of moisture on the pavement, dry salt triggers the formation of an aqueous solution content (Ketcham et al., 1996) by dissolving in water or melting snow. Regarding the pre-wetted method, solidified salt is wet before being spread on the road surface. The wet salt adheres easily to the pavement, weakening the blowing off process (Lysbakken, 2013). When moist, the salt's solubility is faster; it also melts the snow/ice interfacial media faster. Pre-wetting also binds the smallest fraction of salt particles which would otherwise be lost as salt dust. Next, the term slurry is defined as pre-wetted, fine-grained salt that produces strong salt adhesion to the road surface. Slurry can be made by using either fine-grained salt or a cruncher on the spreader to reduce particle size. Finally, the brine method consists of having a high concentration of salt in water, which guarantees the highest level of adhesion by mixing a 20-23 wt.% solution of dissolved NaCl in water. This spreading method is highly effective for anti-icing purposes because it acts immediately and is able to melt thin hoarfrost. Nevertheless, in the presence of temperatures close to salt's eutectic point, salt does not work properly on roads. The ability to melt ice particles is ensured only through having temperatures higher than the eutectic point, as salt will not melt ice particles below this point.

Next, there are basically three different reasons to apply salt (or other de-icers) during road winter maintenance; these are known as anti-icing, anti-compaction, and de-icing

- *Anti-icing*:

  Anti-icing operations are performed to prevent the freezing of wet road surfaces or to prevent the formation of hoar frost (humid air that deposits on cold road surfaces). Anti-/de-icing chemical applications lower the freezing point of water. The freezing point of saline water depends on the salt concentrations (Haynes, 2014). Salt is applied to roads when the temperature is expected to drop below 0 °C. This measure is called pro-active. After having been warned by the weather forecast, road maintenance planners determine which anti-icing measures will be used prior to the temperature drops in order to prevent accidents. After these preventive measures have been determined, winter maintenance personnel put them into operation on all necessary roads.

- *Anti-compaction*:

  Anti-compaction operations are performed to prevent the formation of a compacted snow layer on road surfaces. This is a pro-active measure. Prior to, or during a snowfall's early stages, salt is spread on roads to prevent the snow from first compacting and then bonding strongly with the pavement. The amount of salt spread on road increases the presence of an amount of aqueous solution inside the snow. Based on the amount of this solution, the compacted snow has different behaviors and mechanical properties. In the presence of a high amount of aqueous solution, the compacted snow can splash off of tires, or is otherwise easily removable, facilitating close contact between the tire and road pavement.

- *De-icing*:

  De-icing operations are performed for removing the formed ice or compacted snow on roads. This is a re-active measure. When spread on a compacted layer of snow or ice, salt starts to melt. The meltwater dilutes the salt until its melting capacity is reached (Nilssen, 2017). The salt spread on thin ice layers is able to melt the entire layer. On the other hand, in case the compacted snow layer is substantially thicker, the melting will only occur in localized areas around the salt particles, causing the snow/ice layer to merely weaken instead of fully melting. These cases require mechanical action, such as scraping, to effectively remove the ice. The higher the magnitude of the compacted snow layer, the higher the required amount of salt is needed. Typically, de-icing requires a higher dosage of salt (compared to wet road prevention) to freeze (Klein-Paste and Wåhlin, 2013). Therefore, the customary application of salt varies depending on the temperature, and amount of ice that needs to melt (Minsk, 1998). To illustrate this point, let us assume a case where there is 5 kg/m^2 compacted snow on the road that has a temperature of -2 °C. The required amount of salt able to melt the entire layer of compacted snow at this temperature is approximately 170 g/m^2 (Nilssen, 2017). However, for anti-compaction purposes, the typical salting application rate ranges between 5 – 20 g/ m^2 (NPRA, 2017). Further, the de-icing salting application might spread the required salt in order to assist mechanical snow removal. In such cases, the salt melts the compacted snow, or ice, enough to ensure that the plow's blade will both dig into and cut up the compacted snow.

2.2 Sodium Chloride as freezing point depressant

The freezing point of water is depressed when ions or salt particles are dissolved in the solution, and is strongly dependent on the amount of dissolved ions or salt particles (Atkins and De Paula, 2013). At a given temperature, the amount of salt particles, hence its concentration, lowers the freezing point to the eutectic point of the NaCl; at this point, the salt's solubility is reached, and it is not possible to dissolve more salt. The correlation between the salt concentration and temperature is given in Figure 2 by the phase diagram (Haynes, 2014), which shows the possible state combination of H_2O and NaCl when mixed with different concentration and temperatures. This process ends with a salt concentration of 23 wt.% and a temperature of -21 °C. This point is the eutectic point. Above the eutectic point, two lines divide the diagram into three parts. These two lines are the freezing curve (defining the co-existence between the liquid and solid state of the aqueous solution and ice particles) and the solubility curve (defining the degree of saturation of the diluted solution). The phase diagram shows four essential areas:

- The area outlined between the freezing curve and solubility curve describes the combination of NaCl concentration and temperature, which allows the $H_2O_{(l)}$ + $NaCl_{(aq)}$ to remain in a liquid state;
- The area outlined between the freezing curve and temperature of -21 °C describes that the concentration of NaCl does not ensure the co-existence of any solid and liquid state between H_2O and NaCl; therefore, the H_2O begins to freeze until it reaches a temperature of -21 °C, where the snow does not work any longer.
- The area outlined between the solubility curve and temperature of -21 °C describes that the concentration of NaCl is oversaturated in the solution; therefore, solid NaCl is present.
- For temperatures lower than the eutectic point, the NaCl does not work any longer; therefore, H_2O and NaCl remain in a solid state.

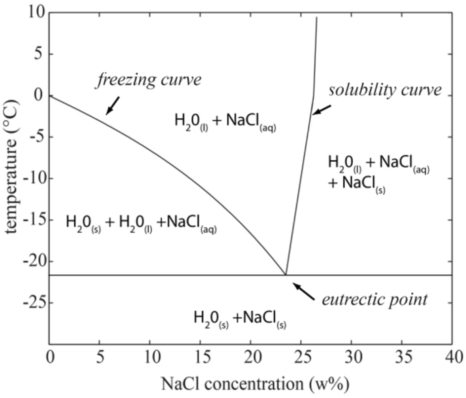


Figure 2 Phase diagram with the different phases denoted. The subscripts (l), (s), and (a1) refer to liquid, solid and dissolved, respectively

In the presence of wet pavement: if the temperature is expected to drop to -2 °C, a NaCl concentration of 3.33 wt.% creates a NaCl solution at liquidus concentration on the pavement. At this concentration and in case of a snowfall, solid ice particles and diluted NaCl solution can coexist.

2.3 Snow

The loose dendritic snow crystal is originally formed in clouds, which are formed by microscopically small water droplets nucleated on dust particles. When the temperature of the cloud is at -10 °C, these small water droplets begin to freeze. The frozen droplets attract water vapor from the air, causing the snow crystal to grow larger. Once the crystal is formed, the interaction caused by the air vapor being close to the snow particle alters the crystal's shape and geometrical pattern (Libbrecht, 2005). As the snow crystal grows, it increases in mass and starts to fall towards the ground. The typical density of newly fallen snow is approximately 50-60 kg/m^3 (Minsk, 1998)$^.$. Under the effect of a rolling tire, the snow is compressed. Experiments on how the compressive load influences the behavior of snow under stress, and how snow structure changes while mechanical actions are applied to it, are provided by (Abele and Gow, 1976, 1975; Voitkovsky et al., 1975). When compressed, the crystal breaks up its shape and begins to accumulate in the snow voids, increasing the snow density. Generally speaking, the ice particles are close to their melting temperature and are therefore thermodynamically active. The ice crystal metamorphism leads to a variety in snow microstructures concerning properties such as size, shape and geometrical pattern (Fierz et al., 2009; Kinosita et al., 1970). This process leads to an increase in ice crystals' contact bonding, which in turns leads to higher snow strength. More specifically, the increase in contact between ice crystals also increases their ability to form bonds with other snow crystals. This process is called sintering (Kuroiwa, 1961). Because the snow is so close its melting point, bonds start to form between the crystals due to this process; thereafter, the snow compacts.

Yet in the presence of liquid water, the snow properties change considerably. For instance, the presence of the liquid content enhances the snow's ability to be compressed under applied weight (Wåhlin, 2014). The presence of liquid content can accelerate snow densification (Wakahama, 1975). As concerns compressed dry snow, the bonds between ice particles create a high level of friction, enhancing the mechanical interlocking between the ice grains. On the other hand, the presence of liquid content between ice particles decreases the friction between ice particles, lowering in turn the mechanical interlocking mechanism. This leads to a higher amount of ice particles and liquid content that is in contact and compressed. Therefore, in the presence of liquid content, higher snow compressibility leads to higher snow densification. The resulting snow compression, densification and sintering processes cause the creation of a compacted snow layer.

2.4 The effect of aqueous NaCl solution on snow

The purpose of the anti-compaction measure is to prevent the formation of a compacted snow layer. The first snow that falls on a salted road will melt. The newly created meltwater dilutes the salt until it reaches the equilibrium concentration at a given temperature and at this point, the salt's melting capacity has been reached. When it continues to snow, the diluted salt gets mixed with / absorbed by the snow that accumulates on the road. The more salt is present in the snow, the higher the aqueous solution content. Hence, it is expected that the salted snow will display more slush-like behavior. In the literature, studies on how aqueous NaCl solution influence the ice crystal bonding have been investigated by (Wåhlin, 2014; Wåhlin et al., 2016; Wåhlin et al., 2014; Wåhlin and Klein-Paste, 2015). The main conclusions of these studies are that the aqueous NaCl solution affects the snow mechanical properties, reducing the overall strength of the compacted snow. Yet when using a different amount of solution content, salted snow displays an entire range of properties. Figure 3 illustrates the reduction of penetration hardness, which is a resistance force encountered by a cone of defined geometry as a function of added salt content (Wåhlin and Klein-Paste, 2015).

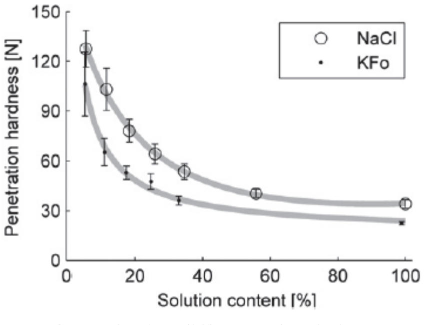


Figure 3 Penetration hardness of snow @-6°C having different salt solution content levels (Wåhlin and Klein-Paste, 2015). Reproduced with permission of the Journal of Cold Region Science and Technology.

Aqueous sodium chloride solution has a great weakening effect on compacted snow, even though it does not melt completely (Wåhlin, 2014). The aqueous solution also plays a role in the physics of ice, as the presence of salt lowers ice cohesion (Wåhlin et al., 2016). In ice grain-grain contact, an NaCl aqueous solution increases the weakness between the grains (Wåhlin, 2014). According to (Wåhlin, 2014), the behavior of salty snow and its mechanical properties is predictable and does not suddenly change. This means that it is possible for snow to accumulate on roads without compromising the traffic safety of roads' infrastructure. However, it remains to be proven how much salt/aqueous solution is required to affect tire-pavement interaction under snowy conditions.

To my knowledge, the literature pertaining to the use of chemicals for anti-compaction purposes is limited to (Schaerer, 1970). (Schaerer, 1970) performed a field study in which he observed three different snow behaviors based on the amount of chemical solution applied to roads. These observations include the following:

- Slushy snow: with a chemical spreading rate able to produce at least 30 wt.% of liquid content inside the snow, the slushy snow easily splashes off roads under the effect of the traffic;
- Loose, or cohesionless, snow: with a chemical spreading rate able to produce a liquid content ranging between the 15 wt.% and 30 wt.%, the mixture of snow and liquid content remains cohesionless on roads;
- Compacted snow: with a de-icing solution able to create a liquid content lower than 15 wt.%

However, the work of (Schaerer, 1970) failed to consider several parameters such as: air and road pavement surface, chemical solution and snow density, traffic load and tire type with relative inflation pressure. Thus, it is not easy to interpret his results. In order to answer the question regarding *what is the minimum amount of NaCl aqueous solution needed on roads for anti-compaction purpose without compromising the traffic safety*, a more detailed description of the tire pavement interaction in the presence of snow mixed with NaCl aqueous solution is required.

2.5 Tire pavement interaction in presence of salted snow

Tire-pavement interaction is a complex phenomenon that involves different physical process acting simultaneously (Moore, 1975). The presence of snow, ice, water, sand and chemicals makes the interaction even more complex (Klein-Paste, 2007). The system consisting of (1) the tire, (2) the pavement, (3) the interfacial medium and (4) the environment, is called the tribosystem. The interactions within this system determine how much shear force can be transmitted to the pavement (Norheim et al., 2001). These shear forces are needed to ensure safe vehicle handling (acceleration, braking and steering).

When a pneumatic tire rolls (or brakes) on the interfacial medium, the latter can squeeze and/or compact under the compression effect of the rolling tire. In the presence of incompressible fluid film layers, the intimate contact between tire rubber treads and road asperities can disappear with a rapid spread of interfacial medium in the contact area between rubber treads and road asperities

(Moore, 1965). This lack of contact in incompressible fluid covered surface conditions is called hydroplaning. Historically, the hydroplaning phenomenon was first investigated for aircraft with the arrival of jet engines, which increased take-off and landings speeds. The National Aeronautics and Space Administration (NASA) performed several experimental investigations, such as (Horne, 1968, 1969; Horne and Dreher, 1963). The aim was to relate the influence of tire skidding/rolling on hydroplaning conditions based on full-scale tests. When a hydroplaning condition prevails, there is significant loss of braking traction and steering control, the combination of which may result in fatal accidents (Kumar et al., 2012). The tire speed at which the loss of braking and steering control of a vehicle occurs is called *hydroplaning speed* (Browne et al., 1972). It is common to distinguish two kinds of hydroplaning: *dynamic hydroplaning* and *viscous hydroplaning.* The total *dynamic hydroplaning* of a pneumatic tire found its explanation for the inertia of the fluid interacting with the tire (Browne et al., 1972). In the presence of a tire speed higher than the hydroplaning speed, the fluid film builds up a hydrodynamic pressure distribution able to constantly support the applied load (Browne et al., 1972) and fully separate the tire from the road surface. However, in the literature there is another hydroplaning explanation called *viscous hydroplaning*. Let us assume a case where an incompressible fluid is laid on the road pavement between road surface micro-asperities. If the pneumatic rolling speed is lower than the hydroplaning speed, there is intimate contact between the pneumatic tread pattern and road asperities. Meanwhile, if the pneumatic rolling speed is higher than the hydroplaning speed due to viscous shearing, the fluid interposed between the road asperities moves from depression to depression in the road pavement, accumulating magnitude. When the fluid's magnitude is higher than the road asperities' height, the fluid prevents close contact between pneumatic tread pattern and road asperities (Moore, 1967). As a result of this process, the tire loosens its grip on the pavement, lowering the controllability of the vehicle. Therefore, the incompressible fluid in contact with the rolling tire forms a hydrodynamic pressure in the fluid reacting on the surface and on the tire. Due to this pressure, the tire floats on the fluid covered wedge. A wedge of fluid progressively penetrates the tire-ground contact region, and a hydrodynamic lift tends to detach the tire footprint from the surface (Horne and Dreher, 1963). At this point true contact between the tire-tread elements and the road surface is established only at the rear of the nominal contact length. This is because the forward part of the contact area exhibits a squeezing-film between the tire band and the road surface, as the former attempts to displace the fluid (Moore, 1965). Squeezing out the fluid, it increases the footprint on the tire pavement and relative grip. Several aspects can influence the squeezing out process, such as: tire speed, tire tread pattern, roughness of the pavement surface and water film thickness. In recent decades, there has been an extensive growth in the literature investigating the hydroplaning phenomenon and focusing on tire performance (Fwa et al., 2010, 2009, Ong and Fwa, 2010, 2007). In case the tire rolls at a speed lower than the hydroplaning speed, the fluid is squeezed out of the rubber tread-road surface contact area.

Hydroplaning only occurs on incompressible media, because compressible media, such as snow, would rather be compacted than squeezed out. A rolling (or braking) tire on snow compresses the snow. Due to the tire's compression effect, the snow begins to densify and compact. The tire traction on snow relies on the transmitted forces between the tread pattern-snow interface. In pure rolling conditions, adhesion (or cohesion, in cases where the tire is covered with snow) and the mechanical interlocking between rubber treads-snow surfaces provide tire traction (Browne, 1974). The rubber treads penetrate the loose snow and shear the compacted snow ridge off (Ripka et al., 2012). The interaction between tire rubber block and snow is also discussed by (Mundl et al., 1997). Therefore, the rubber treads penetrate in the snow until the compressed snow is fully compacted and able to sustain the applied load. Due to the exerted high-pressure levels, the rubber treads interlock with the compressed and compacted snow, enhancing the grip, and friction is created. In optimal conditions, the tire has to exhibit good self-cleaning properties of its rubber treads and grooves from the previously compressed snow (Browne, 1974). On the other hand, the ability of the tire rubber to penetrate the snow and form a grip is highly dependent on the properties of snow at the interface with the rubber treads. For instance, old or icy snow makes the rubber tread penetration more difficult compared to loose snow. Hence, in dynamic tire interaction, a solid understanding of snow properties, such as interfacial medium, are critical for understanding tire traction on snow- covered roads (Browne, 1974). (Ripka et al., 2012) define the importance of having a proper match between tire and weather conditions, shifting the importance of the interaction to the tire performances. Looking at it from a snow-centered view, one of the recent studies defining the tire-snow compression is provided by (Lee, 2009). Using a pressure-sinkage model (Lee, 2009) follow the tire-terrain approach for describing tire-snow interaction. The study defines three compression/compaction zones for fresh snow at different depths. The three zones identified by the study are: elastic, yielding and densification zone. Respectively, when pressure is applied to the upper layer, volume rearrangement occurs with no effect on the lower snow layers (elastic zone), increasing the compression of the ice particles' rearrangement in the bottom snow layer (yielding zone). When compression is high, the ice particles dislocate the entire structure, filling all the snow voids and increasing the contact between ice bonds, thereby forming a denser configuration (densification zone).

Salted snow consists of a mixture of ice particles, air and salt solution. The concentration of this solution reaches equilibrium at a given temperature. Undissolved salt or highly concentrated salt solution melts snow, creating an aqueous solution content inside the snow. The tire-pavement interaction in the presence of snow and NaCl aqueous solution depends on the amount of the solution. By varying the solution content, the consistency of the interfacial medium may be changed. In the presence of NaCl aqueous solution and under compression, the air in the pore space of the compressed interfacial medium is gradually replaced by the aqueous solution. The higher the NaCl aqueous solution content, the higher is the amount of non-compressible fluid inside the interfacial medium. At the end of this process, the pore spaces of the compressed interfacial medium are fully filled with aqueous solution, and the snow becomes a slush of ice particles surrounded by solution Based on its non-compressible nature, the aqueous solution prevents the compression and thereby enhances the squeezing out of the interfacial medium. The composition of the interfacial medium is the key parameter that connects the hydroplaning effect and tire-snow interaction (therefore the snow compaction process). Based on the amount of non-compressible fluid, the interfacial medium has lower compressibility. In such cases, the higher the non-compressible fluid content, the more the squeeze-out process is favored. On the other hand, in the presence of dry snow, the snow pore space becomes filled with ice grains that increase the bonding between ice particles, favoring the compaction of a newly formed layer.

To my knowledge, there is a lack of scientific understanding regarding tire-pavement interaction in the presence of snow mixed with an NaCl aqueous solution, in particular how the solution content affects the compressibility, flow (squeeze-out) and compaction of salted snow changes. Therefore, tire- pavement interaction in the presence of snow mixed with an NaCl aqueous solution is the tribosystem at which this study is aimed.

Chapter 3

Research Methods

The experimental approach carried out in this thesis is divided in two parts: understanding the behavior of salted snow and applying this understanding to field conditions. This comprehension is based on two laboratory studies, the latter of which was performed in the field. This chapter describes the completed studies' research methodology. The indoor studies were made possible due to the facilities located at the winter maintenance center of the Civil and Environmental Engineering Department at the Norwegian University of Science and Technology.

The principle of the three studies remained the same throughout their completion: an NaCl aqueous solution content was first mixed with snow (laboratory-grown snow or natural snow) and then compressed uniaxially (one free-rolling tire). At this point, the salted snow became compressed and dense. The temperatures were always selected close to the snow's melting point, 0 °C, because at these temperatures compressed natural snow quickly compacts into a hard, strong compacted snow layer (Minsk, 1998). During the first study it was observed that the strength of the compressed salted snow varied greatly depending on the solution content. Therefore, mechanical testing of the compressed and compacted salted snow was conducted in Study 2 and Study 3. In the absence of a widely accepted method for assessing the strength of the compacted salted snow, a Snow Strength Test was performed in Study 2, and a scraping test was performed in Study 3.

In order to describe the ability of the salted snow to be compressed, compacted and flowing when the mechanical tire load was applied on it, three terms were used: compressibility, compactibility (Odeku, 2007) and flowability (Giudici et al., 2018). The salted snow's compressibility refers to its ability to vary its volume and thus increase its density. Compactibility refers to the snow's ability to form bonds that will become stronger under the mechanical action. Flowability is the ability to flow under the same mechanical action, and it is an important parameter when snow is mixed with an NaCl aqueous solution content.

3.1 NaCl aqueous solutions

In order to prevent the snow from melting or the solution from freezing, the NaCl aqueous solution was prepared in such a manner that it would remain in an equilibrium state (Haynes, 2014) for the laboratory studies and approximately this state for the field study: the NaCl solution was therefore prepared with a concentration of 3.33 wt.% of NaCl in order to be in an equilibrium state at a temperature of -2 °C. A more concentrated solution would melt until becoming diluted by meltwater so that it would return to to 3.33 wt.% at a temperature of -2 °C. Any weaker solution than 3.33 wt.% would partially freeze. However, in this case only the water molecules would freeze, causing a rise in concentration up to the original equilibrium concentration (3.33 wt.% at a temperature of -2 °C), in this way there were no melting or freezing ice particles in the liquid NaCl. The NaCl aqueous solution content levels used during the three investigations are shown in Table 1. For example, an aqueous solution content of 10 wt.% means that the 10 wt.% of the total snow testing weight is composed of NaCl aqueous solution. Notably, in the laboratory studies it was possible to prevent temperature fluctuations, thereby controlling that the aqueous NaCl solution remained at equilibrium. In contrast, the field study conditions were different due to the unpredictability of the air temperature.

Table 1 NaCl aqueous solution content used in the three investigations.

NaCl aqueous solution content (wt.%)	Experiment 1	Experiment 2	Experiment 3
0	O	O	O
5	O		O
10	O	O	O
20	O	O	O
40	O	O	O

In the papers written during this thesis project, the aqueous NaCl solution was given three different names. In Study 1 the NaCl solution was called Liquid Water Content (LWC), defined as the weight percentage derived from the weight of the total testing mass “wt.%”. In Study 2, the NaCl solution was defined as Diluted Solution Content (DSC) and calculated in “wt.%”. Finally, in Study 3, it was defined as the Solution Content (SC) calculated in “wt.%”.

3.2 Snow preparation

The continuous metamorphical state of snow makes the testing of a specific snowflake rather complicated because of its specific geometrical shape, and it is for this reason laboratory-grown snow was adopted. Yet when using this snow, it was possible to control the test snow’s geometrical shape, so this method was used for the two laboratory studies. According to the international snow classification provided by (Fierz et al., 2009), laboratory-grown snow is fully comparable with natural snow, and was produced at a temperature of -20 °C and tested. (Wåhlin et al., 2014) describe the snow maker used during Study 1 and an improved version, the snow maker Lumi (described in Paper 3), being used in Study 2. Both machines utilize the principle of (Schleef et al., 2014), an already existing snow machine. Laboratory-grown snow as well as different grain shapes are shown in Figure 4.

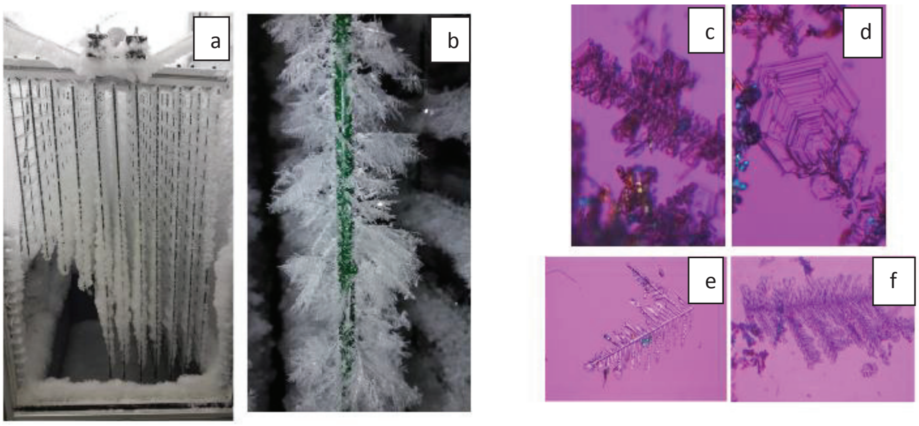


Figure 4 a)-b) Laboratory-grown snow from the snow maker Lumi. c)-d)-e)-f) laboratory-grown ice crystals from Lumi observed using a polarized microscope. Reproduced with the permission of Routes/Road Magazine

Figure 4 a)-b) shows the snow produced by Lumi. Figure 4 c)-d)-e)-f) shows ice crystals created by Lumi and observed using a polarized microscope. The geometrical shape of the ice crystals is influenced by the temperature gradient between the water chambers and cold room temperature.

For the field study and in order to re-create realistic outdoor conditions, naturally harvested snow was used. Loose snow was harvested during a snowfall in February, 2018. A total amount of 120 kg was collected with a shovel and placed into plastic bags, which were then stored in a cold room at a temperature of -20 °C. Figure 5 shows the harvested snow.

Figure 5 Naturally harvested snow

3.3 Sample Preparation

The snow was taken from the snow maker and placed into small boxes. Based on the NaCl solution content aimed at testing this snow, different amounts of solution were placed into the same small boxes along with the snow. These boxes were then vigorously shaken for several minutes.

Eq. 1 shows the definition of concentration in weight percent. Based on Eq. 1, it was possible to calculate how much NaCl aqueous solution mass was required in order to test the desired solution content inside the testing snow.

$$NaCl\ Aqueous\ Solution\ [\%] = \frac{m_{sol}}{m_{sol} + m_{snow}}\ x\ 100\ (1)$$

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

3.4 Snow compression

After preparing the test snow, salted snow samples were compressed under uniaxial compression, a free rolling tire, and winter tires, thereby causing the salted snow to become compressed and dense. In order to understand changes in snow compression and compaction using different solution content, I considered two different densities in this thesis: total density and dry density, respectively. Total density refers to the total amount of ice particles and solution content inside the testing sample divided by the testing volume. The total density is calculated by Eq. 2:

$$\rho = \frac{m_{TOT}}{V_{TOT}} \quad (2)$$

where:

m_{TOT} is the total test mass (amount of ice particles and liquid content) [g];
V_{TOT} is the initial total test volume [cm^3].

Dry density refers to the amount of dry ice particles inside the test sample divided by the test volume. Before calculating the dry density, the dry mass must be calculated. Eq. 3 shows the dry mass calculation:

$$m_{Dry} = m_{TOT}\, x \,\frac{(100 - Liquid\ Content)}{100}\ [g] \quad (3)$$

where:

The m_{TOT} is the total snow mass in grams, including liquid content [g];

Liquid Content is the amount of NaCl aqueous solution expressed in weight concentration [%].

After calculating the dry mass, it was possible to calculate the dry density as shown in Eq. 4:

$$\rho_{dry} = \frac{m_{dry}}{V_{TOT}} \quad (4)$$

where:

m_{dry} is the dry mass (only ice particles)

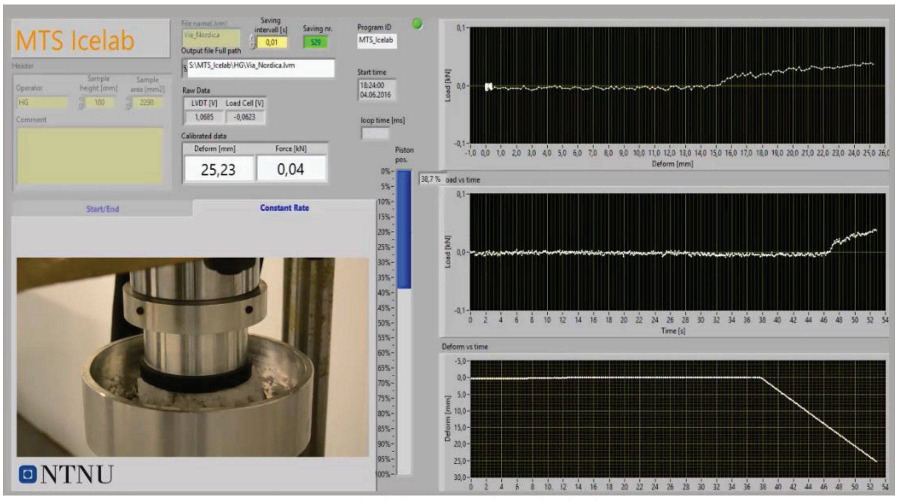
V_{TOT} is the total test volume

ρ_{dry} is the dry density

The total and dry densities were calculated before and after compression and had initially been called initial total density and initial dry density in addition to final total density and final dry density. During the three studies, an assumption was made: the NaCl aqueous solution content does not change during compression. This assumption was essential for calculating with Eq. 4 the initial and final dry mass with relative density.

3.4.1 *Study 1*

Once the desired test snow was prepared and ready to test, it was placed above an asphalt plate and constantly compressed using an MTS piston. As the piston started to move, it recorded the forces, the load on the plate as well as this plate's displacement. The test ended when the applied forces reached 2.3 bars. Once the desired test snow was ready for testing, it was placed into the mold, a plexiglass cylinder having a diameter of 12 cm and height of 4 cm. The test snow was weighted before and after placing it into the mold, as by doing this, it was possible to determine the test mass and calculate the test snow's density. Figure 6 shows the testing set-up and the data recording.



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Saving intervall [s]: 0,01
Saving nr.: 529
Program ID: MTS_Icelab
Output file Full path: S:\MTS_Icelab\HG\Via_Nordica.lvm
Start time: 18:24:00 04.06.2016
Operator: HG
Sample height [mm]: 100
Sample area [mm2]: 2290
Raw Data: LVDT [V] 1,0685; Load Cell [V] -0,0623
Calibrated data: Deform [mm] 25,23; Force [kN] 0,04
Piston pos.: 38,7 %

Figure 6 Uniaxial compression of salted snow

After the compression phase was over, the snow pushed aside under the effect of this compression was classified as material loss during the sinkage with the result that the mass after compression was first weighed and then subtracted from the initial test mass. Afterwards, the final dry snow density was calculated.

3.4.2 *Study 2*

As a follow-up to Study 1, Study 2 studied the effect of rolling compression on the test snow, and for this particular study, the Linear Analyzer of Road Surface (LARS) was used. The linear testing apparatus consisted of a free rolling or braking tire that was able to run up to a maximum of 10 m/s over a length of 8 m in a cold laboratory. Figure 7 describes the components of the linear test track.

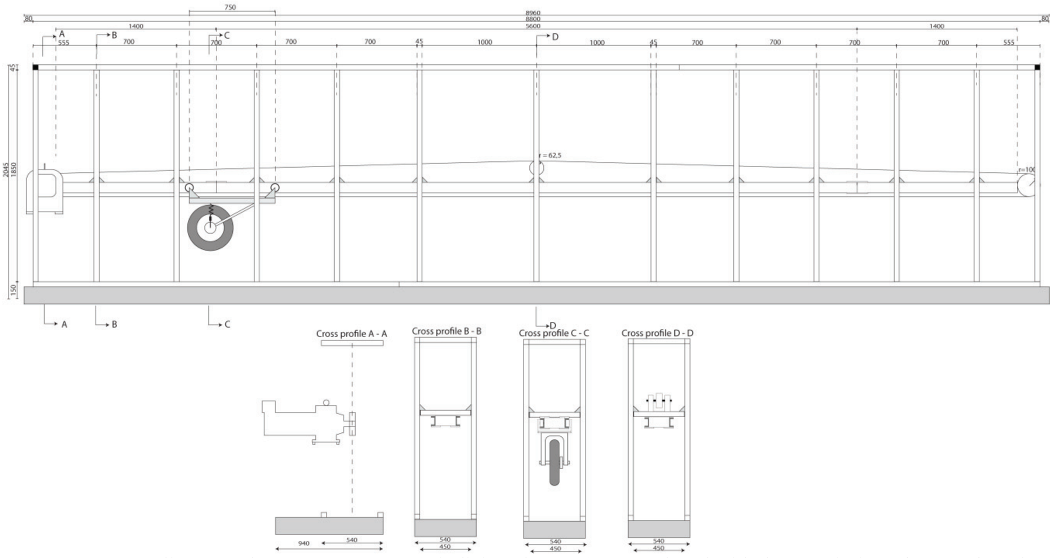

Figure 7 LARS linear track apparatus source (Giudici et al., 2017). Reproduced with the permission of Routes/Road Magazine

A test tire is mounted on a sledge that is able to move transversally through the entire length of the test apparatus. When activated, the test tire starts running, accelerating to the desired test speed within the first 3 meters. It runs at this speed for 2 m; afterwards, it decelerates, reaching the steady position. Once the test has ended, the tire returns to its original position, allowing a new test. The linear apparatus is also equipped with a digital high-speed camera, a Phantom VEO 410L, which is able to record videos at a maximum of 6100 fps with 1280x800 pixel resolution. Then, from the captured motion, the camera is able to extract measurements reliably and repeatedly as shown in Paper 3.The extracted measurements from the captured videos allow the measurement of the test snow's height during the rolling compression, which in turn allows the calculation of the compressed snow's volume in relation to the test snow's density. Figure 8 shows an illustration of the capture motion of the tire pavement interaction in the presence of water and snow.

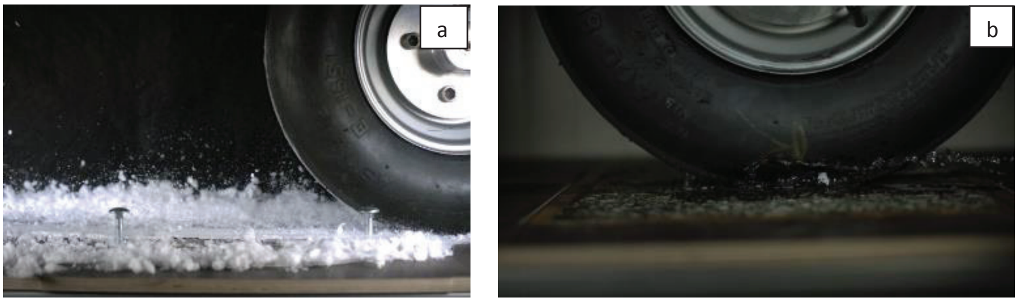

Figure 8 a) Tire pavement interaction in dry snow conditions b) tire pavement interaction in wet conditions

The principle of the testing procedure for the laboratory experiments was the same: Once the desired test snow was ready to be tested, it was placed into the molded wood frame measuring 6 cm in width, 6 cm in length and 5 cm in height. The snow was weighed before and after placing it into its mold because this made it possible to determine the mass and calculate the initial snow density. After the rolling test was finished, the snow that had been pushed aside under the effect of the compression was measured and classified as material loss or squeeze-out. The mass of snow that was squeezed out was collected and weighed. Subtracting the material loss from the initial testing mass produced the mass of compressed snow in the wheel track. Each test was documented using a digital high-speed camera, the Phantom VEO 410L. The camera recorded the tire motion, using 2000 films per second at 1280x800 pixel resolution. While the tire was compressing the snow, the height of the compacted snow layer was measured from the captured video through which it was possible to track a reference point mounted on the arm connecting the tire and moving sledge. The reference point was tracked for the entire video; hence before, during and after compression. The reference point is shown in Figure 9 by the red square.

Figure 9 Tracked reference point for calculating the snow's height

The y-pixel of the reference point provides a measure of change in the height of the arm during the entire motion sequence, including while the tire rolls over the test snow. The height of the compressed snow was calculated by Eq. 5:

$$h_C = y_0 - y_i \quad (5)$$

Where: h_c is the height of compressed snow, y_0 is the height, in pixels, of the reference point before compression, and y_i is the continuous y-pixels measurement of the tracked point.

The methodology developed in this investigation provides an accuracy level of +/- 1 pixel, corresponding to +/- 0.31 mm/pixel. The reliability and repeatability of the camera measurements are described in Paper 3. After having measured the height of the compressed snow, it was possible to calculate the final test volume by multiplying the area of the compressed snow by the measured height (h_C) so that the final dry density was calculated. Initial and final dry snow density was calculated using the Eq. 4. Figure 10 illustrates the compression of a snow sample.

Figure 10 Snow sample before the test (a), during compression (b), after compression (c)

Mechanical testing of compressed snow

During Study 1, I observed that the salted snow having a high NaCl solution was weak after being compressed. Nevertheless, I did not quantify how weak the salted snow actually was. For this reason and during Study 2, part of the test snow aimed to assess the strength of the compacted snow based on the amount of aqueous NaCl solution inside the test snow. Due to the absence of a suitable established method for quantifying the snow's strength, the decision was made to develop it. The test was called the Snow Strength Test. A Skid Resistance test (ASTM, 2013) was adapted to imitate the mechanical traffic load. A rubber block, 75 mm in width and 25 mm in length, was mounted on the pendulum. Once released, the pendulum dumped a load on the compacted salty snow. The pendulum test aimed to describe the strength level of the test snow. The test was performed 5 times on each test snow sample. Paper 2 describes the Snow Strength test in detail. Comparing the test area both before and after the pendulum test, it was possible to estimate the fraction of compacted snow remaining on the asphalt and therefore not detached by the applied load of the pendulum. A Strength Index (SI) characterized the snow's strength level after the test. The Strength Index (SI) was calculated as shown in Eq. 6:

$$SI\,[\%] = \left(1 - \frac{BAA}{TA}\right) x\,100 \quad (6)$$

Where BAA is Bare Asphalt Area cm^2, TA is Total Area cm^2.

High SI defines a strong resistance by the compacted snow against the pendulum's detachment movement. On the other hand, low SI defines the compacted snow's easy removability.

The higher the SI, the higher is the compacted snow's strength level; on the other hand, the lower the SI, the weaker is the test snow. Figure 11 shows a typical result of the snow strength test for the different amounts of aqueous NaCl solution that were tested.

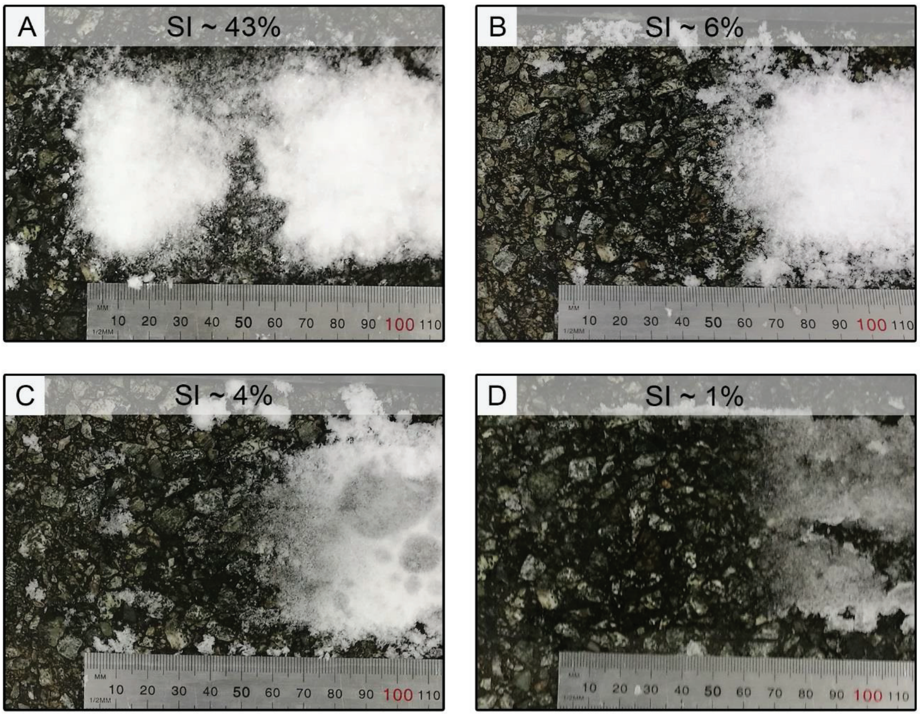

Figure 11 Typical pictures and strength index (SI) after the snow strength test for SC=0 % (a) SC=10 % (b) SC=20 % (c) SC=40 % (d)

3.4.3 *Study 3*

The third experiment was conducted between February and March 2018. These experiments were conducted by using a Mercedes Benz Vito equipped with 4 studded Nokian Hakkapellitta 7 SUV 215/65R16 as tires. The rubber hardness level ranged between 62 and 70 (ASTM, 2015). The inflation pressure inside the tire was 200 kPa. The day before the test, the pavement was rinsed off with water in order to remove any chemical residuals after which the pavement was lit with a flame torch in order to prevent any ice formation. The pavement was left to cool down overnight before testing day. The test area was located in a parking lot close to the Winter Maintenance Research Lab facility. The shade from the building covered the entire testing site area; hence the testing area was not exposed to solar radius. The test car drove multiple times over snow samples containing various amounts of NaCl aqueous solution content. The compacted test snow was photographed and visually inspected after five and twenty vehicle passes, respectively. A scraping test using a metal blade was performed on the remaining compacted snow. The five snow samples containing diverse solutions were placed on the asphalt. To avoid cross-contamination between samples, the 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.

After having been mixed, the test salted snow was placed into a wooden frame of 30x30x3 cm^3 located on the treated asphalt pavement. The test snow was accurately placed inside the wooden frame without becoming compacted. By increasing the amount of NaCl aqueous solution inside the test snow, the initial test snow and density increased. The density was measured for each test, and the average and standard deviation was calculated. Table 2 shows the average density and standard deviation for the test snow.

Table 2 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

Before the test, the wooden frame was removed, and the salty snow was ready to be tested.

Five snow samples using different amounts of NaCl aqueous solution content were placed on the asphalt. Two samples were placed in front of both tires at a distance of 90 cm, and the fifth snow test was placed 9 meters in front of the other four test snow samples. The distance between each amount of test snow was chosen in order to minimize contamination between different samples. Density and air temperature were recorded before each test day so that the test car would drive at a speed of 20 km/h on the test snow. The car drove in one direction: from test snow having an NaCl aqueous solution content 0 wt.% to 40 wt.%. Both the front and rear tires drove on top of the samples during each test. Figure 12 shows the placement of the samples prior to testing.

Figure 12 Placement of snow sample (marked in red) prior to testing

After the car drove on top of it, the snow samples were compressed, compacted and/or squeezed out. Observations made through taking photographs of the compacted salty snow were undertaken after five and twenty car passes, respectively. These observations were made in order to determine if any asphalt asperities were visible, or if the test snow was covering the road surface in relation to the test snow's flowability (Giudici et al., 2018). The test snow was classified based on the amount of visible road asperities in contact with air as shown in Table 3.

Table 3 Pavement classification

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

A scraping test whose aim was to simulate the mechanical removal of a snowplow was performed after the twenty car runs. A stainless steel blade was scraped multiple times over the snow samples, and the pavement was reclassified in the same categories as stated above. A video was recorded for each scraping action. Based on the captured photographs and recorded video, the test snow was reclassified in the same categories shown in Table 3.

Chapter 4

Results

This chapter presents the main results of the three studies carried out during the thesis project. The laboratory studies comprise Study 1 and Study 2, and the outdoor study comprises Study 3.

4.1 Laboratory Studies

4.1.1 *Study 1*

In Study 1, a total of 68 test samples were tested. Figure 13A shows the final dry density after the compression for different liquid water contents at the three compression rates of 30, 60 and 90 mm/min. The average is shown by the "o" markers, while the box-and-whisker diagrams show the 95% confidence interval. In Figure 13A it may be observed that as the LWC increases, there is a higher final dry density after compression of 30 mm/min and 60 mm/min, respectively. This means that when a load is applied to the snow, the LWC facilitates the densification process by lubricating the bonds between the ice particles, even though the contacting ice particles are weakened by the presence of LWC. A compression speed of 90 mm/min shows a different sort of behavior. For LWC=0 wt.% (dry snow), the final dry snow density is higher compared to the final dry density of a compression speed of 30 mm/min and 60 mm/min, but it decreases significantly when LWC=5 wt.%. As the LWC increases, the final dry density increases and remains lower when compared to the other compression speeds. One possible explanation for this result may be that due to the rapid compression of the test snow, the dry snow is not pushed aside, therefore providing a strong counterforce to the applied load. Meanwhile, the salted snow is pushed aside, taking out a part of the applied load from the piston as well, leading to a lower final density.

Figure 13B shows the loss of mass for different LWC under the compression effect of the piston at the three compression rates of 30, 60 and 90 mm/min. The average is shown by the "o" markers, and the box-and-whisker diagrams show the 95% confidence interval. In Figure 13B it may be observed that an increase in liquid water content leads to higher loss of mass, meaning that more material is squeezed out under the piston's action. This is true for each compression speed, implying that the LWC, working as a lubricant, increasing the ice particles' ability to flow and leading to a higher loss of mass based on the amount of liquid content.
Therefore, as shown in Figure 13A, the liquid content facilitates the densification process. At the same time, increasing the liquid content increases the contacting ice particles' ability to flow, as shown in Figure 14.

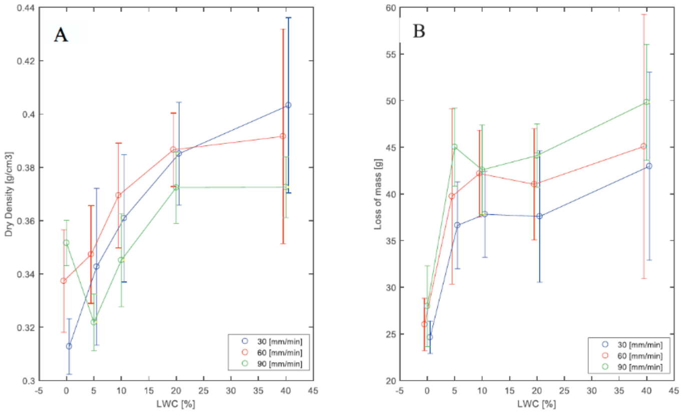

Figure 13 A) Final dry density as a function of snow testing LWC, B) Loss of mass as a function of snow testing LWC

Figure 14 shows the final dry density of the test snow as a function of the three compression speeds for each LWC. The final dry density increases with the increase of compression speed for dry snow LWC=0 wt.%. On the other hand, for LWC=40 wt.% the final dry density as a function of compression speed decreases. However, for LWC from 5 wt.% to 20 wt.% it is not possible to observe the same clear behavior. For LWC from 5 wt.% to 20 wt.% at compression speeds of 30 mm/min and 60 mm/min, respectively, the final dry density remains almost constant, while for a compression speed of 90 mm/min, the final dry density decreases for all the LWC.

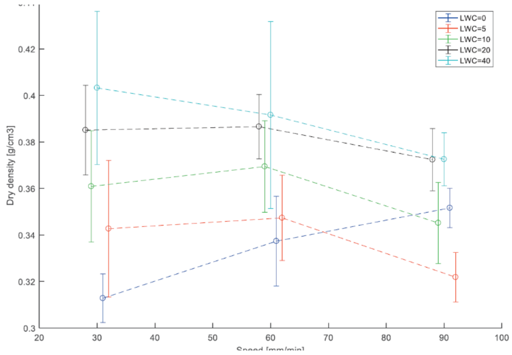

Figure 14 Final dry density for different LWC as a function of compression speeds

4.1.2 *Study 2*

A total of 107 tests were successfully performed. In Figure 15-16-17 for each subset, the average and the Confidence Interval (CI) of 95% is presented. The final dry density as a function of solution content is investigated in Figure 15. For purposes of comparison, the initial dry density is plotted together in order to produce the final dry density in Figure 15. Upon increasing the amount of diluted solution inside the test snow, the initial and final dry snow density increases, as shown in Figure 15 where the red data correspond to the initial dry density and the blue data correspond to the final dry density.

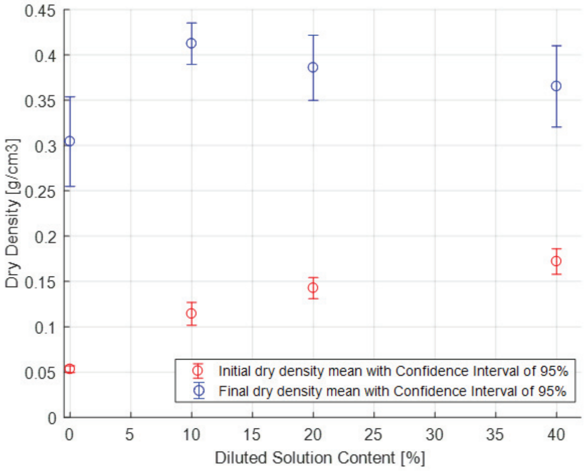

Figure 15 Dry density of the compacted snow as function of the Diluted Solution Content

As regards both the initial and final dry density, upon introducing a solution content of 10 wt.%, there is a significant increase in dry snow density. As regards the initial density from 0.05 g/cm^3 the dry density increases up to 0.11 g/cm^3. The same observation was made for the final dry density: where the dry snow contains a diluted solution content of 0 wt.%, the dry density is 0.30 g/cm^3. Upon introducing a solution content up to 10 wt.%, there is a significant increase up to 0.41 g/cm^3. Beyond a diluted solution content of 10 wt.%, the final dry density does not increase, but rather smoothly decreases, reaching a value of 0.36 g/cm^3 for a diluted solution content of 40 wt.%. This trend was not found in Study 1, signifying that the DSC of 10 wt.% is a threshold, and at a higher DSC, the test snow is pushed aside without becoming more compressed and compacted.

The relative squeeze-out (as the percentage of initial dry mass that was squeezed out to the sides) as a function of liquid content is presented in Figure 16.

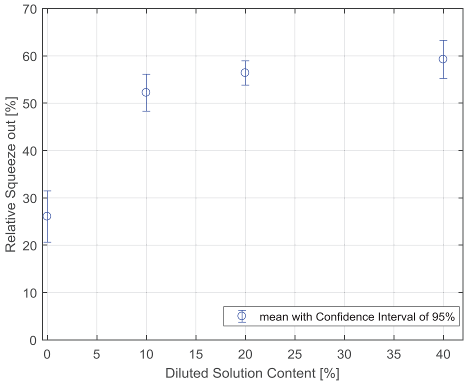

Figure 16 Correlation between the squeeze out as function of diluted solution content

For dry snow, the 26 wt.% are squeezed out of the contact zone from tire and pavement, meaning that the 74 wt.% of ice particles are compressed and compacted. With a diluted solution content of 10 wt.%, the relative squeeze-out increases significantly up to 52 wt.%, meaning that the 48 wt.% is compacted under the effect of the rolling tire. The increase of solution content inside the test snow leads to an increase of squeezed snow dry mass of 60 wt.% for a liquid content of 40 wt.%.

Figure 17 shows the Snow Strength Index for each testing subsets as a function of the liquid content.

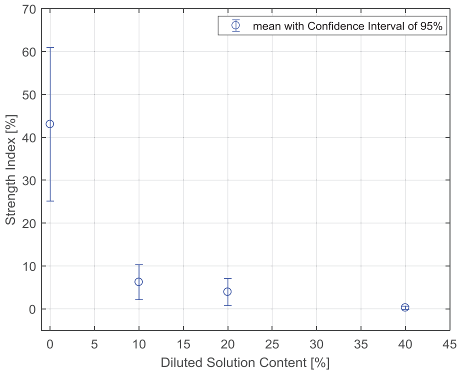

Figure 17 Snow Strength Index as a function of the DSC

The compacted dry snow, DSC= 0 wt.%, the 43 % of the test snow remained strongly attached to the asphalt. This means that 57 % of the test snow was detached under the removal effect of the 5 passes of the pendulum. However, in the presence of solution content, the remaining snow after the pendulum test was extremely lower. With a solution content of 10 wt.%, the 90 % was removed from the pendulum, thereby almost reaching 100 % at a diluted solution content of 40 %.

4.2 Outdoor study

4.2.1 *Study 3*

A total of 6 successful tests were performed under the desired test conditions (air temperature approximately 0°C) during the winter of 2017/2018. Figure 18 shows the compressed and compacted salted snow after 5 passes (first row) and after 20 passes (second row) for different amounts of aqueous solution content, increasing from left to right. After 5 and 20 passes dry snow and snow having 5 wt.% of solution content remain compacted on the pavement. Next, at a solution content of 10 wt.%, the compacted snow easily flowed due to the effect of the tire compression. As the solution content increased, the snow flowed even more easily. Finally, the extreme case, comprised of a solution content 40 wt.%, shows that the snow was completely squeezed out from the contact area.

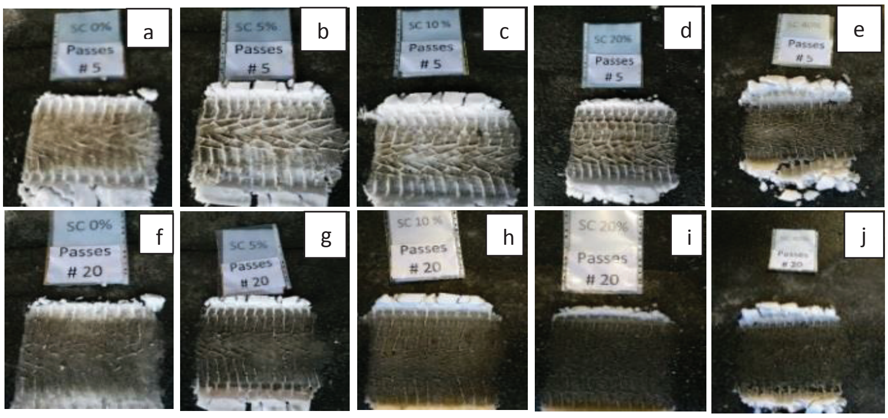

Figure 18 Snow samples containing various solutions after five and 20 vehicle passes for case 1, a) SC=0 wt.% after 5 passes; b) SC=5 wt.% after 5 passes; c) SC=10 wt.% after 5 passes; d) SC=20 wt.% after 5 passes; e) SC=40 wt.% after 5 passes; f) SC=0 wt.% after 20 passes; g) SC=5 wt.% after 20 passes; h) SC=10 wt.% after 20 passes; i) SC=20 wt.% after 20 passes; j) SC=40 wt.% after 20 passes

Figure 19 shows the effect of the scraping action on the test snow.

Figure 19 Showing snow having solution contents of 0.5 and 10 wt.% respectively after a scraping test. The snow, at 0 and 5 wt.% solution contents detached from the pavement in flakes, as can be seen in images 3 a) and b)

The test snow detached itself in irregular blocks for dry snow and salty snow having 5 wt.%. More precisely, the compacted dry snow, having a solution content 0 wt.%, hardly attached itself to the pavement; meanwhile, at a solution content of 5 wt.%, the compacted snow attached itself, albeit weakly, to the pavement. The higher the presence of the solution content, the easier the snow detached itself from the pavement. At a solution content of 10 wt.%, the detached snow was powdery, and at a solution content 20 wt.%, the snow remained slushy and without cohesion on the pavement. At a solution content of 40 wt.%, all the test snow was squeezed after 5 passes of the test car; it was therefore impossible to perform the scraping test.

All images were analyzed by observing if the asphalt asperities were visible at the surface, as described in Chapter 3. This observation indicates if friction can be made between tire and asphalt asperities in the pavement. Table 4 shows the minimum amount of solution content that was needed to make asphalt asperities partially, or totally, visible.

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

Case nr.	Asphalt condition	Vehicle Passes 5	Vehicle Passes 20	Scraping Test
		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

Partial, or total, visibility is achieved after 5 passes of the test vehicles having a solution content ranged between 20-40 wt.%. At 20 car passes this was reached between 10-20 wt.%, while in all the case studies, the scraping test shows the same result, which means that at a solution content of 5 wt.%, the test salty snow was weak enough to be easily detached by the applied shear strength of the blade. No clear difference was observed between the sample placed on dry asphalt and wet asphalt. The results of Study 3 restrict the suggested salt applications by (Schaerer, 1970). A test car rolled over the test snow, including dry compacted snow and salted snow having a solution content of 5 wt.%. After 20 passes the snow remained compacted on the road pavement. A partial road pavement asperities visibility is observed for salty snow having a solution content 40 wt. %; after 5 passes, solution content was 20 wt.% after 10 passes, and it was 10 wt.% after 20 passes. After the scraping test was completed, partial visibility is also observed for salted snow having a solution content of 5 wt.%. The fully road asperities visibility is observed for a minimum amount of solution content of 20 wt.%, and after the scraping test at a minimum amount of solution content of 5 wt.%.

Chapter 5

Discussion

The original objectives of this thesis were to increase the *behavioral understanding* of salted snow and the *applicability* to roads of this understanding for reduced use of salt in anti-compaction purposes.

The behavioral understanding, Research Question 1, of the snow mixed with different amounts of NaCl aqueous solution was investigated under both uniaxial compression (Study 1) and the effect of a rolling tire (Study 2). The applicability of this understanding, Research Question 2, is investigated in Study 3. This chapter will discuss the results obtained during the 3 studies.

5.1 Behavioral understanding

In pavement engineering, the system composed of tire and pavement is studied in order to restrict the amount of friction to safe levels. The presence of an interfacial medium such as snow, ice, water, sand or chemicals makes the interaction between tire and pavement more complex (Klein-Paste, 2007). Hence friction depends not only on the system to which it belongs but also on the properties of the interfacial medium interposed between the tire and pavement (Xu-dong et al., 2004). This thesis investigated the behavior of snow mixed with NaCl aqueous solution as interfacial medium while under tire compression. The decision was made to describe this behavior using three terms: compressibility, compactibility and flowability. The compressibility of a material is understood as the ability to reduce volume under pressure, while compactibility refers to the ability to become stronger under pressure (Odeku, 2007). In addition, there has been the introduction of new term, “flowability”, which refers to the material’s ability to flow under the effect of pressure.

5.1.1 *Compressibility of snow and NaCl aqueous solution*

When pressure is applied to loose snow (without any NaCl aqueous solution), the first ice particles in contact with the pressure applying surface (in Study 1 a piston, and in Study 2 a rolling tire) are compressed and pushed downwards into the uncompressed snow layer. The ice particles reallocate their positions and move from an elastic zone to a yielding one (Lee, 2009). During this process, the ice particles are compressed layer by layer, increasing the snow density (Lee, 2009). Higher density leads to a higher number of ice particles experiencing this contact (Wåhlin et al., 2016) rapidly forming bonds between them due to subsecond sintering (Szabo and

Schneebeli, 2007) in the first instant of contact and subsequent sintering (Kuroiwa, 1961). During this process, there is an increase in snow strength (Kry, 1975; Voitkovsky et al., 1975). The snow densification and bond formations stop when the densified snow is strong enough to sustain the applied compressing load. Once the compressed snow sustains the applied load, it reaches a highly densified configuration (Lee, 2009): At this point the snow is compacted. Introducing NaCl aqueous solution inside the snow changes this compression process, resulting in a higher final density of ice particles (called the dry density) after compression.

Independently from the mechanical action applied to it, an increase in final dry density has been observed from dry snow (solution=0 wt.%) to NaCl aqueous solution content. This increase in dry density reached a maximum of approximately 30% from dry snow to salted snow with a 10 wt.% of NaCl aqueous solution.

One possible explanation behind the behavioral change between dry snow and an NaCl aqueous solution of 10 wt.% is that the NaCl aqueous solution acts as a lubricant in ice grain-grain contact and facilitates the ice particles in sliding along each other. This is because the presence of NaCl solution lowers the adhesion between ice particles (Wåhlin and Klein-Paste, 2015). At levels beyond the 10 wt.%, the dry density of the compressed snow does not increase but it flattens out, as shown in Figure 13A, Figure 14 and Figure 15. Figure 14 shows that from 5 wt.% to 20 wt.% increasing the compression rate, the dry density does not increase; this occurs only for NaCl aqueous solution 40 wt.%, when the increase in compression rates leads to lower dry density.

One possible explanation for the increase in dry snow density is that once all the grains are lubricated, the compressibility of the dry ice particles is no longer affected by the presence of excessive aqueous solution. Based on the consistency of the salted snow, this grain lubrication is believed to occur around 10 wt.% of NaCl aqueous solution content. Therefore, at a range of NaCl solution of 10 wt.%, or 5 wt.%, the compressibility of the dry ice particles is no longer affected by the presence of excessive aqueous solution.

5.1.2 *Compactibility of snow and NaCl aqueous solution*

In Study 1 it was observed that the compressed dry snow was strongly compacted and firmly attached to the asphalt. Yet with an aqueous solution content of 40 wt.%, the compressed snow was extremely weak and slushy. Although it was not further quantified, the reduction in strength of the compacted snow was evident. In order to more fully investigate the strength of the salty snow, the Snow Strength was quantified in Study 2 using a snow strength index. The strength test demonstrates that 40 % of the tested compacted dry snow is able to withstand the applied load of the pendulum. Meanwhile, in the presence of aqueous solution, the applied force of the pendulum was able to detach 90% and 100% of the compacted salty snow. Therefore, the presence of NaCl aqueous solution reduces the snow's overall compactibility.

The reason for this effect is that the presence of the aqueous solution prevents the formation of bonding between the compressed ice particles (Wåhlin et al., 2016). In the presence of the combination of compressed dry snow and aqueous solution, the resulting compressed snow is extremely weak. Therefore, the required force needed to detach the salty snow is significantly lower.

Once all the contact grains are wetted by the solution, the adhesion between ice grains is lowered enough to not sustain the applied forces, as the shear forces of the pendulum. Figure 17 shows that the presence of 10 wt.% NaCl aqueous solution content substantially weakens the compacted snow.

5.1.3 *Flowability of snow and NaCl aqueous solution*

The results shown in Figure 13B and 16 show that the squeeze out of the compressed dry snow was significantly lower compared to the squeeze out of the compressed salty snow. For instance, with an aqueous solution content of 10 wt.% (Study 2), the amount of dry ice particles squeezed aside is approximately 52 % of the relative mass compared to 24-28 wt.% for dry snow.

At levels beyond a NaCl solution content of 10 wt.%, there is still an increase in squeeze out of dry mass, but the increase is more modest. The increase in dry mass squeezed from dry snow (solution content=0 wt.%) and solution content 5-10 wt.% may be explained in the following manner: in dry snow there is low squeeze out due to the rapid bonding between ice particles. In such cases, the bonded ice particles prefer to remain in the compressing volume instead of being pushed aside. In the presence of NaCl aqueous solution content, there is thus a lower adhesion between ice particles that leads to higher squeeze out. An additional aspect to take into account is the grain shape of the ice crystals; for instance, even though it has been not observed during these studies, it is believed that in the presence of aqueous solution, the ice particles are rounded. Compared to the dendritic ice crystals, the rounded ice grains allow easier squeezing of the ice grains.

The presence of aqueous solution inside the snow plays a significant role inside the pore space volume. The test volume comprises solid ice particles, liquid aqueous solution and air. Figure 20 shows the volume ratio of solid, liquid and air phase for salted snow tests of Study 2 both before compression (Figure 20 (A)) and after compression by the rolling tire (Figure 20 (B)).

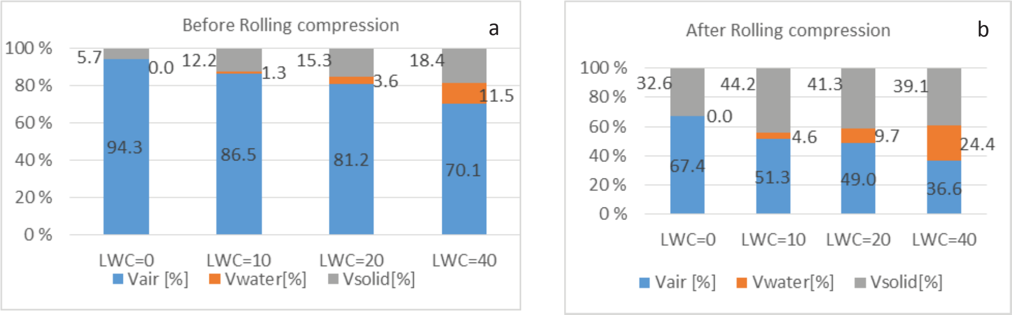

Figure 20. Volume of air, water and solid ice particles for each solution content of Study 2 before compression (a) and after compression (b).

Before compression, the pore space occupied by air ranges from 94% (dry snow) to 70% (LWC=40 wt.%). Increasing the amount of solution content inside the snow, the aqueous solution is added to the test volume, increasing from 0% (dry snow) to 11.5% (LWC=40 wt.%). The volume occupied by ice particles increases from 5.7% to 18.4%. After compression, the pore space filled by air ranges from 67% (dry snow) to 36% (LWC=40 wt.%) of the total compressed volume. The aqueous solution ranges between 0% (dry snow) to 24% (LWC=40 wt.%). The total volume occupied by solid ice particles ranges between 32% (dry snow) to 44 (LWC=10 wt.%). Introducing solution replaces the compressible air with incompressible solution in the pore space. The presence of low pore space voids the flowability that increases when the pore space contains more incompressible solution. Therefore, at a high aqueous solution content, there is lower compressibility and higher flowability, and more ice particles are required to sustain the applied load.

5.1.4 *Implications of changing mechanical behavior*

(Schaerer, 1970) suggested an application rate of chemicals that creates a liquid content in snow of at least 30 wt.%, because it makes slushy snow that splashes off the road under the effect of traffic flow. The indoor Studies 1 and 2 as well as the outdoor Study 3 note that an aqueous solution content ranged as low as between 5 wt.% and 10 wt.% had a significant effect on the compacted snow strength. At this range of aqueous solution content, the snow will most likely not withstand the heavy load of traffic flow and might be easily removed.

An aqueous solution content of 5 to 10 wt.% inside the snow lubricates the ice particles enough to enhance high snow compression (high compressibility) and snow flow (high flowability), when a load is applied to it. Reaching the maximum snow volume variation (highest compressibility), the aqueous solution is in a liquid state and co-exists with dry ice particles. The strength test indicates that the 10 wt.% solution content significantly lowers the adhesion between ice particles and between these particles and the road surface. Therefore, with an aqueous solution content of 10 wt.%, the snow is likely to be sufficiently weakened so that it may be easily removed under the effect of a mechanical action (for example, a snow plow or traffic).

It must be mentioned that any achieved result might be affected by our assumption about the constant salt solution before and after compression. In case this assumption is not true, it is believed that the aqueous solution, as a non-compressive fluid, is pushed aside more rapidly during the compression phase. This means that snow having a lower aqueous solution content than 10 wt.% can reach the same results in terms of snow variation, snow flow and snow strength. This might provide a reasonable explanation for the results shown in Study 1 with an aqueous solution of 5 wt.% in Study 1.

5.2 Applicability

The second research question addressed in this thesis is ” *What is the minimum amount of de-icer solution needed to sufficiently weaken the snow so that it will not become compacted after compression by tires?”*. The aim is to find the minimum amount of de-icers, specifically NaCl, that is possible to use for anti-compaction purposes for the bare road strategy. It must be remembered that the minimum amount of NaCl is not a suggested application rate, but only the amount of NaCl, in aqueous solution, that actively weakens the snow while it is compressed and compacted under the effect of the tire. A safety factor that compensates for the salt losses has to be added to the minimum amount prior to salt spreading. The safety factor takes into account the possible salt losses due to either the spreading method or blow-off/spray-off mechanisms (Lysbakken, 2013, 2011). The combination of the minimum amount of salt and the safety factor can be considered tobe the optimal amount of salt spread for anti-compaction purposes on the bare road strategy.

The findings of Study 3 confirm that an NaCl aqueous solution content ranging between 5 and 10 wt.% is able to keep the snow cohesionless or easily removable under the effect of traffic or mechanical action. This is true in the presence of an air temperature close to 0 °C, the temperature where most severe snow compaction occurs, and with a traffic load of passenger cars driving 20 times at a speed of approximately 20 km/h on the salty snow.

When a temperature gets close to its melting point (Minsk, 1998), there is a higher snow densification. In addition, at low driving speeds, for example 20 Km/h, the snow has more time to re-arrange its structure in a denser configuration (Lee, 2009). At lower temperatures, or upon increasing the driving speed (60-80 Km/h), the time for rearranging the snow into a denser configuration is reduced. Therefore, the flowability of snow increases.

The scraping test undertaken after the 20 car passes shows that an aqueous solution content of 5 wt.%, substantially weakens the snow, making the mechanical removal of the snow by the blade's mechanical action easier. Even though the share strength of the blade is not comparable with the shear strength of a plowing machine, it is believed that a plowing machine is able to remove the compacted snow having an aqueous solution of 5 wt.% easier. Hence a partial or total bare road surface can be achieved by the combination of 20 vehicle passes and mechanical action. The partial, or total, visibility of road pavement having an aqueous solution ranging between 10-20 wt.% due to the traffic flow and plowability of the snow having an aqueous solution of 5 wt.% reduces the suggested chemical rate by (Schaerer, 1970) to less than one third under the same conditions.

As state in the introduction, the cycle time for a plowing machine on Norwegian roads having highest LoS is 1.5 hours. During this time, the fallen snow can compact on the ground; for this reason salt has to be applied within this period of time for anti-compaction purposes. In this particular road network, the Annual Average Daily Traffic (AADT) is higher than 1,500 vehicles/day, meaning that the 20 passes of the test vehicle are conservative in comparison with the expected real vehicle passes between the cycle time of a snowplow and salting.

An aqueous solution of 5 wt.% is able to weaken the snow substantially, assisting the mechanical snow removal of a plowing machine, while an application rate of salt able to produce 10 wt.% of aqueous solution allows the partial asphalt condition while tires are driving over it. These results lead us to the possibility of calculating the required amount of salt to spread during the cycle time.

5.2.1 *Salt application rate*

This paragraph provides an example of salt application rate based on an NaCl aqueous solution of 5 wt.% and 10 wt.%.

Let's assume an expected snowfall of 5 cm with a temperature of – 2 °C. Assuming a snow density of 100 kg/m^3, meaning 5 kg of snowfall in each m^2 of road surface. Let's assume that during the salt application, there is no loss of mass due to wind or spreading method. Using the criterion of a minimum salt solution content of 10 wt.%, it is possible to calculate the amount of required salt for anti-compaction purposes.

Salt applied to roads prior to a snowfall will melt the snow until the melting capacity of the de-icer is reached. The concentration of the meltwater/de-icer solution is given by the following:

$$C\ (wt.\%) = \frac{m_{NaCl}}{m_{sol}}\ x\ 100\ (7)$$

where:

C= Deicer Solution Concentration [wt.%];

m_{sol} = mass of NaCl solution = m_{water} + m_{NaCl} [g];

The meling capacity is reached when the meltwater/de-icer solution is diluted to its equilibrium concentration (freezing point concentration). The equilibrium concentration C_{eq} can also be expressed as a function of the temperature by using the equation (Nilssen, 2017):

$$C_{eq} = -3.6233\ x\ 10^{-4}\ x\ T^3 - 3.8985\ x\ 10^{-2}\ x\ T^2 - 1.7587\ x\ T\ (8)$$

where:

T = temperature [°C];

Equation (9) shows the definition of concentration in weight percentage and the correlation between the NaCl aqueous solution mass and the snow of the expected snowfall.

$$NaCl\ Aqueous\ Solution\ [\%] = \frac{m_{sol}}{m_{sol} + m_{snow}}\ x\ 100\ (9)$$

where:

m_{snow} = is the mass of the expected snowfall [g]

Using 5 wt.% and 10 wt.% in *NaCl aqueous solution* and the expected snowfall of 5000 g/m^2 in equation 9, the required amount of m_{sol} may be calculated. Using the temperature T= -2 °C during the expected snowfall it is calculated that the equilibrium concentration of the solution is 3.33 wt.%. Finally, in Eq. 7, the required amount of salt for g/m^2 is calculated. Regarding Eq. 7, it is possible to calculate the amount of salt required for g/m^2.The required salt application in order to produce an NaCl aqueous solution of 10 wt.% is approximately 18 g/m^2. Same calculations can be made for producing an NaCl aqueous solution content of 5 wt.%. In this case the required salt application rate is approximately 9 g/m^2. The typical salt application rate recommendation from the Norwegian Public Road Administration during snowfalls is between 5 – 20 g/m^2. Therefore, the suggested application rates of NaCl aqueous solution of 5 wt.% - 10 wt.% are in line with the recommendations of the Norwegian authorities.

5.3 Further works

In this thesis the long-term effects of NaCl aqueous solution on compacted snow have not been taken into consideration. Once compressed, the compacted snow enhances higher ice grain-grain contact (Wåhlin et al., 2016). The strength in the grain-grain contact increases due to sintering (Kuroiwa, 1961). In the presence of a liquid phase sintering of snow, the shape of the bond between the grain-grain in contact bonding may vary (Blackford, 2007). The presence of aqueous solution in the long term on compacted snow may affect the snow compaction, increasing the strength of the grain-grain ice contact in the long term. Therefore, an example of a future research questions could be the following:

How is the strength of the compacted snow affected by the presence of deicer solution after 0.5 -1 -2 hours from the compaction action?

Afterwards (Wåhlin, 2014), this thesis investigates the mechanical behavior of salted snow for anti-compaction purposes. In this thesis a criterion for a minimum solution content is suggested. However, the results are knowledge-based on compacted salted snow buildup from (Wåhlin, 2014), and in this thesis have had to be applied in outdoor conditions. In outdoor testing conditions, salt losses due to spreading methods and trafficability are described by (Lysbakken, 2013, 2011). Combining the suggested minimum NaCl solution content of this thesis and the loss of masses from (Lysbakken, 2013, 2011), it is possible to find the optimal salt doses. Once the optimal salt doses have been understood, the combination of the winter maintenance actions (plowing and salt spreaders) can be investigated in order to improve anti-compaction winter maintenance operations. Therefore, possible future research questions could be:

What is the most effective spreading method for reducing the salt losses and reaching the optimal salt doses for anti-compaction purposes?

What is an appropriate safety factor for different spreading methods?

How is it possible to combine the optimal salt doses and mechanical removal during snowfalls for anti-compaction purposes?

Chapter 6

Conclusions

This thesis investigated the effect of (diluted) NaCl solution on the behavior of snow when it gets compressed by tires, and attempted to find the minimum amount of NaCl that is needed to get sufficient anti-compaction.

All experiments used NaCl solution that was diluted to, or near to, its equilibrium concentration. At -2°C this corresponds to a concentration of 3.33 w%. This represents the situation where salt applied prior to, or during the first stage of a snowfall has melted the first fallen snow, got diluted by the created meltwater, and reached its melting capacity. The findings apply for temperatures near 0°C where compaction of non-salted snow is most severe.

The main conclusions are:

- For a given load, the snow containing NaCl solution gets compressed to a higher density, compared to snow without NaCl solution. A solution content of 10 wt.% inside the snow increased the density of the snow crystals with up to 30%, compared to pure snow. Beyond 10 wt.% solution content, the density of the compressed snow does not increase but it flattens out.
- Despite the higher density, the presence of NaCl aqueous solution weaken the compressed snow. An solution content of 5wt.% - 10 wt.% is able to substantially reduce the strength of ice in grain-grain contact, such that snow is easily removed mechanical action.
- During the mechanical compression, the presence of NaCl solution increased significantly the flowability of the snow. With 10 wt.% solution content the amount of snow that was squeezed out of the contact area of a rolling test tire (7.2 km/h) increased by more than 50 %, compared to pure snow. Further increase in solution content (up to 40 wt.%) does only slightly increase the squeeze out.
- The field investigation suggest that a solution content of 5-10 wt.% (diluted) NaCl solution is enough to prevent compacted snow formation. 10 wt.% was enough to get the snow removed by the effect of 20 vehicle passes, whereas 5 w% was enough to remove the snow by a scraping blade. These estimates are considered conservative as they were obtained under conditions of that create most severe snow compaction (slow driving, close to 0°C).
- The minimum amount of salt (in g/m^2) is calculated for a given snow fall, using the criterion of 5 and 10 w% NaCl solution content. To determine an actual application rate, a safety factor remains to be determined to account for salt loss during and after spreading.

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Appendices

Appendix A:

Uniaxial Compression of Salted Snow

Giudici H., Wåhlin J., and Klein-Paste A. (*2018*) Uniaxial Compression on Salted Snow. Tire Science and Technology: January-March 2018, Vol. 46, No. 1, pp. 16-26.

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Appendix B:

Tire-pavement interaction in contact with presence of salted snow:

How an aqueous solution affects the compression, squeeze out and compaction of snow

Giudici, H., Wåhlin, J. and Klein-Paste, A. (accepted with minor revisions). Journal of Cold Region Engineering.

Tire-pavement interaction in contact with presence of salted snow:

How an aqueous solution affects the compression, squeeze out and compaction of snow

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Abstract:

During winter, large amounts of salt are used on roads to keep them safe for vehicular traffic. However, applying high levels of salt is harmful to the environment, vehicles and infrastructure. In order to optimize the amount of salt used on roads without compromising traffic safety, it is useful to increase our knowledge about how salt affects snow properties. This study investigates the effects of salt solution on snow when a tire rolls over it. An indoor test experiment was developed to study the compression, compaction and squeeze out mechanisms of salted snow. Dendritic artificial snow was mixed with different amounts of salt solution from 0 wt.% to 40 wt.%. The main findings of this study are that snow containing a salt solution compresses to a higher density; more snow gets squeezed-out of the contact area compared to fresh snow. The snow that becomes compacted under the weight of tires is weaker when a salt solution is present. These effects take place using relatively small amounts of salt solution (10 wt.%). These results can be used to optimize salt applications rates during a snowfall, an assertion that is discussed in this paper.

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Introduction:

During snowfalls, loose snow sticks to the road surface pavement and rapidly compacts under the effects of traffic load (Kobayashi et al., 2004). The buildup of the slippery compacted snow layers mainly occurs at temperatures close to 0º C (Ketcham et al., 1996). This slippery layer causes lower tire pavement friction, which in turn increases accident rates (Hanbali, 1994). To prevent the formation of this kind of compacted snow layer, salt (typically NaCl) is applied to roads. This measurement is called anti-compaction (Wåhlin, 2014). In Norway, more than 200,000 metric cubic tons are used during winter, the majority during snowfalls (Vaa, 2005). Large amounts of salt have a negative impact on the infrastructure, environment, cars and city inhabitants (Fay and Shi, 2012; Shi et al., 2013). Moreover, a high level of salt use is financially challenging (Hanbali, 1994). Therefore, there is a growing desire to minimize the amount of salt used on roads. In order to safely reduce the amount of salt applied to roads during snowfalls, the minimum amount of salt needed to create a sufficiently large anti-compaction effect has to be investigated. This study has been inspired by two previous studies (Haavasoja et al., 2012; Klein-Paste and Wåhlin, 2013), which used a physics-based approach to find the minimum salt amount required to prevent wet pavements from freezing (anti-icing measures). However, before this can be done for salting during snowfalls, the effect that salt containing snow has on tire-pavement interaction needs to be better understood.

Salt is typically applied before, or in a very early stage of, a snowfall. Snow falling on a salted road melts, and the resulting meltwater forms a diluted salt solution. This melting process may continue until the solution is diluted to a concentration that is in equilibrium with the ice (snow); the melting capacity of the salt is thus reached (Nilssen, 2017). After this point, snow begins to accumulate on the wet road. As more snow falls, the relative amount of ice particles in the solution increases. Consequently, the snow on the road changes consistency - from slush to wet snow and, finally, to relatively dry snow. Meanwhile, cars drive over it and splash water/slush out of their wheel paths compressing the snow to even higher densities. At the end of this process, given that enough snow falls, a compacted mixture of ice particles and diluted salt solution lies on the pavement surface. The salt solution lowers cohesion between the ice particles, making the compacted snow weaker (Wåhlin and Klein-Paste, 2015). The more aqueous solution present, the weaker the salted snow becomes. As a consequence, salty snow is a very different material than pure snow, having as it does a much higher tendency to flow when mechanical actions are applied to it (Giudici et al., 2016).

Having made several observations in urban areas, (Schaerer, 1970) suggested an application rate of chemicals able to create a liquid content in snow of at least 30 wt.%. In such conditions the slushy snow splashes off the road due to the effects of traffic flow. However, it is extremely difficult to accurately control all the variables in field observations. It is for this reason that in order to study tire-pavement interaction in contact with salted snow in more detail, we have developed an indoor test track. The details of the facility have previously been described in detail (Giudici et al., 2017).

In the present study we have investigated the effects of diluted salt solution content on the densification, squeeze out and compaction of snow after the passing of a free-rolling tire. Quantifying these effects, we shed light on how tire-pavement interaction on snow is affected by salt. We hope that these insights will aid the search for finding the minimum salt amount required to use on roads during snowfalls.

Methods

A free rolling tire runs over salted snow samples containing different amounts of Diluted Solution Content (DSC) at a constant speed. During this process, each snow sample was compressed, compacted and partly flowed out of the contact area. The mass and density of the snow was measured both before and after the compression and strength of the compacted snow was tested. Both the density measurements and strength tests were destructive tests, therefore requiring separate snow samples. Table 1 shows the characteristics of the selected test tire for this investigation.

The test snow was placed on top of a smooth, removable asphalt plate, classified as densely graded asphalt with a maximum aggregate size of 11.

Snow preparation

Natural snow is a complex material that strongly changes in microstructure over time. Hence, storing and testing a specific type of natural snow is extremely difficult. Therefore, laboratory grown snow comparable to naturally loose dendritic snow, classified as DFdc by (Fierz et al., 2009), was produced at -20º C. This was carried out by a snowmaker (Lumi). Lumi is a modified version of the snowmaker found at the WSL Institute for Snow and Avalanche Research SLF in Switzerland (Schleef et al., 2014). Artificially loose snow was produced by blowing air from a water bath (temperature 35º C) into a chamber. The vapor nucleated in the chamber, in turn becoming loose dendritic snow. (Giudici et al., 2017) provide the full description of Lumi's characteristics as well as the test procedure.

Once the artificial dendritic snow was produced, it was placed into small boxes and left to heat up from -20º C to -2º C.

Diluted solution was made by dissolving solid NaCl in distilled water. Based on the desired test temperature of -2° C, NaCl solution was prepared using a 3.33% concentration of NaCl (Haynes, 2014). To ensure that the solution was at freezing point, the NaCl solution was prepared with the same methodology used by (Giudici et al., 2016).

Based on the DSC desired for testing, different amounts of solution were inserted into the small boxes containing snow and mixed by being vigorously shaken for several minutes.

DSC is defined as the amount of diluted solution content inside the testing snow. DSC for each testing snow was calculated as:

$$DSC\ [\%] = \frac{m_{sol}}{m_{sol}+m_{snow}} x100 \quad (1)$$

Where: m_{sol} is the mass of the NaCl solution, m_{snow} is the mass of the snow.

The density of snow is strongly affected by solution content; hence, changes in snow compression in samples containing various DSC is best expressed by considering only the density of the snow/ice particles rather than the overall density. We named this latter type of density “dry density”, and in order to calculate it , we need to calculate the dry mass of each snow test: This was done as shown in Eq. (2):

$$m_{Dry} = m_{TOT}\, x \frac{(100-DSC)}{100}\, g \quad (2)$$

Where: m_{TOT} is the total snow mass in grams, including the solution.

The measurements performed in this investigation aim to

- Calculate the final dry density, as the density of the dry ice particles along with the relative squeeze out of the dry mass;
- Estimate the snow strength of the compressed and compacted snow lying on the asphalt.

The experiment was conducted at -2º C: 4 different DSC were tested, from 0 wt.% to 40 wt.%.

Testing design

The Linear Analyzer of Road Surface (LARS) (Giudici et al., 2017) was used for testing the effect of a free rolling tire on the tested snow. Figure 1 shows the salted snow before being tested.

During the test, a tire was accelerated up to a constant speed of 2 m/s, rolled over the snow test and, finally, braked and reached the final position at 0 m/s. Once the tire was in the final position, it was returned to its starting position, and a new test was performed.

Video Documentation:

Regarding each test, the tire motion was documented using a Phantom VEO 410L digital high-speed camera producing 2,000 frames per second at 1280x800 pixel resolution. The height of the compacted snow layer (under the tire's compression) was measured by the recorded video. From reviewing the video, it was possible to track and extract the motion of specific reference points. Therefore, a reference point was placed and tracked on the arm connecting the tire and the sledge. The y-pixels of the tracked point provide a continuous measurement of the change in height of the arm throughout the video, including when the tire compresses the snow. Hence the compressed snow height was calculated by Eq. (3):

$h_c = y_0 - y_i$ (3)

Where: h_c is the height of compressed snow, y_0 is the height in pixels of the reference point before

compression, and y_i is the continuous y-pixels measurement of the tracked point.

The reliability and repetition of the camera measurements has been described by (Giudici et al., 2017) by tracking a reference point for 50 tire runs within the same tire condition described in this paper. This method provides an accuracy level of +/- 1 pixel, which corresponds to +/- 0.31 mm/pixel.

Testing procedure

After the mixing process, the salty snow was placed in a bucket, weighed and finally placed in a wooden frame measuring 6 cm in width, 6 cm in length and 5 cm in height, on the asphalt plate. After filling the wooden frame, the bucket with the remaining test material was weighed again. To determine the initial mass of the snow samples, the difference between the weight of the bucket before and after filling the frame was made. After the test was completed, the snow was collected within the track to determine the final mass, or the snow's strength.
The material outside the initial width of 6 cm was first defined as squeeze out and then discarded. The final total mass was weighed, and the squeeze out mass was quantified from the subtraction of the final total mass to the initial one. The final testing volume was calculated by multiplying the area of the compressed snow by the height of the tested snow. Thus, the final dry density was calculated as shown by Eq. (4) for each snow test.

$$\rho_{Dry} = \frac{m_{Dry}}{V} \frac{g}{cm^3} \quad (4)$$

Where: m_{Dry} is the final dry mass g (the mass of the snow without the solution), the volume V is equal to A x h (A is the area of the compressed snow and h is determined by the video analyses).

One assumption was made during the tests: the snow's solution content does not change during the compression. This was necessary to be able to calculate the snow properties such as final dry density and snow mass squeezed out. The implications of this assumption are addressed in the discussions.

Snow Strength test

The assessment of the strength of compacted snow is important when it comes to the degree of road surfaces' slipperiness. In the absence of a standard method for testing snow strength, a Skid Resistance test (ASTM, 2013) (British Pendulum Test), was adapted in order to simulate the traffic's mechanical load. The pendulum test described the strength of the compacted salty snow layer. When released, the pendulum accelerated up to 3 m/s before a rubber block of 75 mm in width and 25 mm in length slid over the tested snow layer having a nominal contact pressure ~117 kPa. The sliding tested length was set to 60 mm. After the tire rolled over the snow, the Snow Strength Test (SST) was performed. Five pendulum passes were performed for each snow sample. By comparing the total testing area and the area of the snow that detached under the pendulum load, it was possible to estimate the fraction of snow remaining on the asphalt after the SST. A description of the snow's strength was indicated by the Strength Index (SI), which was calculated as shown by Eq. (5):

$$SI\ [\%] = \left(1 - \frac{BAA}{TA}\right) x100 \quad (5)$$

Where: BAA is Bare Asphalt Area cm^2, TA is Total Area cm^2.

A high strength index means that the compacted snow was strong and largely able to withstand the shearing forces of the pendulum. A low strength index indicated that the compacted snow was weak and had been removed by the pendulum. Figure 2 shows a typical result of the Snow Strength Test for different DSC.

Results

A total number of 107 tests were prepared and successfully tested. Table 2 shows the performed tests.

Figure 3 shows the initial and final dry density of the snow tests as a function of the solution content with the mean and Confidence Interval (CI) for each subset of DSC. The data marked in red describe the initial dry density before testing, and the data marked in blue describes the final dry density after testing.

The mean of the initial dry density for 0 wt.% DSC is 0.05 g/cm^3. Introducing solution content to the snow test, the dry density significantly increases (t-test, $p<0.05$) up to 0.11 g/cm^3 for DSC= 10 wt.%. Upon increasing from DSC= 10 wt.% to DSC= 20 wt.%, there is a significant increase in dry density up to 0.14 g/cm^{3,} and with a DSC= 40 wt.%, the dry density reaches 0.17 g/cm^3. However, the situation is slightly different with regard to final density, as its mean for 0 wt.% DSC is 0.30 g/cm^3. Introducing solution content to the snow significantly increases the dry density (t-test, $p<0.05$) up to 0.41 g/cm^3 for DSC= 10 wt.%. Beyond DSC= 10 wt.%, the dry density did not increase any further, but rather decreased slightly, reaching a value of 0.36 g/cm^3 for DSC= 40 wt.%. However, the decrease beyond DSC= 10 wt.% was not statistically significant.

The relative squeeze out was defined by the percentage of initial dry mass that was squeeze to the sides, rather than getting compacted by the rolling tire. The relative squeeze out as a function of diluted solution content is shown in Figure 4.

Figure 4 shows that without the presence of a solution, 26% of the ice particles were pushed aside by the rolling tire. In other words, as regarded the dry snow (DSC= 0 wt.%), the 74% of ice particles were compressed and compacted under the effect of the rolling tire. Adding 10 wt.% diluted solution to the snow increased the relative squeeze out to 52%; hence, the addition of solution facilitated the squeeze out. Between DSC= 0 wt.% and DSC= 10 wt.% there was a significant increase (t-test, $p<0.05$) in relative squeezed mass. Beyond DSC= 10 wt.%, the relative squeezed dry mass continued to increase gradually to 60% at DSC=40 wt.%.

Figure 5 shows the Strength Index as a function of the liquid content.

In the case of dry snow (DSC= 0 wt.%), the remaining snow lying on the asphalt was 43%, meaning that 57% of the snow in the pendulum track was removed after 5 passes. When it was above solution content 0 wt.%, the percentage of snow remaining on the asphalt after the pendulum test was significantly lower. At DSC= 10 wt.% about 90% of the snow had been removed. Upon increasing the amount of solution content from DSC= 10 wt.% to DSC= 20 wt.%, there was no significant difference between SI. Meanwhile, between DSC= 40 wt.% and DSC= 20 wt.% there is a significant difference in SI, and the same significant difference is found between DSC= 40 wt.% and the others' DSC.

This means that regarding DSC= 10 wt.% and 20 wt.%, the snow removal due to the pendulum test was above 90%. Yet as concerns DSC= 40 wt.%, the remaining snow after the pendulum test was 0%, meaning that all the snow was removed by the pendulum test. In other words, while there was a significant difference in strength of compacted snow layers between DSC= 0 wt.% - 10 wt.% and DSC= 20 wt.% - 40 wt.%, there was not for DSC 10 wt.% - 20 wt.%.

Discussion

As stated in the introduction, the purpose of salt on roads both prior to and during snowfalls is to weaken the snow and facilitate its mechanical removal by plowing and traffic itself. In this discussion we have described the behavior of ice particles when mixed with different amounts of DSC. Further, in order to describe these particles' behavior when mixed with DSC, it may be useful to adopt the terms *compressibility* and *compactibility* (Odeku, 2007) for this mixture: Compressibility is the ability to reduce volume under pressure, and compactibility is the ability to become stronger under pressure. In an earlier paper (Giudici et al., 2016) we suggested adding another property, flowability, as the ability to flow while under the effect of a mechanical action.

As Figure 3 shows, the dry density of compacted dry snow is significantly lower than the dry density of compacted snow containing a diluted solution. When pressure is applied to dry snow, the first layer of ice particles coming into contact with the load collapses and is pushed downwards to the underlying layer. In this process the ice particles start to reallocate layer by layer, increasing the snow density (Lee, 2009). The higher density means more grain-grain contact-points (Wåhlin et al., 2016), and due to rapid sintering (Szabo and Schneebeli, 2007), bonds are almost instantly formed at these new contact points. This leads to a rapid increase in grain-grain contact area and, hence, an increase in snow strength (Kry, 1975; Voitkovsky et al., 1975).

The two processes of compression and bond formations continue until a certain limit. Compression continues until the compressed snow is strong enough to carry the applied load, and at this point, the snow is fully compacted.

The strength of the compressed and compacted snow layer is able to carry the load; hence, the tire does not sink any further into the snow but now rolls over its surface. However, in the presence of diluted solution content, compression and compaction change. Diluted solution content lubricates the grain-grain contact. Therefore, the grains in contact with one another have a lower level of adhesion (Wåhlin and Klein-Paste, 2015). The result is that the weakened snow becomes compressed to higher density levels before starting to carry the normal load. Interestingly, when having a 10 wt.% solution content or higher, the material's compressibility did not continue to increase, but rather flattened out. Our hypothesis regarding this occurrence is that once all the contact points are wetted and lubricated by the solution, the material's compressibility is not further affected by adding more solution.

The solution content also affected the amount of mass being squeezed out of the contact area.

The increase in solution content in the test snow leads to an increase in the relative squeeze out of dry ice particles. The difference in squeeze-out is greatest between 0 wt.% and 10 wt.%, after which it continued to increase more gradually.

One possible physical reason for this might be the following: concerning dry snow, the relative squeeze out of the dry mass is low because of the rapid bonding taking place at the grain-grain contact points. This means that dry ice particles attach to each other and remain in a compressed volume state instead to squeeze out under the rolling tire. Adding a relatively small amount of solution (10 wt.%) significantly facilitates the squeeze-out due to the solution's lubricating and adhesion-lowering effect. It has to be mentioned that this threshold between 0% and 10 wt.% might be affected by our assumption on the constant solution content inside the testing snow before and after rolling compression. In case the solution content is not constant before and after compression, most likely the solution content is squeezed out rather than to be compressed under the effect of the rolling tire. This leave relatively more snow than solution in the wheel track, implying that an even lower solution content than 10 wt.% might be sufficient to weaken the snow considerably. For example, the dry snow density shown in Figure 3, would be higher also with lower amount of diluted solution content if compared to the DSC=0 wt.%. Same consideration can be made for Figure 4 where the amount of dry snow mass squeezed would be lower but still different from the squeeze out of dry snow mass at DSC=0 wt.%. But based on our assumption we refer to DSC= 10 wt.% as the minimum amount of diluted solution able to affect the testing snow.

This phenomenon has previously been observed by (Schaerer, 1970) and (Giudici et al., 2016). Therefore, with a DSC as low as 10 wt.%, the physical mechanism of the salty snow will have changed significantly. Increasing the amount of DSC from 10 wt.% to 20 wt.% or 40 wt.%, the voids inside the snow start to fill up with solution, replacing air; subsequently, it takes more solution to fill up the voids than to lubricate the bonds. This makes the material less compressible, which in turn facilitates further flowability. When the liquid content fills the voids, the ice particles cannot fill them, so it is easier to be pushed aside.

The strength index of the compacted snow shown in figure 5 demonstrated that as concerns dry snow, (DSC= 0 wt.%), the pendulum was able to remove about 60% of the compacted test snow. Meanwhile, in the presence of solution content, the pendulum test was able to remove between 90% and 100% of the compacted test snow. When increasing the amount of solution in the snow, the strength of the compressed salted snow decreased. In the case of dry snow, DSC= 0 wt.%, the pendulum was able to remove about 60% of the compacted test snow. However, in the presence of solution content, the pendulum test was able to remove between 90% and 100% of the compacted test snow. These results might also be affected by our assumption on the constant salt solution before and after compression. In case the snow solution content is not the same after compression as before, then with an assumed lower amount of solution content; it means that snow with a solution content less than 10 wt.% has a strength index of 90% or higher/lower. Our assumption of constant solution content before and after compression, does in other words not affect the validity of our results, but rather adds a saftety factor to them.

This means that for dry snow, the adhesion between grain-grain bonds was strong enough to support the forces applied by the pendulum. Yet at a diluted solution content of 10 wt.% and above, there is low adhesion between grains, and the compacted snow is therefore weaker. It is highly probably that at this diluted solution content, the adhesion between snow and pavement is also lowered. The higher the amount of solution content, the weaker the snow became. However, the effect flattened out rapidly beyond 10 wt.% diluted solution, so increasing the solution content past this point did not provide a very positive effect in terms of snow weakening.

Practical implications

As mentioned in the introduction, early work from (Schaerer, 1970) suggested an application rate of chemicals that creates a liquid content in snow of at least 30 wt.%, because it makes slushy snow that splashes off the road under the effect of traffic flow. Although our results are from an indoor experiment, it is interesting to note that only one-third of (Schaerer, 1970) early estimates (10 wt.%) had a significant effect on the strength of the snow that became compacted. Snow having 10 wt.% diluted solution most likely will not withstand the heavy load of traffic flow and will therefore be easily removed after multiple vehicular passes. Obviously, this minimum diluted solution content should be verified by field studies under realistic conditions; but for now, we are assuming that 10 wt.% is sufficient to achieve a satisfactory anti-compaction effect. Based upon this assumption, we can theoretically calculate how much road salt is needed during a snowstorm.

Let us assume that the weather forecast predicts 5 cm of snowfall at -2º C. Assuming an initial density of 100 kg/m^3, this means that 5 kg of snow will fall per m^2 on the road surface. To simplify the calculation, we further assume that all the salt spread remains on the road without any loss due to wind or turbulence. The melting capacity of NaCl at -2º C is approximately 29 g of ice for g of NaCl (Nilssen, 2017). If winter road maintenance personnel had intended to melt all the fallen snow, it would require an application rate of 168.2 g/m^2. This is well above typically recommended application rates. In comparison, the Norwegian Public Roads Administration recommend application rates before and during snowfall between 5 to 20 g/m^2 (NPRA, 2017). However, creating snow with 10 wt.% diluted salt solution content requires melting 0.5 kg snow/m^2. This requires an application rate of 17 g/m^2, which is in the range of typical application rates.

Conclusion

An indoor laboratory study was performed to investigate the effect of diluted NaCl solution content on the compression, squeeze out and compaction of snow. The conclusions reached in this study are:

- During the compression phase, snow containing a salt solution reached a significantly higher dry density compared to pure snow.
- A Diluted Solution Content of 10 wt.% is able to substantially weaken the compacted salted snow and facilitates the squeeze out of snow from the contact area;
- Salted snow has a significantly reduced tensile strength among its grains compared to pure snow, and this helps to keep the snow plowable and allow traffic to contribute to snow removal.

- The findings of this study contribute to the optimization of salt usage for anti-compaction purposes on roads without compromising traffic safety.

Acknowledgments

The authors wish to acknowledge their discussions with Kai Rune Lysbakken as well as the technical contribution made by the following engineers and laboratory technicians at NTNU: Mathis Dahls Fenre, Frank Stæhli, Tage Westrum, Per Asbjørn Østensen, Bent Lervik, Jan Erik Molde.

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Table Caption list

Table 1 Test tire properties

Table 2 Data tests collected

Table 1. Test tire properties

Tire characteristics	Property
Tire	ASTM E1551-16
Wheel load	85 kg
Inflation pressure	2 bar
Speed	2 m/s
Tire width	6 cm
Tire surface	Smooth
Tread Pattern	None
Grooves	None

Table 2. Data tests collected

DSC	Dry Density	Snow Strength
[wt. %]	Number of Samples	
0	14	14
10	14	14
20	14	12
40	12	13

Figure Caption list

Figure 1 a. Snow sample before the test.

Figure 1 b. Snow sample during compression.

Figure 1 c. Snow sample after compression.

Figure 2 a. Typical pictures and strength index (SI) after the Snow Strength Test for DSC= 0 wt.%.

Figure 2 b. Typical pictures and strength index (SI) after the Snow Strength Test for DSC= 10 wt.%.

Figure 2 c. Typical pictures and strength index (SI) after the Snow Strength Test for DSC= 20 wt.%.

Figure 2 d. Typical pictures and strength index (SI) after the Snow Strength Test for DSC= 40 wt.%.

Figure 3. Dry density of the compacted snow as a function of the Diluted Solution Content.

Figure 4. Correlation between the squeeze out as function of Diluted Solution Content.

Figure 5. Strength Index as a function of the DSC.

Figure 1

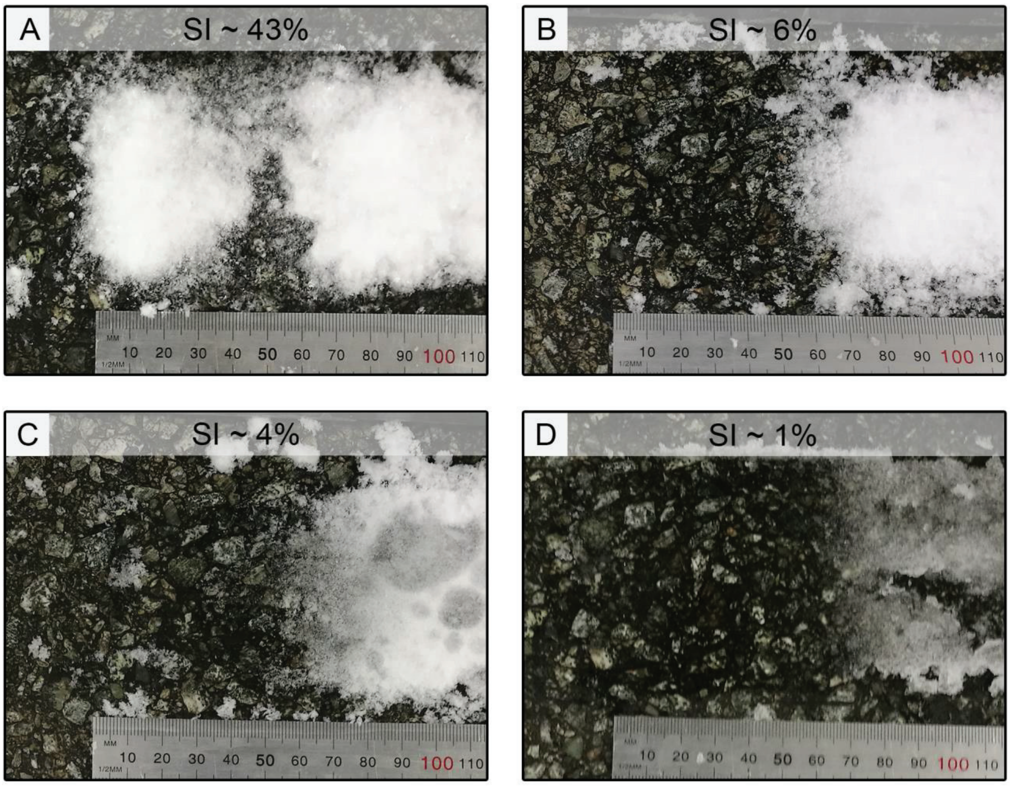

Figure 2

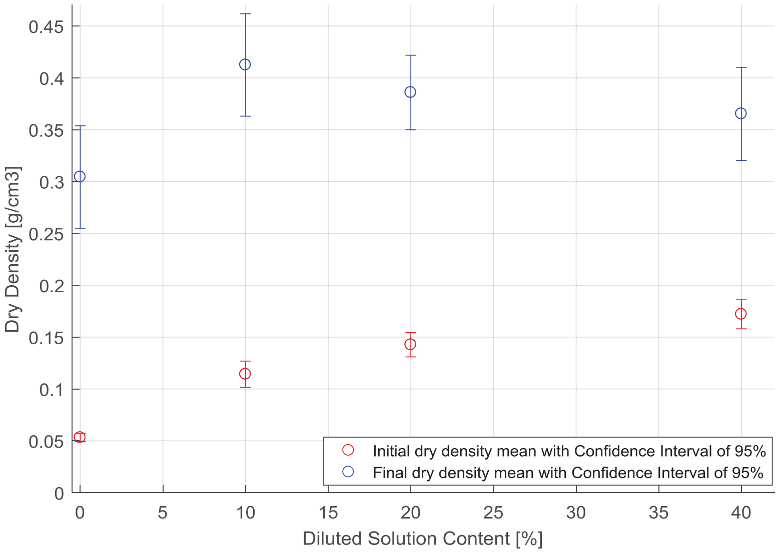
Dry Density [g/cm3]
Diluted Solution Content [%]
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
Initial dry density mean with Confidence Interval of 95%
Final dry density mean with Confidence Interval of 95%

Figure 3

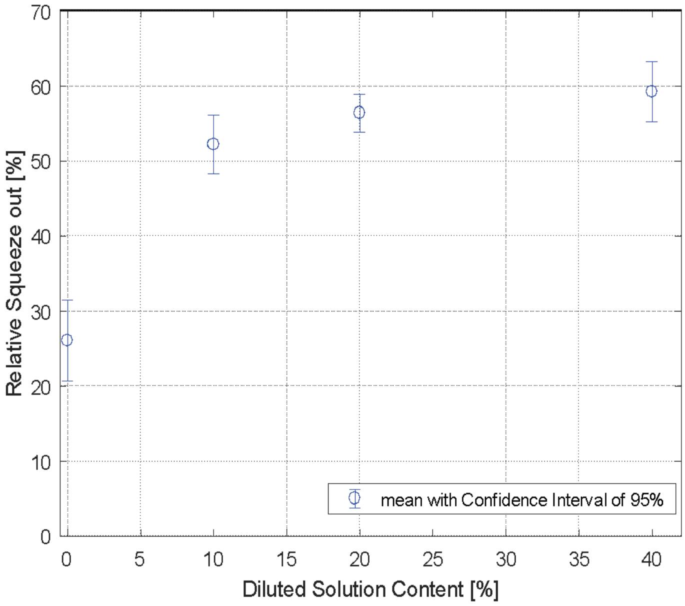
70
60
50
40
30
20
10
0
Relative Squeeze out [%]
0
5
10
15
20
25
30
35
40
Diluted Solution Content [%]
mean with Confidence Interval of 95%

Figure 4

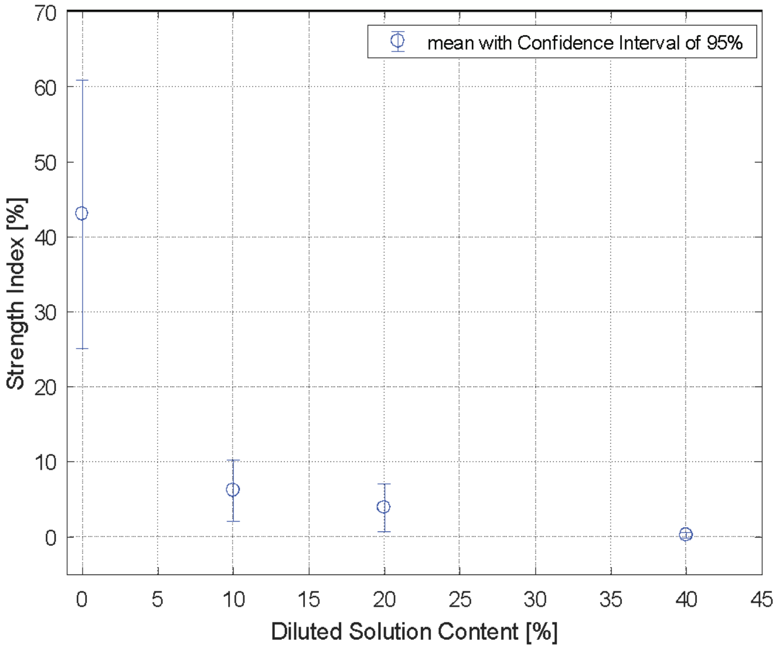
mean with Confidence Interval of 95%
Strength Index [%]
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
Diluted Solution Content [%]

Figure 5

Appendix C:

A Technical Description of LARS and Lumi: Two Apparatus for Studying Tire-Pavement Interactions

Giudici, H.., Fenre, M.D.., Klein-Paste, A.., Rekilä, K.P., 2017. Routes/Roads n. 375, pp. 49-54.

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A Technical Description of LARS and Lumi: Two Apparatus for Studying Tire-Pavement Interactions

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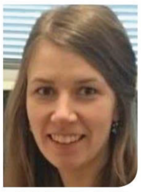
All three at the Department of Civil and Transport Engineering, University of Norwegian Science and Technology, Trondheim
and **Katja-Pauliina Rekilä**, Engineer, Norwegian Public Road Administration, Oslo, Norway

Henri Giudici

Mathis Dahl Fenre

Alex Klein-Paste



Katja-Pauliina Rekilä

The controllability of a vehicle equipped with tires decreases under certain circumstances. One of these circumstances is in winter, where snow and ice affect tire-pavement interaction and thus friction. In such conditions, the control of the vehicle might be lost, which results in longer braking distances or unsafe steering. The presence of snow, ice, water, sand or chemicals makes the interaction between tire and pavement extremely complex. As interfacial property, the frictional phenomenon, depends on both the tire and the underlying pavement. Therefore, friction on ice and snow depends both on the material (snow/ice) in itself and on the system which it belongs to. In pavement engineering, the typical system composed by tire, pavement, interfacial medium such as snow/ice, and environment is defined as tribosystem. Several outdoor and indoor tests are performed during winter time to increase the knowledge of this system in snowy and icy conditions. Nevertheless, outdoor testing is challenging due to the unpredictability of the weather conditions and test area. On the other hand, indoor tests allow the understanding of the whole system in controlled conditions. Several known indoor facilities investigate tire pavement interaction and thus the frictional phenomenon. However, most of them lack the linear testing of a real tire moving at high testing speed, especially for underlying pavement surface such as snow or salted snow. The Linear Analyser of Road Surface conditions (LARS) at our research center aim to fill this gap. LARS and a snow producing machine (Lumi) forms the core of this laboratory. The object of this paper is to provide a detailed description of our facilities.

THE LINEAR TEST APPARATUS: LARS

LARS is a linear test track with a length of 8.8 meters. LARS allows linear tests of a freely rolling tire within a maximum speed of 10 m/s in a cold laboratory within test temperatures controlled from -25 °C up to + 25 °C. *Illustration 1* describes the components of the linear test track.

The system design

The beam (1) is LARSs *"spine"*. An electrical motor (2) is mounted on the left side of the beam. A sprocket wheel (3) is mounted to the electrical motor and another sprocket wheel (4) is mounted at the end of the beam. An encoder, placed on the motor counts the revolutions of the sprocket wheel. A tensioned belt (5) is mounted around the sprocket wheels and the tension wheel (6) Underneath the beam, a sledge (7) displaces transversally for the whole length of the beam. A desired testing tire (8) is attached to the beam with an aluminium arm, and rolls over a desired pavement, for example asphalt concrete (9). The beam can be raised or lowered to allow wheels of different diameter. The test tire is pressed on the pavement within a maximum applied normal force of 1500 N. An air bellow in pressure (10) controls the applied normal force on the tire. In the current set-up, the braking torque, rotational speed and acceleration of the tire are measured. The whole facility is fitted into an aluminium frame (11).

Test procedure

A specifically designed LabView software enables the control of LARS. When activated, the motor transfers energy to the sprocket

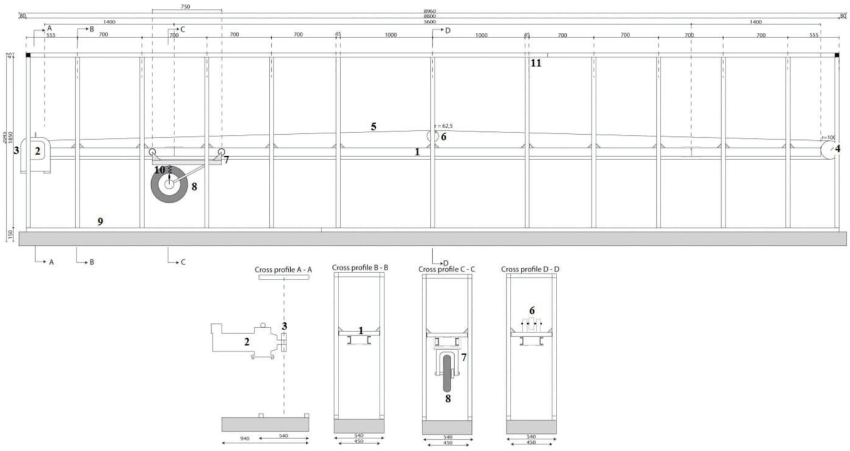


Illustration 1 - LARS linear track apparatus © [12]

Illustration 2 - Tire Pavement Interaction in water and snow condition

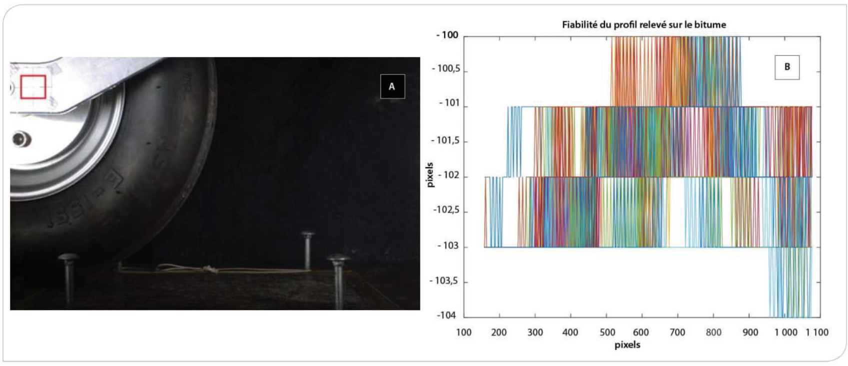


Illustration 3 - Tracking Reference Point (A), Reliability measurements of tracking point (B) wheel, which further induces transversal movement of the sledge through the belt. This enables free rolling of the tire. During a test run a rolling tire is accelerated up to maximum 10 m/s within the first 3 meters of the track. Over the next two meters at the centre of the track, the tire is rolling at constant desired speed. Finally, the tire begins to brake reaching the final position with a speed of 0 m/s. After the test, the tire can be returned to the start point. Hence, the test can be repeated.

Video documentation

Lars is equipped with a Phantom VEO 410L, digital high-speed camera. The camera captures the tire motion within a maximum of 6,100 frames per second with 1,280 x 800 pixel resolution. The recorded video is processed and analysed with the Vision Research software. *Illustration 2* shows the effect of a free rolling tire on water *(illustration 2 A)* and snow *(illustration 2 B)*.

From the documented video it is possible to extract measurements. To test the reliability of the camera measurements, a reference point has been tracked over 50 test runs. The reference point, marked in red in *illustration 3A*, has been placed on the arm connecting the tire and the sledge. The testing tire was running with 2 [m/s], a wheel load of 85 [kg] and an inflation pressure of 2 [bar] on bare asphalt and the reference point was tracked for the whole tire motion captured within 2,000 fps. *Illustration 3B* shows the results of the test runs.

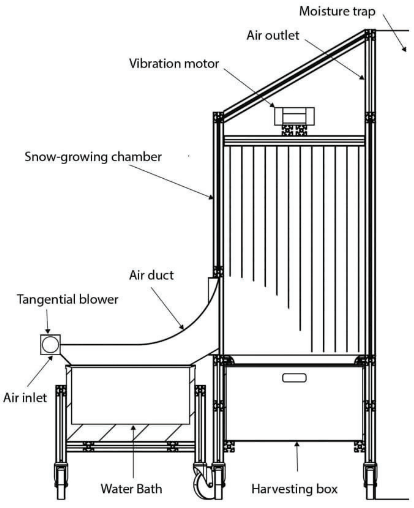


Illustration 4 – Design of Lumi apparatus

For each test run, the reference points pixels coordinate was tracked from the first frame until the last one. With a total of 50 test runs, 47 tests show a variation of +/- 1 pixel, in y-coordinate, for the whole captured motion of the reference point. 3 tests show a variation of +/- 2 pixels.

THE SNOW MACHINE: LUMI

Natural snow comes in a variety of shapes, sizes and densities. This makes testing on natural snow very difficult and test results tend to be largely scattered. Storing natural snow over time is difficult as the snow changes important properties such as grain shape and size over time. Our snow machine Lumi ("snow" in Finnish) reduces these problems by producing artificial new snow under controlled conditions. Lumi operates in a cold room laboratory with controlled temperatures down to -25 °C. Temperatures are controlled with an accuracy of +/-0.5 °C. Illustration 4 shows Lumi and its components.

Lumi snow procedure

Two tangential blowers blow the cold laboratory air into an air duct and over the water baths. Two water baths are heating water to a desired temperature, typically within a range from + 30 °C to +40 °C. The warm water provides the water vapour that humidifies the air. The cold, humid air continues through the air duct and into the snow-growing chamber. Snow crystals start growing on a polymer coated steel grid. At set intervals, a motor induces vibrations to the steel lattice, allowing the snow to fall down into a harvesting box. An aluminium frame covered in a fine masked fabric following the snow-growing chamber traps most excess air moisture. Illustration 5a and 5b shows the snow formation in the snow-growing chamber.

The system design

Two water baths, Julabo TW-20, 500x300x180 mm^3 provide PID controlled water heating up to 90°C with a temperature stability of +/- 0.2°C. Running in a temperature range between +30 and +40°C, conditions are ideal for legionella bacteria formation. To avoid formation of legionella, each water bath is equipped with an Aqua Medic Helix Max 5W UV filter.

Two EBM-Papst QLZ06/2400-2212 24VDC tangential blowers allow cold laboratory air to get into Lumi. Maximum air flux is 220 m^3/h. Jtron DC motor PWM controller controls the blowers to operate at around 110 m^3/h to lower the amount of excess humid air flowing in the laboratory.

The stainless steel air ducts leading cold laboratory air over the water baths and into the snow-growing chamber are custom made. In order to obtain an evenly distributed snow-growth, the air ducts half funnel-like design help spread the airflow as much as possible when entering the snow-growing chamber. The plates are welded together and the welds are sealed. A foam tape on the edge between the water baths and the air ducts and two ratchet tie-downs provides a watertight connection between air blowers, water baths and the snow-growing chamber.

An aluminium profile, Bosch-Rexroth, frame 1,955 x 973 x 695 mm^3 with styrene-acrylonitrile (SAN) plastic windows make up the snow-growing chamber. Inside, hangs an aluminium frame with eleven plastic covered steel grids, forming the snow-growing lattice.

The motor regularly inducing vibrations to the lattice is a three-phase Venanzetti Vibrazioni Micro VV002N/2 vibration motor. The motor exerts a centrifugal force up to 0.44 kN. A Siemens SINAMICS G110 converter controls the frequency of the motor by slowly ramping up from 0 Hz to 50 Hz and down again. A digital time clock relay initiates the vibrations every two hours. By slowly changing the frequency, different parts of the steel lattice with different stiffness (and different natural frequencies) will experience heavy vibrations, hence making as much snow as possible fall down into a harvesting box, placed underneath the snow-growing chamber.

The combined use of the linear test apparatus LARS, the snow maker Lumi and the phantom VEO 410L provide the tools for accurate studies and documentation of tire-snow interaction. The focus at our research center is the investigation of the interfacial medium behaviour when tire and pavement are boundaries of the system. Tests on tire-pavement interaction in presence of loose dendritic snow aim to reproduce tire traction during snowfalls. *Illustration 6* shows the ice crystals created with different gradient temperature between the water chambers and the cold room temperature.

Illustration 6A and 6B show ice crystals created with water chamber temperature of + 30°C and cold room temperature of -20°C. *Illustration 6C* shows ice crystal

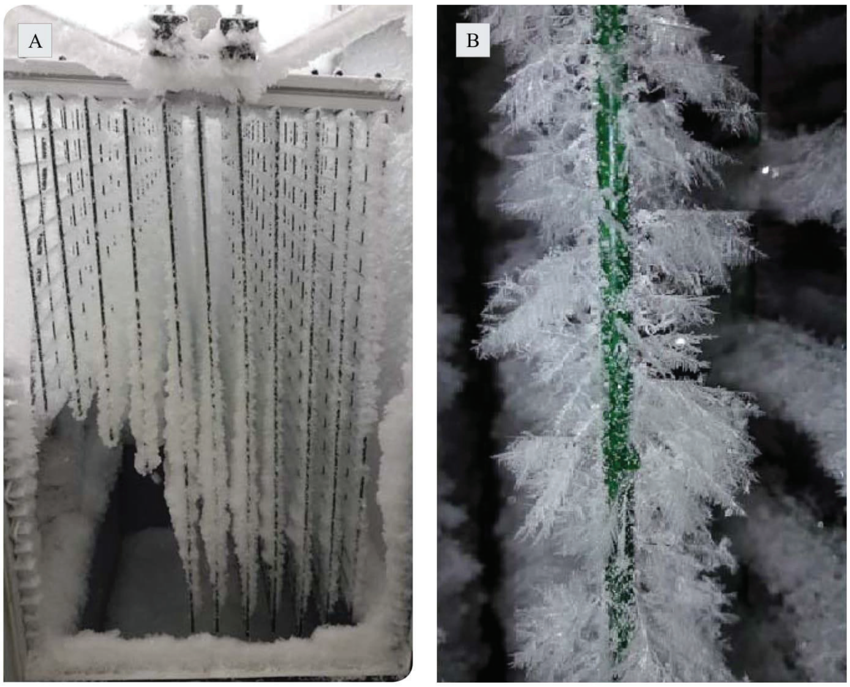


Illustration 5 - Artificial loose dendritic snow produced by Lumi

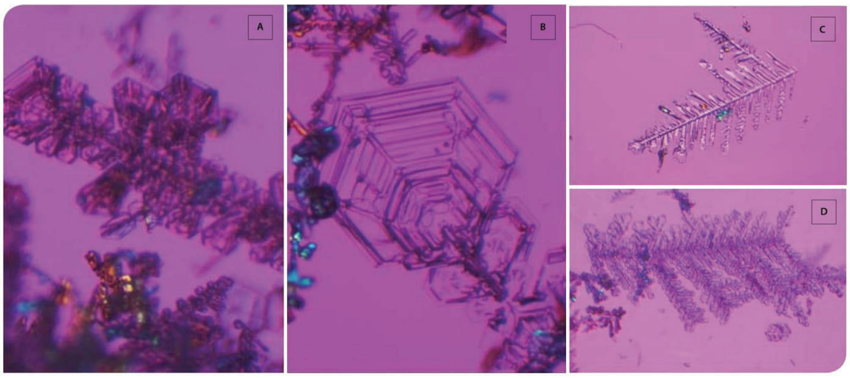


Illustration 6 - Lumis ice crystals observed with a polarized microscope

formation at water chamber temperature of +40°C and cold room temperature of -20°C. *Illustration 6D* shows ice crystal formation at water chamber temperature of +35°C and cold room temperature of -20°C. The density of the produced snow is comprehended within a range from 30 to 80 [g/L], based on the chosen gradient of temperature.

The LARS apparatus offers different possibilities for tire testing. In that case, test runs can be performed with different tire geometry (i.e. car/bicycle), composition (studded tires and frictionless tires) and with different treads and rubber compound. Finally, LARS also allows testing of different pavement surfaces.

CURRENT USE OF THE FACILITIES

LARS apparatus is currently in use for investigating the effect of a free rolling tire on salted snow.

Laboratory grown-snow, classified as DFdc (loose dendritic snow) according to the international classification of seasonal snow on the ground was produced at a temperature of -20°C. *Illustration 6C and 6D* shows the typical test crystals shape. Test snow is mixed with different amount of sodium chloride solution at -2°C. Over a smooth asphalt specimen, classified as AB11 according to [14], a smooth friction testing tire is free rolling on the top of the unconfined testing snow with a speed of 2 m/s, wheel load of 85 kg, and an inflation pressure of 2 bar. Final density and hardness of the salty snow after the tire rolls over it are analysed and discussed.

CONCLUSION

A technical description of LARS and Lumi has been presented as well as preliminary test results. The indoor apparatus offers a realistic tire pavement interaction in icy and snowy conditions. In such conditions, the importance of the artificial snow maker Lumi is explained. Tire-pavement interaction in real test scale is documented with a high-speed quality camera. The development of a test set-up is in progress to enable control of slip ratio and friction measurements for any testing tire in any condition. However, due to the high reliability and reproducibility of its test, the apparatus is currently used for several research purposes. The research carried on wishes to explore the effect of a rolling tire on salted snow and possible optimization of salt uses. Improved understanding about tire traction in snowy conditions will be useful to increase the efficiency of winter maintenance without compromising road traffic safety.#

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Appendix D:

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

Giudici H., Klein-Paste A., Wåhlin J. (Under review). Journal of Cold Region Engineering.

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

Henri Giudici[1], Alex Klein-Paste[2], Johan Wåhlin[3]

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. 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:

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

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.

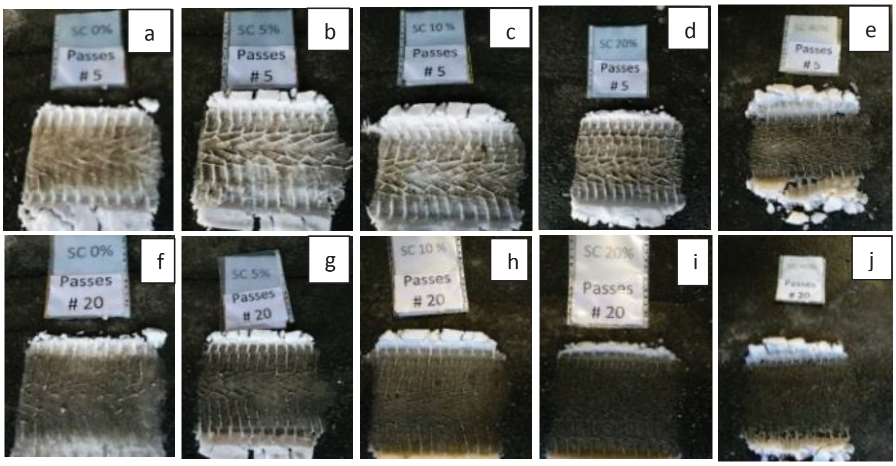

Figure 2. Snow samples containing various solutions after five and 20 vehicle passes on case 1, a) SC=0 wt.% after 5 passes; b) SC=5 wt.% after 5 passes; c) SC=10 wt.% after 5 passes; d) SC=20 wt.% after 5 passes; e) SC=40 wt.% after 5 passes; f) SC=0 wt.% after 20 passes; g) SC=5 wt.% after 20 passes;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

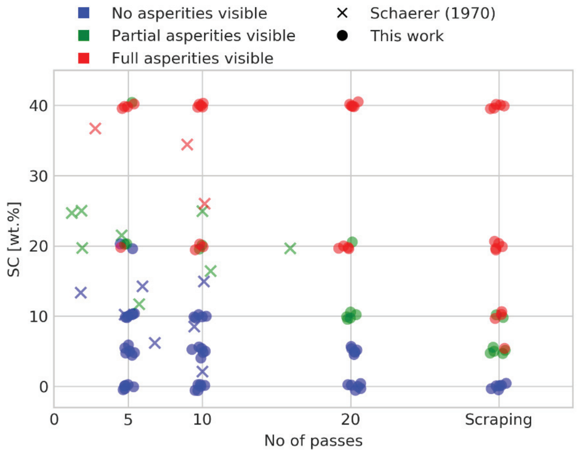

Figure 4. Salted snow compaction/asphalt visibility as function of solution content; regarding visibility, data was moved in both x and y directions.

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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