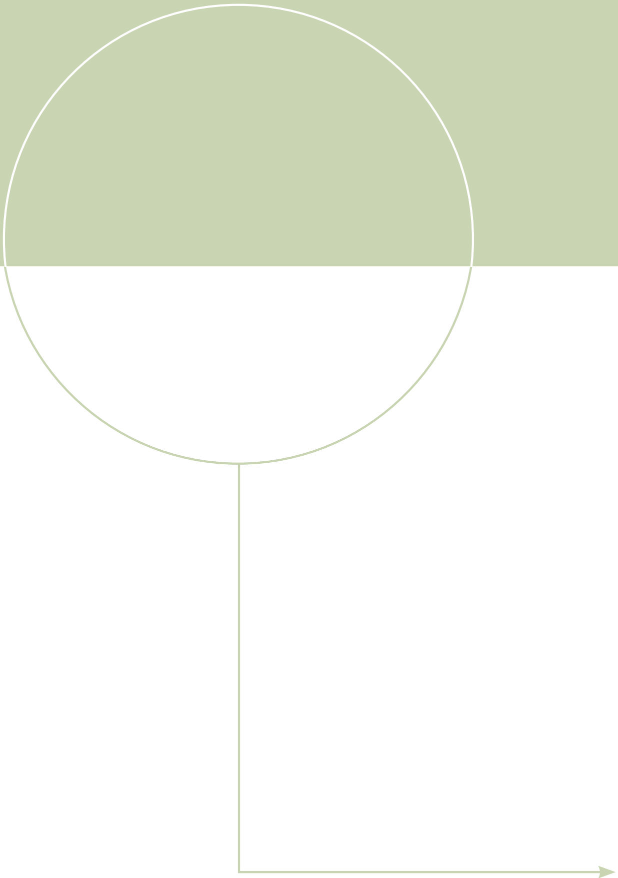

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Effects of temperature and pre-wetting on deicing performance of sodium formate

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Key-words

Runway deicing, penetration rate, deicer performance, sodium formate

Abstract

The two most common deicing products used on Norwegian airports are Aviform S-Solid, a granular deicer consisting of 98% sodium formate (NaCOOH), and Aviform L50, a 50% solution of potassium formate (KCOOH). Earlier research has developed a set of methods quantifying deicer performance, but with limited application in the field. In addition, most experimental data is focused on commonly used road deicers, while the information about formates is limited. This paper aims to increase the knowledge about how different conditions, namely temperature and pre-wetting, affect the deicing performance of formates. A new method for calculating the development of ice melting and penetration based on image analysis is described. Eighteen experiments, including both dry and pre-wetted sodium formate samples in three different temperatures (-2°C, -5°C and -10°C) has been completed. Preliminary results show a satisfactory degree of accuracy, ensured by comparing theoretical and experimental values. The procedure can be used to follow the melting development throughout the process, without disturbing it for manual measurements. Investigation of the effect of temperature on penetration rate and depth concluded that there is a correlation between those properties and the field conditions, resulting in smaller cavities and slower penetration process in lower temperatures. The analysis of the effects of pre-wetting on deicer performance concluded that there is a notable difference in low temperatures (-10°C), while pre-wetting has no significant effect in temperatures closer to 0°C. Implications of the results as well as possible field applications are discussed.

Introduction

Air transport facilitates fast and cost-effective movement of freight and passengers around the world. Because of air traffics importance as a mode of transport in modern society, keeping up a high level of service by preventing delays and cancellation of flights throughout the year is an ambition of most airlines and airport authorities. Accumulation of snow and ice layers on the runway during the winter season is a challenge that makes maintaining sufficient surface friction for safe take-offs and landings difficult. However, preventing build-up of slippery layers of snow and ice is not always possible so reactive methods, such as sanding, plowing and deicing, are often used to control and mitigate the consequences of this accumulation.

Deicing is a method used to remove the ice layer once it has formed. Melting away all the ice would require large quantities of a deicing chemical and a lot of energy, since the transition from ice to water is a highly endothermic process. Therefore, a standard deicing operation is performed in three steps, with the runway temporary closed for air traffic. First, loose snow and ice particles on top of the ice layer are removed by plows. Later the deicing chemical is spread over the runway to achieve two basic goals a) to penetrate through the ice layer, thus making it weaker and b) remove the ice-pavement bonds during a process called undercutting. At the end, the remaining, weakened ice layer is removed mechanically, leaving a clear asphalt surface with high friction.

The two most used deicing products on airfields in Norway are Aviform S-Solid, a granular deicer consisting of 98% ± 1% (by weight) sodium formate (NaCOOH) with corrosion inhibitor(Addcon, 2019a), and Aviform L50, a water-based 50% ± 1% (by weight) potassium formate (KCOOH) solution with corrosion inhibitor

(Addcon 2019b). The solution is used to remove very thin layers of ice (up to 3mm), as a precautionary agent or as a pre-wetting liquid for the granular deicer, while the solid deicer is typically used to remove thicker ice layers.

Despite being an effective method of ice removal, deicing chemicals have some flaws, including negative environmental impact, like ground and groundwater pollution, high relative cost, and causing some degree of corrosion on planes, ground support equipment and electrical systems (Fay, 2017). Based on those concerns there is a wish within the industry to reduce the usage of deicing chemicals by developing comprehensive guidelines for practitioners that optimize their utilization.

Throughout the years, researchers have established a basic understanding about the ice melting process and developed various methods to quantify deicer performance. Research done in association with Strategic Highway Research Program (SHRP) had significant influence on standardizing the performance indicators as well as shaping up methods to measure those properties. In that work, Chappelow et.al. (1992), describes three main measures to quantify the performance of solid deicers are as: melting performance, quantified with "SHRP H-205.1 ice melting test", penetration, tested with "SHRP H-205.3 ice penetration test", and undercutting, specified in "SHRP H-205.5 ice undercutting test". Those procedures were suitable for comparing different deicers, but sine their establishment several weaknesses has been identified, including high variability due to method design, and limited correlation with field observations (Muthumani et.al, 2014). In addition time limits and testing conditions result in SHRP tests giving performance values that are lower than the actual potential (Nilssen et.al, 2016). Recognizing those flaws has led to development of new, improved test methods, amongst them the shaker (Gerbino-Bevins et.al, 2012) and improved shaker test (Tuan and Albers, 2014), ice cube titration (Koefod et.al, 2012) and use of calorimetry. Muthumani et.al (2014) gives an in-depth description of the main pros and cons of various testing methods, but a recurring observation is that the tests lack a direct translation to field performance, thus giving practitioners limited possibility of efficient application of the results in their local environment.

The aim of most of the improved tests is to precisely measure the melting capacity – how much ice it is possible to melt with a known amount of deicer – and melting rate – how fast the deicer can melt the ice. The focus on those properties leaves a demand for reliable and consistent methods for measuring deicer penetration and to some extent undercutting (Muthumani et.al, 2014). In addition, most of the experiments were performed with deicers commonly used for road deicing, namely sodium chloride (NaCl), magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$) (Luker et.al, 2004), (Koefod, 2017), while no documented research data has been found for the melting performance of formates (NaCOOH and KCOOH) using improved methods.

Another aspect that is often discussed in literature regarding deicing operations is the use of pre-wetting liquid as a measure for boosting deicing performance of granular products. Earlier research has shown that blending rock salts with a liquid solution before the application can increase the effectiveness of the deicer in low temperatures (Koefod et.al, 2015). Effect of the presence or absence of a pre-wetting liquid, as well as different pre-wetting ratios for sodium chloride and other commonly used salts has been tested, but also in this subject, there seems to be a lack of quantified results specifically for formates.

The main objective of this study was to increase the knowledge about how selected properties – temperature and pre-wetting – affect the performance of formates commonly used during deicing operations at Norwegian airports. Furthermore, a general goal of the project was to develop a reliable method that can better reflect conditions and development that can be observed in the field. The ambition behind this goal was to make the test results relatable to the actual deicer performance during winter operations as well as make them easily applicable by the practitioners. To narrow down the scope of the study, the evaluation of performance was based on comparison of ice melting rate and penetration development of the solid deicer, sodium formate, in three different temperatures, with and without the addition of a pre-wetting solution. This resulted in following research questions:

- How does the temperature affect the melting- and penetration rates of sodium formate?
- How does the addition of pre-wetting solution affect the performance of sodium formate?

This paper is structured as follows. First a brief description of the ice melting process is given, to facilitate an easier interpretation and understanding of the results. Then a new method for observing and measuring the development of a melting process is presented. In the results section achieved values are presented and compared with the theoretical values. Finally, the meaning of the results and implications for practitioners are discussed, as well as the need of further research is outlined.

The melting process

The ice melting process can be described as a phase transition from ice to water. Klein-Paste and Potapova (2014) states that even at temperatures below 0°C the melting process can occur, with a presence of a solution with a lower freezing point. If a deicer is present and dissolved, the melting will initiate and the melt water will slowly dilute the solution until the freezing point. The dilution makes the freezing point of the solution rise, thus after some time an equilibrium will be reached. At that point the freezing point temperature of the solution will be equals to the ambient temperature. Values for concentration and corresponding freezing point temperatures has been found in various experiments, making it possible to predict a theoretical amount of melted ice, based on the temperature and the deicer that is present. It should be noted that the presence of liquid is crucial to start a melting reaction. Therefore putting a hygroscopic deicer on ice surface can result in a long phase without any melting, until enough moisture is acquired to dissolve the granulate and initiate the melting reaction.

Method

The method consists of three major steps, which are described in detail in this section. First, the ice samples are created following a specific procedure. Later the experiment is initiated and the melting process is documented with cameras. At the end, the results are earned by post-processing and analysis of the photos.

The test procedure required a set of clear, bubble-free, ice samples. To create those, a method for freezing water from the bottom to the top was used. A 55cm x 35cm x 27cm plastic box insulated from the sides and the top was filled with about 27.5L of water (resulting in a water depth of 20cm). The box was placed in a walk-in environmental chamber set to -20°C. An aluminum plate and a fan were placed under the box to achieve constant flow of cooling air for the bottom water layers. Two submersible aquarium pumps were placed near the water surface to circulate the water. Water circulation prevented the water surface from freezing and removed air bubbles from lower water layers. The freezing process went on until the minimal thickness of the ice layer was 10cm. At that point, the ice block was removed from the box and cut into 15 cubic samples with dimensions 10cm x 10cm x 10cm. Ice created by this method had a mean density of $915\,\mathrm{kg/m^3}$. The ice cubes were stored in a freezer at -15°C.

A batch of solid (Aviform S-Solid, sodium formate) and liquid (Aviform L50, potassium formate solution) deicers were received from a Norwegian airport for the experiments. The bulk density of the Aviform S-Solid sample was $950\,\mathrm{kg/m^3}$. Samples were stored in sealed containers in room temperature.

The test was performed in a cold walk-in lab that was set to desired temperature at least 48 hours before the test. At the same time, the ice specimens were moved into the lab. Deicer samples and dye powder (Eosin B, CAS number: 548-24-3) were placed in the lab at least 24 hours before the test. All sodium formate grains were weighted before the test. The biggest grains from the sample, with weight ranging from 0.0553g±0.0001g to 0.1178g±0.0001g, were used for the test.

For test setup, two cameras were placed on tripods around the ice sample, so that they faced perpendicular sides of the ice cube. Both camera models were Canon EOS 100 with standard 18-55mm lens. The tripods were regulated so that the top of the ice cube was placed at the center of the image. A small leveler was used to ensure that top was horizontal, to prevent the runoff of meltwater and pre-wetting solution off the edges.

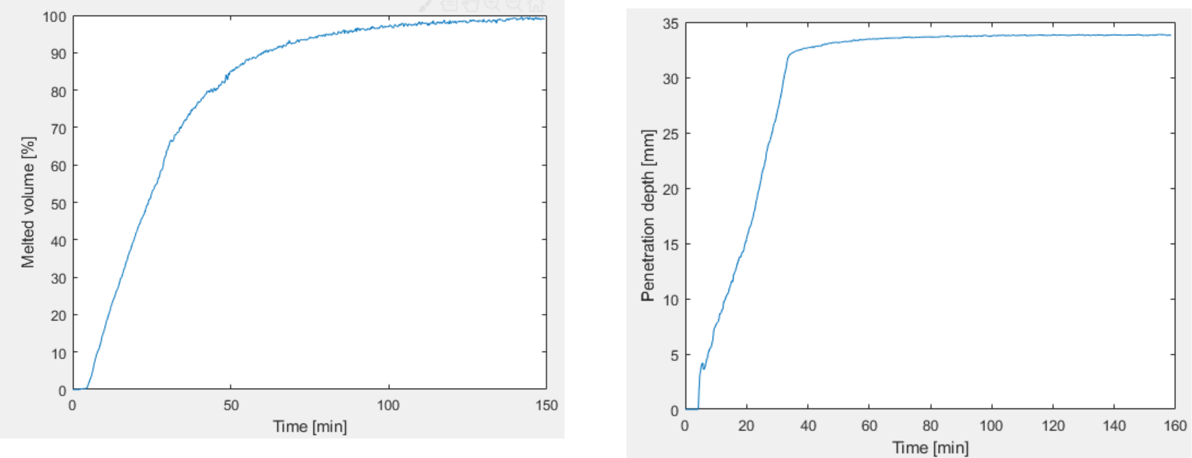
The test had a following procedure. First, a control image was taken with each camera to find a scale for further analysis. For this image, a 25 cm ruler was placed above the middle of the ice cube (where the expected melting would occur). A pixel-to-millimeter ratio was found with ImageJ, an open-source image analysis program. A mean ratio for conducted tests was 24.63±3.10 pixels/mm. Later, both cameras were connected to a computer and set in timelapse mode, making the cameras simultaneously take photos in 15s intervals. Then a single sodium formate grain was rolled in small amount of the dye powder and placed on top of the ice cube. At the end, the pre-wetting solution was added with a micropipette to achieve a pre-wetting ratio of 20% (by volume). Each experiment was repeated three times. Every repetition took between 2.5 and 3 hours to ensure that the deicer is completely diluted, and an equilibrium is reached. This was also ensured by temperature measurements that displayed meltwater temperature equals to ambient temperature of the room. After the experiment was completed, a control-measurements of the end meltwater temperature (using Ebro TFX 410-1 thermometer), total volume (using a 3mL syringe) and maximal penetration depth (with a ruler on placed at the side of the ice cube) were performed.

The photo series from each camera was then put through a post-processing procedure. The procedure started off with clipping out the area of interest to minimize the color variation and limit the size, and the processing time of the photos. The area of interest contained ice from the top of the cube to the bottom of the melted part. A color thresholding macro was then created based on the last photo of each series. The macro distinguished parts of the photo where the ice has melted. To achieve this, a high enough contrast was required, so red dye (Eosin B) had to be used during the tests. The photo series was then converted to a binary Tagged Image File Format (TIFF) file based on the outcome of the thresholding method. Later any and noise particles not connected to the melted area were removed.

A Matlab script was developed to analyze the photo series. The program downloaded a series of TIFF images and calculated the penetration and volume development based on the pixel-to-millimeter ratio found earlier. The volume calculation was based on an assumption that half of the length of each dyed row is a semi-major or a semi-minor axis in an ellipse. The formula A=$\pi * a * b$, where a and b are lengths of the semi-major and semi-major axis in an ellipse, was used to calculate the area, A, of a horizontal cross-section at any given depth. Then one pixel (height of each row) was set as the “height” of each cross-section and multiplied with that area, resulting in volume of a thin slice/cylinder. The melted volume at a certain time was then calculated as the sum of the volumes of those slices. The resulting volume at each timestamp was then plotted in a graph to enable comparison between the tests.

Results

A total of eighteen experiments were performed, including nine pre-wetted and nine dry samples in three different temperatures. A typical development of melted volume (as percentage of maximal total melted volume) and penetration are illustrated in Figure 1a and b respectively. This example shows one repetition of the experiment conducted at -2°C with a dry sample of the solid deicer. The development of the melting process is characterized by a short initial waiting time, before the dissolution of the deicer initiates. When enough deicer is dissolved an ice melting reaction with a steady ice melting rate occurs. As the amount of melted ice increases the deicer gets diluted and the melting rate slowly decreases. This goes on until an equilibrium is reached and the melting reaction stops, signalizing that the melting capacity of the deicer has been reached. The development of penetration depth followed a similar pattern. The dissolution of the deicer happened during a short initial waiting period, during which any melting occurred just at the surface of the ice cube. Then, the penetration with a constant rate occurred until it abruptly ended when achieving a certain maximum value, dependent on test conditions.



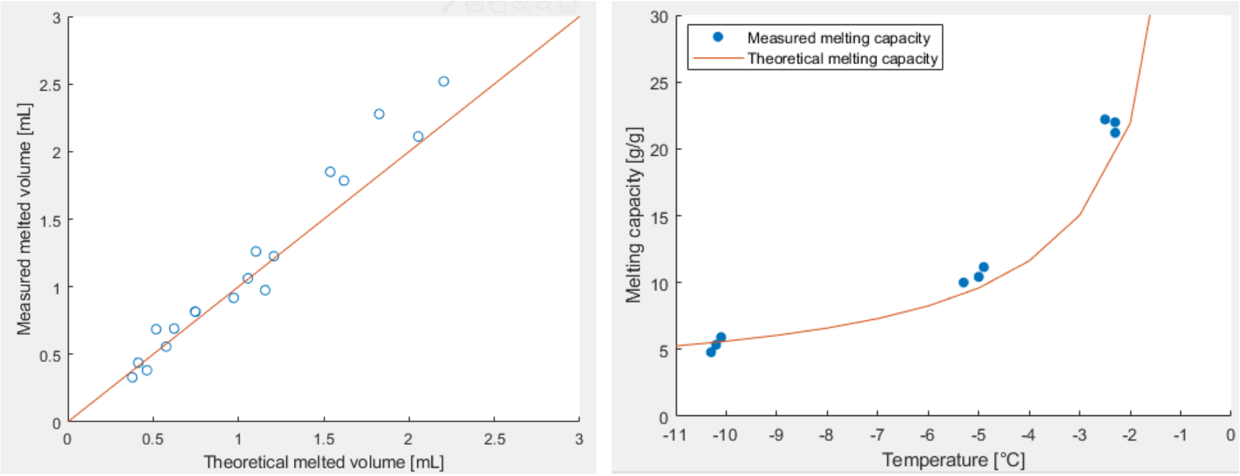
(a) *Development of melted volume, shown as a percentage of maksimum melted volume*

(b) *Development of total penetration depth in millimeters*

Figure 1: *A figure showing a typical volume (a) and penetration (b) development, during a test at -2° C*

In order to check the validity of the method a comparison of theoretical melted volume and measured melted volume has been performed. Theoretical values were calculated based on freezing point curves from Melinder, for potassium formate and from "Characterization of runway deicers" published by French civil aviation authority for sodium formate. The method gave satisfactory correlation between experimental and theoretical values as shown in Figure 2a. The correlation between melting capacity, expressed as grams of melted ice per grams of the deicer, and temperature has been compared exclusively for dry samples, as shown in Figure 2b.

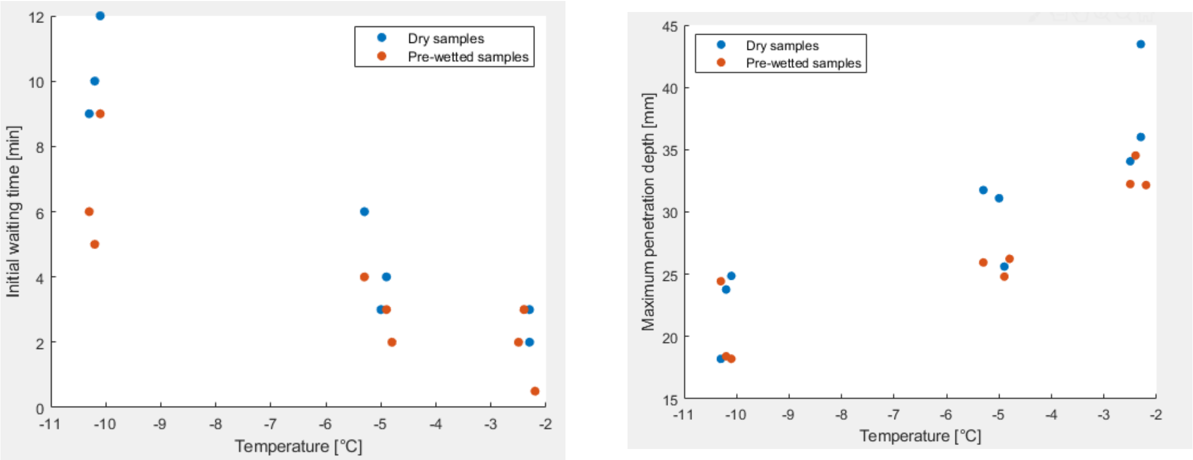
When comparing test performed at different temperatures, a few general trends were observed. First of all, the initial waiting time before the dissolution if the granules started, increased for lower temperatures. For dry samples, this initial phase lasted from 2.5mins±1min in -2°C, though 4.5mins±1min in -5°C, up to 10mins±2mins in -10°C. Figure 3a shows the variation of the initial waiting time. Second trend indicated that the melting reaction itself goes slower in lower temperatures. Combined, those two trends result in a lower overall melting rate for tests performed with colder conditions, with the time it took to reach the melting capacity being 60mins±5mins, 70mins±5mins and 100mins±10mins in -2°C, -5°C and -10°C respectively.



(a) *Comparison between theoretical and measured total melted volume*

(b) *Comparison between theoretical and measured melting capacity of solid deicer*

Figure 2: *A figure showing comparison between theoretical and experimental data*



(a) *The change in initial waiting time for different temperatures, with and without pre-wetting*

(b) *Comparison of maximum penetration depth achieved in different temperatures*

Figure 3: *A figure showing penetration performance of 0.0553g±0.0001g to 0.1178g±0.0001g grains*

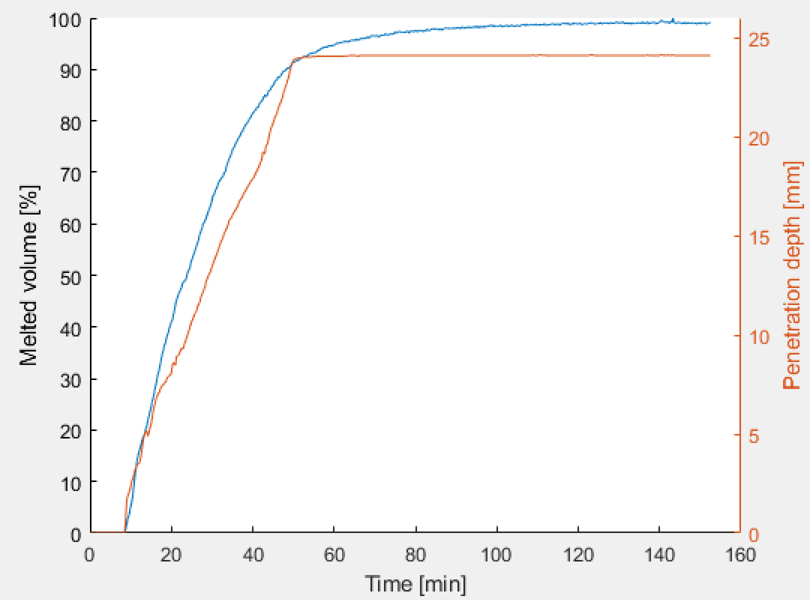


Figure 4: *The development of penetration and achieved melting capacity percentage in one graph. Data for a repetition of dry sample in -5° C*

When it comes to penetration, a clear correlation between the maximum depth and temperature has been observed. The penetration depth varied from 38mm±6mm, through 29mm±2mm until 22mm±2mm in -2°C, -5°C and -10°C respectively. This relation is shown in Figure 3b In addition to the total penetration depth, the diameter of the melted hole decreased in lower temperatures, and varied between 11mm and 5mm in the temperature range.

While maximum penetration depth was strictly dependent on the temperature, it was not entirely proportional with the total melting capacity. In fact, the end of the penetration process did not always occur at the same time as the end of the whole melting process. Instead, it was differing between temperatures, with the end of the penetration process happening at different percentages of achieved melting capacity. This is exemplified in Figure 4 where, in -5°C, the penetration stopped while the melting capacity reached 90% of the total potential. The volume increase past this point consisted of horizontal expansion of the melting area. For -2°C the penetration stopped roughly at 75% of achieved melting capacity, while in -10°C the penetration development and melting process stopped simultaneously, when reaching 100% of melting capacity.

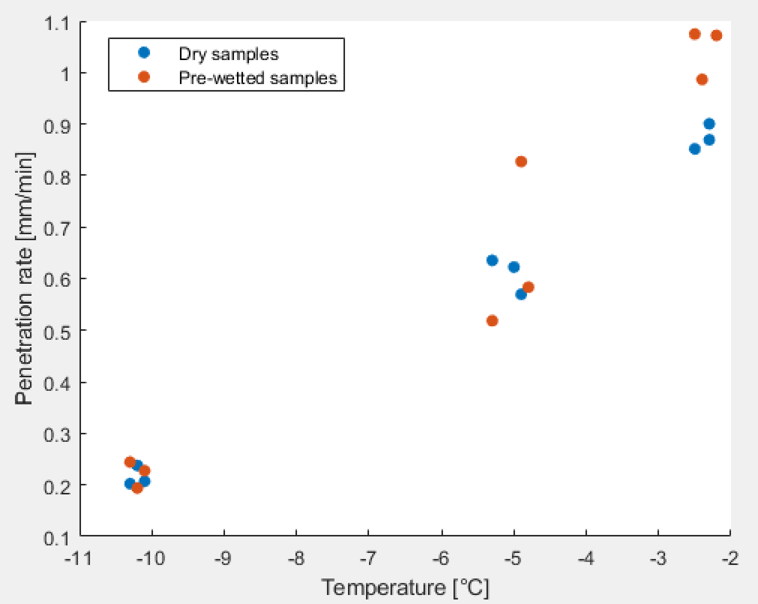


Figure 5: *Overall penetration rate expressed in [mm/min] for pre-wetted and dry samples*

The observed influence of pre-wetting on the process varied greatly based on the temperature. During the tests in low temperature (-10°C), the general trend showed a significant reduction in the initial waiting time. At the same time the melting- and penetration process remained unchanged, even though some variance in data occurred. For higher temperatures (-2°C and -5°C) there was no significant difference between pre-wetted and dry formate, although most of the pre-wetted samples had a shorter initial waiting time compared to their dry counterparts. A relation between the overall penetration rate and temperature for both pre-wetted and dry samples is shown in Figure 5. The overall penetration rate is here defined as the maximum penetration depth divided by the time that was necessary to obtain that depth (including both the initial waiting time and the melting time).

Discussion

As Figure 2a and b shows, the method was able to measure the melting performance of a deicer reasonably well, when compared to theoretical values in the literature. While the results that were compared were solely based on the images of the final situation (after the equilibrium was reached), it can imply that the analysis of the complete photo series will make it possible to follow the development of the whole melting process. That is, from the point when a deicer is placed on the ice surface, until it reaches the melting capacity. Because of that, it can be used to continuously monitor progress in the melting process, thus giving an opportunity to quantify such properties as melting- and penetration rate. Another advantage compared to SHRP and similar tests, is that this method is not dependent on manual measurements of the amount of melted ice with a syringe at set time intervals, so the disturbance of the melting process and random, unregulated heat flows from the environment are minimized. At the same time there are some issues connected to the procedure, namely the use of clear ice. Making bubble-free ice is a slow process, and it can require over one week to prepare the samples. The clear ice is also a denser than most of the ice samples encountered in field conditions. Higher density means that the sample has less voids that can easily be penetrated by the deicer, thus reducing both the total penetration depth and -rate. While dense ice can occur naturally during periods with many melting-refreezing cycles or in case of frequent freezing rains (Nixon et.al, 2003), this method will generally illustrate a worst-case scenario when it comes to measured penetration values.

Another observation that might have an impact on practical application of the results was that the diameter of the cavity created by the deicer varied in different temperatures and reached up to 11-12mm. The standard SHRP penetration test utilizes confined 4mm cavities drilled in a Plexiglas plate, a procedure that heavily restricts the direction in which the melting process can develop and ensures that a bigger part of the melting capacity can be used to penetrate deeper through the ice. Therefore, it might seem that even though the new method could be described as a worst-case scenario, it might give results that are closer to realistic field observations.

The experiments has shown that penetration depth is strictly dependent on the temperature, and that there is some degree of correlation between the achieved penetration depth and percentage of used melting capacity. This suggests that even if the physical properties limit the total amount of ice that a deicing agent can melt, the same penetration depth can be achieved in lower temperature, simply by increasing the grain size (that will increase the available weight of the deicer and, as follows, the total melting capacity). However, more research is required in order to quantify the dependence of penetration depth on grain size.

Considering the effects of pre-wetting, it can be easily concluded that the effect in lower temperatures is favorable for deicer performance. At the same time it should be noted that the gains are mostly achieved because of the reduction of the initial waiting time. As mentioned in the introduction, deicing process requires a dissolved deicing agent to depress the melting point. Hence, the pre-wetting liquid should be applied directly on the deicer grain, to provide enough moisture for the deicer to dissolve and initiate the melting reaction fester. This implies that a method where the granular deicer is pre-wetted prior to spreading on the runway is more favorable than another common method, where the pre-wetting solution is applied directly on the runway, after the spreading of dry granulate.

As noted in the result section, no significant difference was measured when applying pre-wetting liquid in higher temperatures. However, those results alone should not be considered as definitive in a decision-making process. Other considerations, like the pre-wettings reduction of initial loss that occurs because of spray-off, wind or air traffic from neighboring runways, should be investigated and quantified.

Practitioners require guidelines for optimized usage of deicing chemicals. The instructions usually describe the amount (the application rate) of a deicer and the waiting time before mechanical removal can be initiated. While those two parameters are important, the melting efficiency is also dependent on other factors, that should be included in the guidelines. This study shows that both the penetration depth and penetration rate are significantly dependent on temperature as well as, implicitly, deicer grain size. Therefore, in order to achieve maximum efficiency, the temperature should be included in the product usage guide, while airport authorities should define strict product specifications to ensure that the purchased products are as effective in current conditions as possible. While this study is too limited to fully define such guidelines by itself, the developed method as well as obtained results can be used for further investigation of the subject.

Conclusions

In this paper the knowledge gap within airport / runway deicing is defined, as well as some problems, connected to current lab testing methods, are characterized. A brief introduction describing a standard melting process i given. A new method based on image analysis at different stages of the melting process has been developed and tested. The method i used to observe and quantify the influence of temperature on the melting process including quantifying properties such as penetration depth and -rate. In addition effect of prewetting on the deicing performance in different temperatures is investigated. The pros and cons of the method are then discussed, as well as a short description of implications for practitioners is given.

References

Addcon (2019a) Aviform S-Solid Product specification, Retrieved from URL: http://www.addcon.com/en/de-icing/aviform/aviform-s-solid/product-specifications/

Addcon (2019b) Aviform L50 Product specification, Retrieved from URL:: http://www.addcon.com/en/de-icing/aviform/aviform-l-50/product-specifications/

Chappelow, Cecil C., McElroy, A. Dean, Blackburn, Robert R., Darwin, David, Noyelles, Frank G. de, Locke, Carl E. (1992) Handbook of Test Methods for Evaluating Chemical Deicers SHRP-H-332

Fay, Laura, Western Transportation Institute (2017) Field Usage of Alternative Deicers of Snow and Ice Control *Local Road Research Board, Minnesota Department of Transportation* TRS 1706

Gerbino-Bevins, B.M., Tuan, Y. Christopher, Mattison, M (2012) Evaluation of Ice-Melting Capacities of Deicing Chemicals *Journal of Testing and Evaluation* 40. 104460. 10.1520/JTE104460.

Klein-Paste, Alex, Potapova, Julia (2014) Thermal Aspects of Melting Ice with Deicer Chemicals *Transportation Research Record: Journal of the Transportation Research Board* Vol 2440, Issue 1 pp.69-75

Koefod, Scott, Adkins, Jessica, Akin, Michelle R. (2012) Alternative Approaches to Measuring Deicer Ice-Melting Capacity Optimization of Test Accuracy and Precision *Transportation Research Circular* Issue E-C162 pp.432-442

Koefod, Scott, Mackenzie, Rafe, Adkins, Jessia (2015) Effect of Prewetting Brines on the Ice-Melting Rate of Salt at Very Cold Temperatures *Transportation Research Record: Journal of the Transportation Research Board* Vol 2482 Issue 1 pp.67-73

Koefod, Scott. (2017). Effect of Prewetting Brines and Mixing on Ice-Melting Rate of Salt at Cold Temperatures: New Tracer Dilution Method. *Transportation Research Record: Journal of the Transportation Research Board.* 2613. 71-78. 10.3141/2613-09.

Luker, Craig, Rokosh, Barry, Leggett, Timothy (2004) Laboratory Melting Performance Comparison Rock Salt With and Without Prewetting *Transportation Research Circular: Snow Removal and Ice Control Technology* Issue E-C063 pp.585-601

Melinder, Å. (2007) Thermophysical Properties of Aqueous Solutions Used as Secondary Working Fluids Doctoral Thesis By. TRITA REFR Report No 07/60

Muthumani, Anburaj, Fay, Laura, Akin, Michelle, Wang, Shaowei, Gong, Jing, Shi, Xianming (2014) Correlating lab and field tests for evaluation of deicing and anti-icing chemicals: A review of potential approaches *Cold Regions Science and Technology* Vol 97 pp.21-32

Nilssen, Kine, Klein-Paste, Alex, Wåhlin, Johan (2016) Accuracy of Ice Melting Capacity Tests Review of Melting Data for Sodium Chloride *Transportation Research Record: Journal of the Transportation Research Board* Vol 2551 Issue 1 pp.1-9

Nixon, Wilfrid A., Wei, Yingchang (2003) Optimal Usage of De-Icing Chemicals When Scraping Ice *Iowa Department of Transportation and Iowa Highway Research 36Board, IIHR Technical Report* No 434

Schweigert, Nathalie, Poissonnier, Stéphanie (2016) Characterization of runway deicers: Study report *French civil aviation authority, Civil aviation technical center* ISBN 978-2-11-151662-5

Tuan, Y. Christopher, Albers II, Tregan (2014) Development of Shaker Test as a Standardized Test Protocol for Deicing Chemicals Evaluation Paper Numbers: 25-1121-0003-058, MATC-UNL: 058

Wåhlin, Johan, Klein-Paste, Alex (2016) Chemical Melting of Ice Effect of Solution Freezing Point on the Melting Rate *Transportation Research Record: Journal of the Transportation Research Board* Vol 2551 Issue 1 pp.111-117