Effects of Additives in Deicing Salts at Lower Temperatures

Final Report

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Western Transportation Institute

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The goal of this project was to investigate the effects of additives commonly used in deicers for winter road maintenance operations, explore the qualitative and quantitative benefits of these additives, laboratory and performance data, impacts, and relative performance to sodium chloride (NaCl). Additionally, evaluate the impact additives have on solid rock salt performance measured as eutectic temperature. To accomplish a literature review, surveys of state and local agencies and deicing product vendors and manufacturers, and laboratory testing including eutectic temperature and or freezing point, a modified ice melting capacity Rocker Test Method for solids and measuring pavement friction were completed. Conclusion, recommendations, and suggested future research to support this effort are provided.

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Final Report

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LIST OF ABBREVIATIONS

AASHTO – America Association of State Highway and Transportation Officials
APWA - American Public Works Association
ASTM – American Society for Testing and Materials
C - Celsius
$CaCl_2$ – calcium chloride
CCM – complex chloride mineral
CMA – calcium magnesium acetate
CO_2 – Carbon dioxide
DLA – Direct liquid application
DOT – Department of Transportation
DSC – Differential Scanning Calorimetry
F – Fahrenheit
FHWA - Federal Highway Administration
G - gram
Gal - gallon
HCOONa – sodium formate
IMC – ice melting capacity
$IMCRT_{15}$ – Ice Melting Capacity Rocking Test – 15-minute
$IMCRT_{30}$ – Ice Melting capacity Rocking Test – 30-minute
In - inch
ISI (Web of Science) – Institute for Scientific Information
KCl – potassium chloride
K_2CO_3 – potassium carbonate
L - liter
Lbs - pounds
$MgCl_2$ – magnesium chloride, mag
Min - minute
mL - milliter
mm - millimeter
MMZ – Magic Minus Zero
NaCl – sodium chloride
Na_2SiO_3 – sodium metasilicate
NCHRP - National Cooperative Highway Research Program
PIARC – World Road Association
Rpm – revolution per minute
SHRP - Strategic Highway Research Program
T - ton
Tc – characteristic temperature
TRB – Transportation Research Board

UTC - University Transportation Center
Wt.% - weight percent

EXECUTIVE SUMMARY

The goal of this Clear Roads project was to investigate the effects of additives commonly used in deicers for winter road maintenance operations, through collection of information on the qualitative and quantitative benefits of these additives, laboratory and performance data specifically on eutectic temperature, and identification of impacts; all relative to the performance to sodium chloride (NaCl).

Literature Review

This literature review investigated the effects of additives on the three most common chloride-based deicers used in winter road maintenance operations: sodium chloride (NaCl: rock salt or salt brine); magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$), and provides information on the qualitative and quantitative benefits of these additives, laboratory and performance data, and impacts. The literature review provides a discussion of why additives are used by each agency and the influence additives have on deicer performance, specifically focusing on changes in eutectic temperature (freezing point), ice melting capacity, ice under cutting, ice penetration, and road grip (pavement friction coefficient).

Chloride-based salts are cost-effective and practical, making them the most common deicers used in winter road maintenance operations, but these deicers can have negative impacts on infrastructure and the environment. Additives can be used to address some of these issues and may provide benefits including increase deicer efficiency and effectiveness, corrosion protection, cold temperature performance, anti-caking properties, residual effect extenders, and may be "environmentally friendly" compounds. Many test methods have been identified that can help assess the changes in performance of deicing/anti-icing products induced by additives. This project specifically calls out the use of eutectic temperature to show how additives support chlorides working at lower temperatures. Other methods such as calorimetry, measurements of ice melting capacity, ice penetration, ice under cutting, and road grip (friction) are also able to assess the improved performance from additives.

Survey

Two surveys were conducted of state and local agencies and deicer and additive product vendors and manufacturers to gather information on commonly used deicers with additives. The survey sought to learn how they are used, benefits and impacts, and gather available data and resources.

Responses from state and local agencies identified better snow and ice removal performance, cold temperature modification, longer residual on the pavement, cost effectiveness, and reduced corrosion as the top five reasons they use additives in chloride-based deicers. A list of deicers, additives, blend ratios, volume used, and product source; along with details on why specific additives were selected is provided in Chapter 4. Survey Results. Identified benefits of using additives include cost savings, reduced material use, quicker storm clean-up, and visibility on the road. The impacts identified include increased corrosion and sticky residual. A list of deicers and additives manufacturer/vendor and product description is provided in Chapter 4. Survey Results.

Lab Results

Laboratory testing was conducted to characterize the influence of additives on chloride-based deicer performance. Eight solids and prewet solids were evaluated for freezing point or eutectic temperature, ice melting capacity using the Rocker Test, and pavement friction.

Freezing point or eutectic temperature test results found minute differences with all solids and prewet solids having a freezing point or eutectic temperature of -21.19 ± 0.58°C (-6.14°F). Because all of the solids and prewet solids were composed of rock salt (sodium chloride, NaCl), the eutectic temperature for all products were similar.

A modified IMCRT test method was used to allow testing of solid deicers. ***The modified IMCRT is not a validated test method, and the results herein cannot be compared to results from valid test methods***. Ice melting capacity testing found NaCl prewet with Beet Juice to have the highest ice melting capacity (IMC) at both temperatures followed by, NaCl prewet with $MgCl_2$, NaCl prewet with MMZ, IceKicker, NaCl control and NaCl prewet with BEET HEET, NaCl prewet with NaCl, and Ice Slicer. Additional rocking time was found to increase ice melting in all cases.

The influence of the deicers and additives on pavement friction identified similar trends in coefficient of friction for each deicer on asphalt and concrete pavement types, with the pavement type having a significant influence on the results. The coefficient of friction values for each deicer and additive blend varied between test temperatures. There is no clear best performer because the coefficient of friction performance changed over time for each temperature and pavement type. These results suggest that additives may lead to reductions or improvements in pavement friction at varying times and due to varying conditions. By 60 minutes, the coefficient of friction values stabilized for all test parameters to 0.63 ± 0.06. At 15°F and 0.60 ± 0.06 at 30°F.

Recommendations and Future Research

Recommendations, future work, and research ideas that build off of this work and further support transportation agencies include additional testing of additives at higher pre-wet rates and development of a validated IMCRT for solid deicing materials.

1 INTRODUCTION

The objectives of this Clear Roads project were to investigate the effects of additives commonly used in deicers for winter road maintenance operations, explore the qualitative and quantitative benefits of these additives, laboratory and performance data, impacts, and relative performance to sodium chloride (NaCl). Additionally, evaluate the impact additives have on solid rock salt performance measured as eutectic temperature.

This was accomplished through the following work presented here as:

- Chapter 2 Methods
- Chapter 3 Literature Review
- Chapter 4 Survey Results
- Chapter 5 Lab Testing Results
- Chapter 6 Results, Conclusions, Recommendations

2 METHODS

2.1 LITERATURE REVIEW

A literature review was conducted focused on identifying information on chloride deicers and additives (read: mixed salts), qualitative and quantitative benefits of these additives, laboratory and performance data, impacts, relative performance to sodium chloride, etc. The following databases were used to gather relevant information including: Google Scholar, Transportation Research Information Service, ISI Web of Science, and Montana State University Library. A search of documents published by state DOTs, Clear Roads, university transportation centers (UTCs), Strategic Highway Research Program (SHRP), Federal Highway Administration (FHWA), National Cooperative Highway Research Program (NCHRP), PIARC, American Public Works Association (APWA), and AASHTO was performed.

2.2 SURVEY

The research team developed a survey in Qualtrics, a web-based survey tool to collect information from departments of transportation, public works agencies, and the private sector, including product manufacturers and vendors, on commonly used chloride deicers blended with additives. The survey was distributed on October 4, 2023, to the Clear Roads Technical Panel and Members states, the American Association of State Highway Officials (AASHTO) Snow & Ice List Serv, the Transportation Research Board (TRB) Winter Maintenance Committee, the American Public Works Association Winter Maintenance Group, and other relevant transportation agencies and organizations. The survey was closed on November 7, 2023. The survey instrument is provided in APPENDIX A - Survey Instrument.

2.3 LABORATORY EVALUATION

2.3.1 "Mixed Salts" for Testing

The following list of "mixed salts," deicers (re: control untreated white salt, NaCl, rock salt) and liquid additives used for testing are described below.

Rock Salts

- Rock Salt – reagent grade (control) (Flinn Scientific NaCl large-crystal rock salt)
- Ice Slicer®
- IceKicker®

Additives to be used to Prewet (reagent grade) Rock Salt

- Salt brine (23.3%) (control)
- Beet Heet®
- Beet Juice
- Magic -0® (MMZ)
- $MgCl_2$ brine (30%)

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All additives will be used as pre-wet added at 8 gallons per ton (gal/ton). Table 1 provides a description of the sample number, naming, material, product description, and the lab test methods and time intervals that were used in each test.

Table 1. Lab testing matrix

Sample #	Name	Material	Description	Freezing Point (Eutectic)	Modified IMC Rocker Test	Friction (15, 30, 45, and 60 minutes)
1	Solid Control	Rock Salt	Flinn Scientific NaCl large-crystal rock salt		15 and 30 min	x
2	Solid 1	Ice Slicer®		x	15 min	x
3	Solid 2	IceKicker®		x	15 min	x
4	Prewet control	NaCl brine	Rock salt + 8 gal/ton NaCl brine		15 and 30 min	x
5	Prewet 1	Beet Heet®	Rock salt + 8 gal/ton Beet Heet	x	15 min	x
6	Prewet 2	Beet Juice	Rock salt + 8 gal/ton Beet Juice	x	15 min	x
7	Prewet 3	MMZ	Rock salt + 8 gal/ton MMZ	x	15 min	x
8	Prewet 4	$MgCl_2$ brine	Rock salt + 8 gal/ton MgCl2 brine	x	15 min	x

2.3.1.1 Making the pre-wet

The NaCl and $MgCl_2$ brines were made by WTI. The NaCl brine is 23.3 wt. % NaCl, and the $MgCl_2$ brine is 30 wt. % $MgCl_2$. Both brines were made with deionized water (DI water). The prewet materials, including BEET HEET®, Beet Juice, and MMZ, and solid deicers, Ice Slicer® and IceKicker®, were provided by different state DOTs from their stockpiles or inventory shown in Table 2.

Table 2. Source for solid deicers and additive products.

Product	Supplied By
Ice Slicer®	Wyoming Department of Transportation
IceKicker®	Idaho Transportation Department
BEET HEET®	South Dakota Department of Transportation
Beet Juice	North Dakota Department of Transportation
MMZ	Maine Department of Transportation

All additives were used as prewet solutions and were applied at a rate of 8 gallons per ton (gal/ton). For the 1,100 grams (g) of rock salt, this translates to 36.7 milliliters (mL) of prewet solution per sample. One sample of rock salt did not receive a prewet solution and was designated as Solid Control.

To prepare each prewet sample, the required amount of prewet solution was sprayed into a graduated cylinder to determine the number of sprays needed to achieve 36.7 mL. Due to variations in spray bottles, and solution density and viscosity, the number of sprays varied for each prewet sample. For these reasons, for each prewet solution, this method was used three times to determine a consistent number of sprays to reach 36.7 mL.

Each 1,100 g sample of rock salt was spread evenly on a lined metal cookie sheet. The appropriate number of sprays for each prewet solution, as determined from the graduated cyliner test, was then applied as evenly as possible to the rock salt. After applying the prewet solution, the rock salt was mixed with a rubber spatula until salt grains were uniformly coated (Figure 1). The prewet rock salt was then placed in labeled sample containers and shaken for an additional minute to ensure thorough mixing.

Figure 1. Rock salt sample with beet juice prewet solution applied.

Once all samples were prepared, approximately 10% (~110 g) of each sample was reserved for the WTI friction testing. The remaining 90% (~990 g) was shipped to WSU for testing. Each prewet material was stored in a labeled container (Figure 2).

Figure 2. Samples made for testing following gradation analysis and prewetting. Small bottles remained at WTI for testing, larger bottles were sent to WSU for testing.

2.3.1.2 Sieve Analysis, Gradation of Solid Materials

A sieve analysis was conducted on the three solid deicers - reagent grade large crystal rock salt (NaCl), Ice Slicer®, and Ice Kicker®. Approximately 1 kg of each deicer was placed into a stack of sieves (3/4", #4, #8, #30), covered, and shaken manually for 5 minutes over a metal tray to collect fine materials. The weight of the material retained in each sieve was recorded (Table 3). Note that the sieve analysis was performed prior to testing on the nine, 1,000 grams (g), bottles of Flinn Scientific NaCl large-crystal rock salt. The average sieve ratio obtained from the nine bottles of rock salt was used to prepare each rock salt sample to ensure the gradation was in the range of those reported by Ice Slicer® and IceKicker®. Six rock salt samples, each weighing 1,100 g, were created with similar gradation.

For the commercial solid deicers, Ice Slicer® and IceKicker® the sieve analyses were initially obtained from the specification descriptions available on their respective websites. Following testing, sieve analyses were completed for Ice Slicer® and IceKicker®. The particle size distributions of the three solid materials—rock salt, Ice Slicer® gradation reported by the vendor and measured, and IceKicker® gradation reported by the vendor and measured are presented in Table 3. Note that the percent fines, or particles passing through sieves #16, #30, and #50 were much higher for Ice Slicer® and IceKicker® than the reagent grade rock salt, and specifically for Ice Slicer® the percent fine passing through sieve #30 were significantly greater than what is reported on their website, 50.4% measured versus 0 – 15% from the website. The commercial solid deicers were used in their original forms for all lab testing.

Table 3. Gradation results for solid deicers

Sieve Size	Rock Salt (reagent grade) % passing measured	IceSlicer® % passing measured	Ice Slicer® % passing (from website)	IceKicker® % passing measured	IceKicker® % passing (from website)
3/4”	100	100	100	100	-
½”	-	-	-	-	100
3/8”	-	-	-	-	90-100
#4	68.2	80.5	60-100	87.4	75-100
#8	36.4	81.1	10-80	66.7	20-60
#16	-	-	-	-	15-45
#30	4.6	50.4	0-15	46.5	-
#50	-	-	-	-	0-10

2.3.2 Laboratory Test General Procedures

2.3.2.1 ASTM D1177 – Freezing point determination of liquids

The freezing point determination (FPD) test, also known as the freezing point test (FPT), utilizes the ASTM standard test method for the freezing point of aqueous engine coolants (ASTM International, 2007). The setup was modified by utilizing a freezing tube (rather than a custom-made non-silvered and non-evacuated Dewar flask) and a linear actuator to do linear stirring (rather than a conventional rotational stirring) (Liu et al., 2021). A summary of the FPD procedure is provided below.

2.3.2.1.1 FPD TEST PROCEDURE

A detailed procedure is provided in the Missouri DOT project report (#cmr 21-009) (Liu et al., 2021). As per the instructions of ASTM D1177 (ASTM International, 2007) the setup included a freezing tube, a 2100 mL dewar flask (no lid), a linear actuator with controller, a stainless-steel coil stirrer to move vertically up and down in linear motion inside the freezing tube, an Omega® RTD data logger, a platinum thermometer, dry ice, alcohol, and a laptop. Most of these items are shown in Figure 3 and the remaining are shown in Appendix B (Figure 28). The brine concentrations evaluated for all products for freezing point test (FPT) included 5, 10, 15, and 23 wt. %, except for Solid 1 for which 26 wt. % was also tested for its freezing point determination.

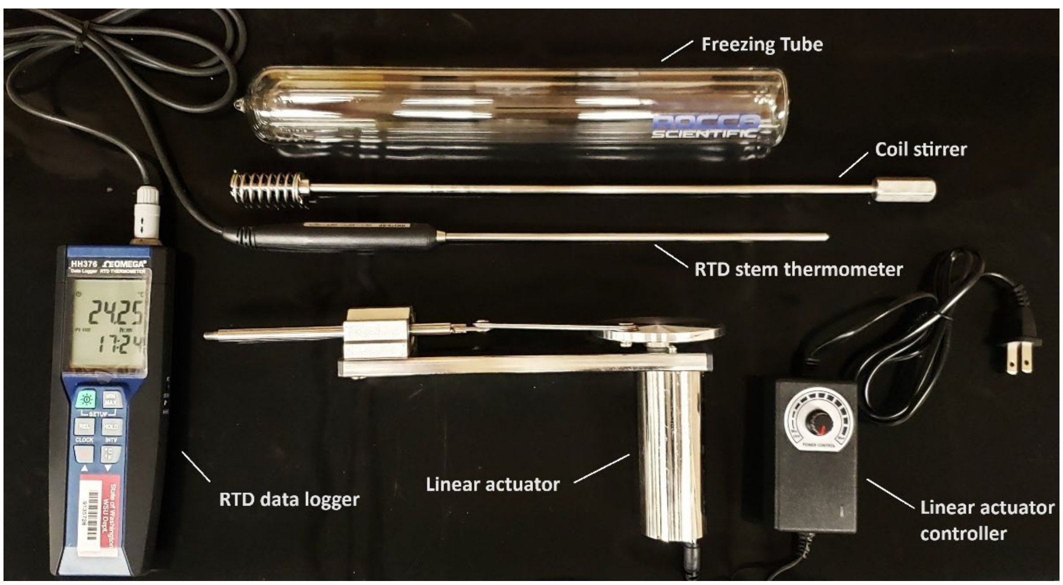

Figure 3. The items used in the freezing point determination test (ASTM D1177)

A summary of the FPT procedure is described below:

1. For any test concentration, brine solution is prepared by careful measurements using the following formula:

Equation 1. Formula for preparing brine solution. (Note all unit measurements are in grams.)

$$\left(\frac{Solute}{Solute+Solvent}\right) * 100$$

2. The solution is then pre-cooled to at least 8°C (46.4°F) in a refrigerator or a freezer for quicker freezing during the test.
3. To prepare the ice bath, the dewar flask (2100 mL) is filled with 140 proof alcohol. Dry ice is added to it slowly (avoiding the spilling of alcohol due to effervescence phenomenon as much as possible), until it reaches a temperature of at least -25°C (-13°F).
4. A clean, dry freezing tube is inserted into the ice bath and then clamped.
5. An overhead stirrer arrangement (Figure 29, Appendix B) is used to insert a stainless-steel coil stirrer (Figure 3) into the freezing tube.
6. The cooled brine solution is carefully added to the freezing tube and the RTD thermometer is inserted into the freezing tube. Ensure that the minimum required length is inserted into the solution to avoid errors. The thermometer is connected to the RTD data logger.
7. The RTD data logger is then connected to the laptop on which the required software is already installed and ready to use. Ensure that the recording function is working properly and that the battery and memory of the data logger are sufficient to run the experiment. One experiment takes 1 to 2 hours.
8. The linear stirring is started. The stirrer coils should not come out of the solution during the stirring and the strokes per minute are kept between 60 to 80 (ASTM International, 2007).
9. Recording is then started on the data logger and a real-time graph is plotted to observe the freezing point whenever possible.
10. During the test, ensure that enough dry ice is added to the ice bath and that its temperature stays between -35 °C and -50°C (-31°F to -58°F) to keep a steady cooling rate of 0.5°C/min but not more than 1°C/min.
11. The freezing point is reported by following the ASTM D1177 instructions by either following the supercooling or seeding approach. Both are acceptable provided that the error is kept to a minimum.

2.3.2.2 Modified Ice Melting Capacity (IMC) - Rocking Test [NOT A VALIDATED TEST METHOD]

The IMC Rocking Test (IMCRT) method developed by NDOT (Hansen & Halsey, 2019) and validated in CR 18-06 (Nazari et al., 2024) only applies to liquid deicers. For this work, the IMCRT was modified to allow testing of solid deicers. ***Note that the modified IMCRT method used in this lab study has not been validated and therefore the reported findings cannot be compared to findings from the approved IMCRT method for liquid deicers.***

A rocking device is used in this test to shake or rock thermoses containing ice cubes and solid deicer for a specific amount of time. A new method was recently adopted to complete IMC tests called the staggering method which saves time, costs, and energy. Usually, only one flask is placed on the rocker at a time until the test is completed; but in the staggering method, multiple flasks (as replicates) are placed on the rocker at intervals. The rocking parameters are listed in Table 16 in Appendix B.

2.3.2.2.1 MODIFIED IMC TEST PROCEDURE

The modified IMC rocking test (IMCRT) method used is described below. A detailed procedure is provided in APPENDIX B - Additional Details: Lab Test Methods, Tables, and Figures to Support lab Results.

1. Prepare the test freezer – set at either 15°F or 25°F.
    a. Carefully weigh and note the weights of six Styrofoam cups up to two digits of accuracy, already labeled as A, B, C, AA, BB, and CC, and then place them in the test freezer. The test freezer should be tested a few weeks before the actual test to ensure the accuracy of temperatures, and then the temperature should be set a day before testing.
    b. Place three empty, cleaned, and dried thermoses and lids, labeled A, B, and C inside the test freezer (Figure 4). Do not secure the lids for now.
    c. Carefully weigh and note the weights of 5g of solid deicer samples, using a flexible plastic weighing dish, with up to two digits accuracy, and then add the deicer to thermos A. Partially secure the lid of thermos A to allow the salt to acclimate. Repeat the process for the thermos B and C using the respective measured deicer samples.
    d. Place a sieve with its bottom pan, a silicon spatula, and a stainless-steel tong inside the test freezer (Figure 5).
    e. All thermoses and items should be acclimated for at least 12 hours before the test begins.
2. Prepare the working freezer – set at a minimum of 0°F.
    a. Fill the ice cube trays (each cube holding 1.3 mL of water) using a pipette (a repeater pipette is recommended) and place the trays in the working freezer for 12 hours. Each IMCRT requires 99 ice cubes to run triplicates tests.
3. On the test day
    a. About one hour before starting the modified IMCRT, take the ice cube trays from the working freezer and place them in the test freezer. This will acclimate the ice cubes to the test temperature.
    b. Make sure a laptop or any other timing device is ready to accommodate three separate times. Also, keep a weighing balance ready (turned ON and tared, zeroed out) before working inside the test freezer. Keep the Rocker ON and set it to the point where it can begin rocking with one click. The following method can be used to run the modified IMCRT using the staggering method.
    c. Open the test freezer and put 33 ice cubes in the Styrofoam cup A, measure their weight and place them inside the thermos A. Quickly and fully secure the thermos's lid and securely place the thermos on the Rocker (leaving space for two more thermoses). Start the rocking and start the timer for thermos A. Three different timers can be named A, B, and C.
    d. When doing a 15-minute modified IMCRT, after about four minutes of rocking thermos A, repeat the above step 3c to add thermos B to the Rocker. Then after waiting for another four minutes, add thermos C to the Rocker.

e. As soon as the timer for thermos A goes off, take the thermos off the Rocker, without disturbing the other two thermoses, and quickly empty its contents onto the sieve inside the test freezer. Work quickly to collect the ice cubes (using the silicon spatula), avoiding the crystalline salt particles, and place them into Styrofoam cup AA in the freezer. Quickly weigh the melted ice cubes and note the weight. The freezer temperature should not rise more than 1 to 1.5°C while working inside the test freezer. After ice cube weights are recorded, the Styrofoam cups can be discarded.
f. Repeat step 3e for the remaining two thermoses, B and C. Use cups BB and CC to measure the weights of melted ice cubes from thermoses B and C, respectively. Then discard those cups. Do not use one sieve for more than three replicates; this will help to keep the error to a minimum.

4. Use the formulae provided in the NDOT report (Hansen & Halsey, 2019) or CR 18-06 final report (Nazari et al., 2024) to calculate the IMC in grams/grams (g/g) of solid deicers. ***Note that these results are not validated for solid deicers and cannot be compared to results for liquid deicers.***

Figure 4. Freezer with thermoses and lids, Styrofoam cups, sieves with pans, brush, ice cube tray, and digital thermometer set up for testing.

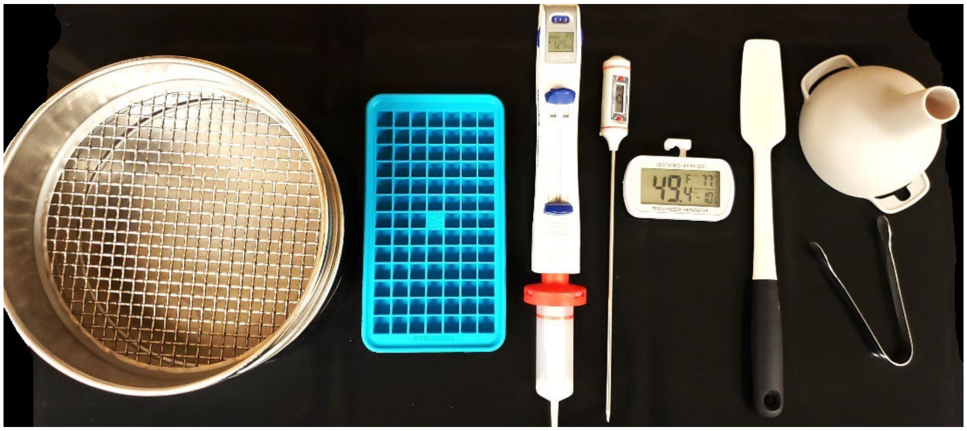

Figure 5. Items used in modified IMCRT (left to right): a #4 sieve (1/4" mesh opening), a mini-ice cube tray made by Casa Bella®, an Eppendorf® repeater pipette M4, a stem thermometer (only for liquid samples), a digital thermometer for freezers, a silicon spatula, a plastic funnel, and a pair of stainless tongs.

Figures of other items used (weighing balance, cups, etc.) are provided in Appendix B (Figure 28).

2.3.2.3 Friction – General Procedure

The objective of the friction, or grip, testing was to assess the grip characteristics of prewet rock salts and compare them to deicers (i.e., rock salt, Ice Slicer®, and IceKicker®)(based on previous friction testing completed by Muthumani et al. (2015) and Akin, Fay, Shi (2020)). The performance of these deicers and additives was evaluated on concrete and asphalt pavements over the course of one hour after the application of the deicer and additives blends. Tests were conducted at 15°F and 30°F. Peak force was measured using a friction pull-device to determine the static coefficient of friction. The coefficient of friction was calculated by measuring the initial pounds (lbs) of peak force required to move the pull-test device and dividing it by the device's weight. The pull-device used in the WTI Subzero Lab is a 4-inch by 4-inch metal block, weighing 4.9 lbs, with a rubber pad on the bottom to simulate tire contact with the pavement surface.

Initial tests revealed that applying the test samples as solids on a thin layer of ice was ineffective because the rock salt did not melt into the ice during the test time period, resulting in inaccurate friction measurements. To address this issue, the research team prepared brine solutions from each deicer and deicer additive blend sample. The deicer application rate was set at 250 pounds per lane-mile (lbs/l-m). Pavement samples used for testing measured 1.19 square feet, requiring 2.14 grams (g) of deicer per test (Equation 2). For each sample 2.14 g of deicer was dissolved in 7.05 g of deionized (DI) water to create 23.3 weight % testing solutions.

Equation 2. Conversion of deicer application rate from lbs/l-m to g/ft^2.

$$\left(\frac{250\ lbs}{1\ l-m}\right)\left(\frac{453.592\ g}{1\ lbs}\right)\left(\frac{1\ l-m}{63{,}360\ ft^2}\right)=\left(\frac{1.8\ g}{1\ ft^2}\right)=\left(\frac{2.14\ g}{1.19\ ft^2}\right)$$

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Clean and dry pavement samples were brought into the Subzero Lab and allowed to reach equilibrium with the test temperature. Each pavement sample was large enough to permit eight peak force measurements at each time interval. The initial peak force measurements were taken on the clean and dry pavement samples. The test solution was then applied to the pavement samples and the liquid was spread evenly using a rubber spatula. Additional force measurements were collected 15, 30, 45, and 60 minutes after application of the test solution.

The following summarizes the friction testing procedure used to evaluate the grip characteristics of prewet rock salts and deicers on concrete and asphalt pavements:

1. **Pavement Sample Preparation:** Clean and dry pavement samples were placed in the Subzero Lab at least 24 hours prior to testing to adjust to the test temperatures of 15°F and 30°F.

2. **Control Measurements:** Initial peak force measurements were taken on the clean and dry pavement samples at the beginning of the test. These measurements provided a baseline for the static coefficient of friction.

3. **Application of Deicers:** The brine solution was evenly spread across the surface of the pavement sample using a rubber spatula.

4. **Peak Force Measurements After Application:** Eight peak force measurements were taken 15, 30, 45, and 60 minutes after the application of the deicer for each sample. The rubber surface of the pull-device was wiped clean between measurements to ensure consistency and accuracy, and to prevent cross contamination.

5. **Cleaning and Reusing Pavement Samples:** After each test, the pavement samples were washed and cleaned thoroughly. The samples were allowed to dry completely before being returned to the Subzero Lab for additional testing.

This procedure ensured that for each deicer and deicer additive blend, and pavement sample consistent and accurate measurement were collected under controlled conditions.

3 LITERATURE REVIEW

Chloride-based salts are the most common deicers used in the winter maintenance operations toolkit, whether applied as deicers or anti-icers to combat snow and slippery conditions. Winter maintenance professionals choose deicing products based on a variety of factors including cost, effective temperature range, performance, corrosiveness, and specific application requirements. Salt-based deicers are relatively inexpensive compared to other products and alternative deicing methods, making them widely accessible and practical. Sodium chloride (NaCl), as rock salt or salt brine, is the most common choice, though magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$), or blends of these with additives are commonly used and often proffered in colder climates (Akin et al. 2013).

Winter road maintenance professionals apply rock salts (solids typically as deicers) and salt brines (liquids typically as anti-icers), to improve roadway and sidewalk safety by expediting the ice melting process and preventing or breaking the bond between snow, ice, and pavement from forming. Deicing products not only reduce snow removal and cleanup (read: plowing) time but also prevent slippery conditions and reduce the possibility of accidents and injuries.

A major challenge faced when using chloride-based deicers is the corrosivity that can cause damage to infrastructure and equipment. Metal surfaces such as vehicles, bridges, utilities, and rebar reinforcement that are exposed to corrosive deicers may require increased maintenance and repair costs (Maeshima et al. 2014; Lee et al. 2017; Shi et al. 2009; Fischel 2001). For example, trucking companies reported increased pitting, corrosion, tarnishing, drying, and rust accumulation on metal and rubber vehicle parts after the Colorado Department of Transportation began using magnesium chloride deicer (Xi and Olsgard 2000). To avoid similar damage to aircraft parts and electronics, U.S. airports are forbidden from using corrosive deicers and, therefore, use non-chloride deicers (Switzenbaum et al. 2001). However, many deicers, even those that are not chloride-based, still require corrosion inhibitors to reduce their impact on vehicles and infrastructure.

Cumulative research has demonstrated that chloride-based deicers run off into neighboring bodies of water and cause significant negative environmental impacts, harming aquatic life and disrupting local ecosystems (Siegel 2007; Findlay and Kelly 2011; Fay and Shi 2012; Sleeper 2013). The high chloride levels in water and soil have adverse effects on plants and animals, including humans, and have caused increased salinization of surface and ground water, including drinking water supplies (Harless et al. 2011; Hintz, Fay, and Relyea 2022). Vegetation, particularly roadside plants, can suffer from salt damage due to the high deicer concentrations (Fay and Shi 2012), such as leaf burn, stunted growth, and even plant death (Sleeper 2013). Deicing salt also mobilizes harmful elements and heavy metals, such as lead, cadmium, copper, zinc, mercury, and radium, that were formerly trapped in contaminated sediment – increasing animal and human exposure to carcinogens and radioactive material (McNaboe, Robbins, and Dietz 2017; Feick, Horne, and Yeaple 1972; Bäckström et al. 2004; Hintz, Fay, and Relyea 2022).

Effects of Additives in Deicing Salts at Lower Temperatures

Additives that are commonly incorporated into deicers include corrosion inhibitors, anti-caking agents, cold temperature modifiers, thickeners, friction enhancers, dye markers, pH buffers, surfactants, environmental-friendly compounds, residual effect extenders, or other products that improve the effectiveness, efficiency, and or safety of deicers during winter maintenance operations (Shi and Jungwirth 2018). Due to issues noted above, it is important to understand why various additives are used and what benefits they provide; in other words, whether or not the addition of the additive is worth the additional cost, effort to blend, store and handle, and potential impacts. For example, corrosion inhibitors aid in reducing corrosion impacts to infrastructure and equipment but add cost. Agricultural or organic based additives have been shown to reduce corrosion, suppress ice nucleation, and increase longevity on the pavement, but depending on the source product can reduce available oxygen in waterways, require separate storage, handling, and blending, and add cost. Anti-caking agents aid in supporting workability throughout winter but add cost and toxicity.

This literature review investigates the effects of these additives to the three most common chloride-based deicers used in winter road maintenance operations: sodium chloride (NaCl: rock salt or salt brine); magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$), explores the qualitative and quantitative benefits of these additives, laboratory and performance data, impacts, and relative performance to NaCl. The literature is presented in two sections. First it explores why these additives are used. The second part of this report presents information on the influence additives have on deicer performance, this review focuses on changes in eutectic temperature (freezing point), ice melting capacity, ice under cutting, ice penetration, and road grip (pavement friction coefficient).

3.1 WHY ARE ADDITIVES USED

Additives are used to increase deicer efficiency and effectiveness while improving mobility and safety. Additives that are commonly incorporated into deicers include corrosion inhibitors, anti-caking agents, cold temperature modifiers, thickeners, friction enhancers, dye markers, pH buffers, surfactants, environmental-friendly compounds, residual effect extenders, or other products that improve the effectiveness, efficiency, and or safety of deicers during winter maintenance operations (Shi & Jungwirth, 2018). This section summarizes the general benefits of commonly used additives in deicing and anti-icing products.

3.1.1 Corrosion Inhibitors

Corrosion inhibitors reduce the corrosive impacts of deicers on infrastructure and equipment by creating a protective barrier. Chromate inhibitors are the greatest performing corrosion inhibitors, however these products have significant toxicity and negative impacts to the environment (Muthumani, Fay, Bergner, & Shi, 2015). Agricultural by-products are increasingly used in part because they provide varying levels of corrosion protection. Green chemicals derived from dry ground plant material (e.g., alfalfa, wheat, grass) and pomaces (e.g., grape, dandelion leaf, etc.) are effective corrosion inhibitors for carbon steel (Shi & Jungwirth, 2018; Nazari et al., 2019). Succinate salts or glycerol have also been used as a brine additive to reduce corrosion to metals and reduce impacts to concrete and asphalt pavements (Shi & Jungwirth, 2018). A survey of user perceived performance of deicers found that chlorides are perceived as the most corrosive and acetates and formates as the least corrosive (Fay, Volkening, Gallaway, & Shi, 2008).

3.1.2 Anti-Caking Agents

Anti-caking agents support the workability of deicing products throughout winter by preventing product clumping. Sodium Ferrocyanide and Ferric Ferrocyanide are common anti-caking agents, however the use of these products can be harmful to aquatic environments (Ohno, 1990).

3.1.3 Cold Temperature Modifiers

Cold temperature modifiers improve deicer performance at lower temperatures by reducing the freezing point of water, or the key deicing ingredient. Acetates and formates have commonly been used as freezing-point depression enhancers in winter maintenance operations. While these alternatives to chlorides are less corrosive, their higher costs have hindered wider adoption by winter maintenance agencies (Fay & Shi, 2012).

A study by Muthumani et al. (2015) found that liquid agriculturally based products when blended with salt brine could significantly lower the freezing point of water but did not produce more ice melt than salt brine alone (Muthumani, Fay, Bergner, & Shi, 2015). In contrast, premixed salt brine blends (as received from the vendors), specifically blends with glycols or glycerol, had the lowest eutectic temperatures overall.

3.1.4 Friction Enhancers

Friction enhancers improve friction between the vehicle tires and the snow and/or ice-covered roadway surface. While many winter road maintenance agencies have preferably used chemicals over abrasives to improve roadway grip, several states especially those with cold temperatures, low volume roadways, or that lack funding for other products utilize abrasives like sand (Du, Akin, Bergner, Xu, & Shi, 2022).

In a study by Muthumani et al. (2015), agricultural by-products were found to provide increased coefficient of friction during extreme cold snow events (5°F (-15°C)) and during repeated warmer snow events (15°F to 25°F (-9.4°C to -3.9°C)) (Muthumani, Fay, Bergner, & Shi, 2015).

3.1.5 Dye Markers

Dye markers are used to provide color to a deicer to indicate where product has been applied and can be used to trace deicer input into stormwater in the airport environment (Duke Environmental Analytical Chemistry Laboratory, n.d.). A study conducted by Druschel (2017) noted that dyes can increase warming in bright sun conditions and pavement temperatures between 2°F to 4°F (-16.7°C to -15.6°C), but that this warming became insignificant around temperatures of 5°F (-15°C) (Druschel, 2017). This study noted that molasses can be used as a weak dye (Druschel, 2017).

3.1.6 pH Buffers

To avoid detrimental impacts, deicers are generally required to have a pH value between 7.0 to 11.0 (Shi & Jungwirth, 2018). The Clear Roads QPL requires a pH range of 6.0 to 10.0 (Clear Roads, 2021). The following additives are commonly used as pH buffers: hydroxides, phosphates, and ethanol amines (Shi & Jungwirth, 2018).

3.1.7 Surfactants

Surfactants are used to lower the liquid surface tension, which then helps increase deicer coverage and reduce snow and ice adhesion on the roadway surface. Nonylphenol ethoxylates and organophosphates are commonly used surfactants in deicers (Muthumani, Fay, Bergner, & Shi, 2015).

3.1.8 “Environmentally Friendly” Compounds

The environmental impacts of winter maintenance operations have become a priority for many winter road maintenance agencies. Additives are used to enhance performance of a deicer in order to reduce application rates and thus reduce environmental impacts of winter maintenance operations.

Compared to salt brine alone, agricultural-based products have been shown to significantly reduce the bond strength between ice and pavement, improve product longevity on the roadway surface, and provide better roadway friction values during extreme cold snow events (around 5°F (-15°C)) as these products act as an ice crystal nucleation point inhibitor (Muthumani, Fay, Bergner, & Shi, 2015). A study by Nazari et al. (2018) examined 21 anti-icer mixtures which had minimal toxicity to the environment, finding that the one that performed the best contained 0.89 percent Concord grape extract, 4.57 percent glycerin, 4.54 percent sodium formate, 0.19 percent sodium metasilicate, 18.4 percent sodium chloride, and water (Nazari , et al., 2018).

Work by Fay et al. (2008) examined the user-perceived performance of deicers based on various environmental impacts. Regarding impacts to water quality, users ranked acetates and formates as least impactful and abrasives as most impactful (Fay, Volkening, Gallaway, & Shi, 2008). For impacts to soil, vegetation and wildlife and humans, acetates and formates were ranked as least impactful, with abrasives, agricultural products, and chlorides ranking as impactful (Fay, Volkening, Gallaway, & Shi, 2008). Overall, chlorides were ranked as most impactful to infrastructure and the environment (Fay, Volkening, Gallaway, & Shi, 2008).

3.1.9 Residual Effect Extenders

The residual effect of deicers can help reduce labor and costs as more products remain on the roadway surface. Liquid deicers have shown longer residual effect than solids that bounce and scatter from the roadway surface with traffic (Muthumani, Fay, Bergner, & Shi, 2015). Thickeners also work to increase the viscosity of liquid deicers which can help the deicing product remain on the roadway surface for longer periods of time. Thickeners are commonly long-chain, water-soluble polymers (e.g., polysaccharides) containing carboxylate salts (Shi & Jungwirth, 2018).

While minimal testing has been done on this, many have felt that agricultural by-products can increase the amount of product left on the road. Work by Muthumani et al. (2015) conducted laboratory testing and found that agricultural by-products (both preblended by the manufacturer and when blended with a salt brine) greatly improved longevity on the roadway surface when compared to salt brine alone. Additionally, these products weakened the bond between snow, ice, and pavement, and resulted in less snow and ice left on the roadway after plowing (Muthumani, Fay, Bergner, & Shi, 2015). At lower temperatures (15°F (-9.4°C), the deicing products remained on the pavement longer, allowing for lower application rates when retreating a roadway.

3.2 INFLUENCE ADDITIVES HAVE ON DEICER PERFORMANCE

The three salts most commonly used for winter maintenance operations are NaCl, $MgCl_2$, and $CaCl_2$. Sodium chloride (NaCl), also referred to commonly as salt, rock salt, or, in liquid form, as brine, is the most widely used freezing point depressant. It is readily available, affordable, and effective at melting snow and ice, and preventing or breaking the bond between snow, ice, and pavement. The application of sodium chloride as a deicer lowers the freezing point of water, creating a brine solution that further melts snow and ice and improves traction on road surfaces. However, sodium chloride should not be applied below its effective temperature of 15°F (-9.4°C), at which the ice melting speed and application quantities become impractical (Fischel 2001).

Magnesium chloride ($MgCl_2$) is another commonly used freezing point depressant. Because it is more effective at cold temperatures than NaCl, it is often the deicer of choice in colder climates or when the ambient temperature drops below the effective range of sodium chloride. The effective temperature for $MgCl_2$ is around 5°F. Magnesium chloride is also hygroscopic, or a substance that absorbs moisture from its surroundings, which facilitates the creation of salt brine and rapid ice melting. However, its ability to absorb moisture can lead to the formation of wet, corrosive layers on surrounding infrastructure (NCHRP 577 2007). Under specific relative humidity conditions, the application of magnesium chloride onto roads can lead to potentially slippery conditions on the pavement (Perchanok et al. 1991; Leggett 1999).Magnesium chloride can be more expensive than sodium chloride (Clear Roads 2023).

Calcium chloride ($CaCl_2$) is another highly effective freezing point depressant that functions at even lower temperatures than sodium chloride and magnesium chloride, with an effective temperature around 0°F. $CaCl_2$ is exothermic and generates heat when in contact with water, accelerating the ice-melting process. Calcium chloride is also hygroscopic, like magnesium chloride, under specific relative humidity conditions can cause slippery road conditions and is often used for fast-acting deicing or anti-icing applications though its corrosiveness requires precautions for certain surfaces and vehicles. Calcium chloride can be more expensive than sodium chloride, but this is regionally dependent (Clear Roads 2023).

This section summarizes test results that analyzed the influence additives have on deicer performance including changes in eutectic temperature (freezing point), ice melting capacity, ice under cutting, ice penetration, road grip (pavement friction coefficient), and bond strength.

3.2.1 Eutectic Temperature

Knowing the eutectic temperature of a deicer is invaluable when selecting the correct product for road conditions. Eutectic temperature refers to the lowest possible melting temperature for a eutectic mixture – any colder and the mixture will freeze. The eutectic temperature also corresponds with a solution concentration and a eutectic point, "at which all allowable phases may occur and are in equilibrium" (Fay et al. 2022). For NaCl brine, the eutectic point is equal to approximately -6°F (-21°C) and a concentration of 23.3%, at which point liquid brine, solid ice, and salt crystals can all be present. The eutectic temperature for $MgCl_2$ -28°F (-33°C) and for $CaCl_2$ is -60°F (-51°C).

A summary of research that has been conducted using eutectic temperature to note the influence various additives have on deicer performance is provided here. Koefod (2008) measured the freezing point for potassium carbonate (K_2CO_3), which he notes has similar ice melting effectiveness to a 30% $MgCl_2$ solution, was blended with 10, 25, and 50% agricultural byproducts by mass. The freezing point for K_2CO_3 was 19°F (-7.2°C), K_2CO_3 + 10% agricultural byproducts was 6.4°F (-14.2°C), K_2CO_3 + 25% agricultural byproducts was -35°F (-37°C), and K_2CO_3 + 50% agricultural byproducts was -27°F (-33°C). Showing that more additives are not always better in terms of lowering the eutectic temperature. He also looked at the change in freezing point between $MgCl_2$ and xylitol at varying concentrations and found the freezing point for 31.2% $MgCl_2$ was 3°F (-16°C), 23.4% $MgCl_2$ + 15% xylitol was -27°F (-33°C), and 15.6% $MgCl_2$ + 30% xylitol was -35°F (-37°C).

Achkeeva et al. (2015) tested blends of NaCl, $MgCl_2$, $CaCl_2$, and potassium chloride (KCl) at varying concentrations and found the coldest eutectic temperatures were associated with NaCl (33%) + $MgCl_2$ (66%) [eutectic temperature of -28°C (-18.4°F)] and NaCl (25%) + $MgCl_2$ (25%) + $CaCl_2$ (50%) [eutectic temperature of -30°C (-22°F)]. Other blends that had eutectic temperature of -27.5°C (-17.5°F) included NaCl (33%) + $CaCl_2$ (66%) and NaCl (33%) + $MgCl_2$ (33%) + $CaCl_2$ (33%). The poorest performing blends all had KCl present. This work also looked at blends of chlorides with sodium formate but none of these provided improvement to eutectic temperature. Similar work from the same lab found that the concentrations of sodium formate when added to chlorides and chloride blends should be above 7% to see significant changes in eutectic temperatures (Kondakov et al. 2021).

Nazari et al. (2016) measured the eutectic temperature of NaCl and Mix 1 (23% salt brine + 3 wt% sugarbeet leaf extract + 0.67 wt% sodium formate) and found eutectic temperatures of -22.8°C (-9°F) and -15.7°C (-3.7°F), respectively.

3.2.2 Differential Scanning Calorimetry

To better understand the thermal properties of deicers including eutectic temperature, melting behavior, phase transitions, and heat capacity a Differential Scanning Calorimetry (DSC) or calorimeter can be used. The DSC measures the heat flow of a sample as a function of temperature while subjecting it to heating or cooling. By analyzing the DSC curve, the eutectic temperature can be determined as the point where a sharp endothermic peak occurs, representing the melting of the eutectic mixture (Maria, Millam, and Wright 2011). The heat flow that occurs during the eutectic melting process indicates the efficiency of different deicer formulations or additives and the DSC can be used to study the compatibility of different deicer formulations or the influence of additives on the thermal properties of a deicing product. A summary of research that has been conducted using calorimetry to note the influence various additives have on deicer performance is provided here and in Table 4.

Abbas et al. (2021) used a DSC to test multiple combinations of agricultural products and their impact on the freezing point of brine. Beet juice, corn juice, and polyols, including sorbitol, maltitol, and mannitol, were mixed in different concentrations with a 23.3 wt% NaCl and water. A high concentration of sorbitol in brine solution had the lowest freezing point: -38.1°C (-36.6°F). The same concentration of maltitol in brine had a similar freezing point of -35.6°C (-32.1°F). When 100% beet juice and 70% corn juice were tested, they had freezing points of -6.8°C (19.8°F) and -2.9°C (26.8°F), respectively. When 23.3 wt% NaCl brine was added to the beet juice, the freezing point dropped to -28°C (-18.4°F) and the corn juice freezing point was reduced to -23.5°C (-10.3°F) (Abbas et al., 2021).

Nazari et al. (2019) conducted a similar experiment comparing dandelion leaf extract and sugar beet leaf extract to different concentrations of sodium metasilicate (Na_2SiO_3), sodium formate (HCOONa), sodium chloride, and water – all common roadway deicing ingredients, such as corrosion inhibitor additives. The eutectic temperature for a mix of 3 wt% sugar beet leaf extract, 0.67 wt% sodium formate, 23 wt% NaCl, and 73.33 wt% water was found to be −26.5°C (-15.7°F) at a concentration of 25 wt%, while the eutectic temperature for 23 wt% NaCl solution was −22.8°C (-9°F). Since the mix had a lower eutectic temperature than salt brine, it may also have a lower effective working temperature – showing the potential of additives to improve performance of deicers.

Shi et al. (2018) investigated the effectiveness of bio-based renewable additives, including apple pomace, apple fiber, cherry pomace, Concord grape fiber, blueberry fiber, orange peels, and potato peels, for anti-icing applications using DSC thermograms. Concord grape extract and glycerin were mixed with sodium chloride, sodium metasilicate, and sodium formate for experimental testing. The DSC revealed the role of glycerin and sodium formate in the mixture's relatively low characteristic temperature (T_c) of -11.7°C (11°F) and its lower T_c than a beet juice and salt brine blend. By adding 0.19 wt% sodium metasilicate to the sample, the T_c became -19.2°C (-2.6°F). The addition of 4.54 wt% sodium formate to the deicer reduced the T_c to approximately -22°C (-7.6 °F) - a 2.8°C (3°F) decrease in the freezing point. Adding another 4.57 wt% of glycerin dropped the T_c a further 1.5 degrees to -23.5°C (-10.3°F). Since nearly the same percentage by weight of sodium formate and glycerin was used but the change in T_c was greater for sodium formate, it can be concluded that sodium formate was the more effective freezing point depressant in the examined deicer. The same mixture, but with the addition of 0.89 wt% concord grape extract, reduced the T_c to -23.9°C (-11°F), which indicated that Concord grape extract made a minor improvement in the T_c. The combination of 18.4 wt% NaCl, 0.19 wt% sodium metasilicate, 4.54 wt% sodium formate, 4.57 wt% glycerin, and 0.89 wt% concord grape extract had the lowest T_c of the tested mixes (-23.9°C [-11°F]), even compared to that of the beet juice blend, which had a T_c of -22.8°C (-9°F) (Shi et al. 2018).

Nilssen et al. (2018) used a custom-made calorimeter to study the effects of additives on ice melting capacity on blends of NaCl with $MgCl_2$, $CaCl_2$, potassium formate, calcium magnesium acetate (CMA), sugar (as sucrose) at -18°C (0°F). Average ice melting capacity results for <u>liquid</u> products from highest to lowest are as follows 35% potassium formate (0.25 g/g), 25% $CaCl_2$ (0.24 g/g), 20% $MgCl_2$ (0.17 g/g), 80% NaCl + 20% CMA (0.14 g/g), 35% CMA (0.09 g/g), 80% NaCl + 20% $MgCl_2$ (0.09 g/g), 80% NaCl + 20% $CaCl_2$ (0.08 g/g), 82% NaCl + 20% potassium formate (0.04 g/g), and 70% sugar (0 g/g). Average ice melting capacity results for <u>solid</u> products from highest to lowest are as follows 80% NaCl + 20% $MgCl_2$ (3.36 g/g), 80% NaCl + 20% $CaCl_2$ (3.42 g/g), 80% NaCl + 20% potassium formate (3.08 g/g), $CaCl_2$ (2.76 g/g), potassium formate (2.56 g/g), 80% NaCl + 20% CMA (2.27 g/g), CMA (2.12 g/g), $MgCl_2$ (1.75 g/g), sugar (0 g/g). A key finding from this work is that solids have much higher ice melting capacity than liquids.

Muthumani et al. (2015) also used DSC thermograms to compare the T_c of deicer additives. The complex chloride and mineral (CCM) based products, Ice Slicer and Thawrox, and as-received agro-based additives, Beet 55 (sugar beet molasses), Boost SB, Snow Melt, and Geomelt 55 (beets), did not exhibit significantly lower T_c than reagent grade NaCl, which ranged between -3.9°C (25°F) and -1.1°C (30°F). However, the deicers Apogee (glycerin), Boost CCB, Ice Ban 305 (corn and $MgCl_2$), and ThermaPoint IB 7/93 (lignin) had significantly lower T_c than NaCl, but the higher (~10%) coefficient of variance during testing indicated "the challenge of obtaining consistent and uniform results" (Muthumani et al. 2015). DSC thermograms also show that CCM- and agro-based deicers have lower enthalpy of fusion, *H*, (89-176 J/g) than reagent grade NaCl (197 J/g); it is thermodynamically more difficult to freeze a solution with a lower *H* value. The CCM-based products tested by (Muthumani et al. 2015) failed to significantly improve freezing point depression compared to a 23.3 wt% NaCl solution (ASTM D1177-07) but the agro-based additives and as-received agro-based deicers produced significant freeze point depression compared to brine; with a reduced freezing point of between -18.4°F and -9.52°F compared to -6°F for salt. This indicates that agro-based products are freezing point depressants.

Fay and Shi (2011) used a DSC to collect heat flow data and report effective temperature on NaCl, $MgCl_2$, agricultural product, sodium acetate and sodium formate blends. Characteristic temperatures (T_c) results are as follows $MgCl_2$ -11.3°C (11.6°F), NaCl -4.6°C (23.7°F), CMA -4.7°C (23.5°F), potassium acetate -13.9°C (7.0°F), sodium acetate -7.3°C (18.8°F), sodium formate -8.1°C (17.4°F), sodium acetate + sodium formate blend -7.7°C (18.1°F), agricultural products ranged from -3.2 to -11.0°C (26.2 – 12.2°F).

Early work by Iverson et al. (1997) developing cooling curves for blends of $CaCl_2$ and NaCl and found that as more $CaCl_2$ is added, lower freezing points were found.

Shi et al. (2013) used a DSC to characterize various blends of NaCl, $MgCl_2$, $CaCl_2$, sugar beet agricultural additive (AGBP), CCB, FreezGard CI plus, and Shield GLT. The T_c for all products and blends ranged from 21.7 – 23°F, with the exception of $MgCl_2$ having the lowest Tc of 8.5°F, followed by $CaCl_2$ at 16.2°F, and highest T_c for AGBP of 26.2°F.

Shi et al. (2014) used a DSC to characterize rock salts (NaCl), salt brines, and $MgCl_2$ and found that rock salt (NaCl) had T_c -5.2°C (22.7°F), salt brine (NaCl) had T_c of -7.7°C (18.1°F), and $MgCl_2$ had T_c of -13.9°C (7.0°F).

Table 4. A summary of freezing point and characteristic temperature from results reviewed.

Products Tested	Characteristic Temperature (T_c) (°F)	Reference
dandelion leaf extract, sugar beet leaf extract, sodium metasilicate, sodium formate, NaCl	3 wt% sugar beet leaf extract + 0.67 wt% sodium formate + 23 wt% NaCl + 73.33 wt% water at 25 wt%: -15.7°F (eutectic temperature) 23 wt% NaCl: -9°F (eutectic temperature)	Nazari et al. (2019)
NaCl, sodium metasilicate, sodium formate, glycerin, Concord grape extract, beet juice	23% NaCl brine: -1.1 18.4% NaCl brine + 0.19% sodium metasilicate: -2.5	Nazari and Shi (2019) Shi et al. (2018)

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Products Tested	Characteristic Temperature (T_c) (°F)	Reference
	18.4% NaCl brine + 0.19% sodium metasilicate + 4.54% sodium formate: -7.6 18.4% NaCl brine + 0.19% sodium metasilicate + 4.54% sodium formate + 4.57% glycerin: -10.3 18.4% NaCl brine + 0.19% sodium metasilicate + 4.54% sodium formate + 4.57% glycerin + 0.19% Concord grape extract: -11.0 NaCl brine + beet juice: -9.0	
NaCl, Ice Slicer and Thawrox Beet 55, Boost SB, Snow Melt, Geomelt 55, Apogee (glycol), Boost CCB, Ice Ban 305, and ThermaPoint IB 7/93	NaCl: 23.5 IceSlicer: 28 Thawrox: 22.9 NaCl + Beet 55: 24.8 NaCl + Boost SB: 30.4 NaCl + Snow Melt: 25.4 NaCl + Geomelt 55: 28.1 Apogee: 16.2 Boost CCB: 6.1 IceBan 305: 8.9 ThermaPoint: 6.4	Muthumani et al. (2015)
NaCl, $MgCl_2$, agricultural product, sodium acetate, sodium formate, and blends of these	$MgCl_2$: 11.6 NaCl: 23.7 CMA: 23.5 potassium acetate: 7.0 sodium acetate:18.8	Fay and Shi (2011)

Products Tested	Characteristic Temperature (T_c) (°F)	Reference
	sodium formate: 17.4 sodium acetate + sodium formate blend: 18.1 agricultural products: 26.2 – 12.2	
NaCl, $MgCl_2$, $CaCl_2$, sugar beet agricultural additive (AGBP), CCB, FreezGard CI plus, Shield GLT, and blends	NaCl brine: 21.8 $MgCl_2$ brine: 8.5 $CaCl_2$ brine: 16.2 AGBP (ag): 26.2 All blends: 21.7 – 23.0	Shi et al. (2013)
11 different NaCl rock salts and brines, $MgCl_2$	Rock salt (NaCl): 22.7°F Salt brine (NaCl): 18.1 $MgCl_2$: 7.0	Shi et al. (2014)

3.2.3 Ice Melting, Penetrating, and Undercutting

Ice melting, ice penetration, and ice undercutting tests are used to evaluate the performance and effectiveness of deicers. The Strategic Highway Research Program (SHRP) standardized these methods in 1992 (Chappelow et al., 1992), and they play a crucial role in determining the performance of deicers for winter maintenance operations. An additional ice melting test, the Mechanical Rocker Test, developed by Gerbino-Bevins and Tuan (2011) and Tuan and Albers (2014) has been shown to be more accurate and precise for liquid deicers. The results of these tests help identify the most effective deicers for specific snow and ice conditions, temperatures, and thicknesses to optimize their use. A summary of research that has been conducted using ice melting, ice penetration, and ice undercutting to note the influence various additives have on deicer performance is provided here.

3.2.3.1 Ice Melting Tests

3.2.3.1.1 SHRP AND MODIFIED SHRP ICE MELTING TEST

The SHRP Ice melting tests determine the melting capacity of a deicer. They involve applying a set quantity of deicer onto an ice-covered surface and observing the rate at which the ice melts (Chappelow et al., 1992). Ice melting tests may be performed under controlled laboratory conditions or in the field to evaluate the deicer's performance in various freezing scenarios.

Multiple ice-melting capability test methods exist, but this section will focus on results from the SHRP H205.1 test that involves applying solid deicers to a frozen surface and measuring the volume of liquid melted at 15, 30, 45, and 60 minutes (Chappelow et al., 1992). The more ice melted, the higher the ice melting capacity. Work summarized below can be found in Table 5.

SHRP 205.1 ice melting tests were conducted by Zhang et al. (2020) to investigate and compare the performance of prewet applied to dry salt. They tested 23.3 wt% NaCl, 30 wt% $MgCl_2$, 32 wt% $CaCl_2$, 80:20 NaCl brine and beet juice, and 97:3 NaCl brine and grape pomace extract. They found that prewetting was beneficial to initial and terminal ice melting for lower application rates (282 kg/L · km) at both warm temperatures (−3.9°C [25°F]) and cold temperatures (−9.4°C [15.1°F]). The biggest performance difference in the effectiveness of the prewet liquids was observed during tests at −3.9°C (25°F) and 282 kg/L · km at −9.4°C (15.1°F). The prewet liquids performed similarly to each other and better than dry salt. Considering all temperatures and application rates, the most effective prewetting liquids, from best to worst, were: (1) $CaCl_2$, (2) grape pomace blend, (3) beet juice blend, (4) 23% NaCl, and (5) $MgCl_2$ (Zhang et al, 2020).

Nazari et al. (2016) conducted SHRP ice melting tests on 16 combinations of 23% sodium chloride blended with varying concentration of dandelion extract, sugar beet leaf extract, sodium metasilicate, and sodium formate by wt% at 15°F (-9.4°C). The highest ice melt capacity of 3.6 ml/g was associated with the Mix 4 (23% salt brine + 3 wt% dandelion extract + 3 wt% sugar beet leaf extract + 1.34 wt% sodium metasilicate). The final Mixes 1 (23% salt brine + 3 wt% sugar beet leaf extract + 0.67 wt% sodium formate) and Mix 5 (23% salt brine + 2 wt% sodium metasilicate), chosen based on overall performance, had ice melting capacities of 2.32 mL/g (higher than salt brine) and 2.29 mL/g (same as salt brine) at 25°F (-3.9°C), respectively. At 15°F (-9.4°C), Mixes 1 and 5 both similar had ice melting capacities around 1.45 mL/g, lower than salt brine (ice melting capacity 1.58 mL/g).

Nazari et al. (2019) also used the SHRP ice melting test to examine the performance of agricultural (agro)-based solutions mixed with 23 wt% sodium chloride brine and commercial additives. Dandelion leaf extract and sugar beet leaf extract, derived from locally sourced feedstock, were compared to multiple concentrations of sodium metasilicate, sodium formate, sodium chloride, and water. The average 60 minute ice-melting capacity of the anti-icer solutions were 90% or greater when compared to the capacity of salt brine at −3.9°C (25°F). Some of the dandelion and sugar beet mixes had an ice-melting capacity of at least 12% (0.3 mL/g), greater than the NaCl solution, which makes them potential anti-icer replacements for salt brine (Nazariet al. 2019).

More testing of the agro-based anti-icers including concord grape extract, beet juice, glycerol, sodium formate and sodium metasilicate was conducted by Nazari and Shi (2019). They used the SHRP ice-melting test to determine the performance of multiple combinations and concentrations. The most effective mixture (1.94 wt% concord grape extract, 1.94 wt% glycerol, 2.86 wt% sodium formate, and

1.46 wt% sodium metasilicate) outperformed 23% NaCl by more than 0.2 mL/g and a beet juice + salt brine blend by 0.13 mL/g, making it a potential product replacement for roadway anti-icing (Nazari and Shi 2019).

Taylor et al. (2014) used a SHRP test to determine that of the many combinations of glycerol, Geomelt (sugar beet based), Ice B'Gone (IBG; molasses, other sugars/carbs), E310 (corn hulls), BioOil, $MgCl_2$, and NaCl tested [80 wt% glycerol + 20 wt% NaCl, 90 wt% glycerol + 10 wt% $MgCl_2$, 80 wt% Ice B'Gone + 20 wt% NaCl, 90 wt% IBG + 10 wt% $MgCl_2$, and 40 wt% E310 (corn hulls) + 40 wt% glycerol + 20 wt% NaCl] had the lowest freezing and eutectic temperatures in a 75% concentration with water. The freezing and eutectic temperatures were -46°F (-43.3°C) and -48°F (-44.4°C), -44°F (-42.2°C) and -45°F (-42.8°C), - 50°F (-45.5°C) and -50°F, and -41°F (-40.5°C) and -42°F (-41.1°C), respectively. The ice-melting capability was greatest for 80 wt% glycerol + 20 wt% NaCl, 90 wt% glycerol + 10 wt% $MgCl_2$, 80 wt% Ice B'Gone + 20 wt% NaCl, 90 wt% IBG + 10 wt% $MgCl_2$, and 50 wt% glycerol + 50 wt% $MgCl_2$, which melted 25 ml, 24 ml, 25 ml, 25 ml, 25 ml, and 25 ml of water over 240 minutes, respectively. The research concluded that a diluted 80% glycerol + 20% NaCl solution was the most promising agro-based additive that was tested.

Muthumani et al. (2015) used a modified SHRP test to determine that the tested CCM- (Ice Slicer and Thawrox) and agro-based deicers (Beet 55, Boost SB, Snow Melt, Geomelt 55, Apogee (glycol), Boost CCB, Ice Ban 305, and ThermaPoint IB 7/93) were effective. Each melted 1 g/g solid or 1 ml/ml liquid deicer within 60 minutes and did not refreeze at 15°F or higher, though the solid deicers took 60 or more minutes to achieve their melting potential while the liquid deicers reached their potential in 10 to 20 minutes. The CCM-based products were more effective ice-melters than the other agro-based products, regardless of temperature. They also melted more ice at 15°F (-9.4°C) than the NaCl control, though the difference was not significant, as the improved melting effect was gone by 25°F (-3.9°C). Additionally, Ice Slicer experienced diminished ice melt at 5°F (-15°C) when compared to NaCl. The diluted liquid deicers (Beet 55, Boost SB, Snow Melt, and Geomelt 55) experienced mixed ice-melting results at both 15°F (-9.4°C) and 25°F (-3.9°C) when compared with the control brine, but there was no significant overall difference in ice melting capacity at 5°F (-15°C), 15°F (-9.4°C), or 25°F (-3.9°C) (Muthumani et al. 2015). "These results suggest that the agro-based additives may act as 'cryoprotectants,' which tend to inhibit freezing without melting the ice (Koefod 2008)." However, the as-received deicers (Apogee, Boost CCB, Ice Ban 305, and ThermaPoint IB 7/93) melted significantly more ice at all test temperatures than salt brine, though the difference in volume was not as significant as the volume of melt from rock salt. Muthumani et al. (2015) attributed the increased effectiveness to the inclusion of $MgCl_2$, $CaCl_2$, and other chlorides.

Another aspect of a product's ice-melting capability is its color and capacity for light absorption. Muthumani et al. (2015) noted that ThermaPoint IB 7/39 (lignin) and Geomelt 55 (beet) were darker in color and produced more ice melt at 5°F (-15°C) and 15°F (-9.4°C) than salt brine. All of the products tested produced more ice melt in simulated sunshine than salt brine or rock salt, though the CCM-based products did not produce enough for the difference to be significant. "For CCM-based products, at higher intensity sunlight, ice melting capacity was similar, irrespective of product type at 5°F (-15°C) and

15°F (-9.4°C). At medium intensities of sunlight, ice melting capacity of CCM-based product was slightly higher than NaCl. For agro-based products, at higher intensity sunlight, ice melting capacity was similar irrespective of product type at 5°F (-15°C) and 15°F (-9.4°C) [but] at lower temperatures, darker colored agro-based products (ThermaPoint IB 7/39 and Geomelt 55) had higher ice melting capacity than lighter color agro-based products and salt brine" (Muthumani et al. 2015).

Sajid et al. (2021) used an in-house ice melting test to compare the capabilities of three corn-derived polyols (e.g., sorbitol, mannitol, and maltitol) with a 23.3 wt% NaCl brine deicer. When 27.7 wt% mannitol was added to salt brine, a 93%, 112%, and 81% increase in the volume of ice melting was observed at -10°C (14°F), -20°C (-4°F), and -30°C (-22°F), respectively, when compared to the salt brine control. The addition of 27.7 wt% sorbitol resulted in a 43% and 13% increase at -10°C (14°F) and -20°C (-4°F), respectively. However, at -30°C (-22°F), the addition of 27.7 wt% sorbitol failed to improve the ice melting capacity. When 27.7 wt% maltitol was added to the salt brine, the ice melting capacity of the deicing solution increased by 17% at both -10°C (14°F) and -20°C (-4°F) but showed not improvement to the ice melting capacity at -30°C (-22°F) (Sajid et al., 2021).

Koefod (2008) measured ice melting capacity using the SHRP method for potassium carbonate (K_2CO_3) blended with 0, 10, 25, and 50% agricultural byproduct at 15°F (-9.4°C) and reported rates of 0.87 g/g, 0.58 g/g, 0.25 g/g, and -0.21 g/g, respectively. Similarly, K_2CO_3 blended with 0, 10, and 25% agricultural byproduct at 5°F (-15°C) and reported rates of 0.43 g/g, 0.18 g/g, -0.06 g/g, respectively. Ice melting capacity was also measured for $MgCl_2$ blended with xylitol at 0, 15, 30, 45, 60% and reported rates of 1.22 g/g, 0.76 g/g, 0.39 g/g, 0.08 g/g, and 0.02 g/g, respectively. Results indicate that ice melting capacity is highest with the largest percent concentration of K_2CO_3 with no agricultural byproduct and for $MgCl_2$ when no xylitol is added, therefore in these instances the additive does not add any value to ice melting capacity.

Achkeeva et al. (2015) measured ice melting capacity of blends of NaCl, $MgCl_2$, $CaCl_2$, KCl varying concentrations and found the highest ice melting capacities at -5°C (23°F) were associated with NaCl (33%) + $MgCl_2$ (66%) with an ice melting capacity of 12.5 g/g, and with NaCl (50%) + $MgCl_2$ (50%), NaCl (50%) + $CaCl_2$ (50%) both having ice melting capacity of 11.5 g/g. At -10°C (14°F) results were similar with NaCl (33%) + $MgCl_2$ (66%) with an ice melting capacity of 7.1 g/g and with NaCl (50%) + $MgCl_2$ (50%), having ice melting capacity of 6.9 g/g. At both temperatures, the lowest ice melting capacities are associated with blends including KCl. This work also looked at blends of chlorides with sodium formate but none of these provided improvement to ice melting capacity. Similar work from the same lab found that the concentrations of sodium formate to chlorides and chloride blends should be above 7% to see significant changes in ice melting capacity (Kondakov et al. 2021).

Nixon et al. (2007) conducted ice melting capacity testing (SHRP method) for NaCl, $CaCl_2$, CMA, potassium acetate, CM-1000, Mineral Brine, and IceBan Ultra at 0, 10, 20, and 30°F (-17.8, -12.2, -6.7, -1.1°C). Results varied by temperature, and for all products, less ice was melted as temperatures decreased. Additionally, for all but one product, the ice melting rate was highest in the first 10 minutes of the 60 minute test. For all temperatures, Mineral Brine, CM-1000, and $CaCl_2$ had the highest ice melting capacities, with CMA having the lower ice melting capacity.

Fay and Shi (2011) conducted SHRP ice melting testing on NaCl, $MgCl_2$, agricultural product, sodium acetate and sodium formate blends at 0, -5, and -18°C (32, 23, 0°F). Results varied by temperature. At 0°F NaCl, $MgCl_2$ blend, agricultural product and NaCl blend the ice melting capacity was approximately 0.73 – 1.80 g/g, with no melt from sodium acetate and sodium formate blended products. At 23°F all products' ice melting capacity was between 2.57 – 5.27 g/g with the exception of NaCl with an ice melting capacity of 8.48 g/g. At 32°F all product ice melting capacity ranged from 7.87 – 10.93 g/g. Fay and Shi (2011) noted that while ice melting capacity test results provide an easy to understand comparison of product performance, reproducibility issues with the test method and modifications to the test method, add to inconsistency in results between studies.

Shi et al. (2013) used a modified SHRP ice melting test on various blends of NaCl, $MgCl_2$, $CaCl_2$, sugar beet agricultural additive (AGBP), CCB, FreezGard CI plus, and Shield GLT. At 0°F (-17.8°C), solid $CaCl_2$ had the largest ice melting of 2.1 mL. At 15°F (-9.4°C), solids had larger ice melting than liquids, with NaCl having the highest at 3.5 mL. The liquids with the highest ice melt capacity were 23% NaCl brine and 32% $CaCl_2$ brine after 20 minutes of testing of 1.8 mL, suggesting that refreeze may have occurred because of lower ice melting at 60 minutes. At 30°F (-1.1°C), solids had larger ice melting than liquids, with NaCl and $MgCl_2$ having the highest at 5.3 mL. The liquids with the highest ice melting were $MgCl_2$ and 80% NaCl + 20% $CaCl_2$ of 4.0 mL.

Shi et al. (2014) measured the ice melting capacity at 15°F (-9.4°) for 11 rock salts (NaCl) and salt brines, and $MgCl_2$ and found rock salts (NaCl) to have an ice melting capacity of 3.15 mL/g, salt brines (NaCl) to have an ice melting capacity of 1.10 mL/g, and $MgCl_2$ to have an ice melting capacity of 2.19 mL/g.

Table 5. A summary of ice melting capacity results reviewed that used the SHRP or modified SHRP methods.

Products Tested	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
NaCl, $MgCl_2$, $CaCl_2$, beet juice, grape pomace	25 15	For all application rates and pre-wet rates for all products: 8 -10 mL/g Pre-wet rate 33 L/t for all products: 4 – 4.8 ml/g Pre-wet rate 67 L/t for all products: 4.2 – 5 mL/g	Zhang et al. (2020)
NaCl, sodium metasilicate, sodium formate, glycerin, Concord grape extract, beet juice ***Ranked as overall best performing based on multi-criteria analysis**	25 15	NaCl + 1.94% Concord grape extract + 1.94% glycerol + 2.86% sodium formate + 1.46% sodium metasilicate: 2.51 mL/g* Salt brine + beet juice: 2.38 mL/g* 18.4% NaCl + 0.89% Concord grape extract + 4.57% glycerin + 4.54% sodium formate + 0.19% sodium metasilicate: 2.7 mL/g* All other products: 1.5 – 2.3 mL/g	Nazari and Shi (2019) Nazari et al. (2016)
Combinations of glycerol, Geomelt, Ice B'Gone, E310, BioOil, $MgCl_2$, and NaCl	-10.4	80% glycerol + 20% NaCl, 90% glycerol + 10% $MgCl_2$, 80% Ice B'Gone + 20% NaCl, 90% IBG + 10% $MgCl_2$, and 50% glycerol + 50% $MgCl_2$: 24 – 25 mL Glycerol: 22 mL 40% E310 + 40% glycerol + 20% NaCl: 20 mL	Taylor et al. (2014)

Effects of Additives in Deicing Salts at Lower Temperatures

Products Tested	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
		All other products: 9- 17 mL	
NaCl, Ice Slicer and Thawrox Beet 55, Boost SB, Snow Melt, Geomelt 55, Apogee (glycol), Boost CCB, Ice Ban 305, and ThermaPoint IB 7/93	25 15 5	Thawrox: 7.25 mL/g IceSlicer: 7.15 mL/g Rock salt: 6.99 mL/g All other products: 2.44 – 4.48 (mL/g (solid) or ml/ml (liquid)) IceSlicer: 4.46 mL/g All other products: 1.36 – 4.16 (mL/g (solid) or ml/ml (liquid)) ThermaPoint: 1.72 mL/mL All other products: 1.10 – 1.58 (mL/g (solid) or ml/ml (liquid))	Muthumani et al. (2015)
Salt brine and corn-derived polyols (e.g., sorbitol, mannitol, and maltitol) blends	14 -4	NaCl + 27.7% mannitol: 93% increase in ice melt compared to NaCl NaCl + 27.7% sorbitol: 43% increase in ice melt compared to NaCl NaCl + 27.7% maltitol: 17% increase in ice melt compared to NaCl NaCl + 27.7% mannitol: 112% increase in ice melt compared to NaCl	Sajid et al. (2021)

Effects of Additives in Deicing Salts at Lower Temperatures

Products Tested	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
	-22	NaCl + 27.7% sorbitol: 13% increase in ice melt compared to NaCl NaCl + 27.7% maltitol: 17% increase in ice melt compared to NaCl NaCl + 27.7% mannitol: 81% increase in ice melt compared to NaCl	
Blends of potassium carbonate with agricultural byproduct. $MgCl_2$ and xylitol blends	15	Potassium carbonate: 0.87 g/g Potassium carbonate + 10% ag: 0.58 g/g Potassium carbonate + 25% ag: 0.25 g/g Potassium carbonate + 50% ag: -0.21 g/g $MgCl_2$: 1.22 g/g $MgCl_2$ + 15% xylitol: 0.76 g/g $MgCl_2$ + 30% xylitol: 0.39 g/g $MgCl_2$ + 45% xylitol: 0.08 g/g $MgCl_2$ + 60% xylitol: 0.0.2 g/g	Koefod (2008)
	5	Potassium carbonate: 0.43 g/g Potassium carbonate + 10% ag: 0.18 g/g Potassium carbonate + 25% ag: -0.06 g/g	
Blends of NaCl, $MgCl_2$, $CaCl_2$, KCl, and sodium	23	NaCl (33%) + $MgCl_2$ (66%): 12.5 g/g	Achkeeva et al. (2015)

Products Tested	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
formate at varying concentrations	14	[$CaCl_2$ (25%) + NaCl (25%)] +10% KCl +7% sodium formate: 13.3 g/g [$CaCl_2$ (25%) + NaCl (25%)] +7% sodium formate: 13.3 g/g All other blends: 9.0 - 11.8 g/g NaCl (33%) + $MgCl_2$ (66%): 7.1 g/g [$CaCl_2$ (25%) + NaCl (25%)] +10% KCl +7% sodium formate: 7.3 g/g All other blends: 4.6 - 6.9 g/g	
NaCl, $CaCl_2$, CMA, potassium acetate, CM-1000, Mineral Brine, and IceBan Ultra	30	Mineral brine: 11.8 g CM-1000: 11.5 g $CaCl_2$: 10.5 g NaCl: 9 g Potassium acetate: 8.8 g IceBan Ultra: 8 g CMA: 7 g	Nixon et al. (2007)
	20	CaCl2: 7.6 g CM-1000: 6.8 g Mineral Brine: 6.2 g Potassium acetate: 3.8 g NaCl: 2.8 g	

Effects of Additives in Deicing Salts at Lower Temperatures

Products Tested	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
		IceBan Ultra: 2.4 g CMA: 1.8 g	
	10	Mineral brine: 4.3 g CM-1000: 3.8 g CaCl2: 3.6 g Potassium acetate: 1.8 g NaCl: 1.0 g	
	0	Mineral brine: 3.0 g $CaCl_2$: 2.2 g NaCl: 1.2 g Potassium acetate: 1.0 g	
NaCl, $MgCl_2$, agricultural product, sodium acetate, sodium formate, and blends of these ***No melt occurred**	32 23 0	All products: 7.87 – 10.93 g/g Al product except NaCl: 2.57 – 5.27 g/g NaCl: 8.48 g/g All products except sodium acetate* and sodium formate*: 0.73 – 1.80 g/g	Fay and Shi (2011)
NaCl, $MgCl_2$, $CaCl_2$, sugarbeet agricultural additive (AGBP), CCB,	30	NaCl brine: 3.5 mL NaCl (solid): 5.3 mL $MgCl_2$ brine: 4.3 mL	Shi et al. (2013)

Effects of Additives in Deicing Salts at Lower Temperatures

Products Tested	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
FreezGard CI plus, and Shield GLT ***Best performing blend.**		$MgCl_2$ (solid): 4.9 mL $CaCl_2$ brine: 4.0 mL $CalCl_2$ (solid): 5.3 mL 80% NaCl + 20% CaCl2: 4.0 mL*	
	15	NaCl brine: 1.1 mL NaCl (solid): 3.5 mL $MgCl_2$ brine: 1.6 mL $MgCl_2$ (solid): 2.5 mL $CaCl_2$ brine: 1.6 mL $CalCl_2$ (solid): 3.2 mL 90% NaCl + 10% CaCl2: 1.2 mL*	
	0	NaCl (solid): 0.1 mL $MgCl_2$ (solid): 1.6 mL $CaCl_2$ (solid): 2.1 mL	
11 rock salts (NaCl) and salt brines, and $MgCl_2$	15	Rock salt: 3.15 mL/g Salt brine: 1.10 mL/g $MgCl_2$: 2.19 mL/g	Shi et al. (2014)

3.2.3.1.2 MECHANICAL ROCKER TEST – ICE MELTING TEST

A more recently developed method to measuring ice melting capacity is the Mechanical Rocker Test, or the shaker test (Tuan 2014). A predetermined mass of ice cubes and liquid deicer are combined in a vacuum-sealed thermos and shaken for 15 minutes on a mechanical rocking platform. Then, the mass of the remaining ice is measured and subtracted from the original, pre-test mass. The difference is equal to the amount of ice melted during the test. The more ice melted, the higher the ice melting capacity. The Mechanical Rocker Test developed by Gerbino-Bevins and Tuan (2011) and Tuan and Albers (2014) is a more accurate and precision method than SHRP (Chappelow et al., 1992) for measuring ice melting capacity for liquid deicers (Hansen and Haley 2019). Future work will need to be done to assess the relative precision and accuracy of the mechanical rocker test method for solid and pre-wet deicers. A summary of ice melting capacity results using the mechanical rocker test are presented below and in Table 6.

Foundational work establishing the mechanical rocker test (also known as the Shaker Test) protocol conducted testing on NaCl, various $MgCl_2$ blends, $CaCl_2$, potassium acetate, and two beet juice additives at 0, 10, and 20°F (-17.8, -12.2, -6.7°C) (Gerbino-Bevins and Tuan 2011). At 20°F (-6.7°C) potassium acetate had the highest ice melting capacity at 1.38 g/mL, with all $MgCl_2$ blends ice melting capacity ranging from 0.90 - 1.02 g/mL, and beet juice and NaCl ice melting capacity rate from 0.55 – 0.61 g/mL. At 10°F (-12.2°C) $CaCl_2$ and one of the $MgCl_2$ blends had the highest ice melting capacity at 0.90 mg/L, followed by potassium acetate at 0.84 mg/L. All other $MgCl_2$ blends ice melting capacity values ranged from 0.67 - 0.76 g/mL. Again, the lowest ice melting capacity ranges were for NaCl and the beet juices at 0.21 – 0.31 g/mL. At 0°F (-17.8°C) $CaCl_2$ and potassium acetate had the highest ice melting capacities ranging from 0.64 – 0.67 mg/L, with all $MgCl_2$ blend at 0.55 – 0.68 mg/L, and no melting occurring for NaCl and the beet juices.

Work by Hansen and Haley (2019) provided an ice melting curve over 90 minutes at 0°F (-17.8°C) for two commercially available $MgCl_2$ based products with additives produced by Envirotech. Typically, the ice melting capacity is noted at 15 minutes in this test method, which ranged from 0.40 – 0.57 g/mL. Ice melting continued throughout the 90-minute test period, and the final ice melting capacity measured at 90 minutes was 0.79 - 0.82 g/mL.

Table 6. A summary of ice melting capacity results reviewed that used the Mechanical Rocker Test method.

Products Test	Test Temperature (°F)	Results – Ice Melting Capacity	Reference
NaCl, various $MgCl_2$ blends, $CaCl_2$, potassium acetate, and two beet juice additives	20	Potassium acetate: 1.38 g/mL $MgCl_2$ blends: 0.90 - 1.02 g/mL Beet juice and NaCl: 0.55 – 0.61 g/mL	Gerbino-Bevins and Tuan 2011
	10	$CaCl_2$ and one $MgCl_2$ blend: 0.90 mg/L Potassium acetate:0.84 mg/L Other $MgCl_2$ blends: 0.67 - 0.76 g/mL NaCl and beet juices: 0.21 – 0.31 g/mL	
	0	$CaCl_2$ and potassium acetate: 0.64 – 0.67 mg/L all $MgCl_2$ blends: 0.55 – 0.68 mg/L NaCl and beet juice: no melt	
Two commercially available $MgCl_2$ brines	0°F	@ 15 min: 0.40 – 0.57 g/mL @90 min: 0.79 - 0.82 g/mL	Hansen and Haley (2019)

3.2.3.1.3 ICE PENETRATION TESTS

Ice penetration tests evaluate a deicer's ability to penetrate and break through existing ice layers (Chappelow et al., 1992) and facilitating subsequent melting. This test is particularly relevant when dealing with thick or compacted snow or ice. The deicer is applied to the ice surface, and the time taken for the deicer to penetrate down an ice column is measured. A summary of results is provided below and in Table 7.

Nixon et al. (2007) conducted ice penetration testing (SHRP method) for NaCl, $CaCl_2$, CMA, potassium acetate, CM-1000, Mineral Brine, and IceBan Ultra at 0, 10, 20, and 30°F (-17.8, -12.2, -6.7, -1.1°C). At 0°F (-17.8°C), no ice penetration occurred for any product. They found the speed of ice penetration for all products decreased at lower temperatures. At all temperatures, the best performing products were CM-1000, Mineral Brine, and potassium acetate, with CMA always having the least amount of ice penetration at all temperatures. In follow up discussion Nixon et al. (2007) did not recommend the ice penetration test for quality control testing purposes but did not state why. It is likely due to high potential for inconsistent results from variation methods and test personnel error.

Fay and Shi (2011) conducted SHRP ice penetration testing on NaCl, $MgCl_2$, agricultural product, potassium acetate, sodium acetate, and sodium formate and blends of these at 0, -12, and -18°C (32, 10, 0°F). Overall, liquid deicers ($MgCl_2$, potassium acetate, and agricultural product) outperformed solids (NaCl, NaCl blend, sodium formate, and sodium acetate) at all temperatures. At 0°F, ice penetration rates ranged from 1.0 – 3.0 mm, with no penetration from sodium formate. At 10°F, liquid ice penetration rates ranged from 13 – 19 mm, with NaCl being only solid with penetration of 3 mm. At 32°F, liquids had ice penetration rates of 30 mm, and solids had ice penetration rates ranging from 7 – 11mm. Fay and Shi (2011) also did not recommend this test method for solid deicers and noted instances of solid particles becoming lodged in the ice column leading to reproducibility issues.

Nazari et al. (2016) reported SHRP ice penetration results for salt brine, and two mixtures (Mix 1 – 23% salt brine + 3 wt% sugar beet leaf extract + 0.67 wt% sodium formate; Mix 5 – 23% salt brine + 2 wt% sodium metasilicate) at 15 and 25°F (-9.4, -3.9°C). At both temperature, salt brine produced the highest ice penetration of 11.5 cm and 3.6 cm after 60 minutes, respectively. At both test temperatures, Mixes 1 and 5 performed similarly with ice penetration of 9 cm and 3 cm after 60 minutes, respectively.

Given the recommendations from multiple research groups to not use the SHRP ice penetration test for various reasons, no additional work summarizing data on ice penetration test has been done because this method will not be used for lab portion of this effort.

A newer ice penetration test developed by Trzaskos and Klein-Paste (2020) was used to test sodium formate and pre-wet sodium formate at -2, -5, -10°C (28.4, 24, 14°F). At -10°C (14°F), the pre-wet material started ice penetration faster and had a penetration rate of 10-15 mm/hr. Whereas at -2°C (28.4°F), the ice penetration rate was about 45-75 mm/hr. This test method is not as simple as the SHRP ice melting test but appears to produce more consistent results.

Table 7. A summary of ice penetration test results reviewed.

Products Tested	Test Temperatures (°F)	Results – Ice Penetration rate	Reference
NaCl, $CaCl_2$, CMA, potassium acetate, CM-1000, Mineral Brine, IceBan Ultra	30 20 10 0	CM-1000, Mineral Brine, and potassium acetate (highest ice melt rate all temps except 0°F) No melting	Nixon et al. (2007)
NaCl, $MgCl_2$, agricultural product, potassium acetate, sodium acetate, and sodium formate and blends	32 10 0	30 mm (liquids) 7 – 11 mm (solids) 13 – 19 mm 1 – 3 mm	Fay and Shi (2011)
Salt brine, sugar beet leaf extract, sodium formate, sodium metasilicate	25 15	11.5 cm (salt brine) 9 cm (salt brine + sugar beet leaf extract + sodium formate) 3.6 cm (salt brine) 3 cm (salt brine + sugar beet leaf extract + sodium metasilicate)	Nazari et al. (2016)
Sodium formate, pre-wet sodium formate	28.4 24 14°F	45 – 75 mm/hr 10 – 15 mm/hr (prewet)	Trzaskos and Klein-Paste (2020)

3.2.3.1.4 ICE UNDERCUTTING TESTS

Ice undercutting tests measure the ability of a deicer to break the bond between the ice and the pavement surface and create a gap by undercutting between the two layers (Chappelow et al., 1992). The deicer is applied in a small hole made in an ice layer, and over a 60 minutes test period the area of undercutting, or separation between the ice and the pavement, is recorded. This test evaluates the deicer's capacity to weaken the bond between the ice and the pavement and facilitate easier removal (read: plowing) or subsequent melting. A summary of ice undercutting results are provided below and in Table 8.

Lammers (2021) evaluated the ice undercutting ability of anti-icers using a previously theoretical method based on the SHRP H205.6 test at 30°F. FreezGard C1+ performed best and, within 30 minutes, undercutting an area 1.5 times that of the next best performer. Second place was tied between Ice B'Gone Magic, a 50:50 mix of distiller' byproducts and $MgCl_2$ with corrosion inhibitor, and Ice Ban 305, made from corn starch and $MgCl_2$, which all performed equally well. $CaCl_2$ and BioMelt AG64 tied for 3rd place and performed comparably. However, BioMelt's higher viscosity may have prevented it from spreading as quickly as the other products, which gave it an initial disadvantage. Overall, $CaCl_2$ was only 60% as effective as FreezGard C1+ when comparing the undercut area at 30 minutes, though Ice Ban 305 had the most consistent undercutting with repeat testing. To estimate the effectiveness of the diluted anti-icer additives, the dilution percentage was added to the values of the full-strength tests. When diluted at the distributor recommended percentage (5-20%), BioMelt AG64 performed best, perhaps because it had the highest percentage (20%) in solution. FreezGard C1+ (10%) and IBG Magic (15%) perform next best (about 80% as well as BioMelt AG64), followed by IceBan 305 and calcium chloride (5%). If $CaCl_2$ dilution percentage is raised to 15%, then the undercutting performance is just below those of IBG Magic and FreezGard C1+ (Lammers 2021).

The initial undercutting rate of undiluted FreezGard C1+ was 25mm^2/min compared to the $CaCl_2$ rate of 11mm^2/min (Lammers 2021) . IBG Magic had a strong initial undercutting rate, but this slowed significantly within the first two minutes. The undercutting rates all slowed with time, regardless of product, and by the end of the 30-minute test the undercutting rates were similar at approximately 3mm^2/min. Based on performance alone (not considering cost, ease of use, and infrastructure and environmental impacts), FreezGard C1+ was the most effective at undercutting. Compared to FreezGard C1+, IBG Magic and Ice Ban 305 were 68% as effective, and BioMelt AG64 and CaCl2 were 63% as effective.

Fay and Shi (2011) conducted SHRP ice penetration testing on NaCl, $MgCl_2$, agricultural product, potassium acetate, sodium acetate, and sodium formate and blends of these at 0, -6, -10, and -16°C (32, 21.2, 14, 3.2°F). Results were highly variable, with limited to no undercutting occurring at 3.2 and 14°F. Overall liquid products created undercutting. Overall, $MgCl_2$, agricultural product, and potassium acetate had the highest undercutting rates. Ice undercutting rates ranging from 250 – 750 pixels/min/g at 3.2°F, 1000 – 2000 pixels/min/g at 14°F, 1700 – 6000 pixels/min/g at 21.2°F, 2000 – 5600 pixels/min/g at 32°F.

Table 8. A summary of ice undercutting test results reviewed.

Products Tested	Test Temperature (°F)	Results – ice undercutting	Reference
FreezGard C1+, Ice B'Gone Magic, distillers by product, $MgCl_2$, Ice Ban 305, $CaCl_2$, BioMelt AG64	30	25 mm^2/min (FreezGard C1+) 11 mm^2/min ($CaCl_2$)	Lammers (2021)
NaCl, $MgCl_2$*, agricultural product*, potassium acetate*, sodium acetate, and sodium formate and blends of these	32 21.2 14 3.2	2000 – 5600 pixels/min/g* 1700 – 6000 pixels/min/g* 1000 – 2000 pixels/min/g* 250 – 750 pixels/min/g*	Fay and Shi (2011)

3.2.4 Road Grip

Deicers can have both positive and negative effects on road grip. The primary purpose of deicers is to aid in the removal of snow and ice, which in turn improves road grip, or friction, by exposing the underlying pavement. When deicers are applied to icy roads, it lowers the freezing point of water and facilitates the conversion of ice and snow into liquid brine. As noted previously, when $MgCl_2$ and $CaCl_2$ are applied under high humidity conditions, there is a risk that roads can become more slippery. To mitigate this and other potential negative effects on road grip, winter maintenance professionals must incorporate road weather data, such as air and pavement temperature, relative humidity and dew point, wind speed and direction, and precipitation type and amounts into their decision-making process (Weiner et al., 2023). Additionally, they must carefully manage application rates of deicers; working dynamically to shift application rates based on weather conditions and temperature fluctuations to strike a balance between effective ice-melting and minimizing adverse impacts on road grip, infrastructure, and the environment.

Various test methods exist and are used to measure road surface grip. The Skid Resistance Tester applies a known force to a rotating wheel to determine the road's skid resistance. The British Pendulum Tester uses a pendulum with a rubber slider, measuring the distance it swings to assess friction. The GripTester employs a rolling wheel to measure the force required for rotation, indicating the friction coefficient.

The Dynamic Friction Tester utilizes a trailer-mounted unit with a spinning tire to measure resistance, considering factors like vehicle speed. Friction measurements are also collected using non-invasive sensors, which are commonly mounted at the roadside or onto vehicles and take real-time, and continuous, friction measurements of the road surface. A summary of research that has been conducted using grip, or friction, to note the influence various additives have on deicer performance is provided here and summarized in Table 9.

Sajid et al. (2021) used a skid resistance tester to examine the influence of polyol-based deicing solutions on road grip. They found the application of corn-derived polyols (e.g., sorbitol, mannitol, and maltitol) on pavement reduced the skid resistance of Portland cement concrete by up to a 33% compared to the skid resistance of dry pavement. This suggests that polyol-based deicers may decrease roadway grip, which could potentially lead to unsafe conditions for drivers and pedestrians.

Zhang et al. (2020) conducted trafficking and snow-pavement bonding tests for dry salt, 23.3 wt%. NaCl, 30 wt% $MgCl_2$, 32 wt% $CaCl_2$, 80:20 NaCl brine and beet juice, and a 97:3 mix of NaCl brine and grape pomace extract. Prewetting did not show a consistent increase in grip or reduction in snow–pavement bond strength, and many scenarios resulted in reduced grip or increased snow–pavement bond strength. The best performing prewet liquid was beet juice-modified salt brine applied at a rate of 33 L/t.

Nazari et al. (2016) a static friction tester to measured grip for no deicer, 23% salt brine and Mix 1 (23% salt brine + 3 wt% sugar beet leaf extract + 0.67 wt% sodium formate) at 25°F (-3.9°C), and reported friction coefficients of 0.41, 0.64, and 0.79, respectively. Note that the salt brine and Mix 1 were applied to pavement at 30 gal/l-m. These results then published in journal as Nazari et al. (2019) noting the same results found that the application of 3 wt% sugar beet leaf extract, 0.67 wt % sodium formate, 23 wt% NaCl, 73.33 wt% water resulted in significantly higher friction coefficient than that of salt brine. This mixture was also found to decrease the bond strength between the snow and ice and pavement requiring less shear strength to remove the material than salt brine.

Nazari and Shi (2019) used a static friction tester to investigate the effects of anti-icers on roadway grip. Applying 23% NaCl solution increased the friction coefficient of the icy asphalt pavement by 67.3%. After sodium metasilicate, sodium formate, and glycerin were added to the salt brine, the friction coefficient of the anti-iced asphalt pavement decreased. However, by adding Concord grape extract, the friction coefficient increased, and the grip improved slightly creating higher grip than the pavement treated with the beet juice and salt brine blend. This may have been due to the grape extract inducing a larger contact area (Nazari and Shi 2019).

Muthumani et al. (2015) conducted trafficking tests to assess grip performance of Geomelt 55, Apogee, and ThermaPoint IB 7/39. Snow was compacted onto a non-permeable pavement treated with liquid anti-icer, trafficked for 250 passes with a tire, then the snow was plowed from surface. If the product was solid rather than liquid, it was applied to the top of compacted snow as a deicer. The process was repeated for 500 and 750 trafficking passes, respectively, though the deicing/anti-icing products were not reapplied between trafficking cycles. Overall, all three products performed better than rock salt or brine at 15°F (-9.4°C); they stayed on the pavement surface longer and had a higher friction coefficient by 500 passes, perhaps due to their high viscosity and ice-melting capacity. Apogee had higher viscosity and ice-melting capacity than Geomelt 55, ThermaPoint IB 7/39, and salt brine. Apogee had the highest coefficient of friction at 15°F (-9.4°C), and it performed as well or better at reducing bond strength than all three other products during repeated trafficking cycles at both 5°F (-15°C) and 15°F (-9.4°C). However, at 5°F (-15°C), all three products had a higher friction coefficient than brine at 250 passes, but equally low coefficients after 500 and 750 passes.

Taylor et al. (2014) determined that of the many combinations of glycerol, Geomelt (sugar beet based), Ice B'Gone (IBG; molasses, other sugars/carbs), E310 (corn hulls), BioOil, $MgCl_2$, and NaCl that were evaluated , 80% glycerol + 20% NaCl and 90% Geomelt + 10% $MgCl_2$ had the greatest skid resistance on pavement. The percent skid resistance relative to the British pendulum number (BPN) of a pavement surface treated with 100% water (ASTM E 303, 2007) was 79% and 77%, respectively. The research concluded that a diluted 80% glycerol + 20% NaCl solution was the most promising agro-based additive tested.

Fu, Omer, and Jiang (2012) tested two organic beet juice deicers, M1 and M2, as prewet and direct liquid applications (DLA). The two deicers were mixed with 23% NaCl solution at a 30:70 ratio and compared with the brine. Results indicated that there was no significant improvement in performance by M1 or M2 when compared with brine or when used for prewetting at low temperatures. However, DLA tests showed that the organic deicers had higher average grip than brine; aggregate grip readings indicated a positive performance difference of more than 30% in some cases. M1 also outperformed M2 by up to 10% and sections of road treated with DLA significantly outperformed untreated sections, which warrants the use of DLA for snow and ice control.

Table 9. A summary of road grip test results reviewed.

Products Test	Test Conditions	Results – grip (coefficient of friction (μ))	Reference
corn derived polyols (sorbitol, mannitol, maltitol), NaCl	British Pendulum Test, Concrete pavement	All products had lower BPN values than the control. With NaCl brine blended with sorbitol, mannitol, maltitol showing a reduction in BPN than NaCl alone by 7 – 23%.	Sajid et al. (2021)
Dry salt, 23.3 wt%. NaCl, 30 wt% $MgCl_2$, 32	25 and 15°F, asphalt pavement, snow and	No deicer: 0.53	Zhang et al. (2020)

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Products Test	Test Conditions	Results – grip (coefficient of friction (μ))	Reference
wt% $CaCl_2$, 80:20 NaCl brine and beet juice, and a 97:3 mix of NaCl brine and grape pomace extract	trafficked for 500 passes, pre-wet rates of 8, 16, 24 gal/t, applied at 250 lbs/l-m	Dry NaCl: 0.52 NaCl prewet with salt brine: 0.31 – 0.48 NaCl prewet with Beet Juice: 0.31 – 0.56 NaCl prewet with Grape pomace extract: 0.35 -0.39	
NaCl, sugarbeet leaf extract, sodium formate	25°F, asphalt pavement, 30 gal/l-m, snow on pavement, trafficking for 500 passes	No anti-icer: 0.41 23% NaCl brine: 0.64 3 wt% sugar beet leaf extract, 0.67 wt% sodium formate, 23 wt% NaCl, 73.33 wt% water: 0.79	Nazari et al. (2019) Nazari et al. (2016)
NaCl brine, sodium metasilicate, sodium formate, glycerin, beet juice, Concord grape extract	Simulated black ice on asphalt pavement, 15°F, 80% humidity	23% NaCl = 18.4% NaCl + 0.19% sodium metasilicate > 18.4% NaCl + 0.19% sodium metasilicate + 4.54% sodium formate + 4.57% glycerin + 0.89% Concord grape extract = Beet juice blend > 18.4% NaCl + 0.19% sodium metasilicate + 4.54% sodium formate = 18.4% NaCl + 0.19% sodium metasilicate + 4.54% sodium formate + 4.57% glycerin	Nazari and Shi (2019)
NaCl, Geomelt 55, Apogee, and ThermaPoint IB 7/39	Snow on asphalt pavement samples, trafficked with tire for 250, 500, 750 passes,	15°F – Apogee (highest μ)	Muthumani et al. (2015)

Products Test	Test Conditions	Results – grip (coefficient of friction (μ))	Reference
	liquid (anti-iced), solid (deiced), at 5 and 15°F	5°F - Geomelt 55 = Apogee = ThermaPoint IB 7/39 > NaCl @ 250 passes 5°F - Geomelt 55 = Apogee = ThermaPoint IB 7/39 = NaCl @ 500 and 750 passes	
glycerol, Geomelt (sugarbeet based), Ice B'Gone (IBG; molasses, other sugars/carbs), E310 (corn hulls), BioOil, $MgCl_2$, and NaCl	British Pendulum Test, concrete pavement	80% glycerol + 20% NaCl and 90% Geomelt + 10% $MgCl_2$ = 77 – 79% BPN (greatest skid resistance)	Taylor et al. (2014)
NaCl brine, organic beet juice deicers	DLA Prewet	NaCl + beet juice > NaCl No difference in μ at low temps.	Fu, Omer, and Jiang (2012)

3.2.5 Bond Strength

Muthumani et al. (2015) conducted trafficking tests to assess the degree to which deicers assist in reducing the bond strength between snow and ice and the pavement for salt brine, Geomelt 55, Apogee, and ThermaPoint IB 7/39. For these tests, snow was compacted onto a non-permeable pavement treated with liquid anti-icer, and then trafficked for 250 passes with a tire. If the product was solid rather than liquid, it was applied to the top of compacted snow as a deicer. The process was repeated for 500 and 750 trafficking passes, respectively, though the deicing/anti-icing products were not reapplied between trafficking cycles. After each series of tire passes (250, 500, and 750) the bond strength was measured between snow and pavement. Pavement treated with Apogee and Geomelt 55 did not require significantly increases in bond strength with repeated snow applications, trafficking, and plowing, but pavement treated with ThermaPoint IB 7/39 experienced significant increases in bond strength with repeated cycles. Muthumani et al. (2015) found that both CCM- and agro-based products reduced the bond strength between snow, ice, and pavement at 25°F (-3.9°C). At 15°F (-9.4°C) and 5°F (-

15°C). Thawrox reduced the bond strength by a significant amount compared to the rock salt control and the agro-based deicers Geomelt 55 (beet-based), Apogee (glycerin), and ThermaPoint IB 7/39 (lignin) significantly reduced the bond strength compared to salt brine. Geomelt 55 was found to be less effective at 5°F (-15°C) than 15°F (-9.4°C), but bond strength increased with decreasing temperatures regardless of the product tested.

Muthumani et al. (2015) hypothesized that higher viscosity made Geomelt 55, Apogee, and ThermaPoint IB 7/39 more effective at reducing bond strength than pure salt brine. All three products were more viscous than the 23.3% NaCl solution at 68°F (20°C) and their viscosity increased with decreasing temperature. Also, the addition of 30% Geomelt 55 to the brine nearly doubled its viscosity. "Higher viscosity liquids do not mix as well with snow and ice (Wahlin and Klein-Paste, 2015). Instead, the more viscous products remain on the pavement surface, to support prevention of the bond forming between snow and ice and pavement, instead of being wicked up into the snow pack via capillary forces (Muthumani et al. 2015)," which results in more time to spread across the pavement surface and a greater reduction in bond strength.

3.2.6 Discussion

In relation to this effort to determine additives-induced changes in the performance (eutectic temperature) of blended deicers, Koefod (2008) found using freezing point, ice melting capacity, and calorimeter measurements that there is no simple correlation between freezing point and ice melting capacity. This is corroborated by the study by Muthumani et al. (2015) where they concluded that "the agro-based additives may act as 'cryoprotectants,' which tend to inhibit freezing without melting the ice." Therefore, finding a reduction in freezing point from the addition of an additive may not lead to additional ice melting from that product. To address this, Danilov et al. (2019) developed the following formula to consider both eutectic temperature and ice melting ability to compare the efficiency of blended deicers:

Equation 3. Formula to compare the efficiency of blended deicers:

$$A_t = (100 - C_t) / C_t$$

Where A_t = the ice melting ability at temperature t, C_t = is the concentration in the solution. Further investigation into the validity of this method is needed as limited information and explanation is provided in this paper, including a lack of detail on how eutectic temperature and ice melting capacity were measured.

Shi et al. (2014) assessed a number of highway deicing/anti-icing products used by various Idaho maintenance districts, based on quantitative analysis of cost, performance, impacts to vehicles and infrastructure, and environmental impacts. The analysis revealed that $MgCl_2$ and Pocatello brine were overall ranked the best, whereas BLKFT brine and AF salt were ranked poorly.

Nazari and Shi (2019) used a multi-criteria decision making framework to identify best-performing blends that considered ice melting capacity at 20 minutes and 60 minutes, corrosion rate to metal, and impacts to pavement materials.

4 SURVEY RESULTS

This survey saw a total of 24 complete responses which are presented here. Respondents were asked whether their organization uses chloride-based deicers (NaCl: rock salt or salt brine, $MgCl_2$: mag chloride, $CaCl_2$: calcium chloride) that contain additives (for example treated rock salt or blended brine) in their winter maintenance operations. There were 17 (71%) who responded yes, they use chloride-based deicers with additives and seven responded no (29%), that they do not use chloride-based deicers with additives. The seven respondents who indicated that they do not use deicers with additives were not asked any additional questions. The remaining survey results presents information provided by the following 17 respondents, three of whom chose to remain anonymous (Figure 6 and Table 10).

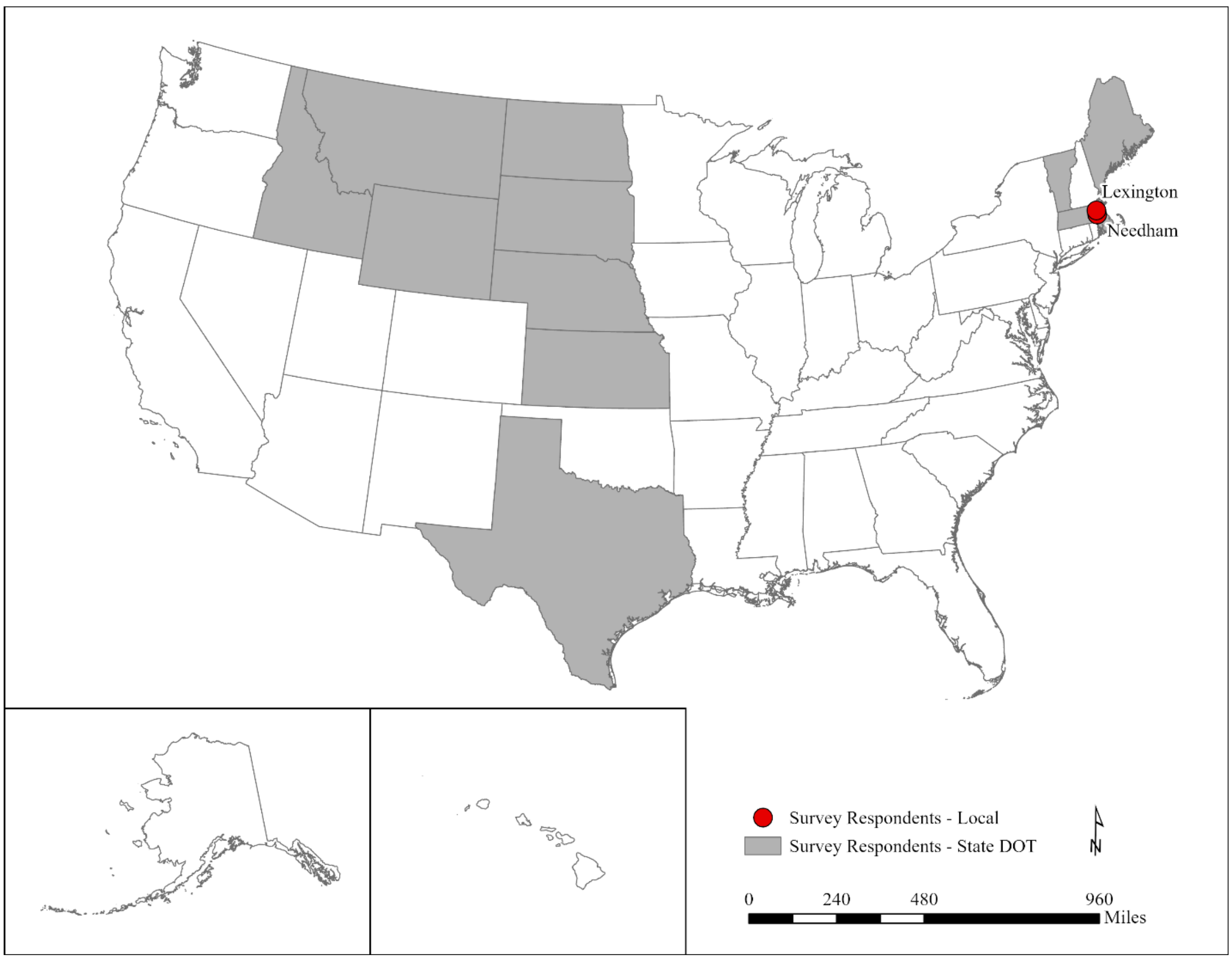

Figure 6. Survey Respondent Locations

Table 10. Respondent Organizations

Organization	Title	State
Idaho Transportation Department	Maintenance Operations Manager	ID
Kansas Department of Transportation	Director of Field Operations	KS
Kansas Department of Transportation	Staff Engineer	KS
Maine Department of Transportation	Transportation Snow and Ice Supervisor	ME
Massachusetts Department of Transportation	Lead Statewide Snow & Ice Engineer	MA
Montana Transportation Department	Maintenance Reviewer	MT
Nebraska Department of Transportation	Winter Maintenance Engineer	NE
Needham Department of Public Works	Assistant Director of Public Works	MA
North Dakota Department of Transportation	Assistant Division Director of Maintenance	ND
South Dakota Department of Transportation	Winter Maintenance Engineer	SD
Texas Department of Transportation	Emergency Management Center (EMC)	TX
Town of Lexington	Manager of Operations	MA
Vermont Agency of Transportation	Acting Director District Maintenance and Fleet Division	VT
Wyoming Department of Transportation	Maintenance Staff Engineer	WY

Respondents were asked why they use additives in their chloride-based deicers. The majority of respondents indicated they use additives in chloride-based deicers because they provide better snow or ice removal performance (n=17 or 100%), for cold temperature modification (n=13 or 76%), because they provide more or longer residual on the pavement (n=13 or 76%), they are cost effective (n=12 or 70%), and they reduce corrosion to metals and infrastructure (n=11 or 65%) (Figure 7). To a lesser extent, additives were indicated as being used to improve friction (n=5 or 29%), as anti-caking agents (n=4 or 23%), and as dye markers (n=2 or 12%).

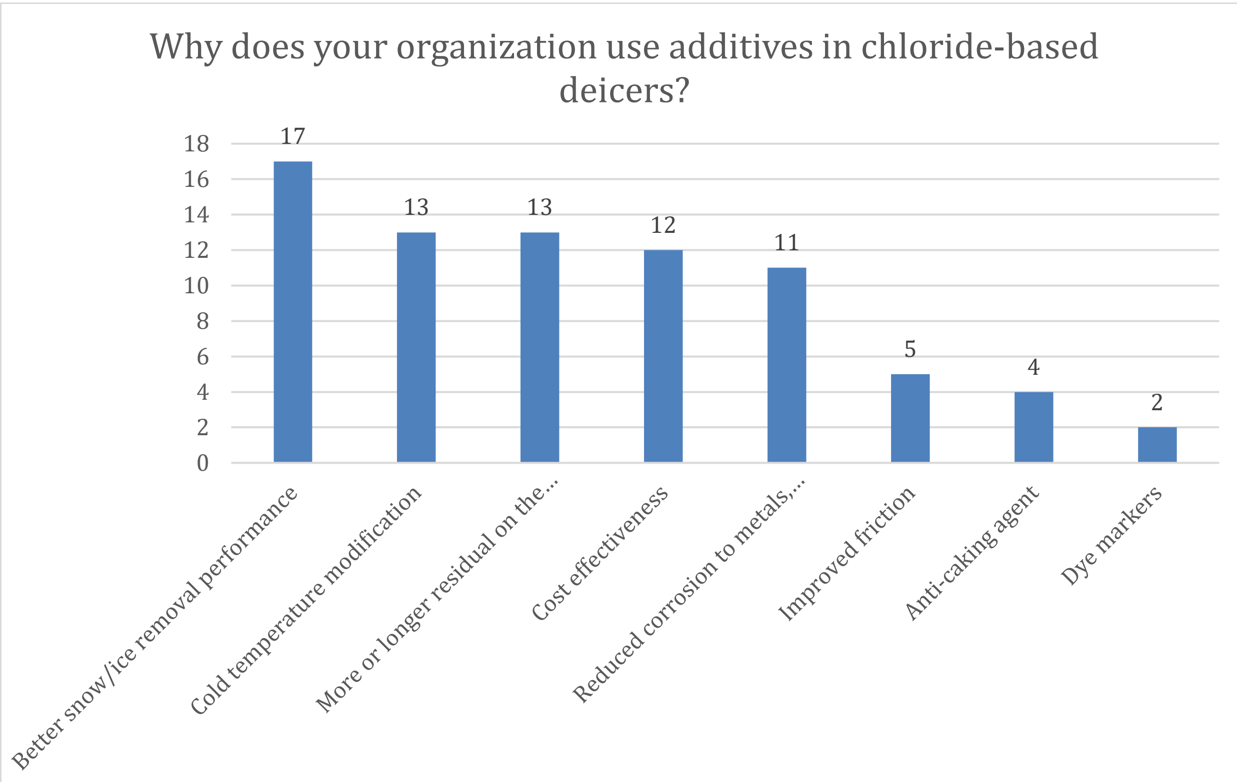

Figure 7. Responses on why additives are used.

Respondents were asked to provide a list of all the additives used by their organization (Table 11). Additional feedback provided by many respondents is also summarized in Table 11.

Table 11. Additives used by agencies.

Organization	Additives Used	Additional feedback
Idaho Transportation Department	IceKicker from Saltworx use 7000 tons	
Kansas Department of Transportation	Beet Juice from SF Fertilizer at 10 – 20% to NaCl brine	
Kansas Department of Transportation	Beet Juice, Magnesium Chloride	
Maine Department of Transportation	-Rock salt at 300 lbs/l-m (avg) -Magic-O 70% salt brine with 30% MMZ at 6 gal/ton (avg) -Salt brine 70% with 30% MMZ at 6 gal/ton (avg)	MMZ, or Magic -0, is a proprietary blend of $MgCl_2$ and feed grade molasses made by ProMelt purchased from Innovative Liquids.
Massachusetts Department of Transportation	- Blended brine (NaCl with $McCl_2$); 85% Saturated NaCl solution with 15% of Innovative Surface Solution's Pro Melt 28% $MgCl_2$ use 700,000 gal/year - Innovative Surface Solution's 28% Pro Melt $MgCl_2$ solution has a proprietary corrosion inhibitor ("IMP-AP"), Corrosion inhibitor present at 0.8%	We are trialing a limited quantity of a pretreated salt product, which will consist of rock salt treated with "Type 2" $MgCl_2$, which implies a certain percentage of organics included, for **enhanced deicing performance plus increased capability for the solution to stick to the NaCl crystal**. Our Environmental Services Section is involved in the trial to assess any environmental

Organization	Additives Used	Additional feedback
	- Rock salt pre-wet with Innovative Surface Solution's 28% Pro Melt $MgCl_2$ brine at 8 – 10 gal/ton	susceptibility that the pretreated salt product poses. The presence of organics is the reason for their concern. I anticipate that the additional BOD/COD will prove acceptable. The final component we expect to receive in this integrated product is **dye, which will give the salt a darker color to both distinguish it from untreated salt and enhance its melting capacity by attracting the sun's warmth to the darker crystal**.
Montana Transportation Department	Amp from EnviroTech at 20% by volume	
Nebraska Department of Transportation	-Rock Salt from Nebraska Salt and Grain, Central Salt -Beet 55 from Smith Fertilizer and Grain at 6 – 10 gal/ton	
Needham Department of Public Works	Geomelt S8 from SNI Rock Salt from Eastern Mineral treated with Ice-B-Gone II blended at 8 gal/ton	Geomelt S8 is a premix blend of salt brine and Geomelt 55 80:20 We use it in a DLA primarily for **anti-icing** and sometimes as a shake and bake [slurry spread at 70:30].

Effects of Additives in Deicing Salts at Lower Temperatures

Organization	Additives Used	Additional feedback
North Dakota Department of Transportation	Beet Juice at 20% in brine solution	At 80: 20 salt brine: beet juice mixture eutectic temp is -18°F. Compared to -6°F for salt brine. At 50:50 blend the eutectic is -30°F. We **use the 80: 20 for daily anti-icing and pre-wetting**. We **use the 50: 50 if we get compaction in extremely cold conditions** to remove the compaction. The latter is very seldom. It does lower the working temperature in all conditions which improves performance and provides a longer working timeframe.
South Dakota Department of Transportation	- Ice B Gone Magic from Sears Ecological blended at 80% Salt Brine to 20% IBG prewet rate of 6-8 gal/ton - AMP from EnviroTech Services blended at 80% Salt Brine to 20% AMP prewet rate of 6-8 gal/ton - Beet Heat Mn from K-Tech blended at 80% Salt Brine to 20% Beet Heat prewet rate of 6-8 gal/ton	All inhibitors used are blended with 20% concentrate to 80% Salt Brine. All liquids are used for prewetting at the spinner with a rate of 6-8 gal/ton.
Texas Department of Transportation	MeltDown 20 from EnviroTech Servies	
Town of Lexington	Biomelt AG-64 from SNI Solutions use 30,000 gals, blend with salt brine at 90:10 to 85:15.	Biomelt AG-64 is a brine enhancer composed of sugar beet, soy, and corn derivatives.

Effects of Additives in Deicing Salts at Lower Temperatures

Organization	Additives Used	Additional feedback
Vermont Agency of Transportation	ProMelt Magnesium inhibited at 15 or more gal/ton	
Wyoming Department of Transportation	- Beet Heat from SFG use 318,000 gals, blended with salt brine 30:70 - Ice Kicker from Saltworx use 7520 tons - Ice Slicer from EnviroTech use 2800 tons - Freezgard CI+ from Compass Minerals use 96,000 gals, pre-wet salt/sand 90:10, apply directly at 6 – 10 gal/mile	- MS4 locations like the color of Ice Slicer (brown). The public thinks we are using sand. The material then melts away with the snow as it turns to brine. - The manufacturer recommends 20% beet heat but one of our shops has to store their equipped plow trucks outside. To prevent freezing of the liquid mixture they had to go to 30%. Because they mix their own in central locations the entire district uses the 30% mix. Plus they have shared this story with the rest of the State so they in turn are mixing at 30%. If some is good, a bit more is better.
Anonymous Respondent 1	-Rock Salt at 300 lbs/l-m (avg) -MMZ (mag chloride molasses) at 6 gal/ton (avg) -Salt brine at 6 gal/ton (avg) -Salt brine & MMZ at 6 gal/ton (avg)	

Effects of Additives in Deicing Salts at Lower Temperatures

Organization	Additives Used	Additional feedback
Anonymous Respondent 2	Rock salt from NSC Minerals	

Specific data on deicer performance was provided by Kansas DOT and data on deicer use was provided by Massachusetts DOT.

Effects of Additives in Deicing Salts at Lower Temperatures

Respondents were asked which additives used by their agency have the greatest impacts on deicing, anti-icing, or at cold temperatures, how they know this, and to share data or observations. The following responses were received.

- We don't use additives. We are currently using Ice Kicker to evaluate performance compared to straight white salt to determine cost effectiveness, performance, and potentially salt reduction. To date, all three are being achieved with this product. (ID)
- We tend to use straight salt brine and beet juice to help with colder temperatures. Observed that it seems to stick to the pavement better and helps keep ice from forming. (KS)
- Magic-0, or MMZ, has the greatest impact at cold temperatures. We typically blend our own salt brine which is used at temperatures from 20°F - 32°F. We purchase MMZ for colder temperatures, which works exceptionally well. This has been proven by having our coldest parts of our state run a straight MMZ application versus a cocktail of salt brine blended with MMZ or just salt brine. (ME)
- Prewetting rock salt with 8 - 10 gallons of 28% ProMelt $MgCl_2$ solution from Innovative Surface Solutions has saved us from overapplication of granular NaCl. We have 6 Districts and the District that prewets the most (at 8 gal/ton) is the most efficient District in terms of treatments administered per season per inch of snowfall. (MA) [Data provided that shows this]
- EnviroTech - Amp (Corrosion Inhibitor), Nachurs Alpine - Potassium Acetate (MT)
- Geomelt S8 [works well] particularly with anti-icing events. We have experienced less frost and black ice when using the product. (Needham, MA)
- Beet 55 is the only non-chloride additive NDOT uses. It helps prevent refreeze and the salt sticks to the road better. We know this from field reports and a study done by UNL in 2010. (NE)
- We only use beet juice. (ND)
- Magnesium chloride is our go to product when below 20°F. No data to show, just experience through the years. (SD)
- Melt Down 20 has worked well to deice. It [ha]s residual [effects] and last[s] for a while. Some maintenance offices mix it with sand. (TX)
- We use Biomelt AG-64 with salt brine at 10% - 20% based on weather and roadway conditions. We use 10% for normal conditions for residual benefits and then increase to 15% - 20% for more challenging conditions whether its colder or higher moisture events. Our product is used all the time since we use slurry spreaders dispensing 30% liquid: 70% salt. Most direct liquid applications (DLA) are 10% with some applications of 15%. (Town of Lexington, MA)
- The $MgCl_2$ with corrosion inhibiter works well for de-icing at colder temperatures and provides the corrosion inhibition that is needed for our customer satisfaction. (VT)
- The Ice Slicer and Ice Kicker are observed to do better. They [drivers, road users] can see the application [on the road] and then notice the roadway conditions improve. Magnesium chloride and salt brine work but they do not see the results as quickly because of our 6 - 10 gal/ton application rate out of 100 gallon saddle tanks. It would be better if WYDOT used tankers to apply at 25 - 30 gal/l-m. (WY)

Respondents were asked to describe any impacts from the additives their agency has observed. The following responses were received and include descriptions of benefits, so impacts and benefits are reported separately.

Benefits

- We have reduced the total tonnage applied which has resulted in cost savings while still maintaining the same level of service. (ID)
- Clearer roads, faster after storm clean-up, less pack-on [snow and ice on road]. (ME)
- Enhanced performance of sodium chloride [is a benefit]. The slurry spreaders, along with composite plow blade technology, also enhance the overall operation. We look at it in the way that you need to make incremental improvements to the overall operation to get the best effects; not just one component will solve all of your challenges. (Town of Lexington, MA)
- Ice Slicer provides comfort to the driver that thinks we are dropping sand. The material then turns to brine and dissolves away. (WY)

Impacts

- We hear some complaints that liquid magnesium chloride is increasing corrosion on our or vendor vehicles. We've also heard this from the motoring public. (MA)
- The residue is sticky, but it is said to help prevent corrosion. It works. (ND)
- It has rust inhibitors, however rusting of equipment is still noted as an issue. (TX)
- We used to use another $MgCl_2$ based liquid that we could blend with salt brine, but we cannot with the new product we are using. (VT)

4.1 SUMMARY OF INFORMATION ON DEICING ADDITIVES

The following tables summarize the additives or blended products indicated as used by respondents (Table 12) and the base material or additional deicing materials the additives are blended with, or in some cases used as stand-alone products, e.g., potassium acetate (Table 13).

Table 12. List of products and additives and manufacturers or vendors provided by survey respondents, and product descriptions.

Product/Additive	Manufacturer/Vendor	Product Description
Amp	EnviroTech Services	$MgCl_2$ 13-23%, Corrosion inhibitor blend proprietary
Beet Heet	Smith Fertilizer & Grain	No additional information provided.
Beet Heet (Mn)	K-Tech	Processed beet molasses, 21% chlorides (NaCl, KCl – 6.4%; $CaCl_2$, $MgCl_2$ -15%)

Effects of Additives in Deicing Salts at Lower Temperatures

Product/Additive	Manufacturer/Vendor	Product Description
Beet Juice	Smith Fertilizer & Grain	No additional information provided.
BioMelt AG-64	SNI Solutions	100% organic, No SDS available
Freezgard CI+	Compass Minerals	29 - 33% $MgCl_2$, sulfate 1 -3%, CI Plus inhibitor 1.8 – 2.2%
Geomelt 55	SNI Solutions	No SDS available
Geomelt S8	SNI Solutions	No SDS available
IceKicker	Saltworx	93 – 96% NaCl, 3 - 5% Proprietary (less than 1% each $CaCl_2$, $MgCl_2$, KCl)
Ice-B-Gone	Sear Ecological	50 – 60% $MgCl_2$, 40 – 50% Distillers Condensed Soluble (DCS - distilling industry waste stream – rum, vodka, etc.)
Ice B' Gone II	Innovative Surface Solutions	$MgCl_2$ 22.4% by wt., Molasses
Ice B Gone Magic	Sear Ecological	50% DSC, 50% $MgCl_2$
IMP-AP	Innovative Surface Solutions	In the ProMelt $MgCl_2$ solution as a corrosion inhibitor, proprietary
Magic-0 (MMZ)	Innovative Surface Solutions	$MgCl_2$ 22.4% by wt., Molasses 20% by wt.
Meltdown 20	EnviroTech Services	80 - 90% NaCl, less than 1% $MgCl_2$, $CaCl_2$, KCl_2, Corrosion inhibitor - proprietary
ProMelt	Innovative Surface Solutions	24 - 30% $MgCl_2$

Table 13. Deicing products provided by survey respondents, used either as stand-alone products or as base products that additives are blended with.

Product/Additive	Manufacturer/Vendor	Product Description
IceSlicer	EnviroTech Services	90 – 98% NaCl, less than 1% $MgCl_2$, KCl, $CaCl_2$.
Rock Salt	NSC Mineral, Nebraska Salt & Grain, Central Salt*, Eastern Mineral	NaCl or complex chloride (trace amounts of $MgCl_2$, $CaCl_2$, KCl, etc., *sodium ferrocyanide)
Salt Brine		NaCl 23.3%
Magnesium chloride brine		$MgCl_2$ 30%
Potassium Acetate	Nachurs Alpine Solutions (NASi)	50% by wt. potassium acetate solution

5 LAB TESTING RESULTS

The results of laboratory testing to quantify the influence additives have on chloride-based deicers in terms of freezing point suppression, ice melting capacity, and roadway friction are provided.

5.1 FREEZING POINT

The results for freezing points (for concentrations 5%, 10%, 15%, and 23%) and solubility limits (for concentrations 24%, 25%, and 26%) are plotted to form two curves. Because of impurities present in Ice Slicer, an additional FPT test was performed at 26 wt. %.

Note that in the NaCl-water phase diagram (Farnam et al., 2014) there are freezing and solubility curves, as well as horizontal lines representing a phase change, a reaction, and formation of new phases, as shown in Figure 8. For instance, at a temperature of -23°C (-9.4°F) and concentration of 23.3 wt. %, the salt phase diagram shows a eutectic point, indicating a eutectic mixture. The straight horizontal line roughly at -23°C (-9.4°F) indicates a phase change or a reaction leading to that phase change. Below that line, the contents (eutectic mixture) would be different than the contents above that horizontal line. Also, note that the different phases in the salt phase diagram before the eutectic point (above the eutectic temperature) represent brine (above the freezing curve, the liquidus line) and brine + ice mixture below the freezing curve. Normally, to explain such phase changes straight vertical lines are drawn). To estimate the percentage of a mixture present at any given point in the phase diagram, straight horizontal lines called “tie lines” are drawn (Farnam et al., 2014).

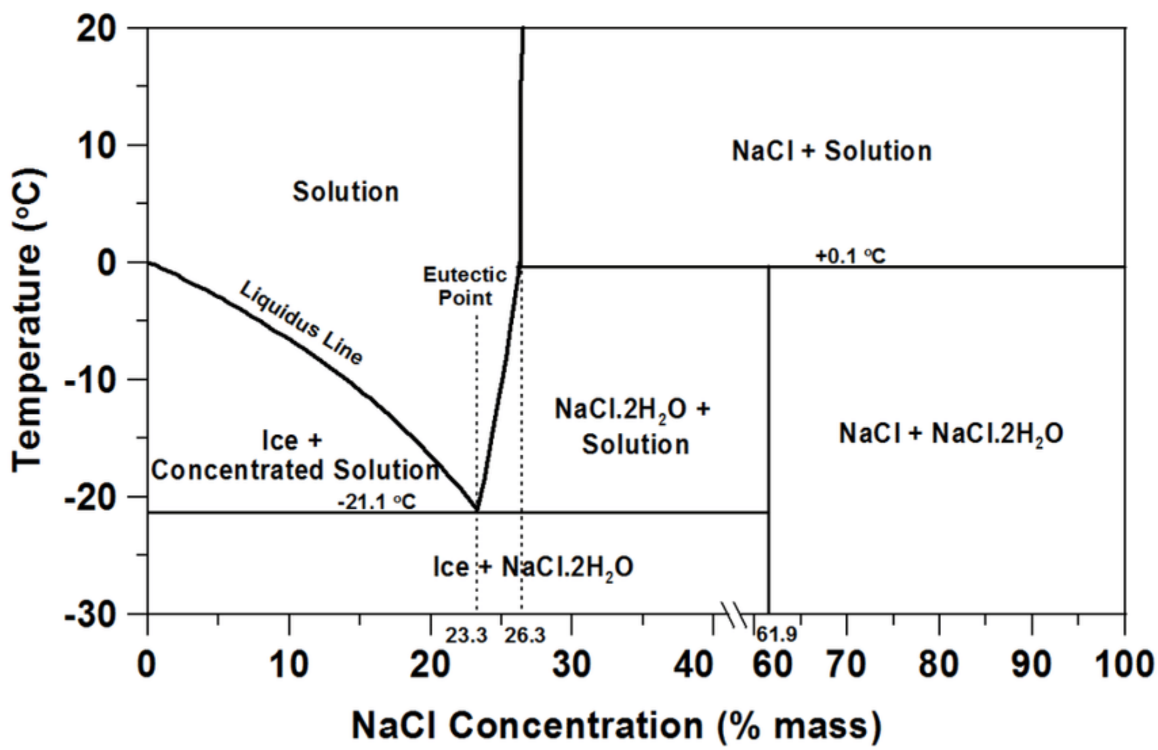

Figure 8: Aqueous-NaCl phase diagram (Farnam et al., 2014).

The results are provided as the freezing point and solubility curves for salt concentrations ranging between 0 to 26 wt. % (Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, Figure 14). Hence, these are not the complete phase diagrams and are only showing data that is validated by tests. Note when generating a phase diagram or obtaining values to develop these curves, for any tested concentration whichever phenomenon occurs before the other needs to be reported. For example, for a salt concentration of 15 wt. %, freezing occurs before the precipitation of salt, the freezing point will be reported on the phase diagram. Whereas, for a salt concentration of 24 wt. %, if salt precipitation occurs before freezing, the temperature for the solubility limit will be reported. Therefore, two different curves are shown on the aqueous-salt phase diagram.

The resulting data is provided below.

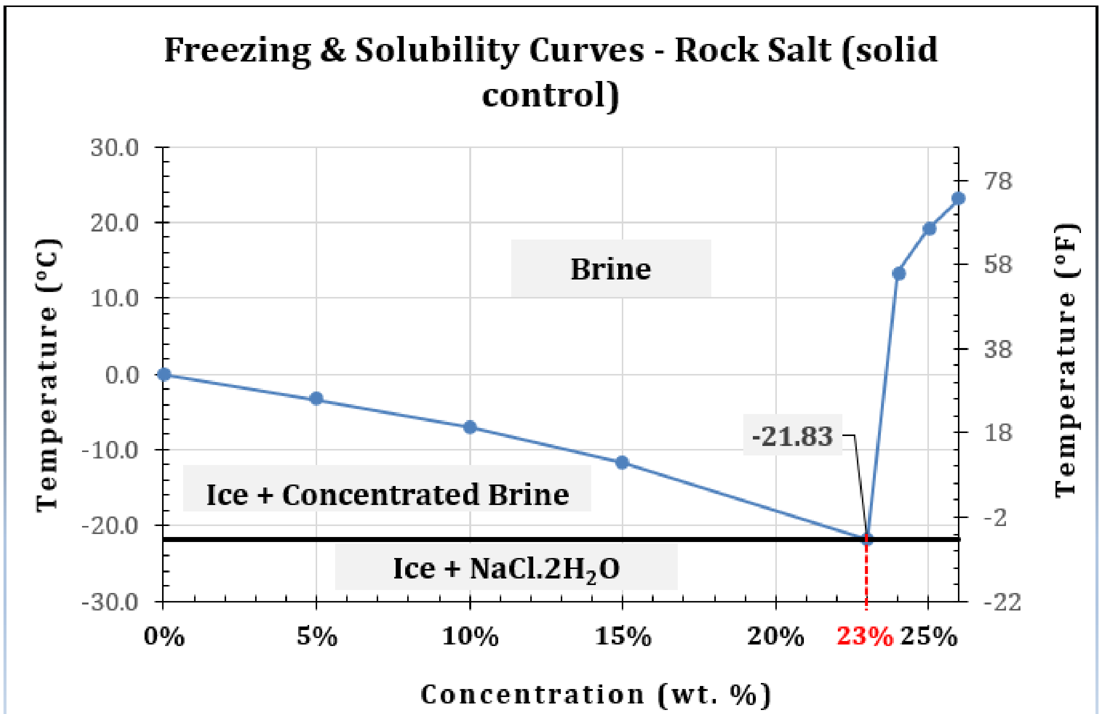

Figure 9. Freezing point and solubility curves for NaCl, rock salt (solid control) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

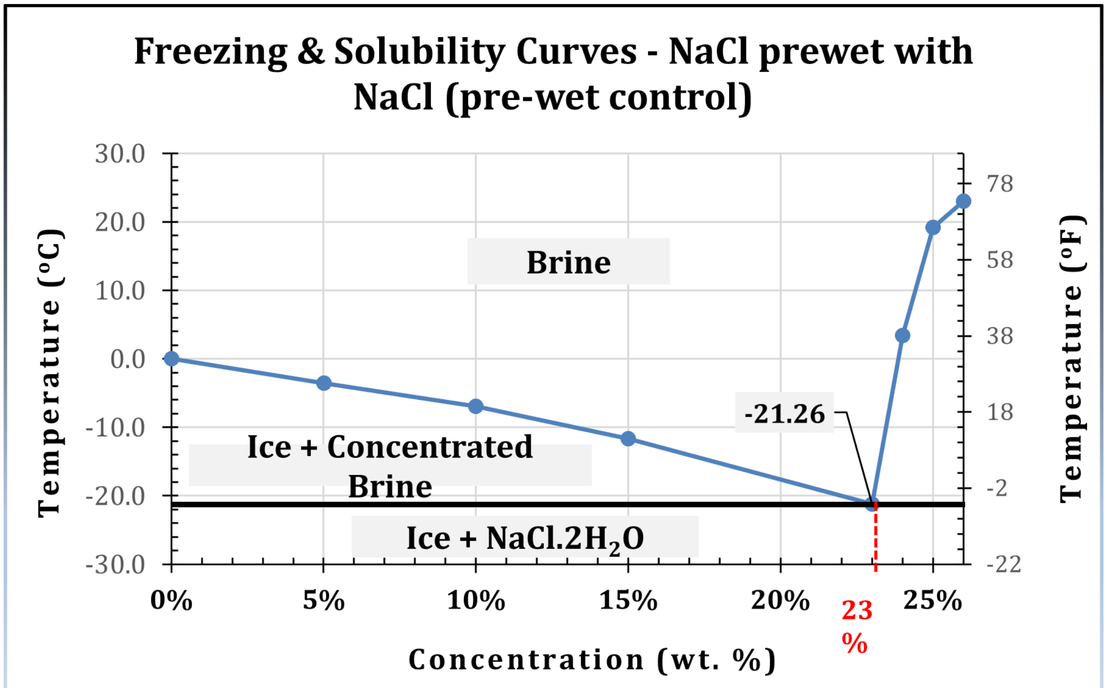

Figure 10. Freezing point and solubility curves for NaCl solid prewet with NaCl brine (prewet control) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

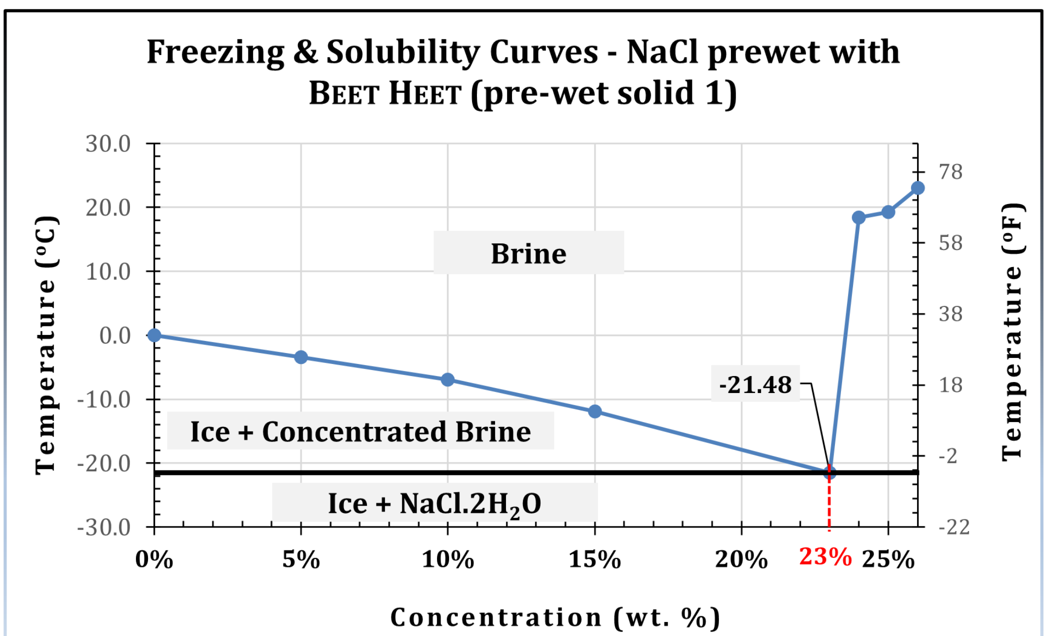

Figure 11. Freezing point and solubility curves for NaCl prewet with BEET HEET (prewet solid 1) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

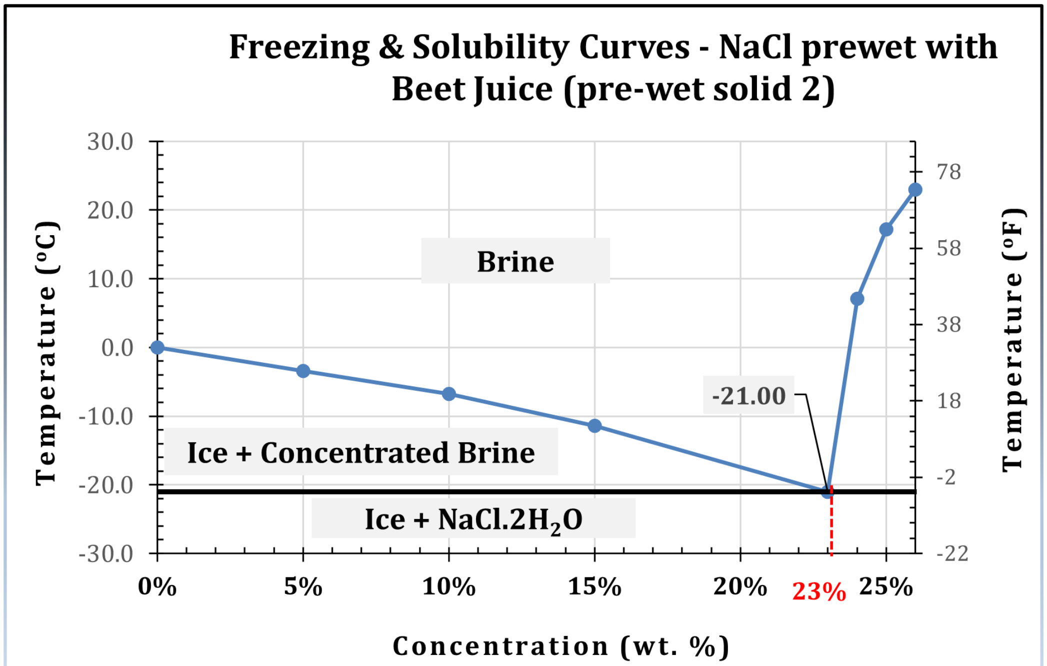

Figure 12. Freezing point and solubility curves for NaCl prewet with Beet Juice (prewet solid 2) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

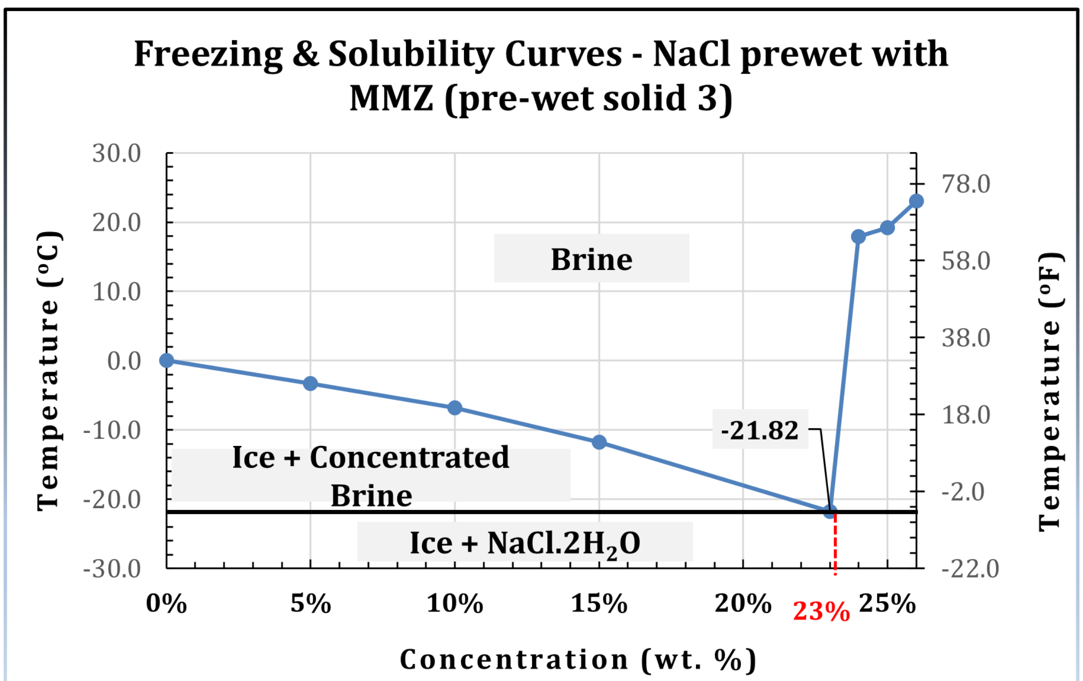

Figure 13. Freezing point and solubility curves for NaCl prewet with MMZ (prewet solid 3) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

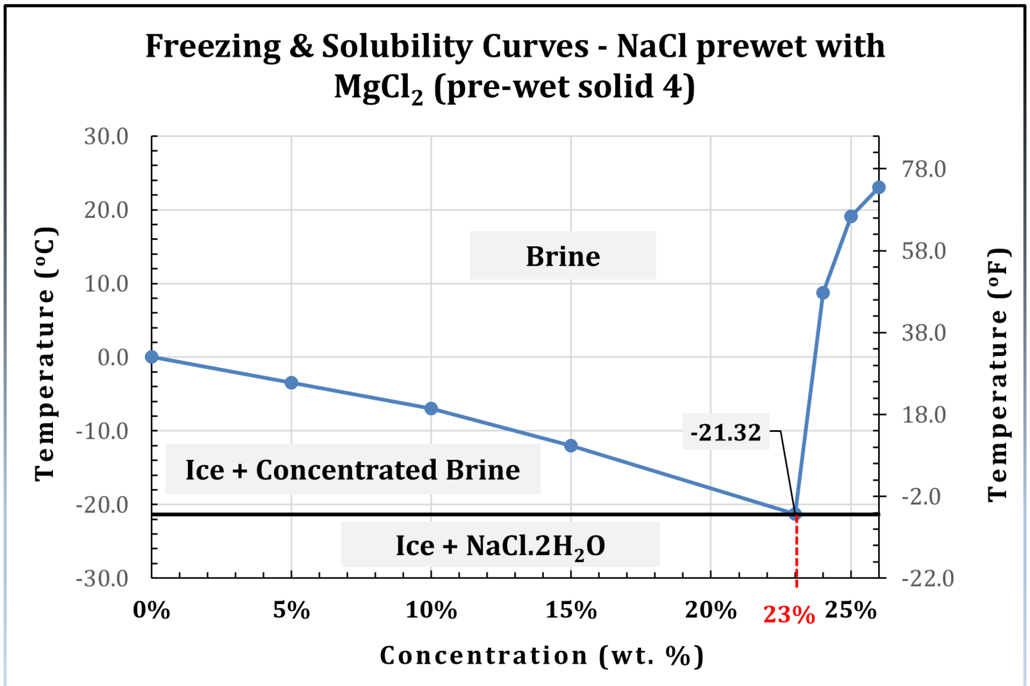

Figure 14. Freezing point and solubility curves for NaCl prewet with $MgCl_2$ (prewet solid 4) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

Solid 1 – Ice Slicer

Note that the visual solubility limit test (the test to identify the precipitation point for a brine solution) could not be done for the Ice Slicer brine solutions due to high amounts of insoluble impurities. The visual solubility test works well for clear and translucent solutions. However, the solutions of Ice Slicer were nearly opaque (Figure 30, Appendix B), particularly those having higher concentrations, and therefore, seeing the salt precipitation in them while cooling was not possible. Hence, only the freezing curve for Ice Slicer is shown in Figure 15. Note that two freezing curves are shown in Figure 15. One represents the solution concentration including all the insoluble impurities (solid line) and the dotted line is based on the actual salt concentrations estimated by filtering out the insoluble impurities. Note that impurities were filtered out of the solution using a 50-micron paper filter. Table 17 in Appendix B shows the calculations used to approximate the salt concentration in Ice Slicer (solid 1). The impurities in Ice Slicer (solid 1) were estimated to be 5% to 15%, depending on the weight of the sample used to form a brine solution. Because the impurities were irregularly distributed in Ice Slicer (solid 1), smaller samples (for a 5 wt. % brine) had lower percentages of insoluble impurities and larger samples (for a 26 wt. % brine) had larger percentages of insoluble impurities (Table 17, Appendix B). For example, if 20 g of Ice Slicer (solid 1) is used to prepare a solution, the actual salt content in that 20 g sample could be 17g, due to 3 g of insoluble impurities. Whereas a 50 g sample of Ice Slicer (solid 1) could have up to 7 g insoluble impurities. This significantly altered the brine concentration of its solutions. Therefore, the actual brine concentrations were estimated by filtering out insoluble impurities and were reported in

Table 17 (Appendix B). Hence two freezing curves are shown in Figure 15. Images of filtered-out insoluble impurities from Ice Slicer (solid 1) samples are shown in Figure 31, Appendix B.

Ice Slicer FPT for both filtered and unfiltered solutions was performed, which confirmed that insoluble impurities play a role in lowering the eutectic temperature but are not the primary driver. These results are compared in Table 17, Appendix B. It was decided to report FPT results of only unfiltered solutions of Ice Slicer (solid 1) because this is how it is used in the field (Table 18, Appendix B).

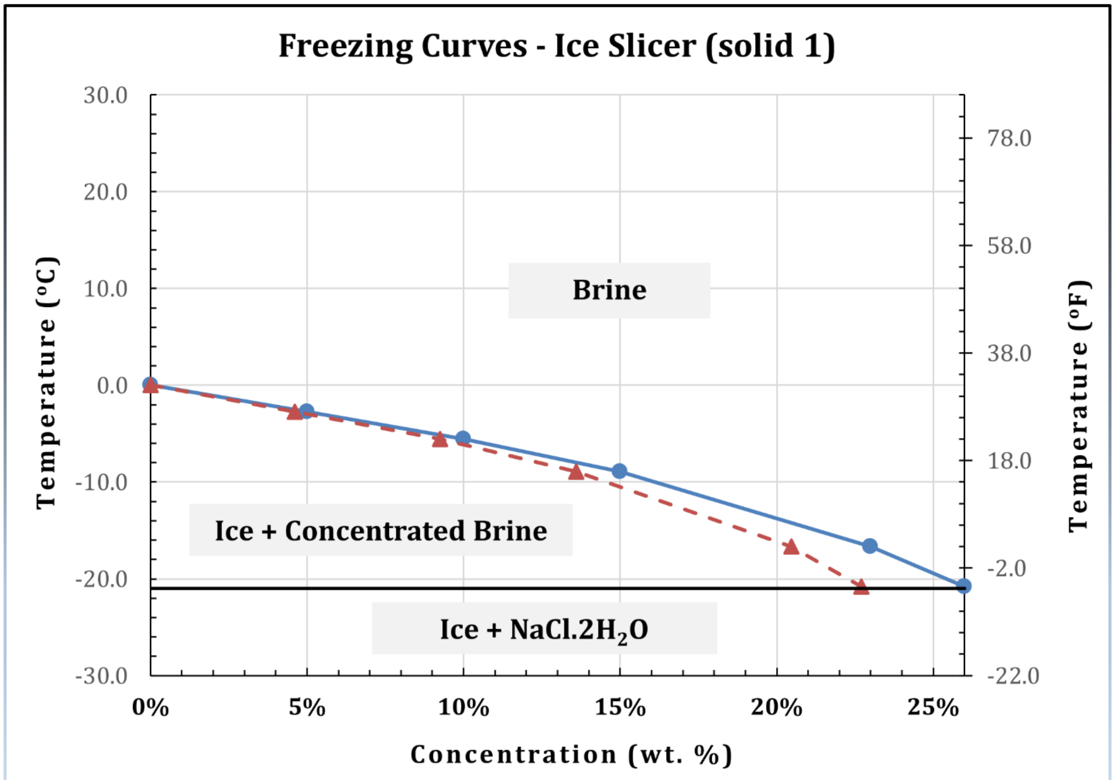

Figure 15. Freezing point curves for Ice Slicer (solid 1) showing temperature versus solution concentration plot (solid line), showing eutectic concentration as 26%, and temperature versus actual brine concentration (dotted line) showing eutectic concentration as ~23%.

Solid 2 – IceKicker

IceKicker (solid 2) had impurities but up to an almost negligible milligram scale (Figure 31, Appendix B). Other products (prewet solids and prewet control) were composed of solid control (purified rock salt) and had no visible insoluble impurities.

For Solid 2, it was also decided to run FPTs using unfiltered solutions; FPTs of filtered solutions were not done. Figure 16 shows the results of the unfiltered solutions of IceKicker (solid 2).

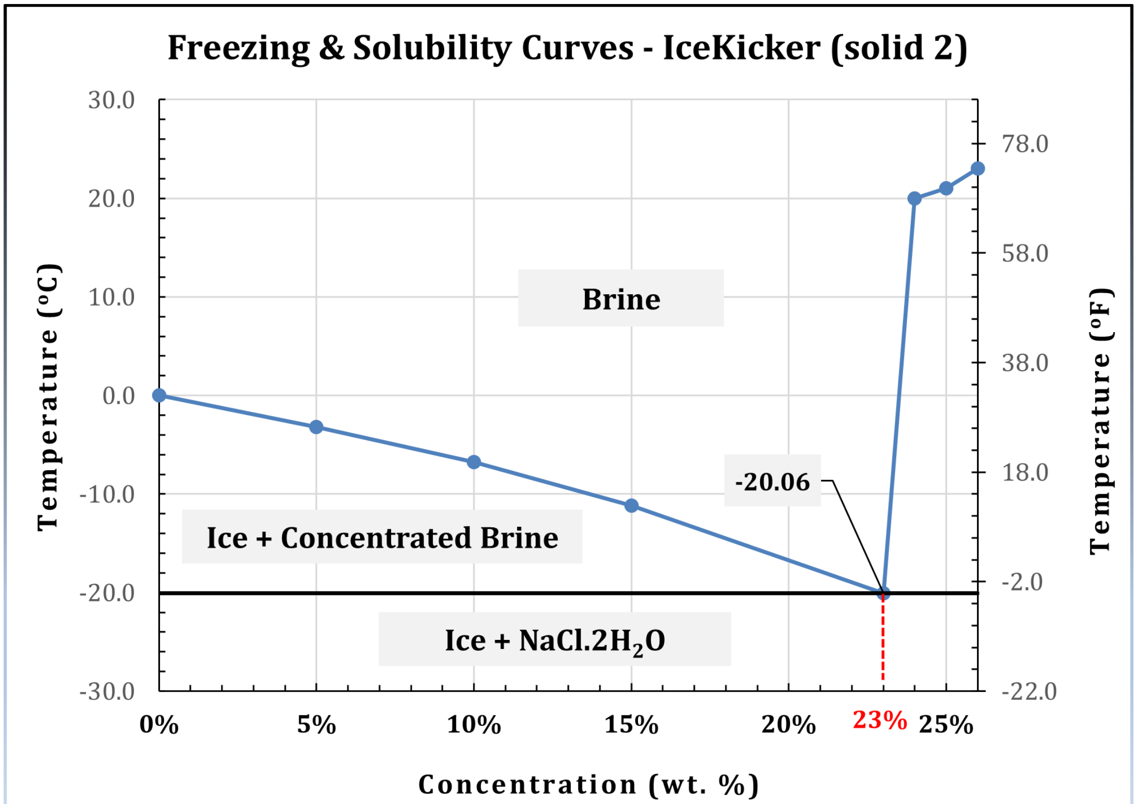

Figure 16. Freezing point and solubility curves for IceKicker (solid 2) – temperature versus salt concentration plot, showing eutectic concentration in red and eutectic temperature in °C.

5.1.1 FPT Discussion

Please note that all the tested products are NaCl based, meaning that up to 98% of the content in is NaCl, and the eutectic temperature ranged between -20.0ºC and -21.9ºC (-4.0ºF and -7.4ºF).

The following bar chart represents the eutectic temperatures for 23 wt. % concentrations of all products except Ice Slicer (solid 1) for which results of two concentrations (23 % and 26%) are shown. This is because Ice Slicer (solid 1) had high amounts of insoluble impurities, shifting its eutectic concentration from 23% to approximately 26%, as shown in Figure 15.

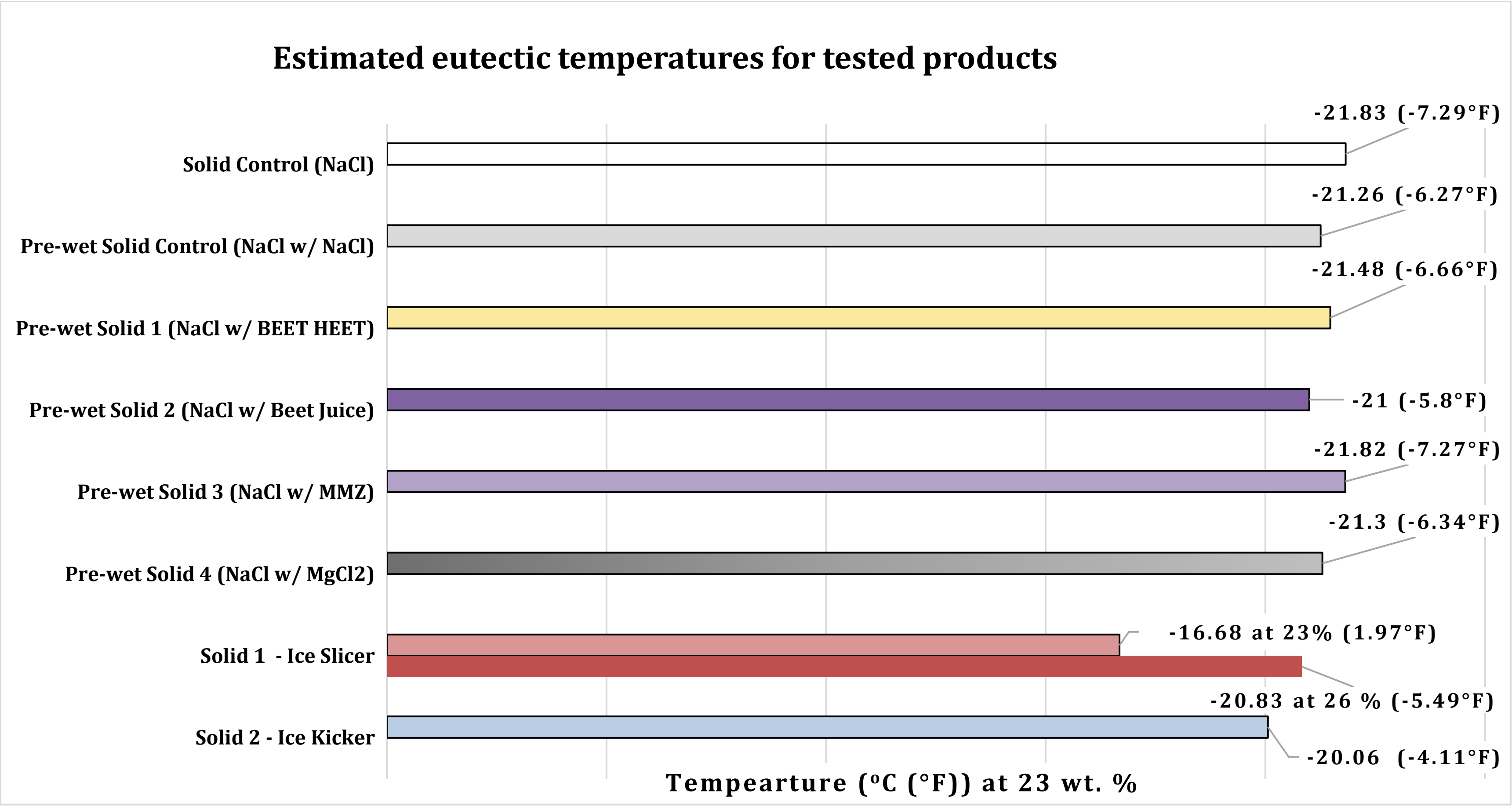

Figure 17. Estimated eutectic temperatures of all tested products at 23 wt. % concentration, except Ice Slicer (solid 1) for which the eutectic composition was estimated to be 26% due to high amounts of insoluble impurities.

Note that the freezing point of 23 wt. % Ice Slicer (solid 1) brine is only -16.68°C (1.97°F) because of high amounts of insoluble impurities in it, thus reducing the actual effective salt concentration as reported in Table 18 (Appendix B). Therefore, it was important to determine the freezing point of concentration(s) higher than 23% for Ice Slicer (solid 1). Hence, the FPT of 26% brine of Ice Slicer (solid 1) was completed, and -20.83°C (-5.49°F) is the estimated eutectic temperature of this product for 26 wt. %.

After the visual solubility test, the 24 wt.% brine solutions of all products showed precipitation at temperatures well above 0°C (32°F). This confirmed that their eutectic composition was lying between 23 and 24 wt. %. The eutectic temperatures for tested solutions are reported as estimated eutectic temperatures in Figure 17.

5.2 MODIFIED ICE MELTING CAPACITY

The modified IMC tests were performed for all deicer and additive blends at 15°F and 25°F. For both temperature ranges the rocking time was 15 minutes, however, for NaCl (solid control) and NaCl prewet with NaCl (prewet control) additional tests were conducted with 30 minutes of rocking time. Ice melting capacities (gram/gram) of all deicer and additive blends at 15°F are shown in Figure 18 and at 25°F are shown in Figure 19.

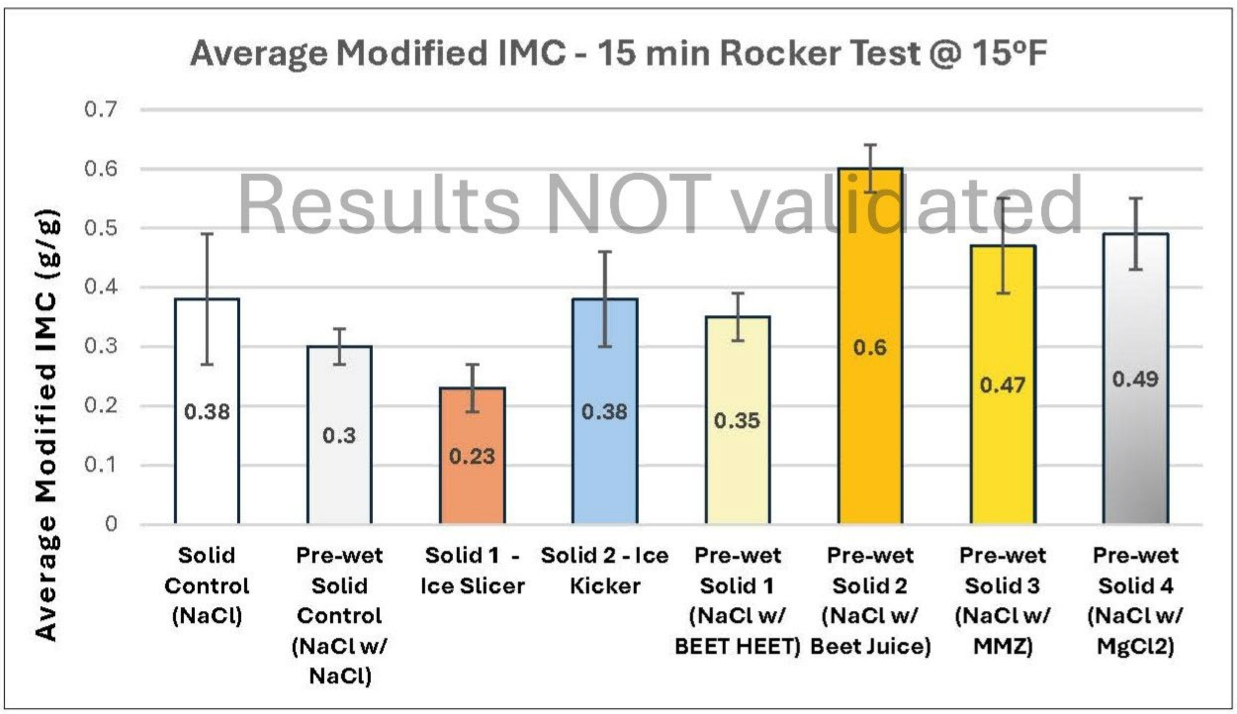

Figure 18. Modified ice melting capacity (IMC) results (g/g) for all the tested products at 15°F and 15 minutes rocking, also showing standard deviation bars for each result.

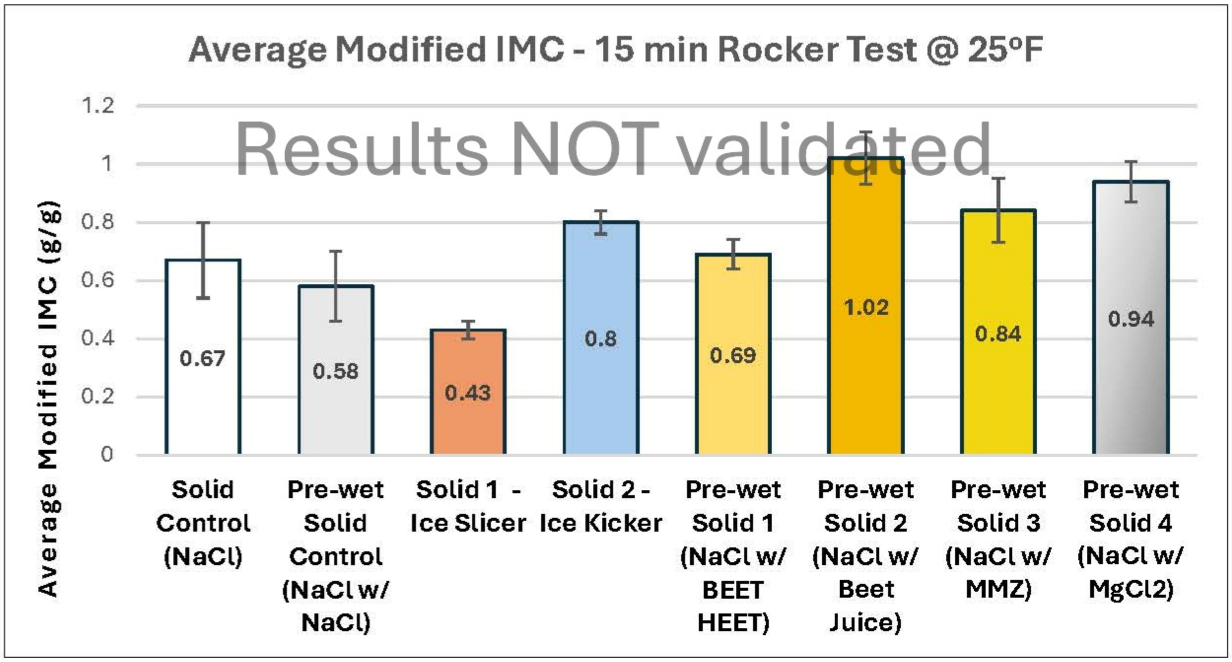

Figure 19. Modified ice melting capacity (IMC) results (g/g) for all the tested products at 25°F and 15 minutes rocking, also showing standard deviation bars for each result.

Results for the modified IMC (g/g) with a 30-minute rocking time for NaCl (solid control) and NaCl prewet with NaCl (prewet control) at 15°F and 25°F are shown in Figure 20 and Figure 21, respectively. The modified IMC rocking test for 30 minutes is referenced as $IMCRT_{30}$.

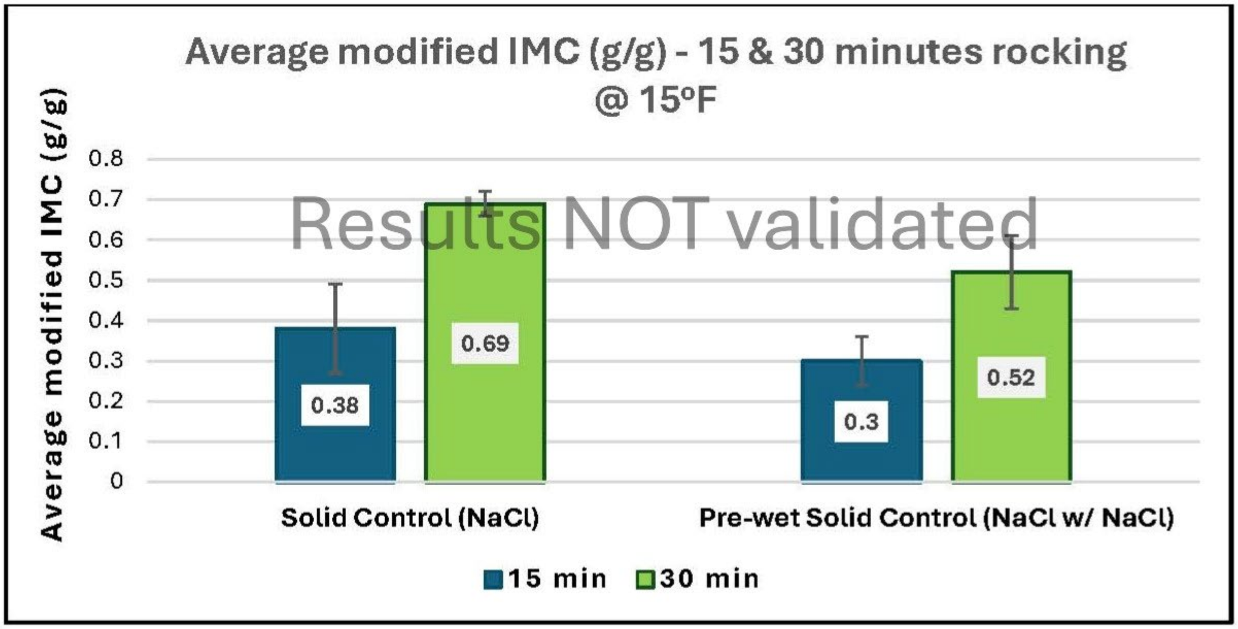

Figure 20. Modified ice melting capacity (IMC) results (g/g) for NaCl (solid control) and NaCl prewet with NaCl (prewet control) with 15 & 30-minute rocking times at 15°F, also showing standard deviation bars for each result.

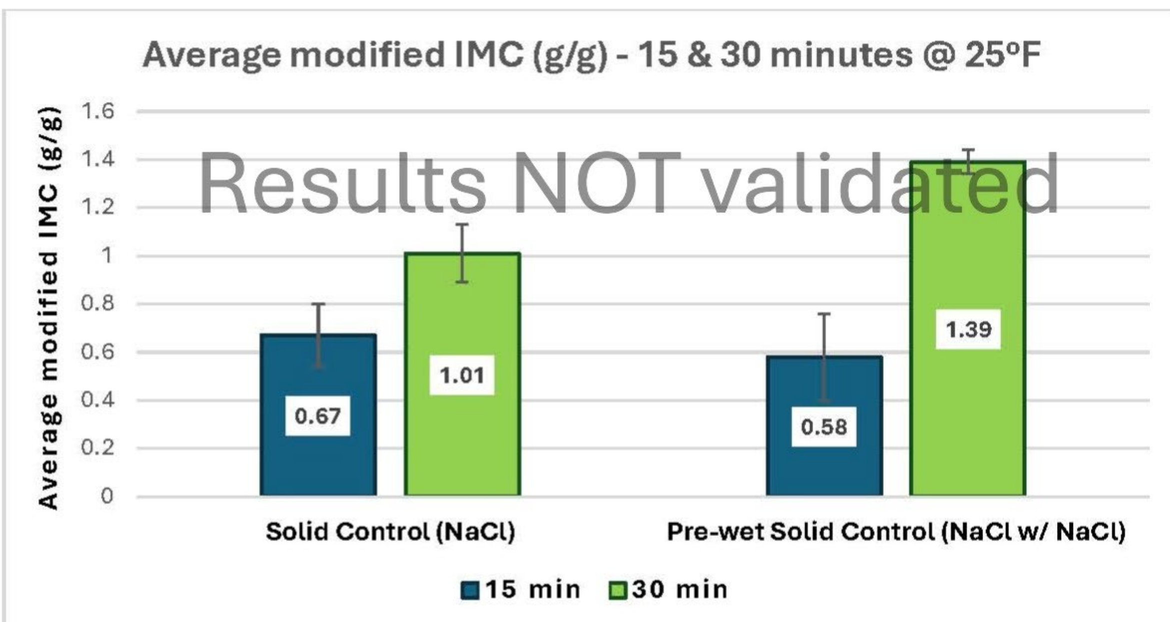

Figure 21. Modified ice melting capacity (IMC) results (g/g) for NaCl (solid control) and NaCl prewet with NaCl (prewet control) with 15 & 30-minute rocking times at 25°F, also showing standard deviation bars for each result.

5.2.1 Modified IMC Discussion

Figure 22 shows the results of the average modified IMC 15-minute rocking test (g/g) for all deicer and additive blends. All the products showed better ice melting performance at the warmer test temperature of 25°F. After 15 minutes of rocking time, the amount of ice melted at 25°F by all products individually was nearly twice that at 15°F.

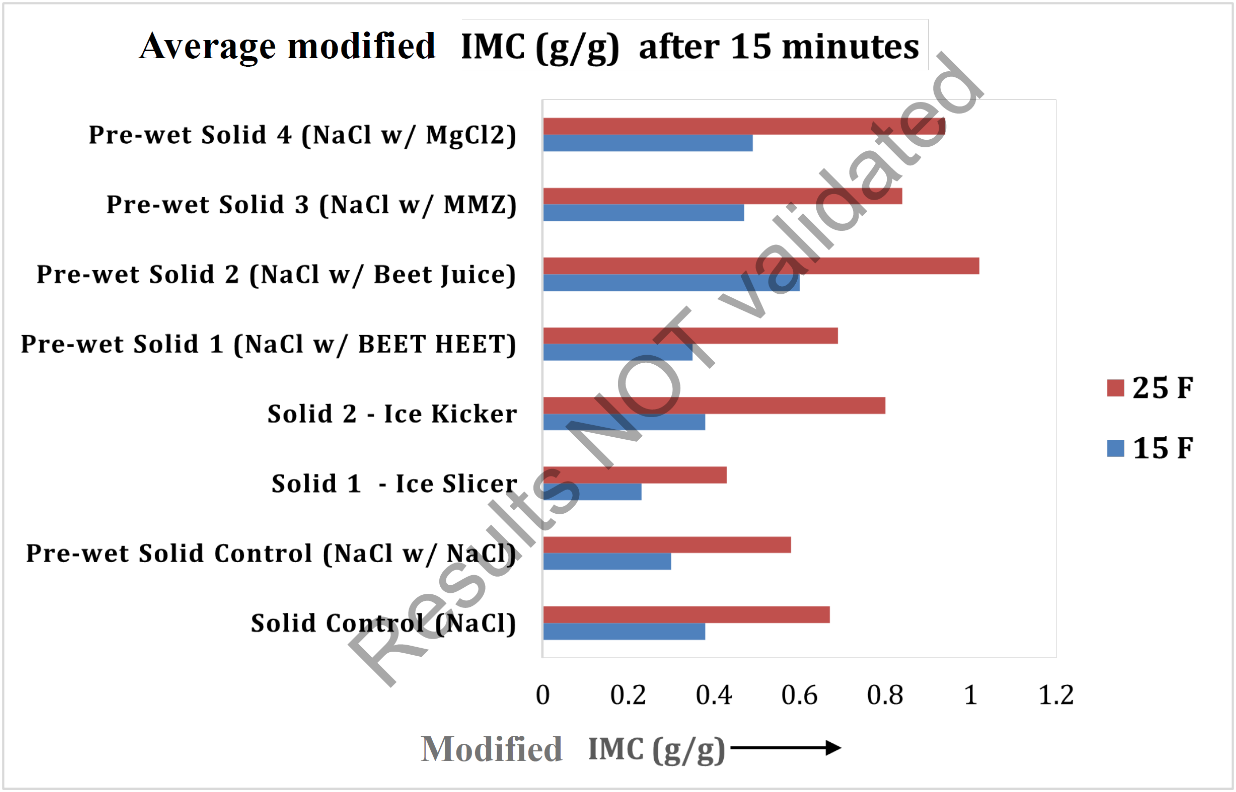

Figure 22. Average modified ice melting capacity (IMC) (g/g) for all deicer and additive blends at 15°F and 25°F, after 15 minutes of rocking.

Figure 23 shows the modified IMC test results at both 15°F and 25°F and with 15 and 30 minutes of rocking times for the control samples, NaCl (solid 1) and NaCl prewet with NaCl (prewet control). In all instances, longer rocking time leads to higher modified IMC.

The gradation analysis for the solid products found that more fines are present in the commercially available products (Solid 1 Ice Slicer and Solid 2 IceKicker) than in the reagent grade rock salt. Specifically, Solid 1 Ice Slicer had significantly more fines, about 50%, than was reported on their website, 0-15%; whereas Solid 2 IceKicker had about 46% fines and reported 0-45% fines. The presence of fine particles of salt can influence ice melting, with more fine particles of salt leading quicker melting over the short term. Whereas larger salt crystals can lead to more ice melting and over a longer period. The inconsistent percent of fine salt particles between the pre-wet products made with the reagent grade salt, Solid 1, and Solid 2 represents an additional variable that may have influenced the modified IMC results in manner that cannot be quantified at this time.

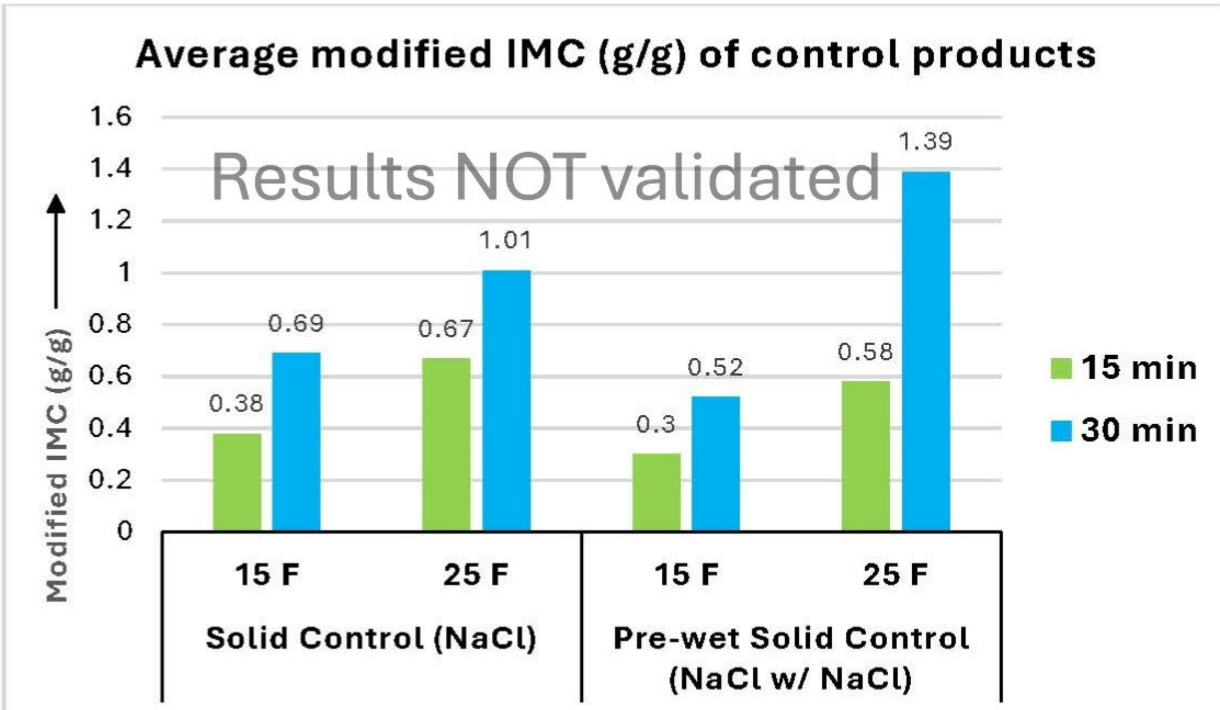

Figure 23. Average modified ice melting capacity (IMC) (g/g) of NaCl (solid control) and NaCl prewet with NaCl (prewet control) at 15°F and 25°F after 15 and 30 minutes of rocking.

5.3 FRICTION

The peak force was measured eight times for each deicer and deicer-additive combination on both concrete and asphalt pavement samples to assess the change in friction overtime follow application at varying temperatures. Measurements were collected before deicer application (t=0), and at four times during testing (t=15, t=30, t=45, and t=60), up to one hour following application. The static coefficient of friction was calculated from the force measurements and the results of the testing are shown in Figure 24 and Figure 26. Statical analysis included use of paired t-tests to compare means and one-way analysis of variance (ANOVA). Detailed ANOVA results can be found in APPENDIX C - Friction Testing Additional Data and Statistical Analysis Results.

5.3.1 Testing at 30°F

Overall, each deicer shows similar trends in friction coefficient values on asphalt and concrete pavements (Figure 24). Figure 24 shows that at the start of testing, asphalt pavement samples had significantly higher coefficient of friction values (0.96 ± 0.07) than concrete samples (0.75 ± 0.07). After 30 minutes of testing, two groups emerge with higher coefficient of friction values (mean = 0.63) associated with NaCl prewet with BEET HEET, NaCl prewet with NaCl, NaCl, NaCl prewet with $MgCl_2$ and lower coefficient of friction values (mean = 0.32) associated with IceKicker, NaCl prewet with MMZ, NaCl prewet with Beet Juice, and Ice Slicer. After 45 minutes of testing all deicers either showed an increase in coefficient of friction or coefficient of friction remained consistent. From 45 minutes to 60 minutes, most coefficient of friction values stabilized. At 60 minutes the coefficient of friction values for all deicers were 0.63 ± 0.06. For all deicers, there was significant difference in before (t=0) and after (t=60) coefficient of friction values, with all coefficients of friction values being lower at t=60. Figure 25 shows that at the end of testing (t=60) coefficient of friction values from asphalt pavements were very consistent while those measured on concrete were more variable. Showing that the pavement type has a significant impact on the measured coefficient of friction using this method.

Another key finding is that some deicer additive blends have the highest coefficient of friction values after 30 minutes (NaCl prewet with $MgCl_2$, NaCl), while others have their highest coefficient of friction at 45 minutes (IceKicker, NaCl prewet with Beet Juice, NaCl prewet with NaCl; all asphalt samples), and others at 60 minutes (Ice Slicer, NaCl prewet with Beet Juice, NaCl prewet with MMZ).

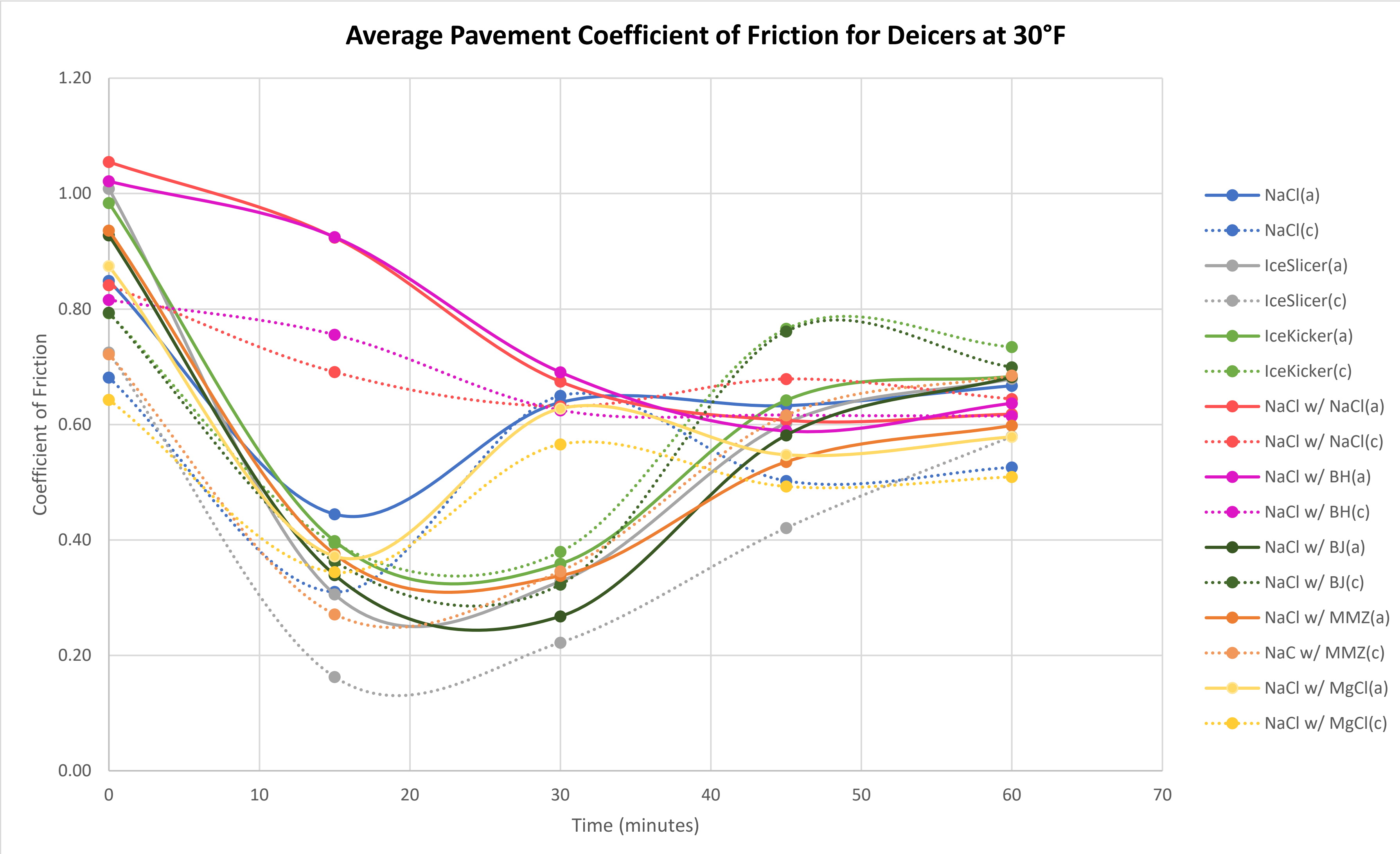

Figure 24. Coefficient of friction for deicers blended with additives over one hour at 30°F, measured on both asphalt (a, solid lines) and concrete (c, dotted lines) pavements.

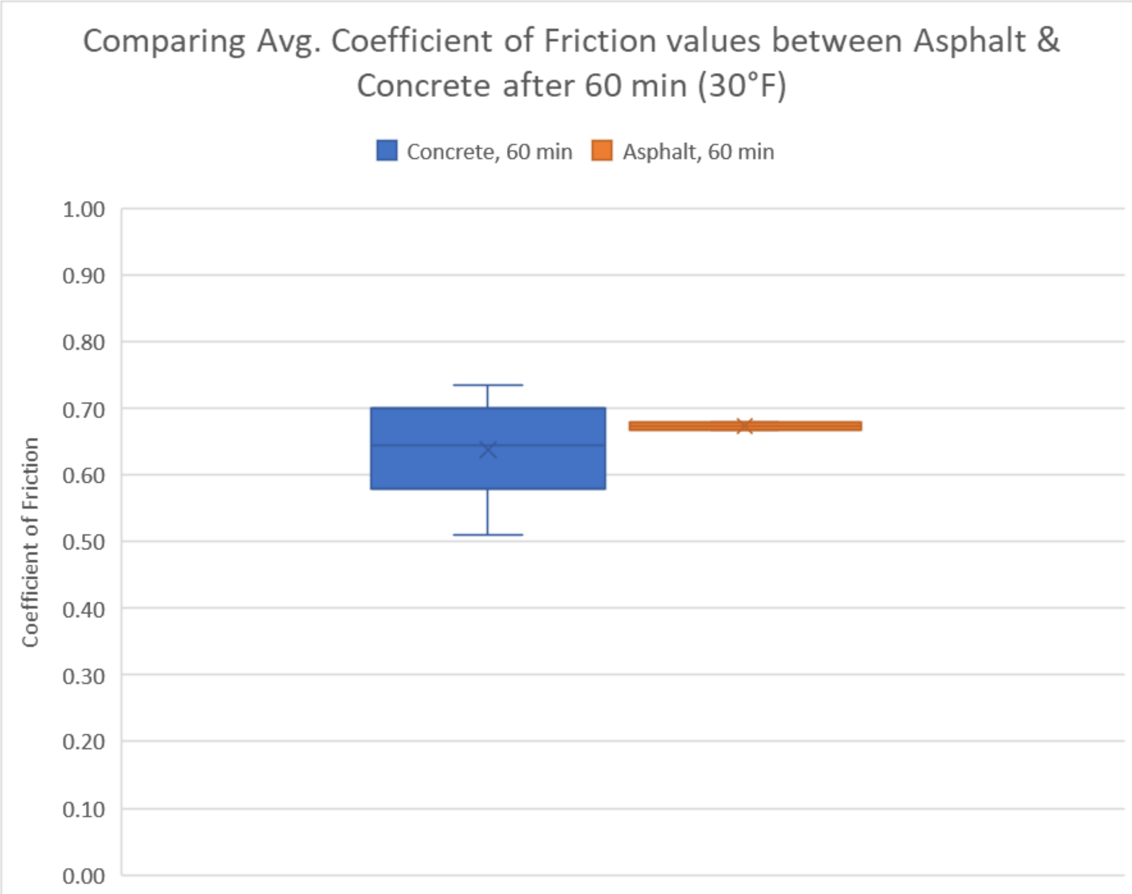

Figure 25. Comparison on final (t=60) coefficient of friction values for asphalt and concrete pavements at 30°F.

5.3.2 Testing at 15°F

Overall, each deicer shows similar trends in friction coefficient values on asphalt and concrete pavements (Figure 26). Figure 26 shows that at the start of testing, asphalt pavement samples had significantly higher coefficient of friction values (0.94 ± 0.04) than concrete samples (0.70 ± 0.06). After 30 minutes of testing, two groups emerged with higher coefficient of friction values (0.55 ± 0.04) associated with NaCl prewet with BEET HEET, IceKicker, NaCl, and NaCl prewet with MMZ and lower coefficient of friction values (0.26 ± 0.03) associated with NaCl prewet with $MgCl_2$, Ice Slicer, NaCl prewet with Beet Juice, and NaCl prewet with NaCl.

From 30 minutes to 45 minutes of testing, four groups emerge 1) products that show no change in coefficient of friction but with higher friction values (IceKicker and NaCl prewet with MMZ), 2) products that show a decrease in coefficient of friction (NaCl prewet with BEET HEET and NaCl), 3) products that show an increase in coefficient of friction (Ice Slicer and NaCl prewet with Beet Juice), 4) products that show no change in coefficient of friction but with lower friction values (NaCl prewet with $MgCl_2$ and NaCl prewet with NaCl).

After 45 minutes of testing, the four groups merged back into two groups with higher coefficient of friction values (0.55 ± 0.03) includes NaCl prewet with Beet Juice, IceKicker, Ice Slicer, and NaCl prewet with MMZ. The second group with lower coefficient of friction values (0.25 ± 0.03) includes NaCl prewet with NaCl, NaCl prewet with $MgCl_2$, NaCl prewet with BEET HEET, and NaCl.

After 60 minutes the coefficient of friction values for all deicers were 0.60 ± 0.06. For all asphalt samples there was significant difference in before (t=0) and after (t=60) coefficient of friction values, whereas for concrete samples there was not always a significant difference in before (t=0) and after (t=60) coefficient of friction values. Figure 27 shows that at the end of testing (t=60) coefficient of friction values from asphalt pavements were very consistent while those measured on concrete were more variable. Showing again, that the **pavement type has a significant impact on the measured coefficient of friction using this method**. At this test temperature it was noted that during lab testing, the peak force measurement could have been influenced by salt crystals on the concrete pavement. It was noted that the asphalt samples appeared to hold the liquid deicers on the surface, whereas with the concrete samples, the liquid deicers either absorbed into the pavement or evaporated, leaving precipitated salt crystals on the concrete pavement surface.

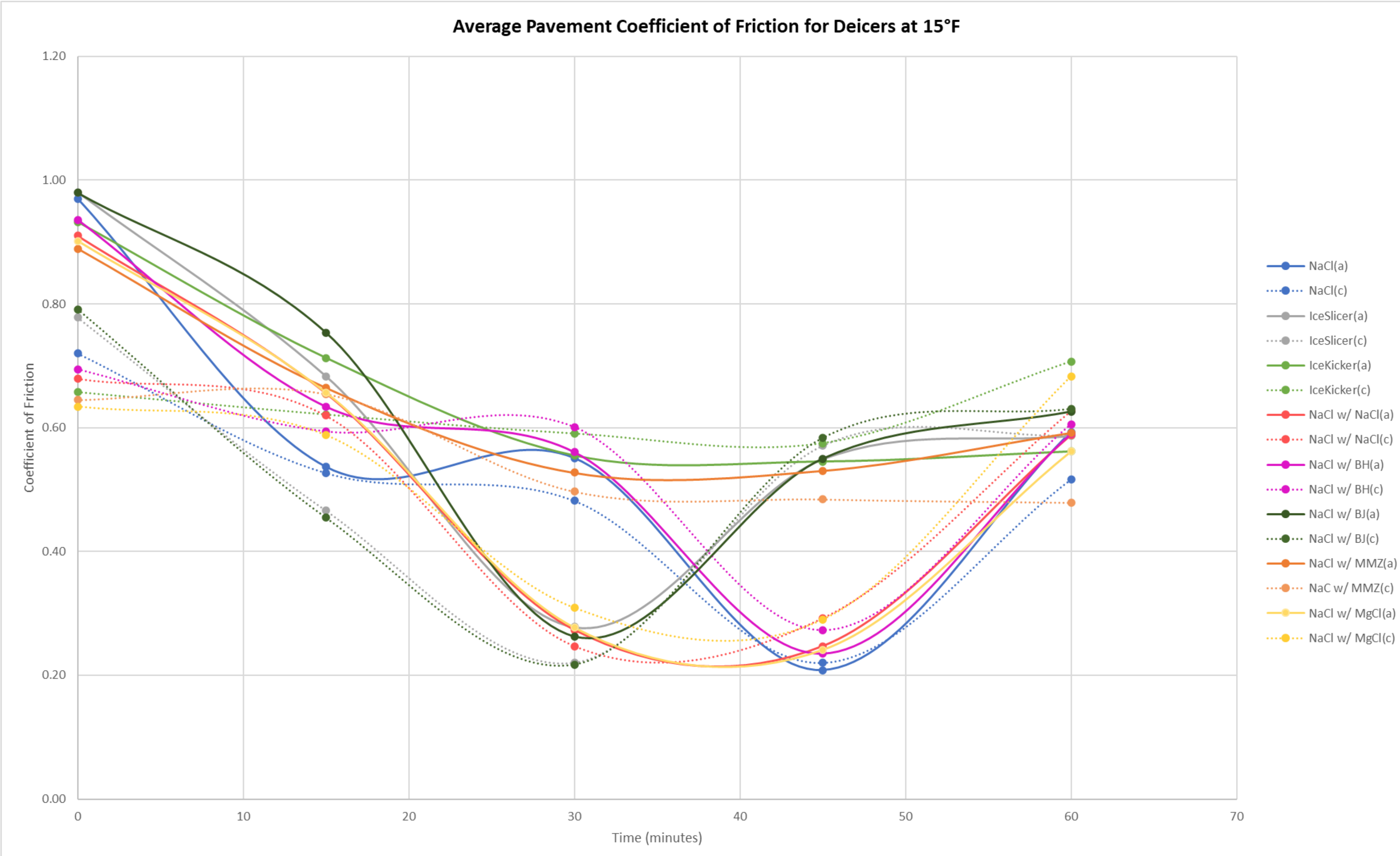

Figure 26. Coefficient of friction for deicers blended with additives over one hour at 15°F, measured on both asphalt (a, solid lines) and concrete (c, dotted lines) pavements.

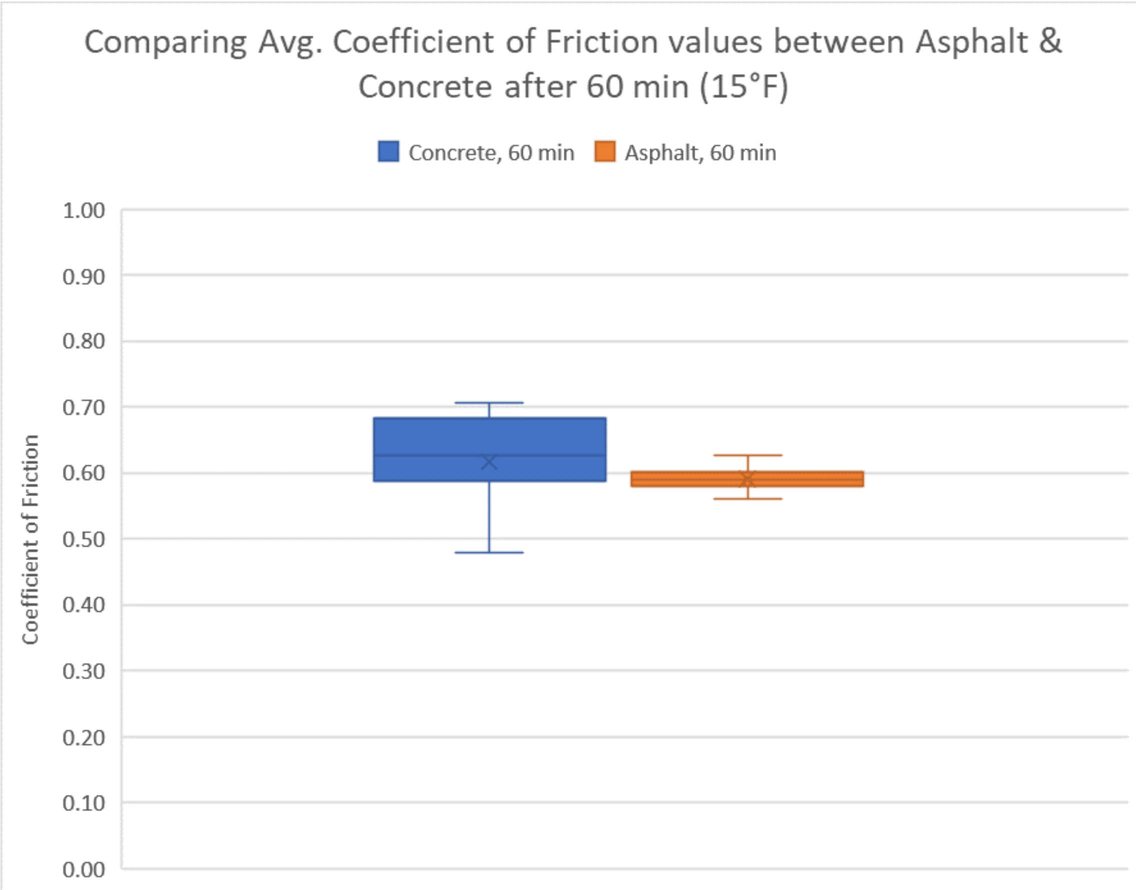

Figure 27. Comparison on final (t=60) coefficient of friction values for asphalt and concrete pavements at 15°F.

6 RESULTS, CONCLUSIONS, RECOMMENDATIONS

6.1 LITERATURE REVIEW CONCLUSIONS

Chloride-based salts are cost-effective and practical, making them the most common deicers used in the winter road maintenance operations toolkit. However, chloride-based deicers/anti-icers can have negative impacts to infrastructure and the environment, which may in part be addressed using additives. Additionally, certain environments and situations (e.g., extreme cold environments) may require the use of additives to effectively treat a roadway. Additives are used to increase deicer efficiency and effectiveness while improving mobility and safety. Some benefits provided by additives, such as corrosion protection, cold temperature performance, and anti-caking properties have been well measured and documented. While other benefits, such as residual effect extenders and "environmentally friendly" compounds lack laboratory testing but with work by Muthumani et al. 2015 and Nazari et al. (2018) starting to fill this gap in the literature.

Many test methods have been identified that can help assess the changes in performance of deicing/anti-icing products induced by additives. This project specially calls out the use of eutectic temperature to show how additives support chlorides working at lower temperatures. Other methods such as calorimetry, measurements of ice melting capacity, ice penetration, and ice under cutting, as well as road grip and bond strength are also able to assess the improved performance from additives.

A summary of deicers and additives discussed in this literature review are provided below in Table 14. From this, we can see a significant amount of laboratory test results are available in the published domain to support this research effort.

Work by Koefod (2008) and Danilov et al. (2019) raised important concerns over what different tests measure, and how additives can modify eutectic temperature and/or ice melting capacity test results differently.

Table 14. An overview of studies with the performance of roadway deicers incorporating additives.

Reference	Deicers and Additives Tested
Abbas et al. (2021)	agricultural byproducts (beet juice, corn juice, polyols (sorbitol, maltitol, mannitol), NaCl
Achkeeva et al. (2015)	NaCl, $MgCl_2$, $CaCl_2$, KCl, sodium formate
Fay and Shi (2011)	NaCl, IceSlicer, $MgCl_2$, agro-based deicers, $CaCl_2$, sodium acetate/sodium formate blend (NAAC/PeakSF), CF7 (potassium acetate), CMA, potassium formate
Fu, Omer, and Jiang (2012)	beet juice, NaCl
Gerbino-Bevins and Tuan (2011)	NaCl, $MgCl_2$, $CaCl_2$, potassium acetate, beet juice
Goyal et al. (1989)	NaCl, $MgCl_2$, lignin sulfinate, sulfate, potassium, sodium, calcium

Reference	Deicers and Additives Tested
Hansen and Haley (2019)	$MgCl_2$
Iverson et al. (1997)	NaCl, $CaCl_2$
Koefod (2008)	K_2CO_3, agricultural by products, $MgCl_2$, xylitol
Lammers (2021)	FreezGard C1+, Ice B'Gone Magic, distillers by product, $MgCl_2$, Ice Ban 305, $CaCl_2$, BioMelt AG64
Muthumani et al. (2015)	IceSlicer, Thawrox, Beet 55, Boost SB, SnowMelt, Geomelt 55, Apogee, Boost CCB, IceBan 305, ThermaPoint IB 7/93, NaCl
Nazari et al. (2016)	NaCl, sugar beet leaf extract, sodium formate, sodium metasilicate
Nazari et al. (2019)	dandelion leaf extract, sugar beet leaf extract, sodium metasilicate, sodium formate, NaCl
Nazari and Shi (2019)	NaCl, sodium metasilicate, sodium formate, glycerin, Concord grape extract, beet juice
Nilssen et al. (2018)	NaCl, $MgCl_2$, $CaCl_2$, potassium formate, CMA, sucrose
Nixon et al. (2007)	NaCl, $CaCl_2$, CMA, potassium acetate, CM-1000, Mineral Brine, IceBan Ultra
Sajid et al. (2021)	corn derived polyols (sorbitol, mannitol, maltitol), NaCl
Shi et al. (2013)	NaCl, $MgCl_2$, $CaCl_2$, sugar beet agricultural additive (AGBP), CCB, FreezGard CI plus, Shield GLT
Shi et al. (2014)	11 different NaCl rock salts and brines, $MgCl_2$
Shi et al. (2018)	apple pomace, apple fiber, cherry pomace, Concord grape fiber, blueberry fiber, orange peels, potato peels, glycerin, NaCl, sodium metasilicate, sodium formate
Taylor et al. (2014)	glycerol, Geomelt, Ice B'Gone, E310, BioOil, $MgCl_2$, NaCl
Zhang et al. (2020)	NaCl, $MgCl_2$, $CaCl_2$, beet juice, grape pomace extract

6.2 SURVEY CONCLUSIONS

Responses from state and local agencies identified better snow and ice removal performance, cold temperature modification, and longer residual on the pavement, cost effectiveness, and reduce corrosion as the top five reasons they use additives in chloride-based deicers. A list of deicers, additives, blend ratios, volume used, and product source is provided; along with details on why specific additives were selected is provided. Other identified benefits of using additives include cost savings, reduced material use, quicker storm clean up, and visibility on the road. Impacts identified included increased corrosion and sticky residual.

6.3 LABORATORY TESTING CONCLUSIONS

The following conclusions can be made based on the test results from FPT, modified IMCRT, and friction testing.

6.3.1 FPT Conclusions

Based on the FPT performed for all products at various concentrations, NaCl (solid control) and NaCl prewet with MMZ (prewet solid 3) had the lowest eutectic temperatures compared to all other products. Note that the differences in estimated eutectic temperature were minute with the average eutectic temperatures being 21.19 ± 0.58°C (-6.14°F) (Figure 17). To summarize these results, a lower eutectic temperature of one prewet salt over another may not directly correlate with more ice melting.

Ice Slicer (solid 1) and IceKicker (solid 2) both showed warmer eutectic temperatures and less IMC compared to the prewet solids. These findings suggest that products with higher IMC will likely have lower eutectic temperatures. This is also supported by the lower eutectic temperatures of $MgCl_2$ and $CaCl_2$ (*CaCl2 Dihydrate Phase Diagram*, n.d.; *MgCl2 Hexahydrate Phase Diagram*, n.d.). Both of these salts show better IMC results and can be used at much lower temperatures compared to NaCl.

An important conclusion was made after the FPT of filtered and unfiltered Ice Slicer (solid 1) was performed, confirming that insoluble impurities play a role in lowering the eutectic temperature but are not the primary driver. Those results are compared in Table 18, Appendix B.

Overall best performer – as per FPT results

If we take a close look at the results yielded from FPT of all products at various concentrations (Table 19, Appendix B), NaCl (solid control) showed the lowest freezing point for its eutectic composition (23%). However, for other concentrations, the results of prewet solids (1 to 4), prewet control, and solid control are very close to each other. Therefore, for prewetted solids and control it cannot be deduced that one product was better than the other for concentrations 5% to 15%. However, for eutectic concentration (23%), prewet solid 3 (NaCl prewet with MMZ) stands out from the rest in terms of its lowest freezing point or estimated eutectic temperature.

However, Ice Slicer and IceKicker (solid 1 and solid 2) had warmer freezing points compared to prewetted solids and controls. This suggests that impurities in Ice Slicer (solid 1) and IceKicker (solid 2) did not aid in lowering the eutectic temperature.

Prewetting of solid salt may lead to significant difference in eutectic temperatures (1 to 3°C) at higher application rates. For instance, rock salt (NaCl) prewet with $MgCl_2$ brine at 30 gal/ton may yield a eutectic temperature of -23°C (-9.4°F) or even lower. However, the prewet rate of 8 gal/ton does not seem to lower the eutectic temperature of NaCl significantly.

6.3.2 Modified IMC Conclusions

Modified Ice Melting Capacity – 15 minutes rocking time (Modified $IMCRT_{15}$)

As can be observed from Table 15, NaCl prewet with Beet Juice (prewet solid 2) melted the most ice (1.02g per gram of deicer, at 25°F) after 15 minutes of rocking in modified $IMCRT_{15}$. Whereas Ice Slicer (solid 1) melted the least amount of ice per gram of deicer at both temperatures in modified $IMCRT_{15}$. All other prewetted solid products showed better performance compared to the controls at both temperatures. NaCl prewet with Beet Juice, NaCl prewet with $MgCl_2$, and NaCl prewet with MMZ (prewet solids 2, 3, and 4, respectively) were the top three modified $IMCRT_{15}$ at both temperatures. IceKicker (solid 2) showed better performance than both controls. NaCl control and NaCl prewet with BEET HEET (prewet solid 1) were the fourth most effective products after completing modified $IMCRT_{15}$ at both temperatures. Table 15 shows the deicer and additives blends ranking based on their modified IMC (g/g) after 15 minutes of rocking at 15°F and 25°F.

Table 15. Product performance ranked by average modified IMC (g/g) after 15 minutes of rocking in modified $IMCRT_{15}$ at 15°F and 25°F. These results were obtained using an unvalidated test method.

Rank	Products tested	Ice melted (g/g) at 15°F	Ice melted (g/g) at 25°F
1.	Pre-wet Solid 2 (NaCl w/ Beet Juice)	0.60	1.02
2.	Pre-wet Solid 4 (NaCl w/ $MgCl_2$)	0.49	0.94
3.	Pre-wet Solid 3 (NaCl w/ MMZ)	0.47	0.84
4.	Solid 2 (IceKicker)	0.38	0.80
5.	Solid Control (NaCl) Pre-wet Solid 1 (NaCl w/ BEET HEET)	0.38 0.35	0.67 0.69
6.	Pre-wet Solid Control (NaCl w/ NaCl)	0.30	0.58
7.	Solid 1 (Ice Slicer)	0.23	0.43

Modified Ice Melting Capacity – NaCl (solid control) and NaCl prewet with NaCl (prewet control)

From Figure 23 it can be deduced that prewetting may not provide any additional benefit in terms of ice melting capacity at colder temperatures. At 15°F, NaCl prewet with NaCl brine (prewet control) showed lower modified IMC (g/g) when compared to NaCl (solid control), after 15 and 30 minutes of rocking. On the contrary, NaCl prewet with NaCl brine (prewet control) showed better modified IMC (g/g) at 25°F but only after 30 minutes of rocking time, suggesting the need for additional time to reach peak ice melting performance. Overall, these results suggest that rock salt prewet with salt brine is less effective than rock salt, unless used at warmer temperatures and when sufficient time (30 minutes) is provided for the ice melting process.

Modified $IMCRT_{15}$ Overall best performer – warmer temperature (25°F)

At 25°F the highest modified IMCs (g/g) are attributed to prewet solids, with NaCl prewet with Beet Juice (prewet solid 2) having the highest modified IMC.

Modified $IMCRT_{15}$ Overall best performer – colder temperature (15°F)

At 15°F the highest modified IMCs (g/g) are attributed to prewet solids, with NaCl prewet with Beet Juice (prewet solid 2) having the highest modified IMC.

6.3.3 Friction Conclusions

The coefficient of friction was measured on asphalt and concrete pavements at 15°F and 30°F for eight unique deicers and additive blends. Overall, similar trends in coefficient of friction were observed for each deicer on asphalt and concrete pavement types, with the pavement type having a significant influence on the results. The coefficient of friction values for each deicer and additive blend varied between test temperatures (15°F and 30°F).

At 30°F the coefficient of friction values separated into two groups after 30 minutes, but by 60 minutes the coefficient of friction values either remained steady or increased to 0.63 ± 0.06. At 15°F the coefficient of friction values separated into two groups at 30 minutes, then between 30 to 45 minutes values separated into four groups, then at 45 minutes values merged back into two groups. At 15°F, by 60 minutes the coefficient of friction value either remained steady or increased to 0.60 ± 0.06.

There is no clear best performer, as the coefficient of friction performance changed over time, for each temperature and pavement type. These results suggest that additives may lead to reductions or improvements in pavement friction at varying times and due to varying conditions. What can be stated is that at 30°F NaCl prewet with Beet Heet and NaCl prewet with NaCl and at 15°F IceKicker and NaCl prewet with MMZ showed the least reduction in friction, or most consistent friction, throughout the 60-minute test.

6.4 RECOMMENDATIONS AND FUTURE RESEARCH

Recommendations for the use and application of these findings will vary based on each agency's needs. Such that laboratory testing of each unique blend of deicers and additives used or developed by an agency is recommended to provide similar performance information to aid in field deployment.

Future work to support agencies could include the following:

Effects of Additives in Deicing Salts at Lower Temperatures

- Development of a public-facing or Clear Roads managed database of freezing point, ice melting capacity, and other deicer performance test results.
- Further improve upon and work toward standardization of the IMCRT for solid deicers.

Research needs identified in the research process to build upon this work, and support agencies includes:

- Investigation of the role of rock salt gradation in deicer performance.
- Conduct similar laboratory testing using higher prewet rates.

REFERENCES

Achkeeva, M.V., Romanyuk, N.V., Frolova, N.V., Kondakov, D.F., Khomyakov, D.M., Danilov, V.P. 2015. *Deicing properties of sodium, potassium, magnesium, and calcium chlorides, sodium formate and salt compositions on their basis*. Theoretical Foundation of Chemical Engineering 49(4)481-484.

Abbas, T., Lavadiya, D.N., and Kiran, R. 2021. *Exploring the Use of Polyols, Corn, and Beet Juice for Decreasing the Freezing Point of Brine Solution for Deicing of Pavements*. Sustainability 13 (11): 5765. https://doi.org/10.3390/su13115765.

Akin, M., Fay., L., Shi, X. 2020. *Friction and Snow-Pavement Bond after Salting and Plowing Permeable Friction Surfaces*. Transportation Research Record. 2674(11): 794-80

Akin, M., Huang, J., Shi, X., Veneziano, D., Williams, D. (2013) *Snow removal at extreme temperatures*. Clear Roads and Minnesota DT.

ASTM International. (2007). Standard Test Method for Freezing Point of Aqueous Engine Coolants (D 1177 – 07). ASTM International.

Bäckström, M., Karlsson, S., Bäckman, L., Folkeson, L., and Lind, B. 2004. *Mobilization of Heavy Metals by Deicing Salts in a Roadside Environment*. Water Research 38 (3): 720–32. https://doi.org/10.1016/j.watres.2003.11.006.

Chappelow, C.C., McElroy, A.D., Blackburn, R.R., Darwin, D., de Noyelles, F.G., and Locke, C.E. (1992). *Handbook of Test Methods for Evaluating Chemical Deicers*. Strategic Highway Research Board, The National Academies, Washington, D.C.

Clear Roads (2021) Clear Roads Snow and Ice Control Chemical Product Program, Guidance Document for Material Qualified Products List, Specifications, Test Methods, and Product Purchasing. https://clearroads.org/qualified-product-list/

Danilov, V.P., Frolova, E.A., Kondakov, D.F., Sveshnikova, L.B. 2019. *Application of physiochemical analysis of developing and studying deicing agents*. Russian Journal of Inorganic Chemistry 64(9)1165-1168

Duke Environmental Analytical Chemistry Laboratory. (n.d.). Applications of Organic Dye Measurements in Airport Stormwater as Tracers for Assessing Runoff of Aircraft Deicing/Anti-Icing Fluids. Retrieved from: http://ferguson.cee.duke.edu/research/application-organic-dye-measurements-airport-stormwater-tracers-assessing-runoff-aircraft

Druschel, S. (2017). *Salt Brine Blending to Optimize Deicing and Anti-Icing Performance and Cost Effectiveness: Phase III*. Mankato, MN: Minnesota Department of Transportation

Du, S., Akin, M., Bergner, D., Xu, G., & Shi, X. 2022. *Material Application Methodologies for Winter Road Maintenance: A Renewed Perspective*. Canadian Journal of Civil Engineering, 49(1).

Farnam, Y., Bentz, D., Sakulich, A., Flynn, D., & Weiss, W. 2014. *Measuring Freeze and Thaw Damage in Mortars Containing Deicing Salt Using a Low Temperature Longitudinal Guarded Comparative Calorimeter and Acoustic Emission (AE-LGCC)*. Advances in Civil Engineering Materials, 3. https://doi.org/10.1520/ACEM20130095

Fay, L., Volkening, K., Gallaway, C., Shi, X. 2008. *Performance and Impacts of Current Deicing and Anti-icing Products: User Perspective versus Experimental Data*. TRB Annual Meeting proceedings, Washington, D.C.

Fay, L., and Shi, X. 2011. *Laboratory investigation of performance and impacts of snow and ice control chemicals for winter roads service*. J. Cold Reg. Eng. 25(3): 87-132

Fay, L., and Shi, X. 2012. *Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge*. Water, Air, & Soil Pollution 223 (5): 2751–70. https://doi.org/10.1007/s11270-011-1064-6.

Fay, L., Hetherington, N., Jamal, M., Shi, X., Bell, M., Nazari, M., Brown, P. (2022). *Understanding the Salt Phase Diagram*. Clear Roads and Minnesota Department of Transportation. CR 20-02.

Feick, G., Horne, R.A., and Yeaple, D. 1972. *Release of Mercury from Contaminated Freshwater Sediments by the Runoff of Road Deicing Salt*. Science 175 (4026): 1142–44. https://doi.org/10.1126/science.175.4026.1142.

Fig. 1-Phase diagram of aqueous NaCl. 16. (n.d.). ResearchGate. Retrieved December 20, 2022, from https://www.researchgate.net/figure/Phase-diagram-of-aqueous-NaCl-16_fig1_263963700

Findlay, S.E.G. and Kelly, V.R. 2011. *Emerging Indirect and Long-Term Road Salt Effects on Ecosystems*. Annals of the New York Academy of Sciences 1223 (1): 58–68. https://doi.org/10.1111/j.1749-6632.2010.05942.x.

Fischel, M. (2001). *Evaluation of selected deicers based on a review of the literature*. Final CDOT-DTD-R-2001-15. Colorado Department of Transportation.

Fu, L., Omer, R., and Jiang, C. 2012. *Field Test of Organic Deicers as Prewetting and Anti-Icing Agents for Winter Road Maintenance*. Transportation Research Record: Journal of the Transportation Research Board 2272 (1): 130–35. https://doi.org/10.3141/2272-15.

Gerbino-Bevins, B.M., Tuan, C.Y. (2011). *Performance Rating of Deicing Chemicals for Winter Operations*. Nebraska Department of Roads, Materials & Research, SPR-P1(10)P328.

Goyal, G., Lin, J., McCarthy, J.L. 1989. *Time, temperature, and relative humidity in deicing on highways using sodium chloride or magnesium chloride with metal corrosion inhibitors*. Transportation Research Record 1246: 9-17.

Hansen, D. and Halsey, L. (2019). *Validation of the Mechanical Rocker Test Method for Ice Melting Capacity (MRT-IMC)*. Nebraska Department of Transportation, Lincoln, NE.

Harless, M.L., Huckins, C.J., Grant, J.B., and Pypker, T.G. 2011. *Effects of Six Chemical Deicers on Larval Wood Frogs (Rana Sylvatica)*. Environmental Toxicology and Chemistry 30 (7): 1637–41. https://doi.org/10.1002/etc.544.

Hintz, W.D., Fay, L., and Relyea, R.A. 2022. *Road Salts, Human Safety, and the Rising Salinity of Our Fresh Waters*. Frontiers in Ecology and the Environment 20 (1): 22–30. https://doi.org/10.1002/fee.2433.

Iverson, D.L., McGraw, J.W., Mauritis, M., Jang, J-W. 1997. *Mixing ratio of CaCl2 and NaCl for effective deicer*. Journal of Materials in Civil Engineering 9(2): 62-64

JTRP - Interaction of Chloride-based Deicing Salts with Concrete (cont. A). (n.d.). Retrieved May 30, 2024, from https://engineering.purdue.edu/JTRP/Highlights/nacl-the-most-wellestablished-road-salt

JTRP - Interaction of Chloride-based Deicing Salts with Concrete (cont. B). (n.d.). Retrieved May 30, 2024, from https://engineering.purdue.edu/JTRP/Highlights/cacl2-dihydrate-cacl2-2h2o

JTRP - Interaction of Chloride-based Deicing Salts with Concrete (cont. C). (n.d.). Retrieved May 30, 2024, from https://engineering.purdue.edu/JTRP/Highlights/interaction-of-chloridebased-deicing-salts-with-concrete-cont-c

Koefod, S. 2008. *Eutectic depressants, Relationship of eutectic, freezing point, and ice melting capacity in liquid deicers*. Transportation Research Circular E-C126, Transportation Research Board, The National Academies, Washington, D.C. pg. 73

Lammers, E. (2021). *Evaluation of Liquid Ice Melting Additives for Winter Maintenance Applications*. Theses and Dissertations - Civil Engineering 101, University of Kentucky. Kentucky Transportation Cabinet SPR 18-566. https://doi.org/10.13023/ETD.2021.300.

Lee, B.D., Choi, Y.S., Kim, Y.G., Kim, I.S., and Yang, E.I. 2017. *A Comparison Study of Performance and Environmental Impacts of Chloride-Based Deicers and Eco-Label Certified Deicers in South Korea*. Cold Regions Science and Technology 143 (November): 43–51. https://doi.org/10.1016/j.coldregions.2017.08.010.

Liu, J., Shi, X., Honarvarnazari, M. (2021). *Snow and Ice Treatment Products Evaluation*. Missouri Department of Transportation, TR202002. https://rosap.ntl.bts.gov/view/dot/60854

Maeshima, T., Koda, Y., Tsuchiya, S., and Iwaki, I. 2014. *Influence of corrosion of rebars caused by chloride induced deterioration on fatigue resistance in RC road bridges deck*. Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures) 70 (2): 208–25. https://doi.org/10.2208/jscejmcs.70.208.

Maria, A.H., Millam, E.L., and Wright, C.L. 2011. *Using a Differential Scanning Calorimeter to Teach Phase Equilibria to Students of Igneous and Metamorphic Petrology*. Journal of Geoscience Education 59 (2): 63–70. https://doi.org/10.5408/1.3580766.

McNaboe, L.A., Robbins, G.A., and Dietz, M.E. 2017. *Mobilization of Radium and Radon by Deicing Salt Contamination of Groundwater*. Water, Air, & Soil Pollution 228 (3): 94. https://doi.org/10.1007/s11270-016-3227-y.

Muthumani, A., Fay, L., Bergner, D., and Shi, X. (2015). *Understanding the Effectiveness of Non-Chloride Liquid Agricultural By-Products and Solid Complex Chloride/Mineral Products*. Clear Roads and Minnesota DOT.

Nazari, M.H., Havens, E.A., Shi, X., Muthumani, A. (2016). *Bio-based renewable additives for anti-icing applications (Phase I)*. Center for Environmentally Sustainable Transportation in Cold Climates, University of Alaska, Fairbanks, and US DOT. INCE/CESTiCC 101406

Nazari, M.H., and Shi, X. 2019. *Developing Renewable Agro-Based Anti-Icers for Sustainable Winter Road Maintenance Operations*. Journal of Materials in Civil Engineering 31 (12): 04019299. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002963.

Nazari, M.H., Havens, E.A., Muthumani, A., and Shi, X. 2019. *Effects of Processed Agro-Residues on the Performance of Sodium Chloride Brine Anti-Icer*. ACS Sustainable Chemistry & Engineering 7 (16): 13655–67. https://doi.org/10.1021/acssuschemeng.8b06043.

Nazari, M. H., Jamal, M., Green, D., Gonzalez, J., Beaurivage, S., Smith, H., Mislang, J., Potapova, A., Akin, M., & Shi, X. (2024). *Standard Method of Test for Mechanical Rocker Ice Melting.* Final Report CR 18-06. Clear Roads and Washington State University.

NCHRP 5777. 2007. *Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts*. National Cooperative Highway Research Program, Transportation Research Board, and National Academies of Sciences, Engineering, and Medicine. Washington, D.C. https://doi.org/10.17226/23178.

Nilssen, K., Klein-Paste, A., and Wåhlin, J. 2018. *The Effect of Additives on the Low Temperature Ice-Melting Capacity of NaCl*. Transportation Research Record, 2672(12), 158–166. https://doi.org/10.1177/0361198118767412

Nixon, W., Kockumman, G., Qiu, L., Qiu, J., Xiong, J. (2007). *Evaluation of using non-corrosive deicing materials and corrosion reducing treatments for deicing salts*. Iowa Highway Research Board, TR 463.

Ohno, T. 1990. L*evels of total cyanide and NaCl in surface waters adjacent to road salt storage facilities*. Environmental Pollution, 67(2): 123-132, https://doi.org/10.1016/0269-7491(90)90077-P

Sajid, U., Hizb, Naik, D.L., and Kiran, R. 2021. *Improving the Ice-Melting Capacity of Traditional Deicers*. Construction and Building Materials 271 (February): 121527. https://doi.org/10.1016/j.conbuildmat.2020.121527.

Shi, X., Fortune, K., Smithlin, R., Akin, M., Fay, L. 2013. *Exploring the performance and corrosivity of chloride deicer solutions: Laboratory investigation and quantitative modeling*. Cold Regions Science and Technology, 86, 36-44.

Shi, X., Jungwirth, S., Akin, M., Wright, R., Fay, L., Veneziano, D., Zhang, Y. 2014. *Evaluating Snow and Ice Control Chemicals for Environmentally Sustainable Highway Maintenance Operations*. Journal of Trans Eng., 140(11), 05014005.

Shi, X., Fay, L., Yang, Z., Nguyen, T.A., Liu, Y. 2009. *Corrosion of Deicers to Metals in Transportation Infrastructure: Introduction and Recent Developments*. Corrosion Reviews 27(1-2):23-52

Shi, X., Honavar Nazari, M., Oh, T., Ewing, A., Okon, D., Zhang, Y., Avalos, B., Alnuaimi, E., and Havens, E. (2018). Bio-Based Renewable Additives for Anti-Icing Applications (Phase II). Washington State Department of Transportation, WA-RD 883.1.

Shi, X. and Jungwirth, S. 2018. Chapter 17: The Search for "Greener" Materials for Winter Road Maintenance Operations. In X. Shi, L. Fu (Eds.), *Sustainable Winter Road Operations*, Wiley-Blackwell, 378-401.

Siegel, L. (2007). *Hazard Identification for Human and Ecological Effects of Sodium Chloride Road Salt*. New Hampshire Dept of Environmental Services.

Sleeper, F. (2013). *Literature Review Winter Deicer Maintenance Practices on Impervious Surfaces: Impacts on the Environment*. Water Resource Center, University of Minnesota.

Standard Test Method for Freezing Point of Aqueous Engine Coolants. (n.d.). Retrieved December 20, 2022, from https://www.astm.org/d1177-22.html

Switzenbaum, M.S., Velman, S., Wagoner, B., and Schoenberg, T. 2001. *Best Management Practices for Airport Deicing Stormwater*. Chemosphere 43 (8): 1051–62. https://doi.org/10.1016/S0045-6535(00)00199-5.

Taylor, P., Verkade, J.G., Gopalakrishnan, K., Wadhwa, K., and Kim, S. 2014. *Experimental studies on development of sustainable agricultural-based road transport deicing applications*. International Journal for Traffic and Transport Engineering 4 (2): 128–45. https://doi.org/10.7708/ijtte.2014.4(2).01.

Trzaskos, M. P., and Klein-Paste, A. 2020. *Effect of Temperature and Prewetting for Ice Penetration with Sodium Formate*. Transportation Research Record, 2674(6), 140–150. https://doi.org/10.1177/0361198120917974

Tuan, C.Y. and Alberts, T. (2014). *Development of Shaker Test as a Standardized Test Protocol for Deicing Chemicals Evaluation*. Mid-America Transportation Center, US DOT. MATC-UNL: 058

Weiner, G., Fay, L., Brummet, T., Landolt, S., Lentz, J., Linden, S., Petzke, B. (2023). *Roadway friction modeling: Improving the use of friction measurements in State DOTs*. Aurora Pooled Fund and Iowa DOT, 2020-04.

Wåhlin, J., and Klein-Paste, A. 2015. *Temperature Dependence of Solution-Induced Weakening of Compacted Snow*. Transportation Research Record, 2482(1), 41–45. https://doi.org/10.3141/2482-06

Xi, Y. and Olsgard, P.J. (2000). *Effects of De-Icing Agents (Magnesium Chloride and Sodium Chloride) on Corrosion of Truck Components*. Final CDOT-DTD-R-1000-l0. Colorado Department of Transportation.

Zhang, Y., Akin, M., and Shi, X. 2020. *Laboratory Investigation of Prewet Deicer Performance for Winter Mobility in the Pacific Northwest*. Journal of Cold Regions Engineering 34 (4): 04020022. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000228.

APPENDIX A - SURVEY INSTRUMENT

Effects of Additives in Deicing Salts at Lower Temperatures

This survey has been created to help support Clear Roads and its member states in their understanding of how additives to chloride-based deicers (liquids and solids) modify performance of the mixed product. Specifically, we are seeking information on each additive, why it is used by your agency, and how each additive modifies performance. Information gathered in the survey will be used to support a laboratory evaluation of identified additives and in a report documenting the measured modification of eutectic temperature for chloride-based deicers and various additives.

Participation in this survey is voluntary and you may skip any question you do not want to answer and/or you can stop at any time. Proceeding with this survey indicates your consent to participate. The survey should take about **5** minutes. Any questions or comments can be directed to Laura Fay of WTI/MSU at laura.fay1@montana.edu.

Thank you for your time.

1. Do you or does your organization use chloride-based deicers (NaCl: rock salt or salt brine, $MgCl_2$: mag chloride, $CaCl_2$: calcium chloride) that contain additives? [For example; treated rock salt or blended brine]
    a. Yes
    b. No → If no is selected, end the survey

2. Why do you or does your organization use chloride-based deicers blended with additives? Check all that apply
    - ☐ Cost effectiveness
    - ☐ Better snow/ice removal performance
    - ☐ Cold temperature modification
    - ☐ Reduced corrosion to metals, infrastructure
    - ☐ More or longer residual on the pavement
    - ☐ Improved friction
    - ☐ Anti-caking agent
    - ☐ Dye markers
    - ☐ Other – please explain:
    ____
    ____
    ____

3. Please list the <u>products with additives</u> you use including the trade name and manufacturer or list of <u>additives</u> that are added to your chloride-based deicers and at what quantity they are added.

(For example, Product Name/Manufacturer or Additive 1: Rock Salt/Rock Salt Suppliers; Product Name/Manufacturer or Additive 2: Beet juice, 8 gal/ton)

Product Name/Manufacturer or Additive 1: ____________________ Quantity: ___

Product Name/Manufacturer or Additive 2: ____________________ Quantity:____

Product Name/Manufacturer or Additive 3: ____________________ Quantity:____

Product Name/Manufacturer or Additive 4: ____________________ Quantity:____

Product Name/Manufacturer or Additive 5: ____________________ Quantity:____

If you have additional information to share about the additives your agency uses, please provide that feedback here.

4. Which additives that your agency uses have the greatest impact on the performance of deicing or anti-icing at cold temperatures? How do you know this? Please share your observations or data. Please upload or email any results or resources to Laura Fay at laura.fay1@montana.edu.

5. Please describe any impacts from these additives that your agency has observed.

6. Would you be willing to participate in a follow up conversation so that we can learn more from you about the deicer additives used and their role in improving product performance?
   - Yes
   - No → If no is selected, end the survey.

7. Please provide the following contact information.
   - Name:____
   - Title: ____
   - Organization: ____
   - Where in organization you work (e.g., Headquarters, District, Garage, etc.):____
   - Email Address:____

We thank you for your time spent taking this survey.

APPENDIX B - ADDITIONAL DETAILS: LAB TEST METHODS, TABLES, AND FIGURES TO SUPPORT LAB RESULTS

Detailed Modified IMCRT Procedure for Solids [NOT A VALIDATED TEST METHOD]

NOTE: The warmest temperature setting that can be achieved in the test freezer (Atosa®) is 25°F (-3.9°C). The test could not be performed at 30°F using the chest freezer. Therefore, the two test temperatures were 25°F and 15°F.

The IMC Rocking Test (IMCRT) method developed by NDOT (Hansen & Halsey, 2019) and validated in CR 18-06 (Nazari et al., 2024) only applies to liquid deicers. For this work, the IMCRT was modified to allow testing of solid deicers. Note that the modified IMCRT method used in this lab study has not been validated and therefore the reported findings cannot be compared to findings from the approved IMCRT method for liquid deicers.

1. **Prepare the test freezer (freezer #1)**
    a. Set the freezer temperature range (either 15°F or 25°F) 24 hours before the test day.
    b. Label 6 clean dried Styrofoam cups – A, B, C, AA, BB, CC and weigh them. Place them in the freezer for acclimation 24 hours before the test day.
    c. Place other clean and dried items to be used in the freezer (sieve with its pan, silicon spatula, stainless steel tongs, etc.) in the freezer, for acclimation 24 hours before the test day.
    d. Place 3 empty, clean, dry, and labeled thermoses with their lids completely off in the freezer, for acclimation 24 hours before the test day. Label them A, B, and C for triplicates.
    e. Measure carefully, 3 sets of 5g of solid deicer. If the thermos is not dry and at the test temperature, you can temporarily store the sample in a desiccator without desiccant. This would avoid moisture loss from the prewetted salt and would not disturb the prewetting rate of 8 gal/ton. For one test with triplicates, 15 g of salt is required. Use clean weighing dishes, preferably plastic that are flexible and not rigid. The desiccator should only be used if the salts are not going straight to the thermoses (for example, the thermoses are not ready, need to be cleaned, and/or dried, etc.). After the thermoses have acclimated in the freezer (for 24 hrs) then add the solid deicer (5g) in each thermos, immediately after measuring the weight. The prewetted deicer should not touch the walls of the thermos and mostly should drop at the bottom of the thermos. For the non-prewetted salt, extra care is not needed as dried granules of salt will easily reach the bottom without sticking to the walls of the dried thermos. It is easier to add solid salt to the thermos using a flexible weigh dish. A clean plastic funnel can be used to add the solid deicer as well and a soft brush to wipe all the salt into the thermos from the dish and funnel.
2. **Prepare the secondary freezer #2**
    a. Set a temperature of 0°F for another freezer 48 hours before the test day.
    b. Fill the ice cube trays (each cube with 1.3 mL of deionized water (DI)) and place in the freezer set at 0°F. Gently tap the trays after they are placed at the bottom of the freezer to remove any bubbles. Note that at 25°F complete freezing of ice cubes may not occur, therefore, they need to be placed in another freezer at 0°F overnight.

3. Cleaning the test freezer working surfaces before the acclimation process

a. Make sure the bottom working surfaces of the freezers are cleaned (wiped with alcohol) and no contamination is present. In case any ice cubes fall onto the surface, this allows for it to be picked up with tongs and used.

4. On the test day

a. Set up the Rocker

i. Make sure to set the Rocker to the required parameters (Table 16) – tilt angle, rpm, time, etc.

b. Set a timer

i. Make sure to keep the timer ready to be started for either 15 min or 30 minutes of test duration. (Using a laptop allows for easy access to multiple timers at once.) Set and name or label the timers A, B, and C. See the note below to know the specifics when doing the staggering method.

c. Working inside the test freezer – (phase I):

i. Make sure to perform all actions as quickly as possible with minimum errors when working inside the freezer with its door open. Also, keep an eye on the temperature fluctuations inside the freezer by monitoring the digital thermometer placed on the working surface next to sieves and thermoses. Note the temperature fluctuations while working inside the freezer.

ii. Open the freezer and take out ice cubes from the trays by pressing the silicon trays from behind and aiming to drop the cubes directly into the cup. Count the cubes going into the cup. Cups A, B, and C each should be filled with 33 ice cubes. All ice cubes should be fully frozen and in cubical shapes with no broken cubes. Ice cubes can also be removed from the silicon trays and placed into a stainless-steel pan (used with the sieve), for ease of operation and can then be collected with tongs or a spatula and placed in each cup. However, ice cubes sometimes break when they hit metal surfaces, so be careful.

iii. Now take cup A out of the freezer and quickly measure its weight with 33 ice cubes inside it. Make sure to close the freezer door while weighing. Make sure the reading on the scale is stable, not fluctuating when weighing. If weighing takes a long time, condensation and melting of ice cubes could start, which can cause the reading to fluctuate. Use the 5-second rule to weigh each cup. Tare or zero out the balance before weighing each cup.

iv. Immediately after taking the weight of cup A with ice cubes in it, take cup A, open the freezer, and carefully add the ice cubes from cup A into thermos A. You may use an acclimated spatula from inside the freezer to guide the ice cubes into the thermos or carefully bend the Styrofoam cup to create a little spout and then drop the ice cubes into the thermos. After adding all 33 ice cubes to thermos A, firmly secure its lid and take it out of the freezer.

d. Start the rocking

i. Quickly place the thermos over the Rocker and secure it with the rubber bands. Then immediately start the rocking and the timer A.

e. Working inside the test freezer (phase II) and on the weighing balance

i. After adding the first thermos to the Rocker, start measuring the weight of the next batch of ice cubes to be added to Thermos B, by following the steps in 4cii and 4ciii. DO NOT add the ice cubes into the thermos after measuring the weight of cup B with 33 ice cubes in it, rather quickly place cup B in the freezer and close the freezer door. This is because after adding the ice cubes in the thermos the rocking should be started immediately and there could still be some time left before you add the thermos B on the Rocker. Note the staggering time (4 to 6 minutes) using a stopwatch or a secondary timing device. For instance, if you are already using a laptop for rocking timers (A to C), while the Rocker is running for 60 minutes straight; you can use your cell phone to add 6 minutes of staggering time in between adding replicates to the Rocker.

f. Staggering method – adding thermoses B and C while the rocking is ongoing

i. For the staggering method, 4 to 6 minutes after adding the first thermos (A), open the freezer and quickly and gently add the ice cubes from cup B to thermos B. Secure the lid and cover it up. Take it out of the freezer, close the freezer door, and place thermos B on the Rocker which is already rocking. Be careful not to disturb thermos A or slow down the Rocker for more than 1 to 3 seconds. <u>You may need to practice this before the test by using empty thermoses. This is an important step and if not done correctly, could make thermos A fall off the Rocker.</u> DO NOT panic if thermos A falls off, quickly pick it up and put it back on the Rocker while it is still rocking, and then adjust both thermoses (A and B) on the Rocker. In such cases of errors, note the time wasted in all of this (should not be more than 10 seconds) and report it in the data collection sheet. DO NOT forget to start the timer for the second thermos after it is added to the Rocker.

ii. Add the third thermos (C) after 8 to 10 minutes (if the test time is 30 minutes) and after 6 minutes (if the test time is 15 minutes), by using the same procedure as used for thermos B – steps 4ei and 4fi.

<u>NOTE</u>: *Before adding the third thermos to the rocker (when doing the staggering method), it is possible that the timer for the first thermos (A) would go off. In this case, keep an eye on the timer of thermos A, and if it is less than 2 minutes to be completed, do either of the following:*

a. Either decide if you can measure the weight of the third batch of ice cubes in cup C and place it back in the freezer in less than 2 minutes (which you should be, because taking out 33 ice cubes in a cup and then weighing the ice cubes should not take more than 30 to 50 seconds or max. 1 minute). OR,

b. If you think there is not enough time to weigh the third batch of cubes before the timer of thermos A runs out, then wait until timer A goes off and follow steps 4g and 4h. Remember that because you added 4 to 6 minutes in between thermos A and B rocking times, therefore you will have plenty of time to work in the freezer to measure the weight of the third batch of ice cubes and add the third thermos C to the rocker, before the timer B runs out.

g. When thermos A is done rocking, quickly remove the thermos from the Rocker without disturbing thermos B and the Rocker. Open the freezer door, then open the lid of thermos A inside the freezer close to the sieve and pour the contents of the thermos on the sieve. Make sure no ice cubes remain inside the thermos. Quickly collect all the cubes from the sieve and place them in cup AA.

h. Measure the weight of the cup AA. Do not forget to close the freezer door while weighing. Note the weight carefully out to two digits (e.g., 10.03g). Step 4g should not take more than 30 to 40 seconds. Weighing can be done in 5 to 10 seconds if the balance is already turned ON.
i. If thermos C is not already added to the Rocker, add thermos C to the Rocker by following the similar procedure used for thermoses A and B.
j. Repeat the post-rocking steps 4g and 4h for the remaining thermoses B and C.

NOTE: *For the staggering method, the timer on the Rocker needs to be set for at least 60 minutes, for a 15-minute test and when using triplicates. To be safe set the timer for 80 minutes on the Rocker. The Rocker should not stop until the last thermos has been rocked for 15 minutes. For the 30-minute test, the Rocker timer should be set for at least 90 minutes for triplicates.*

TIPS

A. While taking out cubes from the ice cube tray and adding them to the cups, a good estimate can be made on how many cubes have been taken out by understanding the grid of the trays used. For instance, you can outline with Sharpee on the tray 33 ice cubes sections, this can help avoid any mistakes in counting
B. For the staggering method if you are only using one sieve (not advised when using 5 replicates), it is important to look for too much liquid gathering on the grid (wires) of the sieve. Tissue paper, fully acclimated to freezer temperature, can be placed next to the sieve and after pouring the contents from each thermos onto the sieve, can be used to dry the grid (wires). This should be done quickly because the tissue paper rubbing against the sieve wires could become warm due to friction while the freezer door is also open. This prevents the excess liquid from causing ice cubes from subsequent thermoses to melt. When using 5 replicates and dumping the contents of the rocked thermos on a sieve, it is strongly advised to use another set of the sieve with a pan (also acclimated and ready to be used in the test freezer).
C. It is possible that some of the solid salt may get trapped near the mouth of the thermos during the initial few minutes of rocking and may not return to the bottom. Unlike the liquid deicer which always returns to the bottom during the rocking motion. This could lead to dubious results. At the end of the rocking, before emptying the contents of thermos on the sieve, check for any salt inside near the mouth or upper rim of the thermos. If salt crystals were stuck at the mouth of the thermos and not allowed to interact with ice cubes during the test, consider retesting as this can lead to inaccurate results. This should be noted in the data collection sheet.
D. Concentration is key when doing this modified IMC method with the staggering method. Distractions of any kind, like listening to music or talking with mates in the lab, can easily divert your concentration, so please be cautious. Report the results as honestly as possible.

Detailed visual solubility test procedure

1. Carefully prepare the solution for the concentration to be tested and make sure every bit of the salt particles is fully dissolved.

Note that for making solutions higher in concentration (such as 24, 25 and 26 wt. %) more time may be required to dissolve the salt fully. Since the solubility limit of NaCl at room temperature 77°F (25°C) is ~26 wt. %, it may be hard to observe if all the salt is dissolved in the water particularly in solutions already containing other insoluble impurities. Therefore, sufficient time must be given to allow for complete dissolving of the salt at higher concentration solutions. Moreover, the beakers must be sealed with Parafilm during the stirring for longer times (more than 10 minutes), to avoid any evaporation of water because that would alter the concentration.

2. Transfer the solution to a clean transparent glass beaker, preferably a 50 mL beaker.
3. Make sure to have a stem thermometer (calibrated), paper tissues, and a camera ready before placing the beaker in a freezer for cooling.
4. Take a picture of the beaker bottom to show no precipitation in the beaker before cooling.
5. Place the beaker in a freezer set at 23°F (-5°C) and insert the stem thermometer inside the beaker as well and close the freezer door.
6. Keep observing the beaker for any salt precipitates developing while the solution is cooling. To do this observe the beaker bottom by raising it up in your hands while gently shaking the solution in it.
7. Note the temperature when the precipitates appear in the solution at the bottom of the beaker. Precipitates should not be confused with any other minor insoluble impurities in the solution.
8. After the precipitates have been confirmed at any certain temperature, discard the solution. Always use freshly prepared solutions for visual solubility test.
9. This procedure can be done for concentrations ranging between 23 and 26 wt. % for NaCl-based salt solutions.

Note that NaCl has a solubility limit of 26.3 wt. % at room temperature, meaning that it will not be dissolved in water any more than that at temperatures around 20 to 25°F.

Table 16. Testing parameters for modified IMCRT

Constant Parameters	Constant Parameters	Varying Parameters	Varying Parameters
Degree of rocking	10°	Time of rocking	15 min, 30 min
Rocking RPM*	90 rpm	Test temperatures	15°F, 25°F
Ice cube volume	1.3 mL	-	-
Thermos type	Tall	-	-
Thermos placement	Perpendicular to AOR**	-	-

* *RPM is the rotation per minute of the Rocker*

*** AOR is the axis of rotation of the Rocker*

Table 17. Percent impurities in Solid 1 and the actual brine concentration in its solution for 200 mL, 150 mL, and 100 mL solutions.

Solution Volume (mL)	Concentration (wt. %)	Total weight of Solid 1 (g)	Weight of filtered out insoluble impurities (g)	% Impurities	Actual amount of soluble contents (salts*) (g)	Actual approximate brine concentration (wt. %)
200	5%	10.53	0.57	5.42%	9.66	4.61%
200	10%	22.22	1.56	7.02%	20.36	9.24%
200	15%	35.29	3.54	10.03%	31.45	13.59%
150	23%	44.81	5.71	12.74%	38.60	20.46%
100	26%	35.14	5.27	15%	29.37	22.70%

**It is possible that minute quantities of other soluble minerals could also be present in Solid 1, but most of it would be rock salt, NaCl.*

Table 18. Average freezing points of all tested concentrations for FPT of Solid 1 (filtered and unfiltered solutions).

Concentrations (wt. %)	Filtered solutions	Unfiltered solutions
5%	-2.67° C	-2.75 ° C
10%	-5.54° C	-5.56 ° C
15%	-8.78° C	-8.94 ° C
23%	-15.53° C	-16.68 ° C
26%	-18.35° C	-20.83 ° C

Table 19. Average freeing point (°C) of all the tested concentrations (5%, 10%, 15%, 23%, and 26%) for all tested products using ASTM D1177.

	5 (wt. %)	10 (wt. %)	15 (wt. %)	23 (wt. %)	26 (wt. %)
SOLID-1 (Ice Slicer) Unfiltered Replicate 1	-2.86	-5.51	-8.73	-16.58	-21
SOLID-1 (Ice Slicer) Unfiltered Replicate 2	-2.64	-5.61	-9.14	-16.75	-18.06
SOLID-2 (Ice Kicker) Unfiltered Replicate 1	-3.21	-6.53	-11.12	-20.28	-
SOLID-2 (Ice Kicker) Unfiltered Replicate 2	-3.18	-7.02	-11.27	-19.84	-
Prewet Solid-1 (with Beet Heet) Replicate 1	-3.38	-6.67	-12.02	-21.51	-
Prewet Solid-1 (with Beet Heet) Replicate 2	-3.53	-7.16	-11.78	-21.44	-
Prewet Solid-2 (with Beet Juice) Replicate 1	-3.36	-6.66	-11.66	-20.98	-
Prewet Solid-2 (with Beet Juice) Replicate 2	-3.46	-6.86	-11.14	-21.01	-
Prewet Solid-3 (with MMZ) Replicate 1	-3.44	-6.84	-12.02	-21.8	-
Prewet Solid-3 (with MMZ) Replicate 2	-3.2	-6.86	-11.46	-21.84	-
Prewet Solid-4 (with $MgCl_2$ brine) Replicate 1	-3.53	-7.14	-12.02	-21.46	-
Prewet Solid-4 (with $MgCl_2$ brine) Replicate 2	-3.35	-6.85	-12.02	-21.18	-
Prewet Control (with NaCl brine) Replicate 1	-3.62	-6.81	-11.82	-20.97	-
Prewet Control (with NaCl brine) Replicate 2	-3.56	-7.0	-11.47	-21.54	-
Solid Control (NaCl) Replicate 1	-3.57	-7.09	-11.46	-22.06	-
Solid Control (NaCl) Replicate 2	-3.24	-7.11	-11.78	-21.60	-
Reagent Grade NaCl (2021)	-3.38	-6.95	-11.65	-21.98	-

Table 20. Average modified ice melting capacity (IMC) (g/g) of all the tested products using the modified IMC Rocking Test at 15 minutes for all products and 30 minutes for Prewet Control and Solid Control.

	SOLID-1 (Ice Slicer)	**SOLID-2** (Ice Kicker)	**Prewet Solid-1** (with Beet Heet)	**Prewet Solid-2** (with Beet Juice)	**Prewet Solid-3** (with MMZ)	**Prewet Solid-4** (with $MgCl_2$ brine)	**Prewet Control** (with NaCl brine)	**Prewet Control** (with NaCl brine)	**Solid Control** (NaCl)	**Solid Control** (NaCl)
	15 min	**15 min**	**15 min**	**15 min**	**15 min**	**15 min**	**15 min**	**30 min**	**15 min**	**30 min**
15 °F	0.23	0.38	0.35	0.60	0.47	0.49	0.30	0.52	0.38	0.69
25 °F	0.43	0.8	0.69	1.02	0.84	0.94	0.58	1.39	0.67	1.01

Figure 28. Modified IMCRT: a thermometer showing a test temperature (top left), laptop used for timers (top right), high accuracy weighing balance (bottom left), the Rocker and labeled thermos (bottom middle), and Styrofoam cups used and labeled (bottom right)

Figure 29. Linear agitation, ice bath, and data logger setup for FPT (left); salt precipitates in a 24 wt. % solid control solution at 13.4°C (right)

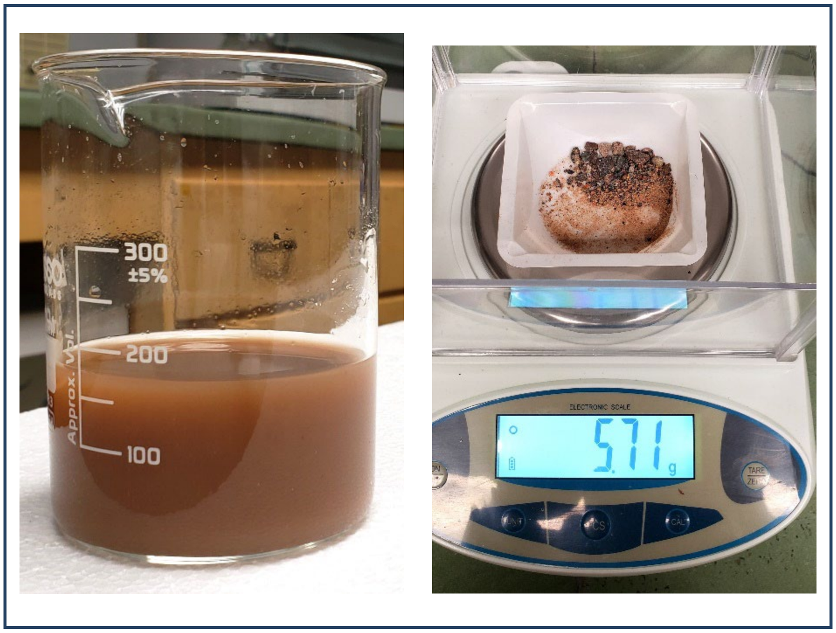

Figure 30. Solid 1 23 wt. % solution, 150 mL and filtered (left); insoluble impurities filtered out of 150 mL 23 wt. % solution of Solid 1, using a 50 micron filter.

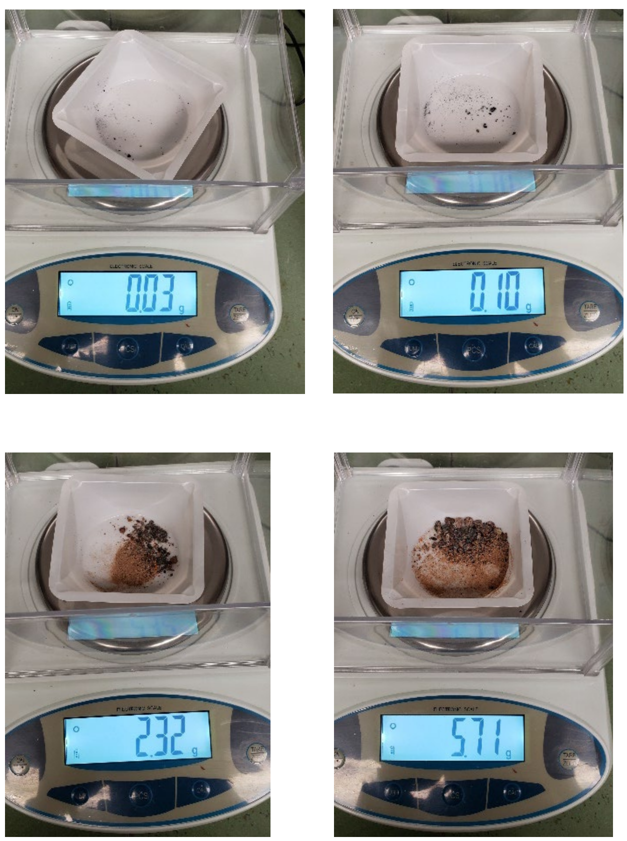

Figure 31. Weight of filtered out impurities: Solid 2, 15% 150 mL solution (top left), Solid 2, 23% 150 mL solution (top right), Solid 1, 15% 150 mL solution (bottom left), Solid 1, 23% 150 mL solution (bottom right)

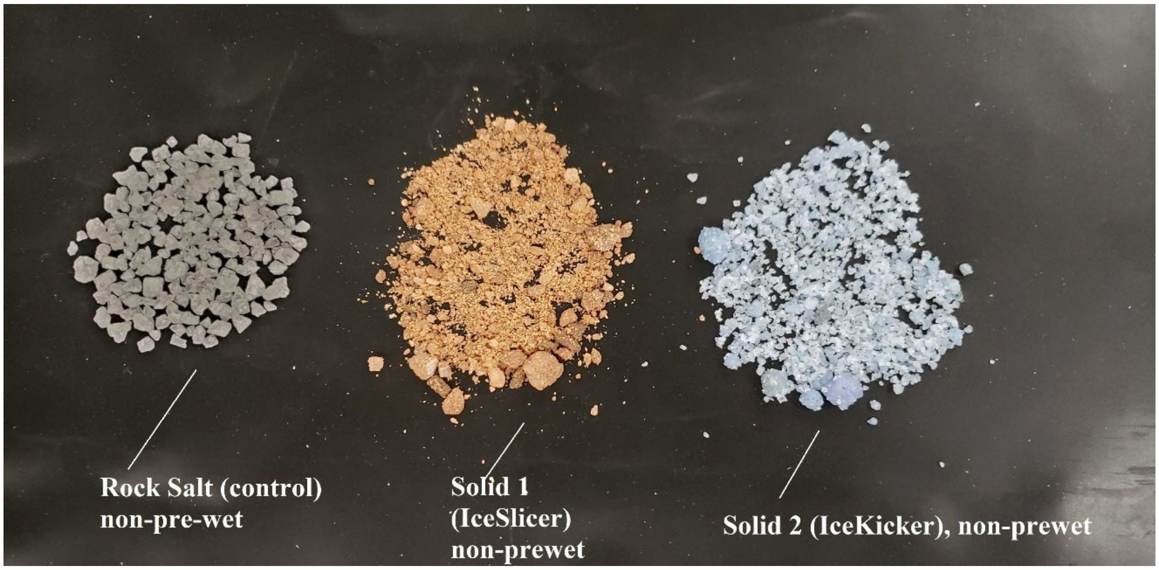

Figure 32. Solid salt samples: Solid control – rock salt (left), Solid 1 – Ice Slicer (middle), and Solid 2 – IceKicker (right); showing variation in gradation, particle size distribution.

APPENDIX C - FRICTION TESTING ADDITIONAL DATA AND STATISTICAL ANALYSIS RESULTS

Table 21. Coefficient of friction data at 30°F.

	Bare	Minutes after Deicer Application			
Deicer Test	0	15	30	45	60
1a-a1	0.78	0.43	0.64	0.61	0.66
1b-a1	0.97	0.35	0.82	0.78	0.75
1c-a1	1.03	0.53	0.80	0.77	0.75
1d-a1	0.89	0.49	0.55	0.56	0.65
1e-a1	0.74	0.43	0.46	0.54	0.66
1f-a1	0.83	0.45	0.70	0.70	0.67
1g-a1	0.81	0.33	0.49	0.55	0.56
1h-a1	0.75	0.55	0.64	0.55	0.65
1a-c1	0.72	0.40	0.64	0.55	0.55
1b-c1	0.73	0.35	0.74	0.54	0.56
1c-c1	0.73	0.31	0.69	0.60	0.51
1d-c1	0.62	0.24	0.67	0.51	0.55
1e-c1	0.66	0.24	0.69	0.46	0.54
1f-c1	0.68	0.36	0.65	0.42	0.47
1g-c1	0.63	0.30	0.54	0.45	0.54
1h-c1	0.68	0.26	0.57	0.48	0.49
2a-a1	1.08	0.26	0.42	0.62	0.76
2b-a1	1.08	0.34	0.39	0.70	0.72
2c-a1	1.11	0.48	0.42	0.75	0.80
2d-a1	1.11	0.20	0.27	0.52	0.60
2e-a1	0.91	0.32	0.25	0.48	0.64
2f-a1	0.95	0.33	0.21	0.67	0.69
2g-a1	0.89	0.29	0.32	0.52	0.58
2h-a1	0.94	0.22	0.34	0.56	0.65
2a-c1	0.77	0.15	0.22	0.51	0.62
2b-c1	0.74	0.24	0.36	0.48	0.63
2c-c1	0.78	0.18	0.22	0.49	0.72
2d-c1	0.73	0.15	0.14	0.35	0.53
2e-c1	0.71	0.19	0.21	0.40	0.55
2f-c1	0.70	0.13	0.25	0.37	0.56
2g-c1	0.63	0.10	0.12	0.37	0.51
2h-c1	0.74	0.16	0.25	0.40	0.52
3a-a1	0.98	0.34	0.28	0.55	0.62
3b-a1	0.99	0.50	0.41	0.76	0.83
3c-a1	1.10	0.49	0.44	0.71	0.75
3d-a1	1.09	0.31	0.23	0.50	0.68
3e-a1	0.89	0.40	0.30	0.65	0.71
3f-a1	0.99	0.36	0.52	0.76	0.69
3g-a1	0.83	0.37	0.27	0.59	0.60
3h-a1	1.00	0.40	0.41	0.61	0.59
3a-c1	0.71	0.42	0.27	0.82	0.79
3b-c1	0.80	0.36	0.33	0.73	0.70
3c-c1	0.79	0.55	0.44	0.77	0.78
3d-c1	0.81	0.35	0.36	0.72	0.75
3e-c1	0.81	0.28	0.41	0.75	0.68
3f-c1	0.82	0.59	0.52	0.77	0.81
3g-c1	0.80	0.24	0.31	0.70	0.64
3h-c1	0.80	0.37	0.40	0.87	0.74
4a-a1	1.03	0.90	0.68	0.65	0.66
4b-a1	1.07	0.99	0.79	0.69	0.69
4c-a1	1.07	0.89	0.74	0.71	0.64
4d-a1	1.20	0.97	0.56	0.54	0.60
4e-a1	1.05	0.93	0.59	0.54	0.58
4f-a1	1.10	0.94	0.76	0.69	0.66
4g-a1	0.94	0.88	0.61	0.49	0.57
4h-a1	0.99	0.90	0.67	0.54	0.54
4a-c1	0.86	0.74	0.63	0.70	0.64
4b-c1	0.85	0.71	0.72	0.79	0.67
4c-c1	0.76	0.68	0.64	0.70	0.60
4c-c1	0.81	0.74	0.64	0.62	0.61
4e-c1	0.95	0.61	0.59	0.70	0.65
4f-c1	0.82	0.63	0.54	0.59	0.62
4g-c1	0.84	0.70	0.64	0.67	0.69
4h-c1	0.84	0.71	0.66	0.65	0.67

	Bare	Minutes after Deicer Application			
Deicer Test	0	15	30	45	60
5a-a2	1.00	1.01	0.75	0.63	0.65
5b-a2	1.04	0.87	0.67	0.59	0.66
5c-a2	1.00	0.92	0.77	0.65	0.62
5d-a2	1.06	0.88	0.62	0.58	0.68
5e-a2	0.96	0.90	0.68	0.59	0.64
5f-a2	1.08	0.87	0.69	0.59	0.68
5g-a2	0.99	0.94	0.62	0.52	0.57
5h-a2	1.05	1.01	0.72	0.56	0.58
5a-c2	0.79	0.80	0.68	0.76	0.62
5b-c2	0.80	0.71	0.57	0.62	0.59
5c-c2	0.82	0.70	0.61	0.59	0.62
5d-c2	0.95	0.82	0.72	0.60	0.61
5e-c2	0.88	0.82	0.62	0.55	0.61
5f-c2	0.80	0.83	0.61	0.57	0.60
5g-c2	0.78	0.66	0.61	0.61	0.63
5h-c2	0.71	0.71	0.58	0.62	0.63
6a-a2	0.89	0.42	0.32	0.67	0.82
6b-a2	0.96	0.26	0.27	0.59	0.81
6c-a2	1.03	0.35	0.24	0.64	0.67
6d-a2	0.90	0.34	0.32	0.57	0.67
6e-a2	0.94	0.33	0.24	0.61	0.64
6f-a2	0.94	0.37	0.23	0.64	0.59
6g-a2	0.83	0.23	0.24	0.44	0.70
6h-a2	0.93	0.40	0.29	0.50	0.56
6a-c2	0.91	0.28	0.45	0.81	0.68
6b-c2	0.79	0.31	0.29	0.79	0.72
6c-c2	0.85	0.53	0.32	0.79	0.70
6d-c2	0.80	0.43	0.49	0.81	0.84
6e-c2	0.73	0.32	0.28	0.76	0.70
6f-c2	0.75	0.38	0.28	0.72	0.63
6g-c2	0.76	0.38	0.25	0.69	0.66
6h-c2	0.76	0.27	0.22	0.73	0.67
7a-a2	0.92	0.41	0.29	0.59	0.64
7b-a2	0.99	0.38	0.32	0.53	0.66
7c-a2	0.95	0.43	0.41	0.60	0.67
7d-a2	0.98	0.43	0.32	0.46	0.55
7e-a2	0.88	0.41	0.35	0.53	0.57
7f-a2	0.97	0.38	0.38	0.59	0.61
7g-a2	0.87	0.35	0.30	0.50	0.54
7h-a2	0.93	0.21	0.32	0.48	0.56
7a-c2	0.75	0.23	0.35	0.66	0.71
7b-c2	0.72	0.22	0.25	0.59	0.61
7c-c2	0.83	0.34	0.34	0.74	0.81
7d-c2	0.75	0.20	0.51	0.66	0.78
7e-c2	0.68	0.33	0.36	0.59	0.59
7f-c2	0.69	0.23	0.33	0.55	0.71
7g-c2	0.64	0.33	0.26	0.57	0.59
7h-c2	0.72	0.28	0.38	0.57	0.69
8a-a2	0.80	0.27	0.65	0.46	0.61
8b-a2	0.86	0.43	0.69	0.51	0.59
8c-a2	1.04	0.42	0.75	0.67	0.61
8d-a2	0.93	0.39	0.59	0.48	0.55
8e-a2	0.85	0.22	0.67	0.63	0.57
8f-a2	0.98	0.47	0.73	0.62	0.65
8g-a2	0.71	0.36	0.38	0.43	0.54
8h-a2	0.81	0.41	0.56	0.57	0.51
8a-c2	0.67	0.33	0.61	0.51	0.52
8b-c2	0.63	0.39	0.55	0.50	0.55
8c-c2	0.60	0.40	0.55	0.49	0.52
8d-c2	0.68	0.32	0.66	0.49	0.53
8e-c2	0.61	0.34	0.53	0.52	0.48
8f-c2	0.65	0.28	0.55	0.51	0.48
8g-c2	0.66	0.39	0.57	0.43	0.45
8h-c2	0.65	0.31	0.50	0.50	0.55

Table 22. Coefficient of friction data at 15°F.

	Bare	Minutes after Deicer Application			
Deicer Test	0	15	30	45	60
1a-a1	0.99	0.56	0.55	0.23	0.52
1b-a1	1.10	0.56	0.57	0.24	0.72
1c-a1	0.98	0.61	0.62	0.19	0.71
1d-a1	0.93	0.47	0.47	0.20	0.59
1e-a1	0.97	0.48	0.52	0.15	0.57
1f-a1	0.87	0.48	0.61	0.29	0.58
1g-a1	0.90	0.58	0.56	0.20	0.55
1h-a1	1.01	0.55	0.50	0.16	0.49
1a-c1	0.70	0.58	0.61	0.17	0.59
1b-c1	0.74	0.59	0.59	0.26	0.56
1c-c1	0.80	0.53	0.47	0.16	0.58
1d-c1	0.69	0.44	0.54	0.24	0.47
1e-c1	0.73	0.45	0.41	0.18	0.47
1f-c1	0.71	0.54	0.43	0.33	0.47
1g-c1	0.69	0.54	0.36	0.19	0.46
1h-c1	0.71	0.55	0.44	0.23	0.52
2a-a1	0.97	0.75	0.34	0.58	0.61
2b-a1	1.07	0.73	0.30	0.67	0.69
2c-a1	0.91	0.63	0.26	0.62	0.52
2d-a1	0.96	0.62	0.13	0.49	0.55
2e-a1	1.02	0.67	0.19	0.38	0.56
2f-a1	1.00	0.71	0.42	0.70	0.64
2g-a1	0.90	0.71	0.30	0.47	0.51
2h-a1	1.02	0.64	0.28	0.47	0.60
2a-c1	0.80	0.56	0.31	0.65	0.61
2b-c1	0.73	0.49	0.15	0.63	0.58
2c-c1	0.83	0.41	0.21	0.62	0.68
2d-c1	0.73	0.46	0.20	0.53	0.55
2e-c1	0.80	0.50	0.23	0.50	0.48
2f-c1	0.84	0.51	0.26	0.56	0.56
2g-c1	0.74	0.42	0.18	0.50	0.67
2h-c1	0.76	0.38	0.23	0.59	0.56
3a-a1	1.03	0.73	0.51	0.40	0.48
3b-a1	0.99	0.72	0.57	0.57	0.61
3c-a1	0.88	0.73	0.57	0.64	0.64
3d-a1	0.95	0.72	0.46	0.48	0.57
3e-a1	0.88	0.71	0.56	0.60	0.56
3f-a1	0.92	0.72	0.68	0.69	0.64
3g-a1	0.87	0.69	0.56	0.60	0.55
3h-a1	0.93	0.67	0.53	0.39	0.43
3a-c1	0.61	0.68	0.68	0.60	0.66
3b-c1	0.68	0.69	0.69	0.57	0.72
3c-c1	0.73	0.73	0.62	0.64	0.76
3d-c1	0.65	0.54	0.54	0.60	0.63
3e-c1	0.62	0.56	0.60	0.46	0.58
3f-c1	0.66	0.56	0.53	0.52	0.76
3g-c1	0.67	0.60	0.49	0.60	0.74
3h-c1	0.64	0.60	0.57	0.60	0.80
4a-a1	0.85	0.56	0.27	0.26	0.54
4b-a1	0.98	0.67	0.28	0.21	0.67
4c-a1	0.94	0.70	0.37	0.23	0.64
4d-a1	0.94	0.70	0.26	0.27	0.60
4e-a1	0.85	0.58	0.21	0.25	0.58
4f-a1	0.83	0.71	0.29	0.34	0.50
4g-a1	0.97	0.66	0.25	0.21	0.57
4h-a1	0.93	0.66	0.25	0.20	0.60
4a-c1	0.71	0.67	0.17	0.37	0.68
4b-c1	0.67	0.70	0.26	0.32	0.59
4c-c1	0.79	0.65	0.28	0.36	0.69
4d-c1	0.68	0.54	0.24	0.26	0.56
4e-c1	0.64	0.62	0.25	0.29	0.63
4f-c1	0.68	0.55	0.26	0.26	0.63
4g-c1	0.62	0.63	0.18	0.28	0.69
4h-c1	0.66	0.59	0.31	0.19	0.55

	Bare	Minutes after Deicer Application			
Deicer Test	0	15	30	45	60
5a-a2	0.99	0.72	0.55	0.32	0.67
5b-a2	0.95	0.66	0.58	0.21	0.55
5c-a2	1.06	0.67	0.69	0.25	0.72
5d-a2	0.94	0.63	0.52	0.24	0.64
5e-a2	0.86	0.52	0.50	0.20	0.54
5f-a2	0.92	0.64	0.58	0.21	0.58
5g-a2	0.88	0.63	0.53	0.25	0.54
5h-a2	0.88	0.60	0.53	0.21	0.49
5a-c2	0.72	0.64	0.68	0.30	0.67
5b-c2	0.78	0.51	0.59	0.24	0.49
5c-c2	0.66	0.56	0.67	0.32	0.66
5d-c2	0.67	0.62	0.58	0.36	0.69
5e-c2	0.74	0.52	0.55	0.26	0.52
5f-c2	0.66	0.64	0.60	0.24	0.69
5g-c2	0.67	0.69	0.62	0.26	0.60
5h-c2	0.65	0.57	0.53	0.22	0.52
6a-a2	0.91	0.76	0.36	0.52	0.62
6b-a2	0.97	0.75	0.22	0.60	0.65
6c-a2	1.09	0.86	0.41	0.63	0.73
6d-a2	0.95	0.76	0.21	0.51	0.62
6e-a2	0.98	0.69	0.22	0.46	0.60
6f-a2	0.99	0.76	0.28	0.67	0.65
6g-a2	0.97	0.74	0.20	0.44	0.50
6h-a2	0.99	0.72	0.21	0.57	0.64
6a-c2	0.87	0.50	0.31	0.68	0.73
6b-c2	0.72	0.43	0.17	0.50	0.61
6c-c2	0.79	0.44	0.18	0.67	0.57
6d-c2	0.79	0.32	0.23	0.57	0.59
6e-c2	0.74	0.48	0.26	0.50	0.58
6f-c2	0.78	0.55	0.20	0.61	0.69
6g-c2	0.88	0.50	0.19	0.63	0.69
6h-c2	0.77	0.41	0.18	0.51	0.59
7a-a2	0.82	0.77	0.50	0.58	0.58
7b-a2	0.97	0.63	0.42	0.56	0.60
7c-a2	0.93	0.72	0.63	0.67	0.68
7d-a2	0.94	0.53	0.53	0.51	0.58
7e-a2	0.88	0.62	0.56	0.55	0.66
7f-a2	0.93	0.66	0.56	0.45	0.56
7g-a2	0.84	0.72	0.49	0.42	0.47
7h-a2	0.82	0.66	0.52	0.50	0.60
7a-c1	0.66	0.73	0.44	0.44	0.52
7b-c1	0.61	0.75	0.50	0.49	0.50
7c-c1	0.65	0.59	0.52	0.52	0.49
7c-c1	0.65	0.64	0.46	0.52	0.49
7e-c1	0.65	0.62	0.53	0.46	0.45
7f-c1	0.62	0.64	0.52	0.48	0.47
7g-c1	0.63	0.63	0.47	0.49	0.43
7h-c1	0.67	0.63	0.53	0.47	0.49
8a-a2	0.84	0.67	0.32	0.27	0.65
8b-a2	0.95	0.56	0.30	0.26	0.55
8c-a2	1.00	0.77	0.26	0.31	0.70
8d-a2	0.95	0.69	0.19	0.23	0.45
8e-a2	0.88	0.61	0.32	0.29	0.55
8f-a2	0.93	0.66	0.36	0.20	0.68
8g-a2	0.80	0.63	0.19	0.18	0.42
8h-a2	0.87	0.66	0.27	0.20	0.49
8a-c2	0.61	0.64	0.39	0.29	0.78
8b-c2	0.67	0.61	0.27	0.17	0.73
8c-c2	0.63	0.62	0.28	0.35	0.77
8d-c2	0.58	0.54	0.25	0.41	0.76
8e-c2	0.69	0.57	0.39	0.31	0.60
8f-c2	0.62	0.57	0.30	0.32	0.61
8g-c2	0.63	0.61	0.24	0.23	0.62
8h-c2	0.64	0.54	0.34	0.23	0.58

ANOVA Analysis of Friction Data

To statistically compare the differences between key groups [Solid control (marked as 1) vs. Solid 2 (marked as 3) and Prewet control (marked as 4) vs. prewet 4 (marked as 8)], the fourth-degree polynomial was employed to fit the friction data against test time (Figure 33). A one-way analysis of variance (ANOVA) was then conducted to compare the linear and constant coefficients, allowing for the assessment of the significance of the differences between these groups (Table 23).

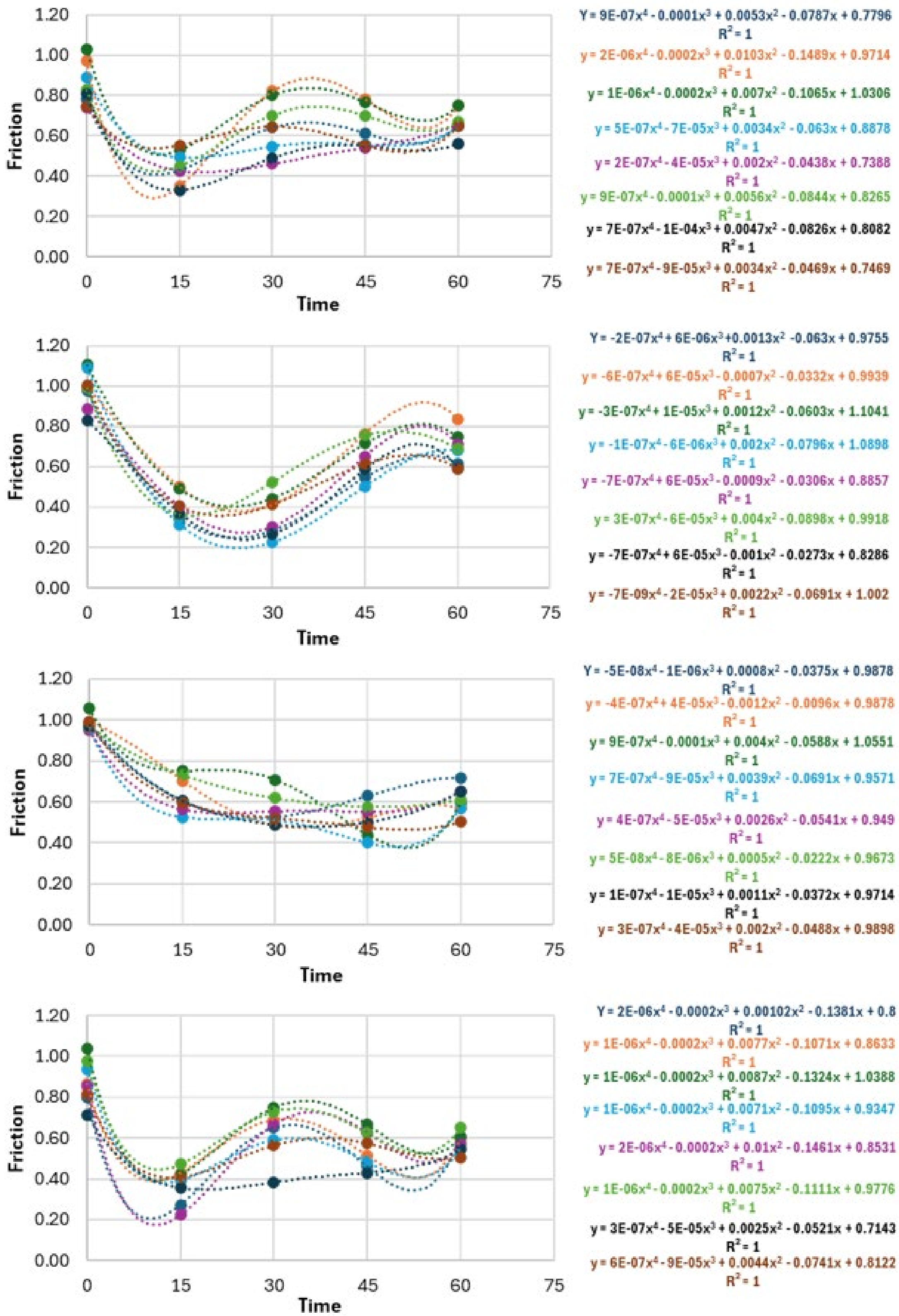

Figure 33. Fourth-degree polynomial fitting for Solid control (1-a1), Solid 2 (3-a1), Prewet control (4-a2), prewet 4 (8-a2) treatment on Asphalt surface.

The linear and constant coefficients are summarized in Table 23, while the p-values and the significance of differences from the paired comparisons are presented in Tables 24 and Table 25, respectively.

Table 23. The linear and constant coefficients of fourth-degree polynomial models for selected key groups.

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
1-a1 at 15min	-0.0861	0.9939	1-c1 at 15min	-0.0598	0.7
1-a1 at 15min	-0.1081	1.098	1-c1 at 15min	-0.0486	0.7367
1-a1 at 15min	-0.0937	0.9816	1-c1 at 15min	-0.0597	0.8
1-a1 at 15min	-0.0885	0.9265	1-c1 at 15min	-0.0743	0.6878
1-a1 at 15min	-0.1072	0.9714	1-c1 at 15min	-0.0541	0.7265
1-a1 at 15min	-0.0991	0.8735	1-c1 at 15min	-0.018	0.7102
1-a1 at 15min	-0.0741	0.9041	1-c1 at 15min	-0.0157	0.6878
1-a1 at 15min	-0.0885	1.0122	1-c1 at 15min	-0.0293	0.7102
3-a1 at	-0.0225	1.0286	3-c1 at	0.0043	0.6082

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
15min			15min		
3-a1 at 15min	-0.0187	0.9918	3-c1 at 15min	0.0086	0.6776
3-a1 at 15min	0.0052	0.8796	3-c1 at 15min	0.0134	0.7327
3-a1 at 15min	0.0034	0.949	3-c1 at 15min	-0.011	0.6531
3-a1 at 15min	-0.0023	0.8837	3-c1 at 15min	-0.0265	0.6163
3-a1 at 15min	-0.02	0.9204	3-c1 at 15min	-0.015	0.6571
3-a1 at 15min	-0.0057	0.8714	3-c1 at 15min	0.0103	0.6714
3-a1 at 15min	-0.00297	0.9347	3-c1 at 15min	-0.0024	0.6429
4-a2 at 15min	-0.0375	0.9878	4-c2 at 15min	-0.0049	0.8796

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
4-a2 at 15min	-0.0096	0.9879	4-c2 at 15min	-0.0015	0.8653
4-a2 at 15min	-0.0588	1.0551	4-c2 at 15min	0.0008	0.6796
4-a2 at 15min	-0.0691	0.9571	4-c2 at 15min	0.0102	0.6816
4-a2 at 15min	-0.0541	0.949	4-c2 at 15min	0.0119	0.7633
4-a2 at 15min	-0.0222	0.9673	4-c2 at 15min	0.027	0.7204
4-a2 at 15min	-0.0372	0.9714	4-c2 at 15min	-0.003	0.7469
4-a2 at 15min	-0.0488	0.9898	4-c2 at 15min	-0.0237	0.7653
8-a2 at 15min	-0.1381	0.8	8-c2 at 15min	-0.0907	0.6694
8-a2 at	-0.1071	0.8633	8-c2 at	-0.059	0.6286

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
15min			15min		
8-a2 at 15min	-0.1324	1.0388	8-c2 at 15min	-0.1075	0.6776
8-a2 at 15min	-0.1095	0.9347	8-c2 at 15min	-0.0525	0.602
8-a2 at 15min	-0.1461	0.8531	8-c2 at 15min	-0.0615	0.6122
8-a2 at 15min	-0.1111	0.9776	8-c2 at 15min	-0.0892	0.649
8-a2 at 15min	-0.0521	0.7143	8-c2 at 15min	-0.0705	0.6571
8-a2 at 15min	-0.0741	0.8122	8-c2 at 15min	-0.0717	0.6469
1-a1 at 30min	-0.0787	0.7796	1-c1 at 30min	-0.081	0.7163
1-a1 at 30min	-0.1489	0.9714	1-c1 at 30min	-0.1177	0.7327

Effects of Additives in Deicing Salts at Lower Temperatures

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
1-a1 at 30min	-0.1065	1.0306	1-c1 at 30min	-0.1115	0.7286
1-a1 at 30min	-0.063	0.8878	1-c1 at 30min	-0.119	0.6245
1-a1 at 30min	-0.0438	0.7388	1-c1 at 30min	-0.1326	0.8671
1-a1 at 30min	-0.0844	0.8265	1-c1 at 30min	-0.0988	0.6816
1-a1 at 30min	-0.0826	0.8082	1-c1 at 30min	-0.0832	0.6286
1-a1 at 30min	-0.0469	0.7469	1-c1 at 30min	-0.1045	0.6816
3-a1 at 30min	-0.063	0.9855	3-c1 at 30min	0.0208	0.7122
3-a1 at 30min	-0.0332	0.9939	3-c1 at 30min	-0.0282	0.8
3-a1 at	-0.0603	1.1041	3-c1 at	0.0025	0.7878

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
30min			30min		
3-a1 at 30min	-0.0796	1.0898	3-c1 at 30min	-0.0379	0.8061
3-a1 at 30min	-0.0306	0.8857	3-c1 at 30min	-0.0653	0.8122
3-a1 at 30min	-0.0898	0.9918	3-c1 at 30min	-0.0048	0.8204
3-a1 at 30min	-0.0273	0.8286	3-c1 at 30min	-0.0577	0.8
3-a1 at 30min	-0.0691	1.002	3-c1 at 30min	-0.0298	0.8041
4-a2 at 30min	-0.0375	0.9878	4-c2 at 30min	-0.0049	0.8796
4-a2 at 30min	-0.0096	0.9879	4-c2 at 30min	-0.0015	0.8653
4-a2 at 30min	-0.0588	1.0551	4-c2 at 30min	0.0008	0.6796

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
4-a2 at 30min	-0.0691	0.9571	4-c2 at 30min	0.0102	0.6816
4-a2 at 30min	-0.0541	0.949	4-c2 at 30min	0.0119	0.7633
4-a2 at 30min	-0.0222	0.9673	4-c2 at 30min	0.027	0.7204
4-a2 at 30min	-0.0372	0.9714	4-c2 at 30min	-0.003	0.7469
4-a2 at 30min	-0.0488	0.9898	4-c2 at 30min	-0.0237	0.7653
8-a2 at 30min	-0.1381	0.8	8-c2 at 30min	-0.0907	0.6694
8-a2 at 30min	-0.1071	0.8633	8-c2 at 30min	-0.059	0.6286
8-a2 at 30min	-0.1324	1.0388	8-c2 at 30min	-0.1075	0.6776
8-a2 at	-0.1095	0.9347	8-c2 at	-0.0525	0.602

Group	Liner coef.	Constant coef.	Group	Liner coef.	Constant coef.
30min			30min		
8-a2 at 30min	-0.1461	0.8531	8-c2 at 30min	-0.0615	0.6122
8-a2 at 30min	-0.1111	0.9776	8-c2 at 30min	-0.0892	0.649
8-a2 at 30min	-0.0521	0.7143	8-c2 at 30min	-0.0705	0.6571
8-a2 at 30min	-0.0741	0.8122	8-c2 at 30min	-0.0717	0.6469

Table 24. P-value and significance of difference from paired comparisons at fixed time via ANOVA.

Groups	1-a1 vs. 3-a1	1-c1 vs. 3-c1	4-a1 vs. 8-a2	4-c1 vs. 8-c2
Linear coef. at 15min	4.08652E-10 (Significant)	0.000341919 (Significant)	0.000192528 (Significant)	2.80181E-07 (Significant)
Const. coef. at 15min	0.254451458 (Not significant)	0.005194062 (Significant)	0.014032379 (Significant)	0.000818016 (Significant)
Summary	Significant	Significant	Significant	Significant
Linear coef. at 30min	0.107617039 (Not significant)	1.16332E-05 (Significant)	0.000192528 (Significant)	2.80181E-07 (Significant)
Const. coef. at 15min	0.015969478 (Significant)	0.012191945 (Significant)	0.014032379 (Significant)	0.000818016 (Significant)
Summary	Significant	Significant	Significant	Significant

Table 25. P-value and significance of difference of selected group from different time via ANOVA.

Groups	1-a1	1-c1	3-a1	3-c1	4-a2	4-c2	8-a2	8-c2
Linear coef. At 15 vs. 30	0.3888 (Not sig.)	2.38E-5 (Sig.)	0.0001 (Sig.)	0.0700 (Not sig.)	0.0001 (Sig.)	0.0030 (Sig.)	9.02E-7 (Sig.)	4.54E-8 (Sig.)
Constant coef. At 15 vs. 30	0.0173 (Sig.)	0.6888 (Not sig.)	0.1895 (Not sig.)	3.27E-6 (Sig.)	0.0086 (Sig.)	0.0215 (Sig.)	0.5439 (Not sig.)	0.5537 (Not sig.)
Summary	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.

As summarized from Table 24 and Table 25 at various periods, even with the same treatment method, the results are significantly different. Conversely, different treatment methods yield significantly different effects under similar conditions.

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