Correlating Lab Testing and Field Performance for Deicing and Anti-icing Chemicals (Phase I)

Western Transportation Institute, Montana State University

CLEAR ROADS

research for winter highway maintenance

Project 0092-10-17/CR09-01
August 2010

Pooled Fund #TPF-5(092)
www.clearroads.org

Correlating Lab Testing and Field Performance for Deicing and Anti-icing Chemicals (Phase 1):

Final Report

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the Clear Roads Program

Date: August 31, 2010

Notice

This research was funded by the Wisconsin Department of Transportation (WisDOT) and the United States Department of Transportation (USDOT) under pooled fund TPF-5(092), WisDOT Project #0092-10-17, and Clear Roads Project CR 09-01. The information reported is the result of research done under the auspices of the Department and the Clear Roads pooled fund research program.

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Acknowledgement

We extend our sincere appreciation to the practitioners and scientists who took the time to participate in the interviews we conducted for this project. The participation of the members of the Clear Roads Technical Advisory Subcommittee during the conference calls is also greatly appreciated, and especially Colleen Bos of CTC & Associates for ensuring broad participation of Clear Roads member states.

1. Report No.	2. Government Accession No	3. Recipient's Catalog No
4. Title and Subtitle Correlating Lab Testing and Field Performance for Deicing and Anti-icing Chemicals (Phase 1)		5. Report Date August 2010 6. Performing Organization Code
7. Authors Laura Fay*, Michelle Akin, Shaowei Wang, Xianming Shi, Dan Williams		8. Performing Organization Report No.
9. Performing Organization Name and Address Western Transportation Institute Montana State University PO Box 174250, Bozeman, MT 59717		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Research and Library Unit Wisconsin Department of Transportation 4802 Sheboygan Ave Room 104 Madison, WI 537070		13. Type of Report and Period Covered Final Report, 3/15/10–8/31/2010 14. Sponsoring Agency Code
15. Supplementary Notes * Principal Investigator (Email: laura.fay@coe.montana.edu)		

16. Abstract

Laboratory tests are often used to evaluate deicer performance, but they have been shown to correlate poorly to actual field performance. This report provides a comprehensive review of literature related to laboratory and field testing of deicers, from deicer performance to friction. Laboratory testing has ranged from simple experiments with few parameters to more complex tests that mimic plowing, pavement type, and a range of temperatures. However, a laboratory experiment that would be expected to correlate well to deicer field performance was not found. Additionally, equipment used to measure friction in a laboratory was very different than the large-scale, high speed devices used in the field. Finally, the state of practice regarding friction measurements in the aviation transportation sector may be de-emphasized in light of complications posed by reliability, repeatability, time-stability, and correlation to aircraft braking performance. After reviewing the literature and interviewing 13 experts with extensive experience testing deicers and measuring friction, the following recommendations were made. Melting rate should be measured. The parameters that should be included in the laboratory test are: air temperature, pavement temperature, relative humidity, pavement type, and uniform snow/ice. Traffic and a plowing mechanism should also be included. Finally, two or three ways to measure friction should be tried in the early stages to ensure reliable measurements for a variety of conditions.

17. Key Words	18. Distribution Statement
Winter maintenance, deicer performance, friction, lab testing, field testing, deicing chemicals, deicer, Differential Scanning Calorimetry (DSC), SHRP ice melting test, Shear and Disbondment tests	No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield VA 22161

18. Security Classif.(of this report)	19. Security Classif. (of this page)	20. No. of Pages	21. Price
Unclassified	Unclassified	106	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Executive Summary

Laboratory tests are often used to evaluate deicer performance, but results have been shown to poorly correlate with field performance. This report provides a comprehensive review of literature related to laboratory and field testing deicer performance, including shear and disbondment testing, friction, the state of practice in aviation, and provides recommendations for design of future research to correlate laboratory and field deicer performance.

The literature review provided information on laboratory and field testing of deicer performance. Laboratory testing of deicer performance has ranged from simple experiments testing only a few parameters to more complex tests that mimic plowing, pavement type, and a range of temperatures. Laboratory methods that report on the shear and disbondment of deicers under varying parameters were discussed and provided insight on incorporation of a plowing mechanism in laboratory testing. However, a laboratory experiment that would be expected to correlate well to deicer field performance was not found.

Equipment used to measure friction in the laboratory and field was discussed. Laboratory equipment used to measure friction was found to be very different from the large-scale, high speed devices used in the field. Correlation between friction measurements in the laboratory and field are poorly correlated, and this may be due to the use of different equipment in the different environments. The state of practice of friction measurements in the aviation transportation sector were discussed and in light of complications posed by reliability, repeatability, time-stability, and correlation to aircraft braking performance, the use of friction measurements may be de-emphasized.

Interviews of experts with extensive experience testing deicer performance and measuring friction were conducted to provide supplemental information to the literature review and to provide insight on how to design a laboratory experiment that will correlate with field deicer performance. The following recommendations were made based on information from the literature review and interviews. Initially testing the melting rate of deicers is recommended as a performance measure with either the SHRP test method or the DSC. The parameters that should be included in the laboratory test are: air temperature, pavement temperature, relative humidity, pavement type, and uniform snow/ice. Trafficking of samples should be conducted, with testing occurring at reasonable and similar speeds in the laboratory and field, ideally at multiple speeds in both environments. A plowing mechanism should also be incorporated. Finally, two or three ways to measure friction should be tried in the early stages to ensure reliable measurements for a variety of conditions and the same equipment should be used in both the lab and field tests.

Introduction

While laboratory and field studies have been conducted to evaluate the performance of deicing and anti-icing products and their resulting friction coefficient of treated pavement, it has proven to be difficult to relate laboratory results to actual field performance. Laboratory testing has been used extensively to quantify deicer or anti-icer performance because of the ease and low cost with which it can be done and the relatively high reproducibility and transferability of results. However, such testing generally has ignored variables such as variations in pavement type, temperature, wind, dynamic traffic, etc., or has held them constant. Field testing is desirable in the effort to provide useful guidance for winter maintenance practitioners. Yet it can be costly and difficult to reproduce because of ever-changing conditions in the field environment where some variables are difficult to control or even to document. In this context, laboratory and field experiments need to be carefully designed to encompass all relevant variables so that better correlations can be developed.

While there are test methods that quantify deicer or anti-icer performance in the laboratory setting, results often do not translate to the field performance. At this point in time, there is no laboratory test method for deicing or anti-icing performance and friction coefficient available that directly correlates with the performance and friction of deicer products in the field. As such, the existing laboratory tests can only provide a baseline to contrast various products under well-controlled conditions and the findings derived from such tests need to be used with caution.

The goal of this project was to utilize previous research to provide guidance on developing a laboratory test, tool or methodology that will quantify deicer and anti-icer performance and friction coefficient on pavement and correlate with results from the field. To accomplish this in Task 1 a literature review was conducted to provide direction for the design of laboratory and field tests. The objective of the literature review was to identify existing laboratory and field test methods for evaluating deicers and/or anti-icers (both referred to as deicers from this point forward) performance and pavement friction coefficient, and to provide guidance on which test methods may be used to develop a direct correlation. In Task 2 key individuals or experts identified in Task 1 were interviewed for additional information on previously conducted laboratory and field research, project costs, equipment design and cost, and important parameters and performance characteristics to consider. Based on information gathered in the literature review and interviews recommendations have been made on meteorological parameters and performance characteristics to consider in laboratory and field testing as well as tools, equipment and methodologies to consider in future phases of this research.

Test Methods to Characterize Deicer Performance

Deicer Performance

Deicer performance can be described in several ways, such as

- melting and penetration ability (when used as a reactive strategy),
- anti-bonding ability (when used as a proactive strategy),
- time until bare pavement is achieved,
- persistence on the road,
- relative performance as compared with other products.

It is crucial to develop a working definition of deicer performance based on your needs prior to conducting laboratory and field research. By identifying the performance goals prior to conducting research you can better design laboratory and field test methods to capture this information. Ultimately deicer performance needs to be considered in light of other maintenance strategies, as agencies tend to use a toolbox approach to snow and ice control. For instance, deicer performance measured in conjunction with plowing will provide very different results than if plowing was not performed. Winter maintenance strategies can vary as a function of the local road weather scenarios, rule of practice, and other constraints. As such, a laboratory experiment that attempts to accurately predict field performance must be able to reasonably simulate plowing, deicing, and/or anti-icing, and the seemingly infinite number of combinations of parameters (like temperature, traffic levels, pavement condition, etc.) that could be present in the field.

SHRP Tests

In 1992 the Strategic Highway Research Program (SHRP) sponsored the development of the *Handbook of Test Methods for Evaluating Chemical Deicers* (referred to as SHRP *Handbook* from this point forward), which provided test methods for eight principal features of deicers, including deicing performance. Three types of test methods for deicing performance were created: Ice Melting Test for solid and liquid deicers (SHRP H-205.1 and H-205.2, respectively), Ice Penetration Test for solid and liquid deicers (SHRP H-205.3 and H-205.4, respectively), and Ice Undercutting Test for solid and liquid deicers (SHRP H-205.5 and H-205.6, respectively) (Chappelow et al., 1992). However, the scientific literature provides many other tests that have been developed for specific research projects, some of which resemble the standardized SHRP tests while others are more unique.

Ice Melting Tests

The SHRP Ice Melting Test (H-205.1 and H-205.2) measures the amount of ice melted by deicers over time. The test should be conducted three times for each deicer at each temperature of interest. It is performed in a dry cold box equipped with hand ports in a cold room or upright

freezer. A ⅛-in layer of ice is created in a 9 in diameter dish. The surface is melted and then refrozen to produce a more uniform surface on the ice sample. The deicer is then applied by uniformly spreading 4.17g of solid deicer or 3.8 mL of liquid deicer. At the required times, the liquid is removed with a syringe for volume measurements. Additional details for this test, including preparation of the liquid deicers and data analysis, are available in the SHRP *Handbook* (Chappelow et al., 1992).

The SHRP Ice Melting Test was modeled after tests conducted by McElroy et al. (1988a, b, c) because a review of several other possible tests indicated limitations or lack of documentation to reproduce the tests. However, there are inherent difficulties presented by any ice melting test, such as the inability to separate the entire melted portion from the remaining ice due to 1) entrapment within ice cavities and 2) absorption of brine on the ice surface and undissolved deicer particles. Other factors affecting reproducibility include the dependence on the rate of dissolution of solid deicers (which also depends on the particle size) and the amount of brine needed for reasonably accurate measurements. Reducing the surface area of the ice can limit the errors resulting from absorption but also the amount of brine generated. Thus, ice melting tests try to strike a balance between generating enough brine for accurate measurements and avoiding too much deicer, which may not represent a realistic application rate for highway operations (Chappelow et al., 1993). Chappelow et al. (1992) decided that the testing of solid deicers with rates about three times higher than highway deicing are the most appropriate. Thus, the standard test incorporates the equivalent of 1,320 lbs/lane-mile for solid deicers. For liquid deicers, the application of 3.8 mL of deicer is equivalent to approximately 144 gallons per lane-mile. Finally, although the test method used by McElroy et al. (1988a, b, c) was only performed on solid deicers, Chappelow et al. (1992) found the test to be suitable for liquid deicers. In this case, the data analysis required different computations, but the standard errors were smaller (Chappelow et al., 1993).

Nixon et al. (2005) performed the SHRP Ice Melting Test with a few deviations on seven liquid deicers and found the test to be sufficient for product comparison and for product selection based on desired performance criteria. The deviations were: 80 mL of water to form ice (instead of 130 mL), 5 mL of liquid deicer applied (instead of 3.8 mL), and a funnel and graduated cylinder were used to decant the melted portion (instead of a syringe). No deviation from the standard 9 in diameter dish was noted. According to Nixon et al. (2005), because the test is performed at four different temperatures, the best product can be selected for the expected temperatures. Furthermore, the volume of melted ice can be compared against the cost of the deicer such that the most cost-effective deicer can be identified.

Shi et al. (2009) performed the SHRP Ice Melting Test with slight variations including the use of 25 mL of de-ionized water in a 3.5 cm (radius) Petri® dish. For solid products, 1 g of solid was broadcast over the ice specimen. For liquid products 0.9 g of liquid deicer was pipetted onto

the ice surface. The testing was conducted at 32, 23, -0.4°F (0, -5, -18°C). Shi et al. (2009) found that the rate of dissolution of solid deicers, which is dependent on the particle size and the amount of brine needed for reasonably accurate measurements, may have been a factor affecting reproducibility. The surface area of the ice was reduced based on recommendations by Chappelow et al. (1993) to limit the errors resulting from absorption but this greatly limited the amount of brine generated, especially at colder temperatures.

Akin and Shi (2010) recommend the SHRP Ice Melting Test be implemented for liquid and solid deicers with brine volumes collected at only 20 and 60 minutes after application. Furthermore, brine volumes should only be reported to the nearest tenth mL, coefficient of variation to the nearest percent, and standard deviation to the nearest tenth mL to discourage inappropriate comparisons determined from this test method. They also caution that this test method mimics deicing practices and therefore cannot be used to predict anti-icing performance of products. Additionally, they state that the Modified SHRP Ice Melting Test should be "taken with a grain of salt" when trying to predict the relative field performance of these deicers because it does not take into account the mixing action and fate/transport of deicers in the field due to traffic, UV absorption, gradation and angularity of deicer particles, moisture content and density of snow, pavement type and condition, wind, relative humidity, and possible other factors.

Goyal et al. (1989) developed an ice melting test before the standardized test procedures were published in the SHRP *Handbook*. After initial attempts to decant the melted portion, the researchers decided to use blotter paper to absorb and weigh the melted portion. Two methods of blotting the melted portion were tested: Blotter-S and Blotter-Z. In the Blotter-S method, weighed blotter paper was placed on the surface of the ice sample at the desired time (4, 8, 15, or 30 minutes) for about 10 seconds, and then placed in a plastic bag until just before it was weighed again. Any visible solid unmelted deicers picked up by the blotter paper were brushed off before weighing. The researchers noted that sometimes two or three pieces of blotter paper were needed. In the Blotter-Z method the sample was inverted and shaken upside down for 5–10 seconds after the blotter paper was placed on the surface. This was done in order to collect the water trapped in pores, and was found necessary for solid deicers, whereas the Blotter-S method was adequate for liquid deicers (Goyal et al., 1989). More specimen samples were needed with this method because the melted portion was not returned to the ice samples for continued testing. Thus, if ice melting over time is desired we feel it is important to collect the brine with a syringe and then return it to the same ice sample. If a measurement of ice melting is only desired at a specific time, we think this blotter method is worth trying because it seems like a reasonable method to increase collectability of the brine.

Variations in results were explained by Goyal et al. (1989) as: 1) variations in experimental temperatures up to ±3.6°F, and 2) variations in ice characteristics. The SHRP *Handbook* has a

strict limit of temperature variation to within ±0.5°F of the set temperature. The SHRP *Handbook* also requires the ice surface to be melted and refrozen to produce more uniform ice samples.

Ganjyal et al. (2007) used a digital camera to test the effectiveness of alternative deicers in melting snow and ice outdoors. Aluminum pans topped with 2 in (5 cm) of a snow–ice mixture compacted to approximately 47 lb/ft^3 (0.75 g/cm^3) were placed outside in an average temperature of 27°F. Dry powders of sodium levulinate, calcium levulinate, and magnesium levulinate in amounts ranging from 2 to 5 percent of the weight of the snow/ice mixture were applied. Digital photos taken every five minutes provided the only indication of melting.

Ice Penetration Tests

The SHRP Ice Penetration Tests (H-205.3 and H-205.4), presented in the SHRP *Handbook*, were developed by Chappelow et al. (1992) to test the ability of deicers to penetrate "ice layers likely to be encountered in highway deicing" (p. 139). A literature review by Chappelow et al. (1993) revealed a few tests, some using a sheet of ice and others in which ice was confined in small cavities that could force the deicer particles to melt vertically. In other cases, penetration data was reported but the methodology was not. Different deicers exhibit dissimilar penetration patterns (size, shape, and degree of horizontal penetration), making a penetration test particularly difficult to define. Two studies by McElroy et al. (1988b and 1990) conducted in Plexiglas® cavities and on a sheet of ice showed agreeable penetration data. This motivated Chappelow et al. (1992) to develop a test method for ice penetration of deicers confined in Plexiglas cavities.

The SHRP Ice Penetration Test measures the depth a particle of solid deicer or 30 µL of liquid deicer penetrates a vertical cavity of ice over time. The test apparatus is made from Plexiglas with drilled holes. De-aerated water is frozen in a conventional freezer to form ice, and the ice surface is melted with an aluminum iron and the apparatus placed in the test chamber overnight at the testing temperature. Dye aids in the visual sampling during the testing. For testing solid deicers a couple of pinhead-sized drops of dye are frozen on the prepared ice surface. With liquid deicers, dye is mixed with the deicer. Five replicates are recommended. Additional details for the test method are available in the SHRP *Handbook* (Chappelow et al., 1992).

Nixon et al. (2005) performed the SHRP Ice Penetration Test on the same seven liquid deicers as used in the SHRP Ice Melting Test. Based on his research, he does not recommend using this test for quality control purposes until the actual processes involved in ice penetration are further understood. There are two primary and conflicting roles played by traffic in which deicing chemicals can be 1) forced into the ice or 2) dispersed from the road. The spread of

data for the replicates is not presented, and the primary motivation for not recommending the test is its inability to accurately simulate field conditions.

Shi et al. (2009) performed the SHRP Ice Penetration Test with limited modifications including mixing 25 mL of liquid deicer with two drops of dye and allowing the mixture to equilibrate to the given test temperature during the freezing of the ice specimen. Three drops of dyed liquid deicer solution were then pipetted onto the ice specimen for testing. Shi et al. (2009) discovered that for solid products single pellets would become lodged in the ice penetration apparatus and penetration below the lodged particle would only occur if sufficient brine was generated to promote additional penetration (which was not the case at colder temperatures). The obstruction problem led to reproducibility issues, and the test was not recommended for use with solid products.

Akin and Shi (2010) performed the SHRP Ice Penetration Test with slight modifications. Dye was not added to the surface of the ice when testing solid deicers. Instead, penetration depth was determined by inserting a small, cold metal tool to determine penetration depth. The Modified SHRP Ice Penetration Test was assessed for variability both among the measurements collected within a single test involving five replicate specimens and between separate tests. Akin and Shi (2010) ignored the maximum and minimum penetration depths when analyzing the data and found this improved the within-test variability without skewing the reported penetration depth. The penetration depth was often not a distinct horizontal interface; rather the deicer penetrated down indiscernible veins within the ice and the maximum depth was recorded. Akin and Shi (2010) concluded that this test method provided very limited information for practitioners, and that the test method had inherently high variability due to the deicer/ice interface and the brine generation and penetration processes. The gradation of solid deicers significantly affected the ice penetration test results and single pellets of solid deicers became lodged in the sample.

Ice Undercutting Tests

The third deicer performance test developed by Chappelow et al. (1992) is the SHRP Ice Undercutting Test (H-205.5 and H-205.6) and is based on the ice undercutting test developed by McElroy et al. (1990). The test method incorporates a pavement-like substrate and is the most representative of actual field performance of deicers, yet maintains several benefits of a standard laboratory test. The specimen preparation for this test is more complicated, but produces more uniform ice samples than those used in the melting and penetration tests. First, a mortar substrate is prepared in accordance with ASTM C 109 with the bottom of the mold sandblasted to create a textured surface when the specimen is removed. The ice is prepared on the textured surface and is frozen slowly from the bottom to the top by placing the mortar sample on a plate maintained at 14°F (-10°C). If the surface does not appear level and smooth, it is melted with an aluminum plate and refrozen.

For testing solid deicers, two drops of dye are added to the surface about 1 in apart using a felt tip marker filled with the dye solution. Each dyed area is intended for one deicer particle and at least five replicates for each material are recommended. With liquid deicers, small cavities are formed by a warmed aluminum rod and melted water extracted with a syringe. Five mL of deicer solution is prepared by adding dye before 30 µL is placed into each cavity with a pipette. For solid products the deicer particle is weighed before being transferred to the ice. Photographs are taken over time with a camera mounted above the specimen and are analyzed for undercut area.

Shi et al. (2009) performed the SHRP Ice Undercutting Test for solid and liquid products. A digital camera was used and analysis of the undercut area was performed on the computer using Adobe Photoshop TM CS2. The magic wand, polygon selection, lasso selection, and pixel count tools were used to select the extent of undercut area. A pixel count was obtained of the given selection and an area of undercut substrate was calculated for each photo. While results from this test method provide insight and performance data that can be used to guide field applications, the method itself is plagued by reproducibility issues that are difficult to address, especially for solid deicers. The authors do not recommend using this test method to evaluate solid deicers. In addition, many deicers initially appeared to be undercutting and breaking the ice–concrete bond, but in fact the dye was moving across the surface of the ice and only giving the appearance of undercutting.

Mauritis et al. (1995) developed a laboratory test of ice undercutting that could be used to screen the effectiveness of solid deicer chemicals. This test is different from the SHRP tests in that the test utilizes Pyrex test tubes and does not incorporate dye. Instead, ice undercutting is detected by the break in an electrical circuit caused by a wire detaching from the test tube coinciding with deicer penetration and undercutting. The test tube was 15 x 85 mm with 0.5 mL of frozen water. The deicer applications were single particles weighing 0.25 g.

Akin and Shi (2010) modified the Mauritis et al. (1995) test method to measure ice undercutting. Tests were run using smooth and roughened test tubes; however the test results for scratched and smooth test tubes were ultimately too variable. After testing various tube sizes and deicer application rates, an interim protocol was defined as a test involving 3.3 x 0.6 in (85 x 15 mm) test tubes, 10 replicates, 0.5 mL of ice, and 100 µL of liquid deicer. For this test, the undercutting times for the 10 test tubes varied from 6 to 45.5 minutes, averaged 21.3 minutes, and had a standard deviation of 12.5 minutes. The test showed large variations between the 10 test tubes, despite well-controlled temperatures. The test was repeated three more times. The average and variance of the four tests indicate this test is not repeatable enough for further development.

The tests presented in the SHRP *Handbook of Test Methods for Evaluating Chemical Deicers* have been used extensively to characterize deicer performance. Many researchers have made

modifications to the original test methods designed by Chappelow et al. (1992, 1993) to improve results. It is important to keep in mind the SHRP tests were not designed such that results could be directly translated to field performance; instead, the SHRP tests provide insight into relative performance between products. See summary Table 1 for test methods.

Table 1 Summary of ice melting, ice penetration and ice undercutting test methods.

Reference	Purpose	Deicing or Anti-icing Attributes	How Experiment Incorporated or Simulated Various Parameters					Pros	Cons
			Temperature	Precipitation	Pavement	Traffic	Humidity		
Chappelow et al., 1992, Chappelow et al., 1993	Ice melting test (SHRP 205.1-2)	NaCl (s) & $CaCl_2$ (s); NaCl (l), $CaCl_2$ (l), ethylene glycol (l)	5, 15, 25°F (-3.9, -9.4, -15°C)	ice	—	—	—	•Inexpensive, short testing time •Recommend running in triplicate •Can test liquids and solids •Modified calculations for liquid products for greater accuracy.	•Only indicates relative performance •Does not predict anti-icing performance
	Ice penetration test (SHRP 205.3-4)	NaCl (s)& $CaCl_2$ (s); NaCl (l), $CaCl_2$ (l), ethylene glycol (l)	5, 15, 20(s)/25(l)°F (-15, -9.4, -6.7(s)/ -3.9(l)°C)	ice	—	—	—	•Can test liquids and solids •Inexpensive, short testing time •Recommend running five replicates. •Can run side by side with a control.	•Only indicates relative performance
	Ice undercutting test (SHRP 205.5-6)	NaCl (s)& $CaCl_2$ (s); NaCl (l), $CaCl_2$ (l), ethylene glycol (l)	solid 5, 25°F (-3.9, -15°C); liquid 5, 15, 20, 25°F (15, -9.4, -6.7, -3.9°C)	ice	Mortar substrate	—	—	•Inexpensive, short testing time •Recommend running five replicates •Can test liquids and solids •Analysis made easier with use of digital images and computer analysis	•Only indicates relative performance •Mortar only pavement type considered.
McElroy et al., 1990	Deicers undercutting	Deicing, $CaCl_2$ pellets, $CaCl_2$ flakes, NaCl, KCl, pelletized urea, NaCl with traces of carboxymethocellulos, mixture of NaCl with KCl and urea, mixture of NaCl and urea, and CMA.	0, 5, 10, 15, 20, 25°F (-17.8, -15, -12.2, -9.4, -6.7, -3.9 °C)	ice	Concrete specimen according to ASTM specifications (ASTM C109-84), lightly broomed	—	—	•Each specimen accommodates 20 undercutting tests	•Overlapping of undercutting area occurred due to high number of replicates per specimen.

Nixon et al., 2005	Modified ice melting test and ice penetration test	NaCl brine (23%), $CaCl_2$ brine, CMA, potassium acetate (KA), Ice Ban Ultra, Caliber M-1000, Mineral brine.	0, 10, 20, 30 °F (-17.8, -12.2, -6.7, -1.1 °C)	ice	—	—	—	•Test uses less water/ice and more deicer than SHRP 205.1-2 to achieve a greater amount of melt. •Test was run with five replicates.	•No usable data was collected for 0 °F. •Ice penetration test not recommended for use as a quality control tool.
Goyal et al., 1989	ice melting and ice penetration tests	Qwiksalt (NaCl, s) with PCI (corrosion inhibitor) and FreezGard ($MgCl_2$, l) with PCI	23, 14, -0.4, -4°F (-5, -10, -18, -20 °C)	ice	—	—	High (90–100%) and low (5–20%)	—	—
Ganjyal et al., 2007	Ice melt	Sodium, calcium and magnesium levulinate	32– -5.8°F (0– -21 °C)	compacted snow-ice mixture	—	Compacted snow/ice to 0.75 g/cm^2	—	•Conducted laboratory and field testing	•Only data collected was visual observations as digital images of melt.
Shi et al., 2009 (CDOT)	Modified ice melting	NAAC, Peak SF, CMA, salt-sand, IceSlicer, NaCl (r,s), CDOT $MgCl_2$ blend (l), Apex Meltdown, IceBan	32, 23, -0.4 °F (0, -5, -18 °C)	ice	—	—	26.6%	•Test was run with three replicates.	—
	Modified ice penetration test	NAAC, Peak SF, CF7, IceSlicer, NaCl (r,s), CDOT $MgCl_2$ blend (l), Apex Meltdown, IceBan	32, 10.4, -4 °F (0, -12, -20 °C)	ice	—	—	—	•Test was run with three replicates.	•Test not recommended for solid deicers—pellets become trapped and un-dissolved.
	Modified ice undercutting test	NAAC, Peak SF, CMA, CF7, NAAC/NaFm blend, IceSlicer, NaCl (r,s), CDOT $MgCl_2$ blend (l), Apex Meltdown, IceBan	32, 21.2, 14, 3.2 °F (0, -6, -10, -16 °C)	ice	Mortar substrate	—	—	•Test was run with three replicates.	•Test not recommended for solid deicers due to reproducibility issues.
Akin and Shi, 2010	Modified ice melting	NaCl (r, s), $MgCl_2$ (r, s), $CaCl_2$ (r, s), NaCl (l), $MgCl_2$ (l), $CaCl_2$ (l)	30, 15, 0 °F (-1.1, -9.4, -17.8°C)	ice	—	—	—	•Ran test in triplicate with an additional 23% NaCl control	•Does not predict anti-icing capability of products.

	Modified ice penetration	NaCl (r, s), $MgCl_2$ (r, s), $CaCl_2$ (r, s), NaCl (l), $MgCl_2$ (l), $CaCl_2$ (l)	30, 15, 0 °F (-1.1, -9.4, -17.8°C)	ice	—	—	—	—	•Not recommended as a method for comparing deicer performance. •Results are highly variable. •Gradation of solid deicers significantly affects results.
	Modified ice undercutting test from Mauritis et al. (1995)	—	—	ice	—	—	—	—	•Test not repeatable on proof testing.
Mauritis et al. (1995)	Ice undercutting test	$CaCl_2$, $MgCl_2$, NaCl, and three types of CMA	Range of 32 – -31 °F (0 – -35 °C)	ice	—	—	—	—	—

Notes: — indicates not available from reference, r indicates reagent grade product, s indicates a solid product, and l indicates a liquid product. None of research described above tested long and short wave radiation or wind.

Eutectic and Effective Temperature

Eutectic temperature is the minimum temperature at which a deicer solution remains in liquid form. It varies as a function of the deicer concentration, usually expressed as percent weight of the solution. During the process of melting snow or ice, additional water is produced and the deicer is diluted, which may cause the solution to re-freeze. Thus, the eutectic temperature can be significantly different from the effective temperature for a deicer.

Eutectic temperature and concentration can be determined using the materials and description in ASTM D 1177 (Chappelow et al., 1992). This method is intended for engine coolants, but is generally accepted by the snow and ice community as a method to determine eutectic curves of deicers. Liquid deicing products from manufacturers can contain trace proprietary compounds; thus, the eutectic curve for one product could be different from a similar product from a different manufacturer (Personal Communication, Ron Wright, February 23, 2010). Some proprietary additives put in deicers by manufacturers are organic and behave as "cryoprotectants," which slow down the freezing process, but do not actually lower the freezing point of water. Furthermore, cryoprotectants have a "glass transition temperature" and do not test well in ASTM D 1177. As Koefod (2009) puts it, cyroprotectants "fool the freezing point test."

Specific tests for effective temperature were not found in the literature search, although effective temperatures may theoretically be deduced from a modified SHRP Ice Undercutting Test using various substrates, test temperatures, and application rates. Usually the effective temperature of deicers is determined by a consensus of field experience and not a laboratory test. Factors that contribute to "effective temperature" include dilution and relative temperatures of pavement versus snow (Resource Concepts, Inc., 1992) as well as UV-absorption and friction characteristics of the deicer. As mentioned in the Snow and Ice Fact Sheet #20 (Anonymous, 2003), the minimum effective temperature is the lowest temperature at which a deicer should be used, for practical purposes, because the amount of deicer needed at colder temperatures may be "unreasonable."

Differential Scanning Calorimetry (DSC)

The use of a differential scanning calorimetry (DSC) thermogram to quantify deicer performance was initially proposed by Shi et al. (2009) based on work by Han and Bischof (2004) who investigated freezing and thawing of salt brine in biological systems. The DSC thermogram can provide information on the characteristic temperature and the heat flow during the liquid/solid phase transition of a given deicer, which also shed light on a more realistic working temperature range than a deicer's eutectic temperature.

Laboratory testing conducted by Shi et al. (2009) using the DSC (TA Instruments Q200) to quantify the thermal properties of deicers was set to run from 77 to -76°F (25 to -60°C) with

cooling/heating rates of 3.6°F (2°C) per minute. All samples were run as liquids. Solid samples were made into saturated liquid solutions with de-ionized water. Samples were run at 1.5:1 dilution. Ten µL of each sample were pipetted into the aluminum test chamber and sealed, and then weighed. All samples were run in triplicate.

A DSC thermogram for deionized water is shown in Figure 1. Note that this work only shows the warming cycle thermogram as it is more reproducible than its cooling cycle counterpart. At around 32°F a drop in heat flow between the water (sample) and air (reference) occurs, corresponding to the phase transition from ice to water. The characteristic is the temperature associated with the lowest (peak) heat flow (shown to be 34.45°F in Figure 1. The area within the peak (shaded blue) is the integrated heat flow in Joules per gram (345.1 J/g), i.e., the amount of thermal energy needed to turn the water from solid phase to liquid phase.

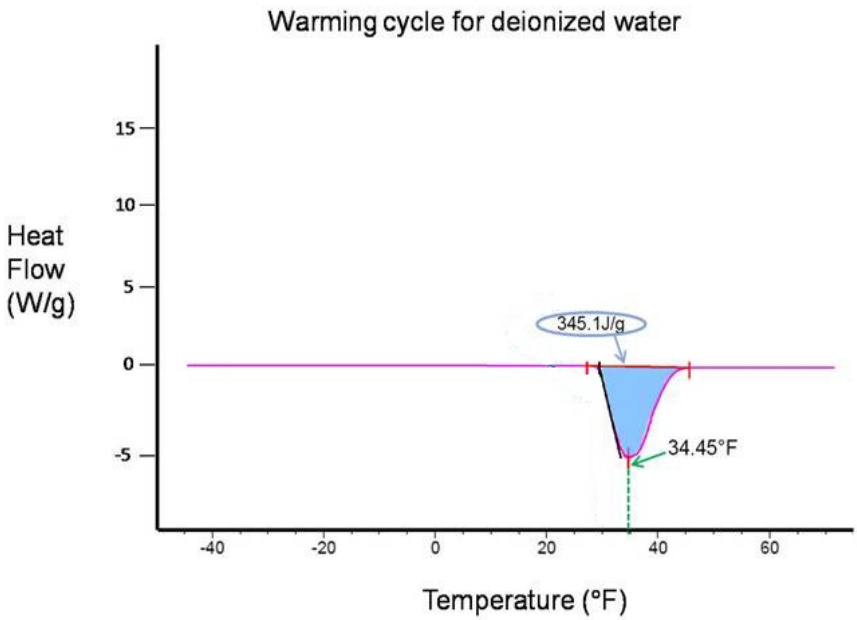

Figure 1 DSC thermogram of deionized water, warming cycle, 3.6°F/minute (modified from Akin and Shi, 2010).

Akin and Shi (2010) utilized the same methods as Shi et al. (2009) for the DSC. They found that the warming cycle was preferred for data analysis because the cooling cycle data was sometimes interfered with by the supercooling effect. Most deicers produced one peak during the warming cycle, but sodium chloride solutions showed two peaks. When more than one peak is present (e.g., NaCl), the temperature and heat flow associated with the warmer peak should be reported. The average and standard deviation of the characteristic temperature (°F) and integrated heat flow (J/g) and the coefficient of variation (CoV) for the heat flow should be reported. It was determined that if the CoV for the heat flow is greater than 10 percent or the

standard deviation for the characteristic temperature is greater than 0.5°F, then additional tests should be performed.

The characteristic temperature for a deicer can be compared to that of sodium chloride, thus indicating its effective temperature range relative to sodium chloride. DSC test results have also been used to predict the performance of chloride-based deicers in the Modified SHRP Ice Melting Test. Akin and Shi (2010) developed three correlation equations (shown below) for 30, 15 and 0°F (-1.1, -9.4, -17.8°C) respectively. The equations for 30°F and 15°F use data from the tests on pure NaCl, $CaCl_2$, and $MgCl_2$ in addition to seven blended deicers. The Modified SHRP Ice Melting Test was not performed at 0°F with the blended deicers. Therefore the third equation is based on fewer data points. The equations are valid for chloride-based deicers. The equations may also be used for blends involving chlorides and agricultural by-product additives, but the equations should not be used for pure agricultural by-products without verification.

$$IMC_{30^\circ\mathrm{F}}(\text{mL brine}) = -0.02265T_c + 1.965\log(\Delta H) + 0.03285t - 2.1761 \quad (\mathrm{R}^2 = 0.94) \tag{1}$$

$$IMC_{15^\circ\mathrm{F}}(\text{mL brine}) = -0.08667T_c - 2.651\log(\Delta H) - 0.000716t + 9.114 \quad (\mathrm{R}^2 = 0.80) \tag{2}$$

$$IMC_{0^\circ\mathrm{F}}(\text{mL brine}) = 0.03869T_c + 6.494\log(\Delta H) - 0.00281t - 14.937 \quad (\mathrm{R}^2 = 0.93) \tag{3}$$

Where:

IMC = expected volume of brine that will be collected in Modified SHRP Ice Melting Test after *t* minutes (mL)

ΔH = 345 J/g minus heat flow (H in J/g) of warmer peak from DSC

T_c = characteristic temperature on warming cycle from DSC (°F)

t = time between 10 and 60 (minutes)

Statistical analysis of the change of heat flow (ΔH) and SHRP Ice Melting Capacity by Shi et al. (2009) yielded a strong correlation at 32°F (0°C) (R^2=0.91).

Akin and Shi (2010) had difficulty characterizing the DSC thermogram of very concentrated deicer solutions. This is an issue that may be addressed with enhanced DSC instrumentation. Conceptually, it may be possible to establish the characteristic temperature of a deicer product as a function of its concentration, but this still needs to be investigated.

Future research may enable the establishment of such a characteristic temperature curve, which would replace the widely used eutectic curve and provide more guidance on the complex dynamics of the ice melting process, the role of deicer, and the appropriate application rate of deicer relative to the amount of accumulated snow and ice. Conceptually, it may be possible to establish the characteristic temperature of a deicer product as a function of its concentration,

but this still needs to be investigated. Work completed for a Pacific Northwest Snowfighters Association (PNSA) Pool Funded project investigating corrosion inhibitor longevity and deicer performance tested four chloride-based deicers using the DSC following the methods established by Shi et al. (2009) and Akin and Shi (2010). Samples tested included brines, corrosion inhibitors, brines with corrosion inhibitors, and samples of brine and corrosion inhibitor collected from of asphalt pavement following exposure to meteorological conditions for up to seven days. Initial results have shown the DSC to be a good quality control tool for deicer performance.

ISO 11078

The International Standards Organization has a specification for aircraft deicing and anti-icing fluids, ISO 11078. Dietl and Stankowiak (2005) used a test analogous to this method by incorporating concrete material instead of aluminum to compare temperature and application rate to icing prevention.

Water Spray Endurance Test

The water spray endurance test (WSET) compares relative performance of aircraft deicing products and simulates deicing fluid behavior in freezing precipitation. The standard WSET, defined in SAE AS 5901, is performed in a climate controlled chamber. Temperatures are set at 23°F (-5°C). Deicing products are then applied to aluminum alloy panels that are tilted at a 10° angle from horizontal. A fine mist of freezing water is sprayed on the panel at the rate of 0.32 mL per square inch per hour (mL/in^2/hr). The deicing product will decrease in thickness from the top of the panel down over time due to gravity, causing ice to form from the top of the panel down. When the ice front reaches 1 in (2.5 cm) from the top of the panel, 0.2 in (0.5 cm) from either edge, or slush is present on 10 percent of the panel, time is recorded as the WSET time.

There is a high humidity endurance test that is a modification of the WSET presented above. The test panel is 23°F (-5°C) and air temperature is set at 32°F (0°C) and relative humidity is more than 80 percent. Moisture should be accumulating on the panel at a rate of 0.02 mL/in^2/hr. When the ice front reaches 1 in (2.5 cm) from the top of the panel or 0.2 in (0.5 cm) from either edge, time is recorded as the high humidity endurance. This test should be performed in the absence of visible precipitation and the test should run no less than two hours.

The WSET and high humidity endurance test methods may be modified so that a pavement surface can be used instead of the prescribed aluminum alloy panels. The WSET test method may be used to test the effects of precipitation type and amount and disbondment of ice for various products. The high humidity endurance test method may be able to better simulate relative product performance and disbondment in a black ice scenario. It seems possible that

with a modern environmental chamber additional parameters could be tested (e.g., air and pavement temperatures, solar radiation, etc.).

Field Performance Testing Guidelines

Minnesota DOT and Clear Roads have developed guidelines for testing deicer performance in the field (http://www.dot.state.mn.us/maintenance/research/; http://www.clearroads.org/downloads/Field-testing-deicers.pdf). These documents are great resources for practitioners but often the data collected is qualitative and only provides the information on relative performance of deicers.

Shear and Ice Disbondment Tests

Many laboratory tests have been performed to evaluate the undercutting and disbondment characteristics of deicers and anti-icers. In those studies, different test methods or instruments have been developed for analysis of the interface bond strength between ice or snow and pavement. The most typical test methods are shear and ice disbondment tests, where a load is applied to induce shear failure on an interface plane. The interface shear strength is based on the measured load at the time of failure. A number of these laboratory studies are summarized in the following section.

Ashworth et al., 1989

Ashworth et al. (1989) developed a shear test to compare the effectiveness of several different deicers when applied as anti-icers to Portland cement concrete (PCC) substrates. The effectiveness of the anti-icers was also compared with reference tests in which no anti-icers were applied. PCC substrates were prepared in accordance to ASTM C 192-76 (historical standard) and could be reused after a verifiable cleaning sequence. Four substrates were used for each test and each substrate accommodates two specimens; thus eight test specimens were prepared for each chemical–temperature combination. The entire substrate surface was brushed with the anti-icer, based on the desired application rate, and air dried. Teflon rings were placed on the substrate and the specimen was kept at -13°F (-25°C) overnight and until one hour after 32°F (0°C) water was introduced in the rings.

The shearing apparatus consists of a Cal-Tester Model TH-5 (5,000 pound tester) mounted just outside of a temperature-controlled chamber (regulated to within 0.2°F) (see Figure 2). The four substrates are placed in the chamber with one hooked up to the loader with two cables, allowing both specimens to be tested without opening the door. After four hours, the first substrate is tested. One hour is needed between testing each of the remaining three substrates so the chamber can return to the desired temperature (Ashworth et al., 1989).

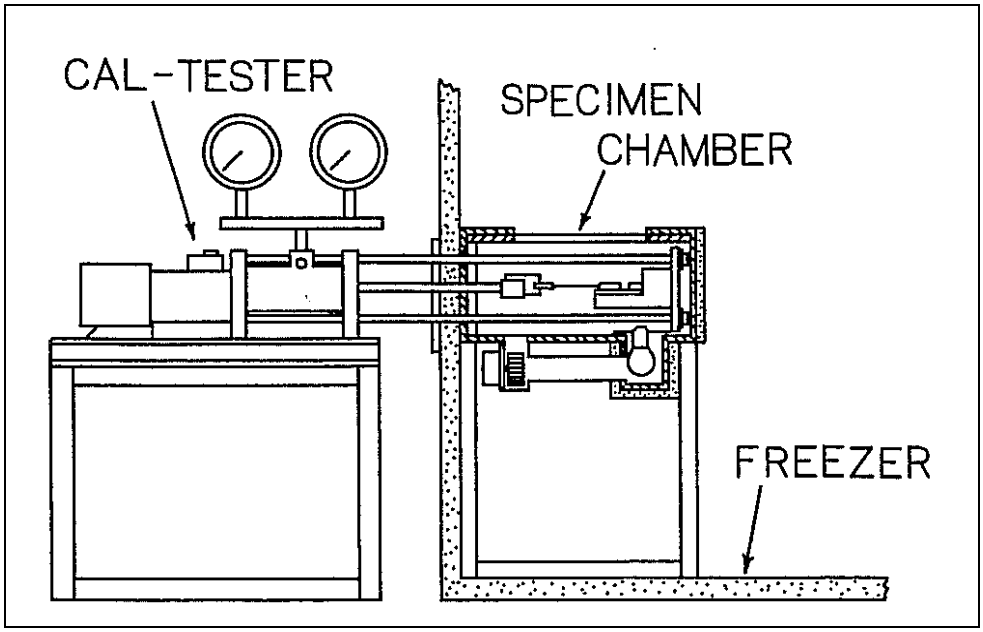

Figure 2 Shear testing system (from Ashworth et al., 1989)

The researchers noted that the chemical-treated substrates generally exhibit clean breaking during shear testing, whereas the reference specimens usually left about 0.04 in (1 mm) thick ice on about 10 percent of the area, especially at lower temperatures. Due to the variability of ice adhesion, comparisons were only made between the two specimens on a given substrate. For untreated substrates, the average standard deviation was reported as 9 percent, but decreased to 5 percent when comparing the same location on a substrate (Ashworth et al., 1989).

Adams et al., 1992

Shear testing of compressed snow on treated and untreated pavement aggregate materials was published by Adams et al. (1992). Granite and limestone coupons 3.3 x 4.6 in (8.6 x 11.7 cm), two common types of aggregate in pavements, were first surface-ground and then treated with 2.5 mL of concentrated brine (CMA, NaCl, or untreated to provide a baseline). Snow was applied to the coupon instead of ice, but to ensure uniformity the harvested snow was stored at -0.4°F (-18°C) until two days before testing at which point it was transferred to a 25°F (-4°C) cold room (the testing temperature). Then 0.26 lbs (120 g) of snow sifted through a 2.0 mm sieve was applied to the substrate and compressed for 10 minutes at 31 pounds per square inch (psi) to simulate the compressive forces exerted by a car or light truck. Two samples measuring 2 x 2 in (5 x 5 cm) were sawed to accommodate a rectangular shear frame. The shear load was applied with a displacement rate of 0.2 in per minute (3 mm/minute) and the shear load at failure was recorded using a precision scale load cell. See Figure 3 for a schematic of the shear

device. To investigate the behavior of residual anti-icing material, the snow application, compression, and shear loading procedure was repeated up to 42 times.

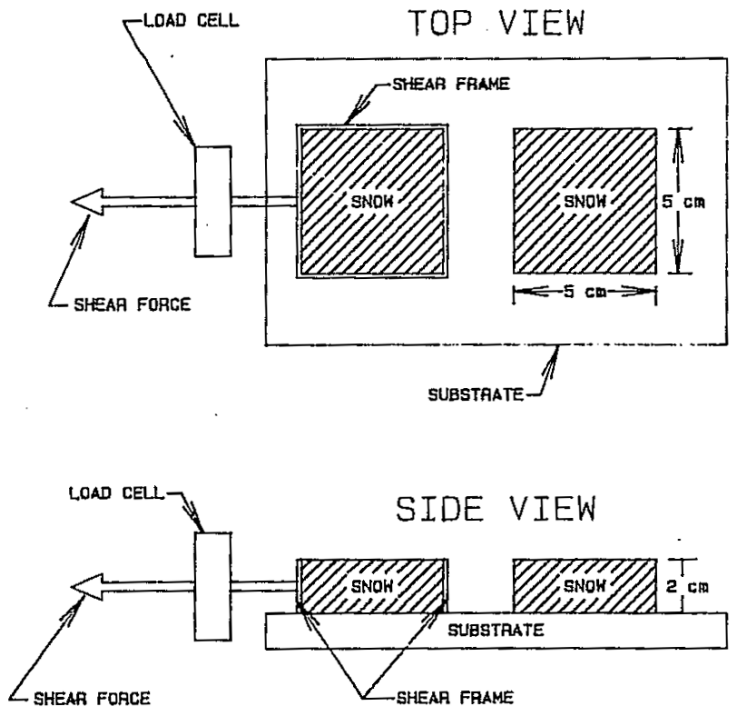

Figure 3 Schematic of a shear device (from Adams et al., 1992)

Four total testing sequences were completed for each of the aggregate types. The average adhesive strength of snow for the four tests at each snow application was reported, but the amount of variation was not mentioned for the treated conditions. For the baseline (untreated), the average adhesive strength of snow was 7.1 psi with a standard deviation of 1.1 psi for granite. For limestone, the respective average and standard deviation was 13.7 and 2.9 psi (Adams et al., 1992).

Anti-Bonding Endurance Test

The Anti-Bonding Endurance Test (ABET) was developed by the Anti-Icing Materials International Laboratory for Transport Canada to measure the effectiveness of anti-icers on concrete surfaces (Bernardin et al., 1996 and Bernardin et al., 1998). Deicers were distributed onto the substrate when the substrate temperature was 23°F (-5°C) and the air was 26.6°F (-3°C). Solid deicers were tested at three application rates: 0.014, 0.027, and 0.041 oz/in^2 (0.6, 1.2 and 1.8 g/dm^2, respectively). Liquid products were applied at 0.013 and 0.026 mL/in^2 (equivalent to 31 and 62 gallons per lane mile). The precipitation was considered to be freezing rain, with droplets measuring about 150 to 200 µm at an intensity of 0.1 in/hr (2.5 mm/hr). The precipitation duration was one of the experimental variables. Six specimens were prepared, three of which were used for verification of the icing intensity. After being subjected to a

specific precipitation duration, the ice was scraped and the friction was measured. The scraping apparatus (Figure 4) was specially designed for the test procedure, taking into consideration typical vertical plow loads. The precipitation duration times at which ice removal was successful make up the ABT (Anti-Bonding Time) range for a deicer. The selected substrate consisted of aluminum plates coated with a proprietary Performance Friction Surface, commonly used on marine helipads. The non-porous high friction surface provided more reproducible and realistic results than concrete or aluminum substrates.

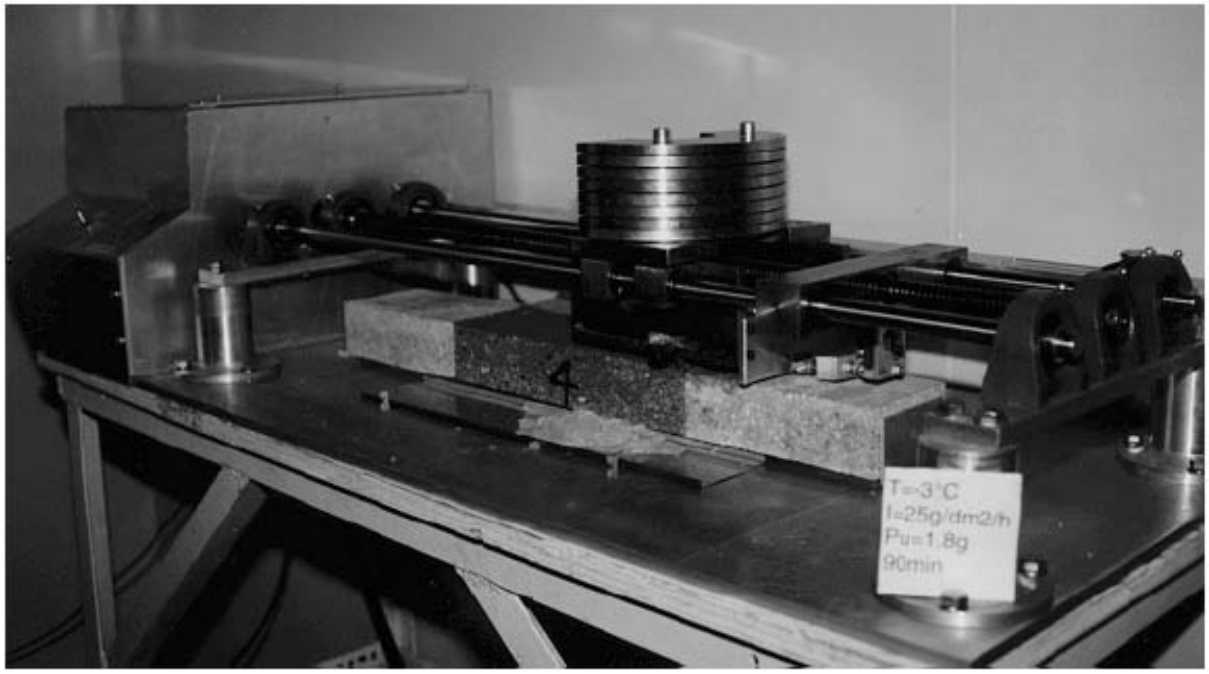

Figure 4 Scraper and Friction System (SFS) (from Bernardin et al., 1998)

Nixon and Wei, 2003

Nixon and Wei (2003) compared the effectiveness of various deicers on three types of ice formed on concrete specimens prepared using an Iowa DOT concrete mix design. The three types of ice studied were refrozen ice, atmospheric ice, and compacted snow ice, all with a thickness of 0.4 in (10 mm). The refrozen ice was prepared on the concrete specimens in 1 mm lifts at 15 to 30 minute intervals until 10 mm of depth was achieved (density was 56 lb/ft^3). Atmospheric ice formation was simulated at 23 and -4°F (-5 and -20°C) by spraying water in a fine mist onto samples until the desired thickness was achieved (density was 54 lb/ft^3). The compacted snow ice was prepared by compressing sifted harvested snow for 10 minutes at 83 psi (density was 43lb/ft^3); cooled water was sprayed onto the snow ice prior to overnight storage. Solid sodium chloride, solid calcium chloride, and 27.3 percent by weight liquid sodium chloride were tested. Four grams of chemical were needed to reduce variability of the results, even though this corresponds to field application rates of 1,760 lbs per lane mile which

is four to six times greater than normal. The solid chemicals were ground and sieved for more even distribution. After 10, 20, 30, or 40 minutes of exposure, the ice was scraped at 23°F (-5°C) at 6 mph using a hydraulic ram scraping machine. The cutting edge has been shown to be representative of field behavior (Nixon et al., 1996). The cutting edge was instrumented with a three-dimensional load cell and provided the horizontal (scraping) and vertical (downward) forces generated during scraping. Tests on 108 ice samples without chemical treatment had 44 "successful" results in which ice bonding to the concrete was statistically significant (scraping and downward forces were both greater than zero with 95 percent level of confidence). With the chemical treated specimens, zero load samples due to poorly bonded ice were not distinguished from zero load samples due to successful chemical performance.

Kirchner, 1992 and McElroy et al., 1990

A disbondment test was reported by Kirchner (1992) and McElroy et al. (1990) in which a ⅛ in layer of ice was frozen on mortar specimens from the bottom up in a controlled chamber (using the same methodology as the SHRP Ice Undercutting Test (Chappelow et al., 1992)). See Figure 5 for a photo of the disbondment apparatus. The ice was exposed to solid deicer for 30 minutes and then pulled under a blade. The 1.5 in wide blade was stationary while the specimen was pulled by vertical and horizontal load cells. The data includes the deicer parameters (loading rate, number of pellets, weight of pellets), estimated percent undercut area prior to loading, the magnitude of the force generated (horizontal, vertical, and resultant with angle), and the estimated percent of ice removed. In most cases, the percent removed equaled the percent undercut.

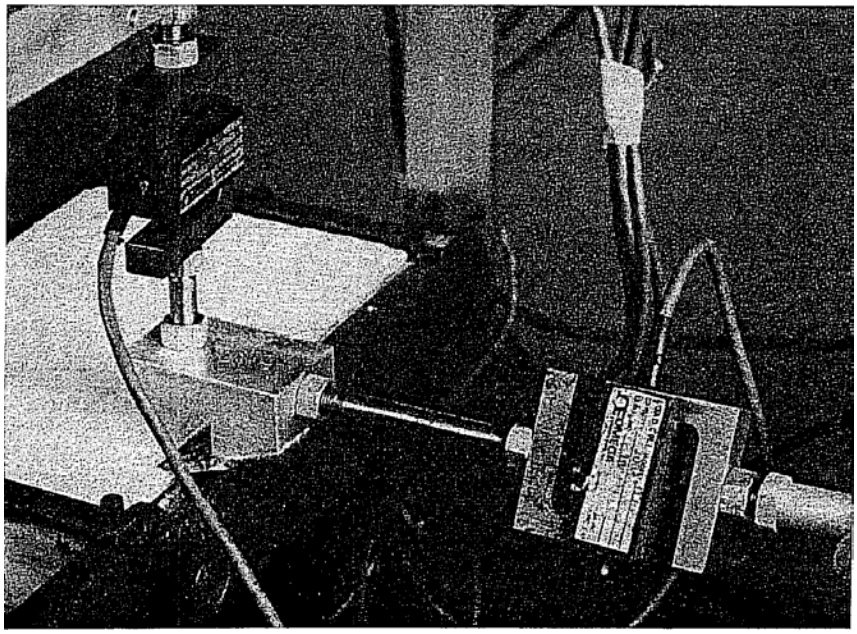

Figure 5 Disbondment apparatus (from Kirchner, 1992)

The deicer application in the disbondment test was based on results of the ice undercutting test (SHRP H-332) and the application rate was increased with decreasing temperature. In all cases the pellets were applied to the surface with a dispenser that arranged the pellets in a "pool ball rack" configuration (McElroy et al., 1990 and Kirchner, 1992).

Each mortar/ice specimen accommodated two disbondment blade tests. Thus, most deicers and deicer combinations were tested twice. The resultant force per 1.5 in (blade width) averaged 32.6 pounds, ranging from 5.3 to 61.9 pounds. The standard error ranged from 0 to 11 with an average of 4.4 pounds.

It is worth noting that the ice disbondment test was not standardized during the development of the SHRP *Handbook*. This is primarily because the disbondment test described above showed relatively easy removal in undercut areas and that excessive force was required in non-undercut areas. Thus, the simpler Ice Undercutting Test provides enough indication of the disbondment characteristics of deicers (Chappelow et al., 1992).

Tazawa et al., 1992

Tazawa et al. (1992) conducted research to clarify the bonding mechanism between ice and asphalt concrete. Two types of asphalt plates were prepared. One was mixed asphalt concrete, and the other was a mortar plate that contained no coarse aggregate. Crushed pelitic hornfels, sea sand, limestone powder and screenings were used as coarse aggregate to treat mixed asphalt. Four types of asphalt concrete surfaces were studied: concrete surface, mortar surface, finished surface of concrete, and cut surface of concrete. One of 13 water repellent agents was applied by brush-painting on the surface of asphalt concrete, or it was mixed with the asphalt. Ice was prepared by placing a specimen overnight in a refrigerator to create an ice layer 0.53 in (13.5 mm) thick. The interfacial debonding resistances were measured by three different methods. The first method used was a single plane shear test, which was originally developed for soil testing (Figure 6). The second method was the impact tension test, in which a Schmidt Hammer—a device commonly used to measure strength of concrete—was repeatedly applied to the thin layer of ice bonded to the asphalt concrete until the ice was debonded. The impact energy of the hammer was 1.8 pound·feet (imagine an object that weighs 1.8 pounds that is dropped a distance of 1 foot). The third method was a compression test. The results show that for a repellent-coated surface, either shear debonding strength or the energy from the impact tension could be used to evaluate the debonding resistance of the ice–asphalt/concrete interface (Tazawa et al., 1992).

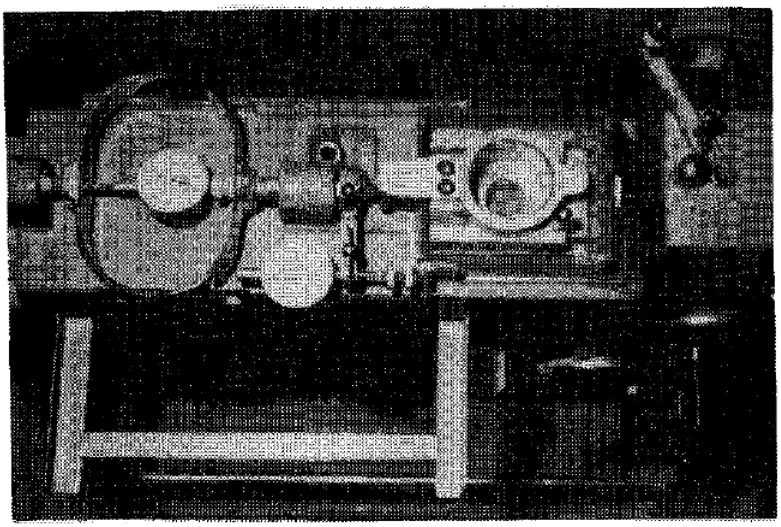

Figure 6 Single plane shear apparatus (from Tazawa et al., 1992)

Schweizer, 1998

A laboratory experiment on shear failure of snow was reported by Schweizer (1998) to understand slab-avalanche formation, using a direct simple-shear apparatus (Figure 7). The snow samples were prepared from snow blocks taken from a homogeneous layer of fine-grained snow. Shear tests were performed in the cold laboratory at temperatures of 5, 14 and 23°F (-15, -10 and -5°C). The data includes the loading rate, snow temperature, strength, toughness and stiffness of natural alpine snow samples.

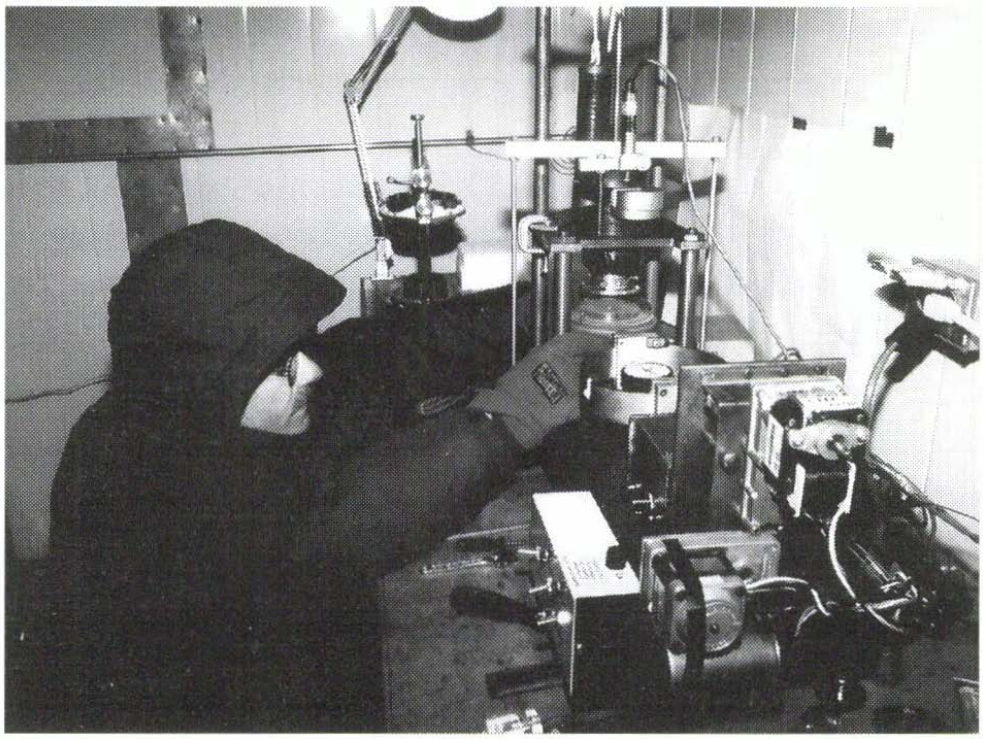

Figure 7 Direct simple-shear apparatus (from Schweizer, 1998)

Cuelho, 2010

A current project at the Western Transportation Institute to study anti-icing in a laboratory setting used a different approach that involved shearing compacted snow (Cuelho, 2010). Asphalt and Portland cement concrete pavement samples were constructed and ground to produce a smooth pavement surface. Tests were conducted in an environmental chamber—this provided a constant cold air temperature. The pavement samples were maintained at a different temperature by placing them on a temperature-controlled table. The insulated table had tubes through which fluid (either heated or cooled) was circulated. Thermocouples embedded in the pavement provided real-time pavement temperatures. The pavement was treated with one of five liquid deicers, or left untreated as a control. Snow harvested from nearby mountains was sifted through a 0.04 in (1 mm) sieve and compacted at 80 psi for 5 minutes. Plow boxes 4 in^2 were inserted through the snow. Each pavement specimen accommodated three replicate plow boxes. The pavement temperature was slowly raised until the constant-load plows sheared the snow. At the higher application rates, the snow did not bond to the pavement. At the lower rates, the temperatures at which the snow sheared were compared to assess the relative performance of the deicers during different storm scenarios.

The review of literature related above indicates that direct interfacial shear testing has been commonly used in the laboratory for assessing the undercutting and disbondment

characteristics of deicers and anti-icers. However, the literature does not show general agreement on the degree to which environmental parameters may influence results. Environmental parameters such as humidity, long and short wave radiation and wind were not considered in those tests. See summary Table 2 for individual test purpose, attributes, experimental factors incorporated, and pros and cons.

Table 2 Summary of shear and ice disbondment tests.

Reference	Purpose	Deicing or Anti-icing; Attributes	How Experiment Incorporated or Simulated Various Parameters					Pros	Cons
			Temperature	Precipitation	Pavement	Traffic	Humidity		
Ashworth et al., 1989	Interfacial shear strength tests of ice formed on pavement	Anti-icing, concentrated solution of South Dakota Deicer No.2 (SD2), CMA, and NaCl.	Laboratory chamber at 23 and 5°F (-5 and -15°C)	32°F (0°C) distilled water poured in Teflon rings to simulate freezing rain	Portland cement concrete (PCC) substrates	—	—	•Each substrate accommodating two specimens allows eight test without opening the chamber door. •Four deicer application rates (100,200,300,400) were considered and compared. •Reference tests are conducted to make sure substrates are clean.	•Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice. •One type of pavement
Adams et al., 1992	Residual anti-icing properties	Anti-icing, concentrated solutions of NaCl and CMA	Laboratory chamber at 24.8°F (-4°C)	Natural aged snow, sieved	smooth limestone and granite coupons	compressed snow with 31 psi for 10 minutes	—	•Natural snow more realistic than ice, but aged snow is different than fresh snow	•No macro texture •Air and pavement were at same temperature •Only considered snow, no ice.
Cuelho, 2010	Anti-icing application rates	Anti-icing, NaCl, $CaCl_2$, $MgCl_2$, Potassium acetate, ag. by-product	Air (A), Pavement (P) Storm 1: A23°F (-5°C), P32°F (0°C); Storm 2: A14°F (-10°C) P 14°F (-10°C); Storm 3: A30°F (-1.1°C), P32° (0°C)	Natural aged snow, sieved 0.04 in.	Asphalt and Concrete pavement, surface ground smooth	compressed snow at 80 psi for 5 minutes	—	•Natural snow more realistic than ice, but aged snow is different than fresh snow •Different air and pavement temperature	•No macro texture—lower application rates than field •Bond force not measured—just temperature when snow sheared
Bernardin et al., 1996, 1998	Anti-icing properties	Anti-Bonding Endurance Test , liquid runway deicers: urea-ethylene-glycol based, acetate of potassium based and FRIGOL	climatic chamber at 23°F (-5°C) and substrate at 26.6°F(-3 °C)	Freezing rain	Concrete plates, molded aluminum plates, polymer concrete and an epoxy-resin coated aluminum plate.	—	—	•Air and pavement were at different temperature •Weight is added to scraper to simulate the action of the plow trucks in airports.	•Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice. •Tests not reproducible because the concrete substrate absorbs part of the deicer and some of the precipitation.

Nixon and Wei , 2003	Scraping resistance of different types of ice on the pavement under different de-icing chemical application	Deicing, Solid NaCl, solid $CaCl_2$, and 27.3 percent by weight liquid NaCl.	Controlled cold room, temperatures at 30.2, 23,-4°F (-1, -5, –20°C) to produce ice. Chemical tests conducted at a temperature of 23°F (–5°C)	refrozen ice, atmospheric ice, and compacted snow ice	concrete specimens prepared using an Iowa DOT concrete mix design	Compressed snow under 83 psi for 10 minutes	—	•More realistic by using three types of ice.	•Only one type of pavement was tested. •Only one deicer application rate of 1760 lbs per lane mile was considered, which is very heavy compared with usual application rate of 300–400 lbs/lane mile.
McElroy et al., 1990	Deicers undercutting and disbondment characteristic	Deicing, $CaCl_2$ pellets, $CaCl_2$ flakes, NaCl (2 products), KCl, pelletized urea, NaCl with traces of carboxymethocellulos, mixture of NaCl with KCl and urea, mixture of NaCl and urea, and CMA.	Controlled temperatures: 0, 5, 10, 15, 20, 25 °F (-17.8, -15, -12.2, -9.4, -6.7, -3.9°C)	Freezing chamber produced ice with surface partially melted with a metal iron.	Concrete specimen according to ASTM specifications(ASTM C109-84), lightly broomed	—	—	•Each specimen accommodates two disbondment blade tests	•Disbondment test was not standardized. •Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice.
Kirchner, 1992	Undercutting and disbondment characteristics	Deicing, pellets of equal weights of $CaCl_2$, NaCl, KCL, pelletized urea, CMA	Controlled temperatures: 0, 5, 10, 15, 20, 25 °F (-17.8, -15, -12.2, -9.4, -6.7, -3.9°C)	Freezing chamber produced ice, surface partially melted with a metal iron.	Lightly broomed concrete slab	—	—		•Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice.
Schweizer, 1998	Behavior of alpine snow under shear to understand slab-avalanche formation	—	Controlled cold room, temperatures at 23°F (-5°C), 14°F (-10°C), and 5°F (–15°C).	Natural alpine snow	—	—	—	—	—

Tazawa et al., 1992	Interfacial bonding between ice and asphalt concrete	Anti-icing, water repellent agents: organic polysiloxane boned with special metal; dimethyl polysiloxane; denatured polysiloxane; silicone water repellent agent; silane; fluorine contained resin; oleic acid; sorbitan ester; mixture of higher fatty acid, zinc naphthenate, polyvinyl resin ester, penetration promoter, solvent and diluents; pulverized silicone polyer; treated hydropholic silica powder.	Temperature normally tested at 9.5, 5, 0.5°F (-12.5, -15, -17.5°C), some test at 14 and -4°F (-10°C and -20°C).	Ice produced in a refrigerator.	Asphalt concrete,	—	—	•Three types of tests for measurement of debonding strength	•Only one type of ice is considered.

Notes: — indicates not available from reference. None of research described above tested long and short wave radiation or wind.

Friction

Friction coefficient is arguably the most important parameter regarding the safety of road surface during winter conditions. Friction is responsible for keeping vehicles on the road, especially when accelerating, braking, or turning. The presence of snow and ice can reduce friction to such levels that "almost any braking or sudden change of direction results in locked-wheel sliding and loss of vehicle directional stability" (Hall et al., 2009). Winter maintenance operations such as anti-icing, plowing, deicing, and sanding are aimed at restoring the pavement friction coefficient to safe levels.

There have been three notable syntheses that explain the concept of friction, measurement techniques, and equipment. Al-Qadi et al. (2002) examines the feasibility of measuring friction during winter conditions to improve operations. Equipment and techniques used for research demand more spatial resolution and accuracy of the data than those needed to assist operational decisions. Domestically, the air transportation sector in the U.S. has contributed to a majority of the research in the field of friction, whereas highway agencies in some European and Asian counties have sponsored a significant amount of research. A more recently completed NCRHP project produced a guide for pavement friction (Hall et al., 2009) that comprehensively examined friction measuring equipment and briefly discussed the complications posed by the effects of winter weather and maintenance activities. Finally, a Swedish-based literature review also examined friction and its correlation to traffic safety (Wallman and Astrom, 2001). These documents provide significant information about the equipment and methods used to measure friction in the field. Other references were included to ensure this review comprehensively examines the options for field measurements and, laboratory measurements, and any possible correlation between them.

Measures of friction can be described in various terms, including friction coefficient (μ), coefficient of static friction (μ_s), coefficient of kinetic friction (μ_k), coefficient of sliding friction, skid number (SN), friction number (FN), Halliday friction number, British Pendulum Number, International Friction Index, International Runway Friction Index, etc. The nomenclature is complicated, but here are some general points. The friction coefficient is the ratio of horizontal (or tangential) friction force to vertical (or normal) load and is usually a number less than one. The skid number is the friction coefficient multiplied by 100. Friction number and skid number are often used interchangeably. The Halliday friction number was coined for the RT3™ device and uses a scale of 0 to 100. The British Pendulum Number refers to measurements made with a British Pendulum Tester, a portable method for measuring skid resistance. The International Friction Index was developed in an effort to harmonize the reporting of frictional properties of pavement surfaces—it requires measurement of pavement friction and pavement texture. The

International Runway Friction Index also represents a harmonization effort and was one result of the Joint Winter Runway Friction Measurement Program that involved extensive testing of 42 different friction measuring devices (Yager et al., 2002).

The friction between a vehicle and the road depends on a variety of factors (Table 3). Winter maintenance activities are focused on improving the friction, but operators have no control over the pavement, vehicle, or tire characteristics. The pavement frictional characteristics during a winter event will probably change with time based on temperature, precipitation, and level of traffic—not to mention the changes produced by plowing, anti-icing, deicing, etc.

Table 3 Parameters that affect road friction (Hall et al., 2009)

Pavement Surface Characteristics	Vehicle Operating Parameters	Tire Properties	Environment
•**Macrotexture** •**Microtexture** •**Material properties** •Unevenness •Temperature	•**Slip speed** ▪vehicle speed ▪braking action •Driving maneuver ▪turning ▪overtaking	•**Tread pattern design and condition** •**Inflation pressure** •Rubber composition and hardness •Footprint •Load •Temperature	•Climate ▪Wind ▪**Temperature** ▪**Water** (rainfall, condensation) ▪**Snow and Ice** •**Contaminants** ▪Anti-skid material (salt, sand) ▪Dirt, mud, debris

Note: Critical factors are shown in bold

A friction measurement must be scrutinized in terms of the measuring device, the specific tire, and the specific operating conditions under which it was measured (Wallman and Astrom, 2001). Measurements of friction are not generally comparable between devices, unless a study is performed to specifically correlate two (or more) particular devices.

Field Methods and Equipment Used to Measure Friction

There are several commercial options available to measure friction on roads or on airport pavements. Most devices utilize an extra wheel that is either installed on a vehicle or towed behind a vehicle. The operating principle for friction measuring devices that use an extra wheel include locked wheel, fixed slip, variable slip, and angled slip. Friction can also be measured by 1) stopping distance, 2) deceleration measurements, or 3) calculations using data provided by instrumentation and data acquisition equipment added to a vehicle equipped with an anti-lock brake system (ABS); these options avoid problems associated with a “fifth wheel.”

Slip speed is a critical factor in friction measurements because the friction changes as the slip speed changes. The ratio of the slip speed to the vehicle speed is the slip ratio, reported as a percentage. When a tire is rolling, the slip speed is zero; thus the slip ratio is 0 percent. A locked tire slides at the speed of the vehicle, so the slip ratio for a locked wheel is 100 percent. The critical slip ratio corresponds to the peak friction (Figure 8). The critical slip ratio for dry and wet roads is usually in the range of 10 to 20 percent, but no such range can be provided for snowy or icy roads (Al-Qadi et al., 2002). As illustrated by Comfort et al. (2006) in Figure 9, the friction curve for winter roads tends to be lower in magnitude and relatively flat. The friction curve is flatter for winter roads. Some friction measuring devices are designed to operate at a certain slip ratio, such as locked-wheel tests and fixed-slip devices.

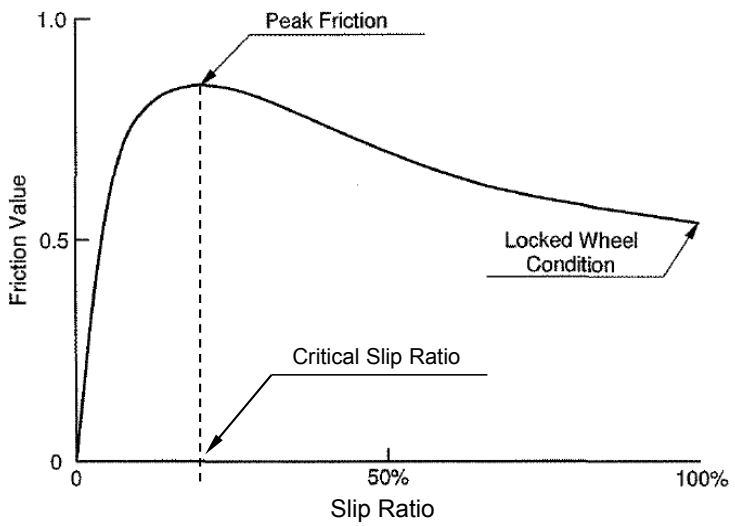

Figure 8 Variation of friction measurement to slip ratio (modified from Nixon, 1998)

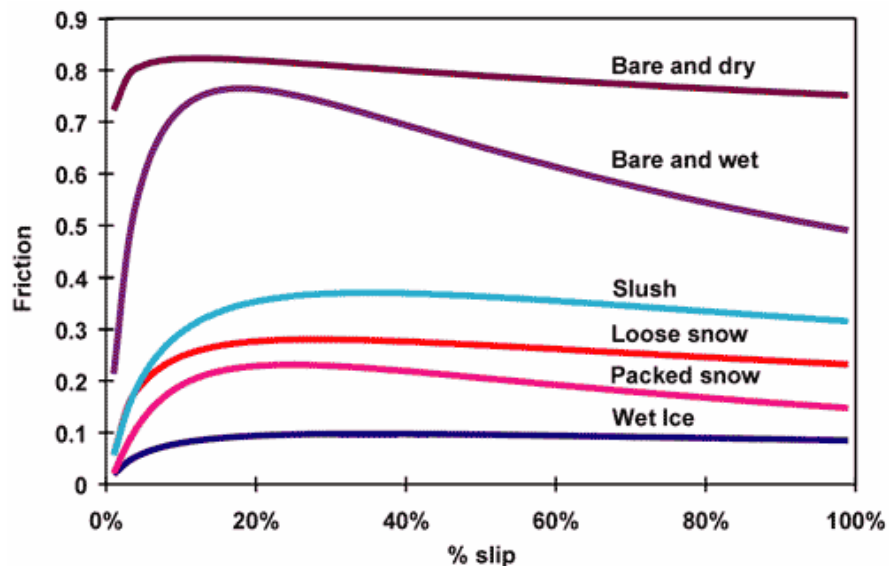

Figure 9 Friction versus slip ratio for winter roads (from Comfort et al., 2006)

The Joint Winter Runway Friction Measurement Program was a large international effort to harmonize friction measurements of runways to a consistent index. The program also wanted to establish a correlation between ground friction measurements and aircraft braking. After testing several aircraft and 42 different friction measuring devices over several winter seasons, the International Runway Friction Index (IRFI) was developed (Yager et al., 2002). ASTM E2100 describes the method for calculating the IRFI for any device that has first been harmonized with the IRFI reference device. However, the use of the index has not been widely implemented (Comfort et al., 2010).

Stopping Distance

Measuring the distance required to stop a vehicle with fully locked wheels is a relatively simple technique for estimating friction. In addition to being relatively easy, this is a standardized method. ASTM E445 describes the method and equipment, including specific tire types (ASTM E501); this ensures measurements are consistent (expected variation is less than 5 percent with the same operator and identical test conditions). However, this particular method is not suitable for winter roads unless some modifications are made to the standard practice. The disadvantages of this method for winter roads are 1) ASTM E445 calls for saturating the road surface with a water-spray truck, and 2) a vehicle not equipped with an ABS must be used.

Deceleration Devices

A short record of deceleration with a normal vehicle for only about 2 seconds can provide a mean friction value. This is a common method for winter roads because a normal vehicle can be used, a full stop is not required, and several measurements can be taken along a stretch of road. Other advantages include the availability of a standard method (ASTM E2101) and the

instrumentation needed to measure deceleration is "easy to use, small, portable, lightweight, and easy to install and remove" (Hall et al., 2009). The deceleration meters also correlate to stopping distance better than variable slip friction devices (Nixon, 1998).

The repeatability and reliability of this type of friction measurement received mixed reviews in the literature, with Al-Qadi et al. (2002) offering good reviews with sufficient training and Wallman and Astrom (2001) citing low precision and high dependence on vehicle and tires. Arsenault (2010) compared the relative performance of several friction-measuring devices based on operational and technical points of views. The decelerometer rated as follows in the technical areas examined: easy calibration, acceptable reproducibility, poor ability to identify changes in surface condition, and not appropriate for measurements on a curved road.

Several decelerometers are available, including:

- Mk III Electronic Recording Decelerometer (Comfort and Verbit, 2003; FAA, 2008)
- Mk II Electronic Recording Decelerometer (Comfort and Verbit, 2003)
- Electronic Tapley model BR 500 decelerometer (Comfort and Verbit, 2003; FAA, 2008)
- Electronic Bowmonk model AMF2 decelerometer (Comfort and Verbit, 2003; FAA, 2008)
- Coralba Meter (Nixon, 1998; Al-Qadi et al., 2002)
- C-mu deceleration meter (Al-Qadi et al., 2002)
- James Brake Decelerometer (Al-Qadi et al., 2002)
- Vericom VC3000 RFM Decelerometer (FAA, 2008)
- NAC Dynamic Friction Decelerometer (FAA, 2008)

Locked-Wheel Devices

Locked-wheel skid tests are widely used in the United States to assess pavement condition during warm weather. ASTM E274 provides information on equipment and the procedure for determining the skid resistance of pavement. The device requires a measuring wheel with either a ribbed tire (ASTM E501) or a smooth tire (ASTM E524), a braking system to lock the tire, and instrumentation to measure force, torque, and speed. In the standard test, water is sprayed on the pavement just before the test wheel is locked—this would need to be omitted for measurements on winter roads. Use of locked-wheel devices to assess friction during winter conditions was not found in the literature.

Fixed-Slip Devices

Similar to locked-wheel devices, an extra measuring wheel is used in fixed slip devices, but instead of a fully locked wheel (slip ratio of 100 percent) most devices operate in the range of 10 to 20 percent slip. The preferred method of determining frictional characteristics of runways at U.S. airports during both winter and summer seasons is with Continuous Friction Measuring Equipment (CFME); many of the FAA-approved products are fixed-slip devices (FAA, 2008). ASTM E2340 has some information about continuous reading, fixed slip friction devices,

but ultimately there are several types of equipment that are designed for a specific slip ratio and/or test speed. Winter operational measurements at airports are usually carried out at 40 mph. Summer testing to schedule pavement maintenance activities usually involves water film thicknesses of 0.04 in, although as low as 0.01 in can be standard for highways.

Examples of fixed-slip devices include:

- Griptester, 14.5 percent slip (Wallman and Astrom, 2001; Al-Qadi et al., 2002; FAA, 2008)
- Surface Friction Tester, previously known as the Saab Friction tester, 17 percent slip (Wallman and Astrom, 2001)
- Dynatest 6875H Highway Slip Friction Tester, 14 percent slip
- BV11, 15 to 17 percent slip (Al-Qadi, et al., 2002; FAA, 2008)
- BV14, 17 percent slip (Nordström, 1998)
- Airport Surface Friction Tester, ASFT, 13 percent slip (Al-Qadi et al., 2002; FAA, 2008)
- Traction Watcher One, 17 percent slip (Arsenault, 2010)

Arsenault (2010) rated the technical and operational performance of the Traction Watcher One friction device as follows: easy to calibrate, satisfactory reproducibility, slightly influenced by changes in direction of the vehicle, very good at identifying changes in surface condition, easy data retrieval, moderately cumbersome to drive while mounted on the vehicle, rapid tire wear, very user-friendly, and slight impact on drivability of the vehicle.

Feng and Perchanok (2010) developed several models to classify data from a Traction Watcher One friction trailer into the following categories: bare-dry, bare-wet, thin snow cover, slushy snow cover, partial snow cover, and mostly snow cover. This seems to be a better application for using friction in operational aspects of winter maintenance but not in research applications.

Vaa (2010) demonstrated that the addition of a new sensor to the Traction Watcher One allowed the device to be used to estimate friction of curved roads. Preliminary tests were positive, but testing will be continued during the 2010–2011 winter season.

Variable-Slip Devices

Friction measuring devices that can operate as variable slip are probably better for winter roads because the critical slip ratio for snowy and icy roads is not known. Variable-slip devices can usually provide the peak friction and corresponding slip ratio, as well as other points of interest or the slope of the friction–slip ratio curve (Fleege et al., 1997). ASTM E1859 provides some information, guidelines, and test procedures about variable-slip friction devices. Notably, the devices should not be used when slush is thicker than 1 in or loose snow is thicker than 2 in. Also, on a winter road, characteristics change with time, and results even differ for subsequent tests on the same location; thus, repeated tests on separate and parallel wheel paths should be performed.

Examples of variable-slip devices include:

- Roar Mark I (Vaa, 2001)
- Roar Mark II (Vaa, 2001)
- OSCAR (Al-Qadi et al., 2002)
- IMAG (Al-Qadi et al., 2002)
- NASA-ITTV (Al-Qadi et al., 2002)
- RUNAR (Al-Qadi et al., 2002; Perchanok, 2008)
- CRREL IV (Al-Qadi et al., 2002)
- SALTAR (Al-Qadi et al., 2002)

Several of these devices have been used as the performance measure in field tests. Vaa (2004a) used the OSCAR and ROAR devices to assess friction improvements in new sanding techniques (heated sand and warm wetted sand). Vaa (2004b) used the Roar Mark I device to compare salt prewet with both liquid sodium chloride and liquid magnesium chloride. Perchanok (2008) used the RUNAR and Roar Mark II devices to measure friction on roads to determine the effect of terrain on the extrapolation of RWIS data. Perchanok found snow cover correlated highly with the friction results of the variable-slip devices.

Side-Force Devices

Angled measuring wheels can be used to quantify friction based on side force components. Side-force friction devices provide continuous measurements. The Sideway Force Coefficient Routine Investigation Machine (SCRIM) has a wheel tilted 20° outward from the direction of travel. The Mu-Meter has two measuring wheels each tilted 7.5° outwards (ASTM E670). The RT3 device (Halliday Technologies, Inc., Plain City, Ohio) was designed specifically for winter roads and uses a smaller angle of only 1.75°. A project funded by the Aurora pooled-fund group is putting the RT3 device through more extensive testing, cross-validation, and data analysis—the project is over 90 percent complete and the report should be available soon.

Examples of side-force devices include:

- SCRIM (Wallman and Astrom, 2001, Al-Qadi et al., 2002)
- Mu-Meter (ASTM E670)
- Halliday RT3—formerly known as Real Time Traction Tool and Road Grip Tester (Evans, 2006)
- Kofriks (Vaa, 2001)

Laboratory Methods and Equipment Used to Measure Friction

In general, techniques and equipment used to measure friction in the laboratory tend to look and operate much differently than devices used in the field. While some standardized equipment is available, several friction measuring devices have been custom designed and built

for specific research projects. Simple devices usually include a metal block with a rubber pad on the bottom that is pulled across the surface. The ratio of the force needed to pull the block (initiate movement) divided by the weight of the block is the coefficient of static friction. According to Forensic Dynamics, this sort of friction measurement is only accurate for dry surfaces because "stiction" generates artificially high friction values (Forensic Dynamics). Stiction is produced by the electrostatic, Van der Waals, and hydrogen bonding forces in liquids. Dynamic friction measurements are not affected by stiction.

Drag Sled

Forensic Dynamics, Inc., (Kamloops, British Columbia) designed and built a friction measuring device to be operated in a temperature- and humidity-regulated laboratory. The "drag sled" uses a full-size passenger tire dragged along a surface at a constant speed of 0.6 mph. A load cell measures the pull force and, with the tire weight, is used to determine the sliding coefficient of friction. Originally, a sandblasted glass surface was used, but subsequent studies utilized an asphalt and concrete surface (Leggett, 1999; Leggett and Sdoutz, 2000; and Sdoutz and Leggett, 2001). The asphalt substrate was from a portion of a 15-year-old well-traveled road surface. The concrete substrate was produced and tined using standard construction practices for bridge decks in British Columbia. Over the course of several projects, the drag sled was improved to provide consistent friction values. The tire needs to be relatively new because friction values decrease as the tire wears. Friction was low on the dry glass surface ($\mu = 0.41$), high on the dry concrete surface ($\mu = 1.11$), and unreported on the dry asphalt surface. When the surfaces were wetted with water, the friction values were 0.37 on glass, 0.71 on concrete, and 0.65 on asphalt (with a new tire—0.48 with a worn tire).

There are a few drawbacks to the drag sled, notably, 1) the tire is unloaded and only weighs between 10 and 20 pounds, and 2) the tire does not spin and thus mimics locked-wheel braking and not slipping. However, the drag sled does utilize a real full-size tire, which is more realistic than other laboratory devices that use flat pieces of rubber or small tires.

In Road Friction Sensor

Traction Technologies, Inc., (Kamloops, British Columbia) developed a friction sensor for InTransTech intended to be installed in roads so friction could be directly measured at discrete locations, such as at RWIS stations (*Personal Communication*, Gerald Sdoutz, P.E., October 14, 2008). The product was never deployed, but was used successfully for a laboratory research project that compared dry rock salt to rock salt prewet with various wetting agents (water and several liquid deicers). The friction sensor operates by a small rubber wheel (picture a model airplane) traveling in an arc across a sample—asphalt or concrete, for instance. The tire rotates until a resisting torque spring offers too much resistance, causing the tire to then drag. A

potentiometer measures the rotation of the tire and is correlated to the coefficient of kinetic friction (Luker et al., 2004).

Figure 10 In Road Friction Sensor measuring friction on a 3 in x 9 in asphalt pavement sample

Scraper and Friction System

The Anti-icing Materials International Laboratory (AMIL) at the University of Quebec at Chicoutimi designed and built a Scraper and Friction System (SFS) to research deicing and anti-icing of runway pavements. The surface is exposed to freezing rain and then plowed with the scraper. The scraper is then removed and the friction coefficient measurement block is installed. The bottom of the metal block has a 0.2 in thick rubber pad supplied by NASA that conforms to ASTM E501. The scraper and friction block are pulled very slowly at 0.28 in/sec (7 mm/sec) (Bernardin et al., 1996).

Simple Skid Friction Measurement Device

Takeshi et al. (2004) reported on the skid friction coefficient of sodium chloride, sodium acetate, and calcium chloride applied as anti-icers. The simple skid friction measurement device consisted of a slider with a 4 x 4 in piece of rubber (same kind as used in tires) fixed to the bottom. The slider was pulled at constant speed with a motor (speed not provided) and the load required to pull the slider was recorded.

Bench-top Tribometer

A tribometer is an instrument used to measure friction on a surface. Laboratory bench-top tribometers are used in many industries to study coatings and mechanical systems. Bench-top

tribometers have rarely been used in the field of winter maintenance, but one project did explore this option to investigate the change in friction over time for iced concrete samples treated with solid and liquid deicers (Shi et al., 2009). The tribometer used in this study could be fitted with a metal ball or pin that traveled in a circle over the substrate. The researchers found the ball clogged during testing, so the pin was used. The test lasted 200 seconds and the pin traveled 100 laps during that time. The tribometer provides a coefficient of friction every 0.1 seconds. All tests were conducted at room temperature (a freezer held the concrete samples until just prior to testing). The concrete specimens were small (1.2 in diameter, 0.4 in thick) and only a thin layer of ice was formed (0.08 in). However, the results did generally coincide with expectations—low friction values in the beginning when there was just ice and the deicer (μ usually less than 0.2) and high friction values in the end when the ice had melted significantly (μ usually greater than 0.4). Shi et al. (2009) had several recommendations to be considered prior to using a bench-top tribometer for winter maintenance studies: 1) use a rubber tip instead of metal, 2) use the tribometer in a chamber where the air and possibly even the substrate temperature can be independently controlled, and 3) compare laboratory test results with friction data from comparable field tests to ensure applicability.

Table 4 provides information about laboratory tests that used friction as the performance measure—there are relatively few cases when compared to the higher use of ice melting, ice penetration, and shear tests.

Table 4 Summary of friction measuring tests

Reference	Purpose	Deicing or Anti-icing; Attributes	How Experiment Incorporated or Simulated Various Parameters					Pros	Cons
			Temperature	Precipitation	Pavement	Traffic	Humidity		
Luker et al., 2004	Performance of prewet solid deicers using friction as performance measure	Deicing; dry rock salt and rock salt prewet with various liquid deicers	Laboratory chamber at 30, 23, 14°F (-1.1, -5, -10°C)	Zamboni snow harvested from ice rink	Concrete substrate	Snow compacted with hydraulic press, then trafficked with loaded (255 pounds) trailer-size tire	—	•Zamboni snow more realistic than ice, but still different than fresh natural snow •Fairly realistic trafficking	•Large deicer application rate (equivalent to 2000 pounds per lane mile) •Deicer application method did not allow "scattering" of dry salt, which would be expected in the field
Leggett, 1999	Friction of anti-icers at various humidity levels	Anti-icing; application rate not reported for all products	Laboratory chamber varied between 23 and 50°F (-5 and 10°C)	—	Sandblasted glass plate	—	Varied from 30 to 50 percent	•Preliminary look at temperature and humidity effects on anti-icers	•Unrealistic pavement •The two glass surfaces did not exhibit comparable friction values
Leggett and Sdoutz, 2000	Friction of anti-icers at various humidity levels	Anti-icing at 25 gal. per lane-mile; 17 products tested	Laboratory chamber at 41°F (5°C)	—	Asphalt substrate taken from in-service road	—	Varied to cause anti-icer to dry out then raised (some products absorbed moisture)	•Gives road friction after anti-icing and prior to precipitation event	•Tire on drag sled friction tester degraded so comparisons across tests could not be made •Testing is limited to above-freezing temperature and no precipitation; would be nice to see friction after "snowing," "trafficking", and "plowing"
Sdoutz and Leggett, 2001	Friction of anti-icers at various humidity levels	Anti-icing at 25 gal. per lane-mile; 15 products tested	Laboratory chamber at 41°F (5°C)	—	Tined concrete made to match bridge decks	—	Varied to cause anti-icer to dry out then raised (some products absorbed moisture)	•Gives road friction after anti-icing and prior to precipitation event •Better use of drag sled friction tester so comparisons between tests can be made	•Testing is limited to above-freezing temperature and no precipitation; would be nice to see friction after "snowing," "trafficking", and "plowing"

Notes: — indicates not available from reference. None of research described above tested long and short wave radiation or wind.

Portable Methods used to Measure Friction for Laboratory and Field Applications

British Pendulum Tester

The British Pendulum Tester (BPT, aka Portable Skid Resistance Tester or TRL Pendulum Friction Tester) can be used to provide a measure of friction in the laboratory or field (Figure 11). The BPT was developed by the Road Research Laboratory, now the Transport Research Laboratory, in the UK. ASTM E303 describes the equipment and operation of the device. The BPT has a pendulum arm that is initially horizontal. When activated by a button it is released, swings down, slides across the pavement, and then swings up. At the bottom of the arm is a rubber slider. The distance the arm swings up is noted along a scale that provides a British Pendulum Number (BPN). On higher friction surfaces, more energy is lost due to the friction and the arm does not swing up very high, which corresponds to a higher BPN. Lower friction causes the arm to swing higher and results in a lower BPN. Four replicate swings are performed to provide the average BPN for a single location. In the field, the BPT should be used in several locations. According to Munro Instruments, the BPT "is intended to correlate with the performance of a vehicle having patterned [tires], braking with locked wheels, on a wet road at [31 mph]."

Figure 11 British Pendulum Tester (picture from http://www.highwaysmaintenance.com/skidtext.htm)

Fujimoto et al. (2010) developed a model to predict the BPN for a pavement topped with freezing water and freezing dilute solutions of sodium chloride. Laboratory experiments performed with the BPT showed good agreement with the model's predictions.

Handheld Tribometer

A handheld tribometer available from Kett (Villa Park, California) provides the coefficient of static friction on the measuring surface (Figure 12). The unit is about 2.5 in wide, 8 in long, and battery operated. The unit measures the force needed to overcome static friction and move a slider on the surface. The slider is about the size of a U.S. quarter. The standard slider is metal, but liquid sliders and rubber sliders are also available. A small motor pushes the slider and the force needed to initiate movement is recorded and used to determine the coefficient of static friction.

Figure 12 Handheld Tribometer available from Kett (picture from http://www.kett.com/prod10.asp)

Dynamic Friction Tester

The portable Dynamic Friction Tester has a disc that spins with three spring-loaded rubber sliders mounted on the underside (Figure 13). ASTM E1911 is the standard test method for the dynamic friction tester. The spinning disc is lowered to the pavement and the friction between the rubber sliders and the pavement causes the rotational speed to drop. Torque measurements are converted to friction measurements. The device is usually operated at several different speeds, corresponding to 12, 24, 36, and 48 mph. The standard test method also calls for a water supply device such that wet pavement is measured—this would have to be omitted for winter research, although no record of this device for research of snowy or icy roads was found.

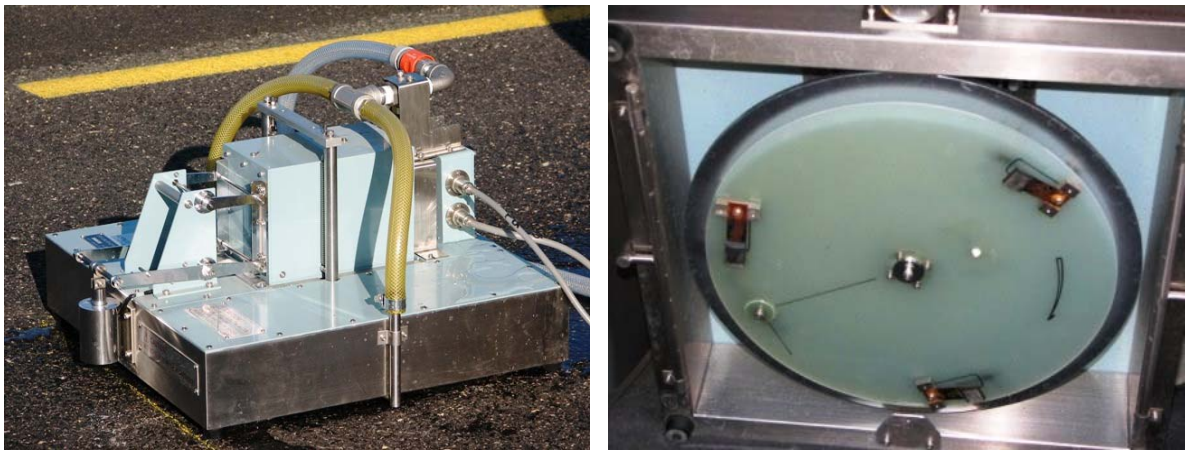

Figure 13 Dynamic Friction Tester (pictures from http://www.michiganltap.org/workshop/materials/2008AsphaltMaintenance/presentations/Wood-Fog_Sealing.pdf)

Comparisons between Laboratory and Field Measurements

There is an astounding variety of methods and equipment for measuring friction on roads and runways. However, methods used in laboratory settings do not exhibit the same variety and, as a whole, seem very different than field devices. This leads to the question of how laboratory or portable devices relate, or correlate, to the friction between a vehicle and the road. No literature was found that addressed this issue. However, one paper was identified that looked at both laboratory and field testing in which friction was measured. Takeshi et al. (2004) measured friction in the laboratory and field, using different devices. The researchers designed a "simple skid friction measurement device" (described previously) for friction measurements of pavement treated with different liquid anti-icers. No snow or ice was used, but the temperature was varied from 36 to 14°F (2 to -10°C). In the field a road surface skid measurement vehicle was used, but the vehicle was not described in the paper. The intent of the laboratory experiment was just a simple assessment of friction to ensure something very slippery was not going to be applied on the road. In general, the friction results from the field test did not match the laboratory tests, but many variables were different—including the friction measurement device—therefore a good comparison or correlation cannot be concluded.

State of Practice in Aviation

Despite previous harmonization attempts, friction measurement in the aviation industry is not uniform. Friction measurements collected during summer are associated with the construction and maintenance of runways and taxiways. Friction measurements are collected for operational reasons in the winter to communicate runway conditions.

In Canadian airports, deceleration measurements are used in the standard winter friction reports. The Canadian Runway Friction Index (CRFI) resulted from a harmonization effort and in 1998 replaced the previously used James Brake Index to reflect the use of various decelerometers available to airports (Layden, 1998). The test vehicle equipped with a decelerometer travels along a runway at a speed of 31 mph and applies the brakes every 1000 feet (Gagné, 2010 and Transport Canada, 2010). Deceleration measurements are converted to a CRFI, which has a scale of 0 to 1, with values above 0.8 representing dry bare pavement (Transport Canada, 2010). Values below 0.4 require a "Notice to Airmen" (NOTAM).

Deceleration devices are also approved for use in U.S. airports during winter conditions, as well as CFMEs. When using decelerometers, a runway is split into three zones and while the vehicle travels at 20 mph at least three braking tests are performed in each zone. If the runway has patches of snow/ice with some bare pavement, the measurements must be taken on the contaminated areas to provide conservative reports. Importantly, the friction measurements are not used in absolute terms and are not correlated to runway surface conditions (good, fair, poor) or aircraft braking action. Rather the trends of friction measurements are used to assess the effectiveness of treatments (FAA, 2008).

There are inconsistencies in the literature regarding vehicles with ABS. According to ASTM E2101, a vehicle with a 4-wheel ABS cannot be used, unless the system can be disabled. However, a vehicle with a rear-wheel ABS is acceptable because the front brakes can still be locked. In contrast, Wallman and Astrom (2001) mention that Sweden, Norway, and Finland frequently measure friction of winter roads using normal passenger cars with ABS and decelerometers. Because the friction value is highly dependent on the vehicle and tires, Sweden requires the car to be calibrated against one of three fixed-slip devices (BV11, BV14, or Saab Friction Tester). In the past, standard Canadian practice was to disable the ABS, but the systems are increasingly more complicated and some cannot be disabled. A Canadian study aimed to assess whether the CRFI value was affected by whether a vehicle's ABS was on or off (Comfort and Verbit, 2003). Ultimately, no universal trends were apparent—that is, sometimes friction was higher with ABS and other times it was lower, and occasionally the friction value was the same whether or not the ABS was disabled. The authors recommended Transport Canada examine whether the variation in the CRFI-inferred aircraft landing distances are significant. According to Nixon (1998), the Coralba Meter (a type of deceleration meter) should be used in a vehicle with ABS and the brakes should be applied such that the ABS is engaged.

The Joint Winter Runway Friction Measurement Program (JWRFMP) between the FAA and Transport Canada developed the International Runway Friction Index, but it is not currently being practiced by the United States or Canada. The JWRFMP "identified serious issues with the present ground-friction measuring devices, related to: (a) the limited number of surfaces on

which they can provide reliable data; (b) the repeatability and reproducibility of the devices and the device families; and (c) the stability of the device readings over time, etc." (Comfort et al., 2010).

A more recent Federal Aviation Administration Aviation Rulemaking Committee for Takeoff and Landing Performance Assessment (TALPA ARC) was formed in 2007 and is promoting a revolutionary process that links information gathering with assessments of aircraft performance. The TALPA ARC developed a Runway Assessment Matrix that stresses contaminant type, depth and temperature above friction measurements. A runway code between 0 (corresponding to the following conditions: wet ice, ice above 27°F, water on top of compacted snow, or snow on top of ice) and 6 (dry pavement) is determined for each third of the runway. Friction measurements are not the primary source of information, and if collected, can only be used to downgrade the runway code and not increase it (Comfort et al., 2010).

A recently completed (March 2010) study for the European Aviation Safety Agency describes the current role friction has in airport maintenance and operations. Notably, runway condition and friction reports are not harmonized, but that is the current objective in order to increase safety. Comfort et al. (2010) looked at existing practices at European airports. During the winter season, three sources of information are generally used:

- friction as determined by a ground-measuring friction device,
- surface conditions, including contaminant type, contaminant depth (measured with a ruler), and cleared width
- pilot reports from previous landings

Air carriers generally consider reports of surface conditions, friction, and braking action to be of high value and high priority. Pilots request information about surface condition and friction values more often than general indications of braking action. However, the recent trend of the TALPA ARC to de-emphasize friction measurements is firmly based in the reality of the complexities of friction measurement and the lack of a device appropriate for all surface conditions. Comfort et al. (2010) indicate a fresh approach is needed to produce "a device that would correlate well with an aircraft on the full range of contaminated surfaces."

Relevant Parameters

Promoting best practices and maximizing the effectiveness and benefits of snow and ice control operations, entails advances in micro-scale road weather forecasting and sensing (especially important to the timing of anti-icing strategies), more integrated and automated onboard sensor technologies, vehicle-infrastructure integration (VII), improved understanding of the "dynamic layer" on the road surface and its relationship with pavement friction, better science to determine the proper timing and frequency of anti-icing and deicing, and better means to quantify the performance and impacts of winter road maintenance.

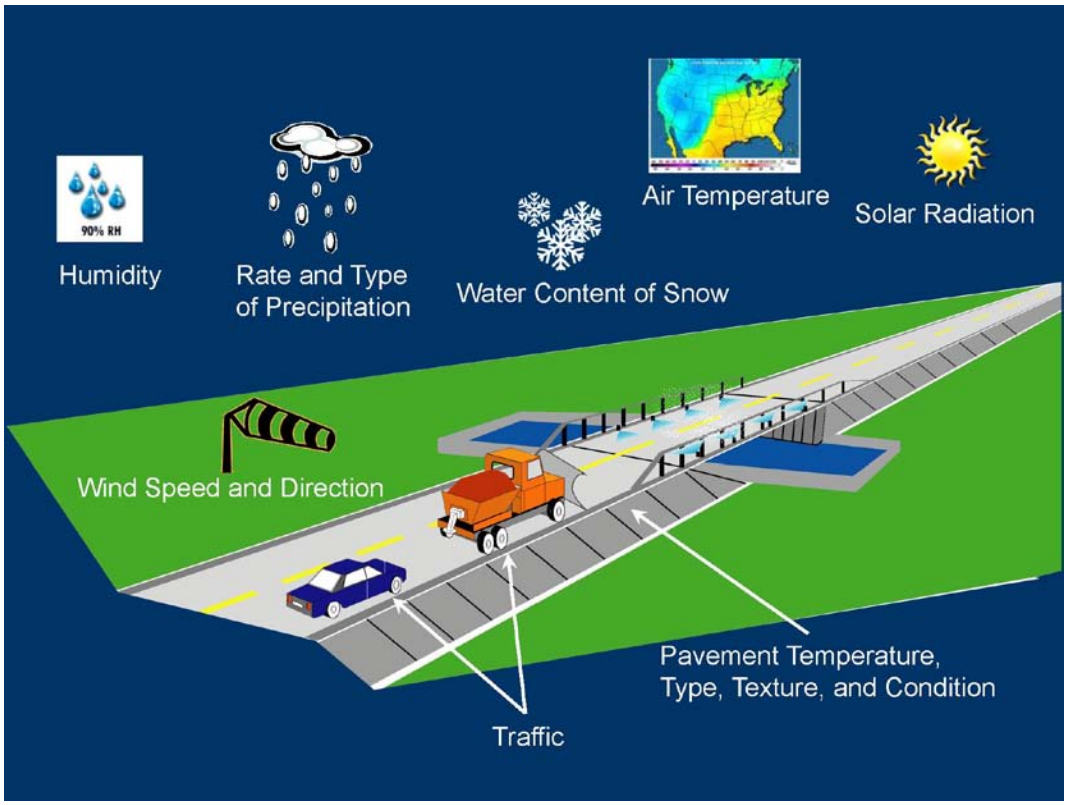

Figure 14 Schematic diagram illustrating the major parameters that influence the deicer performance and friction coefficient on treated pavement.

There are many parameters in the real world that likely play a role in the effectiveness of deicer products used in winter maintenance. These include traffic, pavement type and condition, and meteorological conditions (as shown in Figure 14). The amount and type of traffic influence road conditions, as do pavement temperature, type, texture, and condition. Meteorological conditions that are important include air temperature, wind speed and direction, solar radiation, humidity, rate and type of precipitation, water content of snow, etc. Also important are the physical and chemical properties of deicers such as gradation (for solids), color, and thermal properties. The purpose of this section of the literature review is to establish a

baseline of the current understanding of these parameters from experience gained either in the laboratory, in the field, or from agency surveys. Ultimately many of these parameters are interrelated. For instance, the snow density is to some extent affected by road traffic and the pavement temperature depends on past air temperature, solar radiation, and pavement type. Nature provides an infinite number of combinations that would be extremely difficult to replicate in the laboratory.

This literature review will provide information to identify what parameters and settings will need to be incorporated in a laboratory test to best simulate and predict the actual field performance of deicers.

Traffic

Roads are built for vehicle travel and a significant amount of resources are utilized to keep roads open to traffic during winter conditions. "Traffic can have both positive and negative influences on the effectiveness of snow and ice control operations" (Blackburn et al., 2004). For instance, tires can compact snow and create a bond between the snow and pavement, depending on the temperatures and whether freeze-point depressants are present. However, light, fresh, dry snow can easily be blown off the road by traffic. Heat from the friction between the tires and road can contribute to melting in the wheel paths or help dry the road (Keyser, 1973; Stotterud and Reitan, 1993; and Blackburn et al., 2004). Traffic can also help break up ice cover and improve the penetration of solid deicers (Nixon et al., 2005). Vehicles also play a helpful role in mixing chemicals and creating slush, which is easily displaced by subsequent traffic (Keyser, 1973 and Luker et al., 2004). Unfortunately, traffic can also scatter and displace chemicals from the road (Blackburn et al., 2004 and Nixon et al., 2005) and ongoing research is conducted to improve the application methods and equipment and to minimize this "scattering" effect.

Ultimately, traffic plays a complex role that is notably absent from the vast majority of laboratory tests. Only one test was found in which traffic was incorporated: Luker et al. (2004). In this case a single tire was rolled in a back-and-forth motion across snow-covered concrete pavement samples treated with dry and prewet salt. The procedure was able to simulate some of the benefits of traffic—helping to penetrate and mix deicer with snow and displace the slush—but did not incorporate the "scattering" effect. Other experiments have compacted snow for the purpose of "simulating" this effect of traffic, but do so with means other than rolling tires (Adams et al., 1992; Nixon and Wei, 2003; Cuelho, 2010).

Pavement Temperature, Type, Texture, and Condition

Pavement temperature is a critical factor in the performance of deicers (Keyser, 1973 and Blackburn et al., 2004). It is common knowledge that the melting capacity and melting rate of

deicers is reduced at lower temperatures. In regards to deicer performance, pavement temperature is more important than air temperature—air temperature affects the precipitation, but pavement temperature affects the deicers (Keyser, 1973) and the "dynamic layer" on the road surface.

There are a variety of pavement types, textures, and conditions. In general a pavement surface is either asphalt or concrete. According to Keyser (1973) concrete pavements give up heat more rapidly and therefore the melting process is more rapid. However, dark asphalt pavements heat up faster in sunlight. For identical situations, concrete pavements require higher application rates of liquid products used for anti-icing than asphalt pavements (Cuelho, 2010). The pavement surface type and condition can be a rough or smooth surface. Rough or porous pavements have more surface area and can cool faster than smooth pavements. Rough pavements can also require more chemicals, but offer better friction than smooth pavements (Noort, 1997). In asphalt pavements, snow and ice adhere to the exposed aggregate and not the asphalt bitumen, but snow will bond to the aggregate and mortar phases of concrete pavements (*Personal Communication*, Ed Adams, Ph.D., August 13, 2009).

During the 1976-1977 winter season, FHWA sponsored studies in the states of Maine, Michigan, Utah, and Vermont to determine if more sodium chloride was needed to clear open-graded asphalt friction courses during winter storms than was needed to clear conventional asphalt pavements (Besselievre, 1979). It was found that the clearing rates and appearance of open-graded and dense-graded pavements were different. Dense-graded pavement showed occasional faster clearing than open-graded pavements. The open-graded pavement, however, seemed to provide a superior skid-resistant surface during most storms without more salt used to maintain the surface.

Open-graded asphalt mixes commonly used in asphalt pavements fall into three categories: open-graded friction course (OGFC), stone matrix asphalt (SMA), and open-graded base material (OGBM), of which only OGFC and SMA are used as surface course. Accordingly, previous research related to deicer effects on the skid resistance of pavement surfaces focused mainly on these two types of mixes. OGFC and SMA are generically referred to as open-graded mixes (OGMs) or open-graded pavements (OGPs) in deicer studies. OGMs, especially the OGFC, are known to offer lower noise and higher friction between tires and road surface. However, in terms of the skid resistance when deicers are applied, the limited research efforts thus far have yielded quite contradictory conclusions regarding their performance under winter conditions. While some reports indicated that these mixes were problematic when subjected to wet-freeze conditions (Kandhal and Mallick, 1998; Heystraeten and Diericx, 2002), others reported enhanced performance (Iwata et al., 2002). Such risks, if proven to be true, need to be

addressed, considering the increased wet-freeze frequencies on pavement surfaces when deicers are applied.

The Virginia Department of Transportation sponsored a study (Flintsch, 2004) to examine its winter maintenance techniques of applying sodium chloride in granular, pre-wetted, and liquid forms. The snow removal and ice control operations followed the recommendation by the FHWA Project TE-28. There were no significant differences in the performance of the different surface mixes, including OGFC and dense-graded mixes. A more recent study (Martinez, 2006) by the Oregon Department of Transportation was conducted on the effects of liquid magnesium chloride on OGP. Skid tests were performed on four sections of two different highways in Oregon under three conditions: 1) no deicer application; 2) after a deicer application rate of 15 gallons/lane mile; and 3) after a deicer application rate of 30 gallons/lane mile. The results of the skid tests showed that the application of deicer appeared to have little if any effect on the Friction Number, which were all well above the FHWA recommended minimum values.

There are several examples of research projects incorporating realistic pavement samples in laboratory experiments (Ashworth et al., 1989; Nixon and Wei, 2003; Luker et al., 2004). However, there are few in which the pavement temperature was controlled independently of the air temperature, which is a more natural scenario (Bernardin et al., 1996 and Cuelho, 2010).

Meteorological Conditions

Air temperature and relative humidity

Air temperature affects the density of snow during a snowstorm. During cold storms (air temperature lower than 10°F (-12°C)), advanced (prior) treatment is not recommended because the snow will usually be too dry to easily bond to the pavement (Keyser, 1973). Most laboratory experiments identified in the literature review were conducted at various air temperatures, probably because it is a more easily controlled parameter.

Humidity can play an interesting role in deicer performance, particularly with hygroscopic deicers such as calcium chloride and magnesium chloride. Calcium chloride can attract moisture at relative humidity levels between 46 and 60 percent (Keyser, 1973). Goyal et al. (1989) studied the effects of high (90 to 100 percent) and low (5 to 20 percent) relative humidity on ice melting tests using two solid sodium chloride deicers and a liquid magnesium chloride deicer. One sodium chloride deicer was fairly pure (99 percent NaCl). The other sodium chloride deicer was only 80 percent NaCl, 15 percent corrosion inhibiting compound, and 2.3 percent $MgCl_2$. The liquid $MgCl_2$ melted similar amounts of ice at 14°F (-10°C) in low and high relative humidity scenarios. However, the corrosion inhibited sodium chloride deicer (which contained a minor amount of $MgCl_2$) melted more ice than the other sodium chloride

deicer in the following situations: 1) temperatures greater than 15°F (-9°C) and high relative humidity with high application rate of 745 lb/lane·mile, and 2) temperatures less than 15°F (-9°C) and low relative humidity with low application rate of 126 lb/lane·mile. In most laboratory tests, humidity was not measured or controlled.

Long- and short-wave radiation

Solar (short-wave) radiation contributes to heating road surfaces, which can be more than 10°F (5.5°C) warmer than the air (Keyser, 1973), although the presence of snow can reflect some of the radiation and reduce the heating rate. Thermal (long-wave) radiation occurs at night as roads give up heat and experience lowering temperatures.

Work completed for the Pacific Northwest Snowfighters Association (PNSA) Pool Funded study investigating corrosion inhibitor longevity and deicer performance involved conducting a laboratory experiment to quantify the impacts of UV radiation on corrosion inhibitor longevity. FreezGard CI Plus, Calcium chloride with Boost, NaCl brine with GLT, and an experimental IceSlicer Elite were exposed to UVa[1], UVb, UVa+b radiation at temperatures 104, 82.4, 64.4, and 15.1°F (40, 28, 18, -9.4°C) and for time periods of 24, 48, 72, and 96 hours. A control of no UV exposure was used for each temperature and time period. Preliminary results suggest that under the conditions of accelerated testing present in this experiment no significant degradation of the corrosion inhibitors occurred, likely due to the short experimental duration. Experiments of deicer performance that included long- and short-wave radiation were not found.

Physical properties of precipitation

Air temperature affects the density of falling snow during a storm. However, traffic and pavement temperature can alter the density of snow. Freezing rain, freezing fog, or frozen meltwater can create icy road conditions. The density of ice is greater than compacted snow (Nixon and Wei, 2003). Most laboratory experiments use ice made by freezing water. There are a few studies that incorporated snow (Adams et al., 1992; Nixon and Wei, 2003; Luker et al., 2004; Cuelho, 2010) but in all cases the snow was not fresh. Aged snow begins to resemble porous ice, but Luker et al. (2004) found the density of compacted Zamboni snow, compacted aged natural snow, and compacted fresh snow were all about 44 pounds per cubic foot. However, tests with deicers should be performed with fresh and aged snow to ensure aged snow is appropriate for laboratory use. Harvested snow will likely provide more repeatable initial test conditions and be more available year round, but if deicer performance is significantly different on aged snow versus fresh snow, then it would be important to establish a correlation such that tests with aged snow can be numerically corrected.

[1] Ultraviolet radiation (UV) for wavelengths a (long wave length) or b (medium wave length), and a and b.

Wind

Wind is an important parameter related to cases of blowing and drifting snow, which can contribute to excessive snow buildup on roads (Hershey and Osborne, 2008). Wind can help displace snow from roads, but can also expose the road to more snow. Anti-icing can cause blowing or drifting snow to stick in situations where it might otherwise blow away (Adams et al., 1991 and Mn/DOT, 2010). Weather predictions and models of the terrain surrounding a roadway can indicate places where blowing and drifting snow is likely to occur (Hershey and Osborne, 2008 and Perchanok et al., 2008), but the effect and importance of wind on the performance of deicers has not seen extensive research. No laboratory test was identified that incorporated wind, although Adams et al. (1991) conducted controlled anti-icing field tests during various wind and temperature scenarios and used a Saab Friction Tester to assess performance. They found that the friction of chemically treated test sections decreased as wind speed increased, whereas untreated test sections at low temperatures experienced more scouring under higher winds and had higher friction.

Previous Correlation of Laboratory and Field Data

Many laboratory tests have been conducted to assess performance of deicers, some of which mimic field conditions better than others. However, correlations between laboratory performance and field performance are not addressed in most of the studies that were reviewed and only a few studies were found that involved both laboratory and field tests. There is good reason to believe that many existing laboratory tests do not accurately predict field performance, as illustrated recently by Alatyppö and Jutila (2010). Alatyppö and Jutila (2010) reported on the relative performance of a new airfield deicer (50 percent betaine solution) to two reference deicers (50 percent potassium formate solution and solid NaCl) in laboratory and field tests. Three laboratory tests were performed: SHRP H-205.1 (SHRP Ice Melting Test), SHRP H-205.3 (SHRP Ice Penetration Test), and a new test that combines these two. The laboratory tests showed that potassium formate had twice as much deicing efficiency as betaine, and sodium chloride had twice as much efficiency as potassium formate. Thus, from the laboratory tests conducted at 21 and 28°F (-6.1 and -2.2°C), it appeared that betaine was not going to be an effective deicer. Still field tests on a runway were undertaken using betaine and potassium formate (NaCl is not used on runways and was not included in the field test). Two performance measures were used: ice thickness and runway friction. In both cases, betaine and potassium formate performed very similarly and better than predicted from results in the laboratory—"i.e., the results of the field tests correlate in no way with the results obtained from the laboratory tests" (Alatyppö and Jutila, 2010). Operational use of betaine at two airports since 2005 and a third since 2007 has shown betaine to be an effective and efficient deicer. This stresses the need for more realistic laboratory tests and correlation factors that can be used to predict field performance.

Interview Responses

Key individuals were identified and interviewed to gain their insights on their areas of expertise. Information sought in the interview process included, but was not limited to, lessons learned from laboratory and field research, project costs, equipment design and cost, etc. Provided below are summaries of each interview. The complete interviews can be found in Appendix A: Interviews.

Laboratory and Field Tests to Characterize Deicer Performance

Charlie Pizino works for the Midwest Research Institute (MRI) and helped develop the *Handbook of Test Methods for Evaluating Chemical Deicers* (referred to as SHRP *Handbook*). He did not think that the SHRP tests can directly correlate with field tests, but did state that the laboratory tests may provide some guidance in developing and interpreting field tests. He then quoted the introduction to the test handbook (SHRP H-332), "After initial evaluation in the laboratory, field testing is ultimately required to determine acceptable performance and compatibility." He said he does not feel a laboratory test can be designed to correlate with field performance of deicers, but suggested one way to get close to this would be a gradual scale up starting with laboratory research, followed by research conducted outside on a sidewalk, then a parking lot, and finally on a street section. In addition to the information in Table 5 he suggested that effects the deicers have on humans and the environment need to be considered and that a cost benefit analysis should be completed for each product. In his opinion, it is possible to quantify the identified parameters, at least in a relative way, but it is impossible to design one laboratory test that will be able to test for all of the parameters. This is also true for a field test.

Deicer concentrations used for laboratory testing were based on field concentrations and manufacturer's recommendations and were scaled down as needed for each laboratory test. He identified where assumptions were made or errors could have occurred, including during the laboratory tests, in substrates (corrosion test coupons, concrete test samples, pavement substrates, etc.), in applications rates and test conditions, and in the method of growing ice test substrates (which may or may not have resulted in ice that would be characteristic of a real-world scenario). He does not feel a laboratory test can be designed to correlate with field performance of deicers, but suggested one way to get close to this would be a gradual scale up. Project cost information is provided in Table 6.

Jim McGraw and *Allen Gallistel* work for MnDOT and conduct the laboratory testing on deicing/anti-icing products. MnDOT uses the SHRP ice melting test method to initially evaluate products (they use it as screening tool). If they get good ice melting capacity results MnDOT will then conduct field testing of the product, but if the ice melting results are poor they will not

move forward with that product. MnDOT uses the ice melting capacity to get effective temperature and dilution effects on products as well. They also use chemical analysis to look for active ingredients and corrosion inhibitors, have the ability to conduct the PNS corrosion test, and use the ASTM titration method to evaluate $CaCl_2$ and $MgCl_2$. They both acknowledge that the ice melting test and effective temperature are important parameters to measure in the laboratory but suggested that there is no field equivalent of these tests and one would have to rely on field experience to get this information. They think that humidity, air and pavement temperature, and traffic should be considered in the laboratory if trying correlate results with the field. In their opinion, these parameters are easily quantified in the laboratory and field, with the exception of traffic which may be difficult to quantify in the laboratory. They suggests that one route for field testing would be to survey the drivers while using a specific chemical, measure the times, and collect the data and then try and correlate this with the laboratory data. They acknowledge that the information collected this way would be anecdotal, yet useful.

Tim Kline works for MnRoad of MnDOT and is a pavement engineer. MnRoad was built as a structural design experiment to verify the AASHTO pavement design methods. Over the years they figured out that the environment has more of an effect on the road than traffic. MnROAD currently has 55 different test cells and 20 different ongoing research projects. Research is funded or being conducted for MnDOT, local agencies/government, asphalt and concrete companies, universities and other private vendors. Most projects are material or construction related with a lot of green initiatives—reduce, reuse, recycle.

MnRoad has not conducted laboratory or field testing of deicing performance research other than friction measurements. MnRoad does not own but has used/tested three different friction measuring devices, 1) Dynatest 1295 friction trailer which is locked wheel skid tester, 2) Dynamic friction tester (portable ASTM E 1911 device), and 3) Grip Tester (Virgina Tech design). When conducting friction testing, at least four tests are run for each device and the average is reported, with testing conducted multiple times per year to capture seasonal variation. They also measure the change over time due to traffic. MnRoad has two weather stations which they use to monitor all major parameters.

The parameters MnROAD can closely control include the materials used in the construction of the test cells and the structural specifications of the test cells. MnROAD has a low volume road which they traffic with a fully loaded truck. There is also a main line parallel to Interstate 94 so live traffic can periodically be used—the traffic on this section cannot be controlled and the construction can be a variable because they contract to the lowest bidder so work for different test cells can be done by different companies. At MnRoad a 10 percent or less error rate is targeted for collected field data.

When asked to comment on the best way to determine deicer performance he suggested that there were two ways, 1) the amount of time it takes to get to bare pavement and 2) by looking at accident rates. Of the three friction testing devices used he recommended using the Dynamic friction tester because it only requires 2-3 square feet of pavement to conduct testing, while the other are towed behind a truck.

Wilf Nixon of the University of Iowa has extensive experience conducting laboratory and field research on deicers. When asked if laboratory and field data collected for deicer performance could be correlated he replied with a qualified yes, and suggested that the tests can tell you something about how chemicals perform, but went on to say that the definition of performance is important. For example if performance is defined as persistence on the road that is very different from melting ability. He believed that information gained from laboratory testing could be used to somehow correlate with what is observed in the field. When asked how he would design a laboratory test to correlate with field performance of deicers he commented that you need to identify the important parameters and define them. He went on to say that if performance were defined as persistence, relative performance, and corrosion; each of these parameters would require a different laboratory test. He explained that with laboratory tests you can control everything, and you may see a difference between parameters that ends up not being important or relevant in the field, while in the field you cannot control anything. When asked how he defines deicer performance his response was bare pavement—i.e., how does snow cover on a road change after treatment.

When asked what parameters are important to consider in deicer performance and whether these parameters were quantifiable in the laboratory and field he responded that pavement temperature can be measured in the laboratory and field, dilution of chemicals has been measured in the laboratory but may be more difficult in the field requiring snow density and precipitation rates, persistence of products can be measured in the laboratory but at this point has only been noted anecdotally in the field, and corrosion which has been measured in the laboratory and field (e.g., the Washington State DOT Salt Pilot project). For field testing on corrosion he stated that there are so many materials to test, different metal types, combinations of different metals and welds. He expressed concern with coupons and high corrosion rates from varying combinations of metals that create a cell that ends up increasing corrosion rates. Testing all possible metal types and all possible combinations of metals would be a substantial number of samples to test. He suggested for a field test to consider setting up varying maintenance protocols where you change the types of cleaning for maintenance vehicles (e.g., no washing, water power wash, soap and power wash, etc.). This will only give you qualitative data but it will be usable data (by winter maintenance practitioners). When asked what could go wrong he said that making uniform ice in the laboratory was difficult and

took a long time to master, and that you need to consider how many air bubbles are in the ice. He recommends that once a laboratory test is successfully developed a commercial laboratory should conduct the test to help keep costs down.

Shear and Disbondment Tests

Wilf Nixon of the University of Iowa has extensive experience conducting laboratory shear and disbondment testing on deicers. When asked why he did not use a shear/disbondment test method that was already in place he stated that they tried to use a low rate (slow moving) disbondment test but saw a significant effect in the results with changes in speed. The maximum speed they could attain was $^{1}/_{10}$ mph and they were trying to compare these laboratory results to field speeds of 30+ mph and concluded that the laboratory test was not realistic and highly variable. Instead they came up the idea of using a ram so that they could match the 30 mph speed seen in the field. The experimental design looked at different cutting edge shapes under the SHRP program. Initially up to 10 replicates were required for a given condition but with time and experience the results got better and repeatability increased and they were able to go down to running samples in triplicate. Some conditions were highly variable such as bong strength versus time after chemical application and for these they ran extra samples. They used a factorial approach and a plot of the axis of variability to quickly come up with a working experimental design. The experimental design was based on temperature ranges typically seen in Iowa and Iowa DOT application rates for deicers. The deicer application rates may have been modified to achieve more consistent laboratory results. Ice thickness was another parameter considered in the experiment. When asked if he thought it would be difficult to incorporate other parameters in this test method he said it would not be difficult, but that one thing you need to consider is the size of the equipment (30 x 5 x 5 ft) being housed in an environmental chamber.

One issue they had was that the ram was 6 ft by 1 in steel and required a lot of pressure to travel at 30 mph so the machine jumped (had a “kick-back”). He said they used a brute force method that was not further finessed due to the time crunch of the project but he highly recommends that if this method were to be used that it be refined and housed in a cold room. He is nervous about saying this could be a standard test method because it may not be practical and it was expensive to make, and get up and running. He suggests we get a group of folks together and chew through it. He also questions whether undercutting is the right thing to test. He is skeptical that one test can be developed to adequately test all parameters/variables to predict field performance. For field testing he recommends having two ways to measure each parameter.

Arlene Beisswenger of the Anti-Icing Materials International Laboratory (AMIL) at the University of Quebec at Chicoutimi was involved in the development and testing of airport pavement anti-icers. AMIL had a long history of researching and testing aircraft deicing fluids before Transport Canada (the Canadian equivalent to the FAA in the United States) approached them about looking into runway deicers. They had extensive experience with the Water Spray Endurance Test for aircraft deicers and decided to start with something like that, but with pavement substrates instead of aluminum. They initially looked at performance as whether the freezing rain visibly appeared to bond to the pavement, as well as percentage of ice melted. However, they decided plowing needed to be simulated in the laboratory and developed the scraper system. A rubber pad was used to measure friction to provide a quantitative measure of performance instead of just a visual assessment of anti-bonding performance. They found it was important to find a proper substrate, and while concrete would have been nice, the porosity caused reproducibility problems. They also felt it was important to use realistic stresses on the scraper system. Overall, they caution that laboratory test results will not match field tests due to scaling effects. Instead, they say laboratory tests are better for comparison testing, unless you specifically look at the relationship between laboratory and field testing.

Friction

Tim Leggett and *Gerald Sdoutz* of Forensic Dynamics, Inc (FDi) routinely conduct friction tests on pavement treated with anti-icers. Their drag sled device works well for wet or icy conditions, but they have not used it on snow or slush, which they think would just be plowed from the surface by the locked tire. The drag sled travels slowly across the pavement so the friction results are more comparable to static friction, which is about 15 percent greater than kinetic friction. Since testing is routinely conducted on dry or wet pavement instead of snow, the unloaded tire seems appropriate, but if you have snow or slush, a loaded tire could be more realistic because it could better simulate the mixing and mechanical energy provided by traffic. FDi built a smaller friction tester that used a rolling tire with a resisting spring, so the tire would start out rolling and eventually come to a stop while being pushed across the test surface. Friction was calculated based on the amount of rolling that occurred before sliding. This friction tester (the In Road Friction Sensor) was recently damaged during shipping and is not going to be rebuilt. Instead FDi thinks it would be better to start over with a larger device to avoid scalability issues. They have a few different ideas for something more realistic. One thing that could be tried is to build a trafficking apparatus that could traffic samples for a while and then apply a braking force to measure friction. You could continue trafficking while intermittently measuring friction, as well as simulate plowing at some point. Alternatively, you could try using an existing friction trailer. The ones that have variable slip speed would probably be better so you could observe friction as a function of slip. The friction trailer could

then be used in field studies; you would just want to make sure you did some slow-speed tests like in the laboratory so you could make comparisons. FDi had a few other suggestions, such as making sure you measure humidity because the performance of some deicers (e.g., calcium chloride) is more dependent on humidity than temperature.

Max Perchanok of the Ontario Ministry of Transportation (MTO) has participated in several winter projects that involved friction measurements. MTO has three different friction trailers: a Traction Watcher One, a SCRIM, and a Halliday unit. The tire on the Halliday friction tester definitely lasts longer than on the other two units. When asked about the variance of friction data, he said it is fairly low on bare pavement or uniform snowpack. Once there is partial melt or partial snow cover, the variability is much higher so you may need to collect more data. In the field he always sees a difference between treated and untreated test sections. Laboratory tests can measure a difference in performance between different chemicals, but he thinks the field has so many other compounding factors that you do not necessarily see the same relative performance. He did say if we want to predict how a deicer will react in the field, then we need to try to mimic everything: sunlight, humidity, temperature, and traffic. Video cameras can come in real handy with field testing.

Tom Yager of NASA Langley Research Center was involved in the Joint Winter Runway Friction Program that produced the International Runway Friction Index (IRFI). However, he said the FAA does not currently require airports to report friction in terms of IRFI. Regarding laboratory testing, Mr. Yager recommended we look into the Dynamic Friction Tester because it gives friction readings over a wide range of speeds and can be used in the laboratory and field. It can be used on dry and wet pavement, but he does not know if it will work well on snow.

James Wambold of CDRM Inc and PennState University also indicated the Dynamic Friction Tester might be worth trying. He said the Swedish National Road and Transport Research Institute (VTI) in Sweden had a long temperature-controlled tunnel where friction tests with a full-size tire could be conducted up to 40 mph. Something like this could provide better friction measurements where tire contact pressure, wheel type, and slip speed could be considered. Surface condition can affect friction, so he said we might want to just have one asphalt and one concrete substrate.

George Comfort of BMT Fleet Technology has been involved in laboratory and field testing of winter roads and runways using friction measuring devices. At one time he had a 33 ft long paved track in a cold room in which they could do slow-speed friction tests and look at the effect on loaded aircraft tires. The facility was built for the Joint Winter Runway Friction Program, but more recently the space was needed for other work and was taken down. As for the bigger picture, he was recently part of a project for the European Aviation Safety Agency

which provided recommendations for the role friction measuring equipment has and should have in the airport community. Ultimately, Mr. Comfort was able to provide a lot more literature that should be reviewed prior to Phases II and III for this project.

Dr. Sheldon Drobot of the National Center for Atmospheric Research (NCAR) has been working on a different technique to measure friction. He is pulling data from vehicle systems, such as Anti-lock Brake Systems, Traction Control Systems, windshield wipers (the new automated ones that activate when precipitation is sensed), and other systems. They are developing an algorithm to estimate friction so it can ultimately be displayed to the driver. They are doing the testing in Lebonia, Michigan—a suburb of Detroit—that is outfitted with a communication system so the vehicles only need to be modified with a direct short range communication device; it is an IntelliDrive test bed. Dr. Drobot also recently added Vaisala's DSC111 Remote Road Surface State Sensor—it is a non-contact device that provides a measurement of grip. They have only done preliminary testing, but so far the device seems to work well. He recommends we contact Vaisala and see if they will lend one out for the laboratory and field testing for this project. As for trying friction trailers in the lab, he was not sure how well they would work. He suggested trying the Halliday device (although it might not work at low speeds), or looking into one developed in Minnesota by either the DOT or university. He recommended we talk to Curt Pape at MnDOT. Upon doing this, we learned that the friction device operates similarly to the Halliday friction trailer (with an angled wheel) and it is something MnDOT has used, but is not in production. Mr. Pape was not sure if it operates at low speeds. He said we could try the British Pendulum Tester or the GripTester (this is a fixed-slip device used in England), but he was not sure how much space the GripTester needed. Dr. Drobot's work at NCAR is exciting and, this is just speculation, may be at a point where one of his test vehicles could be used during the Phase III field test to provide a measure of friction that a typical vehicle could expect to see.

Table 5 Identified testing parameters and performance characteristics from the interviews.

Identified test parameters	Identified Performance Characteristics of deicers and anti-icers
Traffic	Melt rate/capacity
Pavement type	Penetration rate/capacity
Air and Pavement Temperature	Undercutting rate/capacity
Wind	Effective temperature range
Uniformity of ice/snow pack	Frictional characteristics
Humidity	Capacity to damage pavement/infrastructure/ metals
Dilution of chemicals during precipitation relative to time	Capacity to prevent ice/pavement bond
Persistence of traffic (does the product stay where you put it and how long does it stay?)	
Corrosion	
Sunlight/UV radiation	

Table 6 Project cost and cost per sample of previous research.

Project	Total Budget	Cost per Sample
Anti-icing field test program	$625,000	NA
Ice/pavement bond nature study	$659,000	NA
Ice/pavement disbonding study	$59,000	NA
Deicer evaluation test method development	$309,000	NA
MnRoad-one test cell per year (multiple parameters)	$10,000 to $15,000	NA
MnRoad-friction only per test cell per year	$1,000 to $2,000	$500
Project for Iowa Dot	$100,000	NA
Nixon shear/disbondment equipment fabrication and test development	$50,000	NA
Drag sled friction tester	$50,000	$1,000

Recommendations

A four-step approach is recommended for developing a laboratory test method that aims to correlate deicer performance in the laboratory with field performance, as shown in Figure 15. The key parameters to be tested need to be identified and agreed upon prior to the design of the experiments. The first recommendation is that the laboratory and field test methods be designed at the same time so that the statistical analysis for correlating the laboratory and field data is planned and key hypotheses are identified before any experimental testing begins. The next recommendation is to use a statistical design of experiments (e.g., uniform design or factorial design schemes) to minimize the number of experiments needed to explore a large unknown domain of factors that affect deicer performance and friction coefficient of treated pavement and to capture their complex interactions.

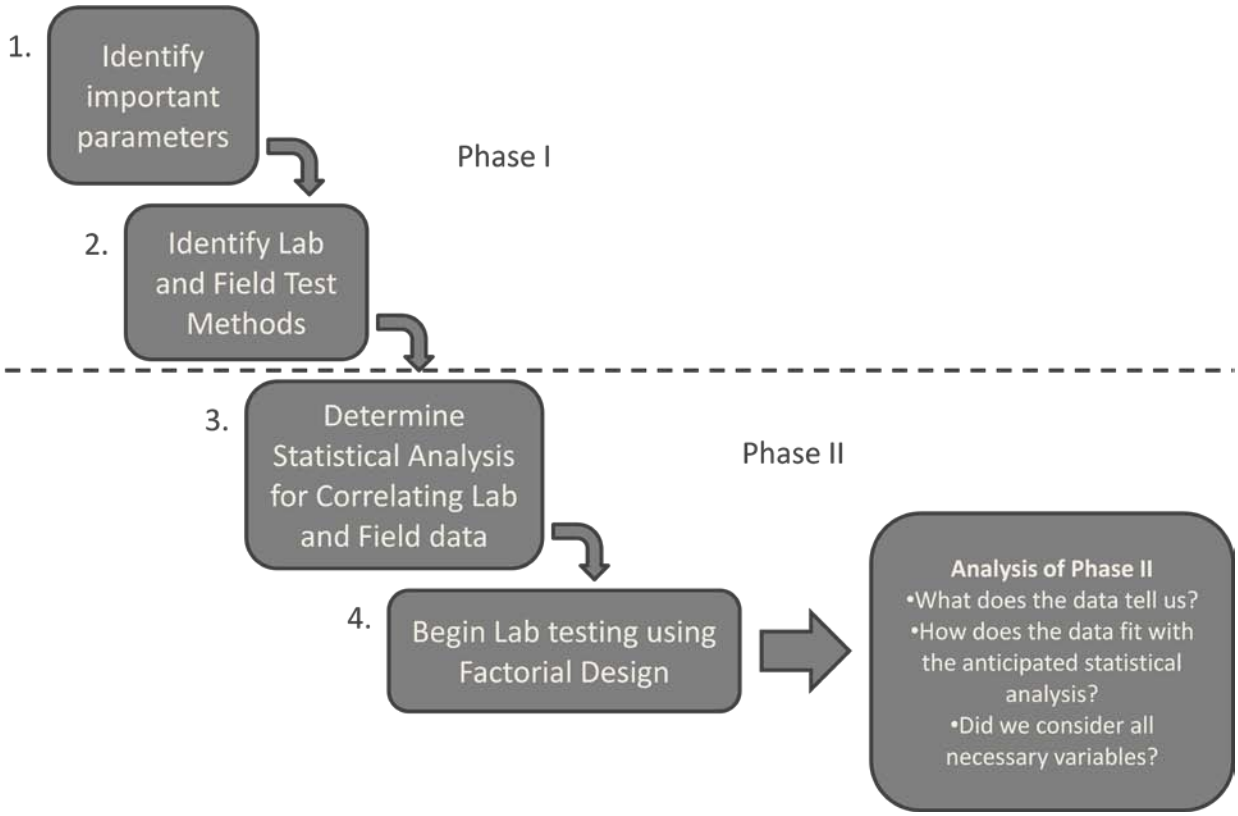

Figure 15 Recommended approach for developing a laboratory test method that will correlate with field deicer performance.

Within Phase I of this research project Item 1 (Identify important parameters) and Item 2 (Identify Laboratory and Field Test Methods) from Figure 15 have been addressed. Items 3 (Determine Statistical Analysis for Correlating Laboratory and Field data) and 4 (Begin Laboratory testing using Factorial Design) should be addressed in Phase II.

Identified Testing Parameters

Table 5 lists parameters that were identified in the interviews that are important to consider in laboratory and field testing of deicer performance. The parameters recommended for consideration are:

- Temperature—air and pavement
- Relative humidity
- Traffic
- Pavement type—asphalt and concrete
- Melting rate of deicers
- Uniformity of Snow/Ice

To quantify the identified parameters recommendations on test methods that can be used in the laboratory are as follows.

Air temperature and *relative humidity* can be controlled and monitored using an environmental or cold chamber. *Pavement temperature* can be controlled independent of air temperature using a heating/cooling table. Temperature sensors will need to be embedded in all pavement samples for accurate pavement temperature readings.

Traffic presents a more difficult parameter to bring into the laboratory. Only one case of trafficking in the laboratory was found while reviewing literature (Luker et al., 2004), and one can argue that it only minimally simulated traffic considering the following: 1) the speed was slow—it was manually operated; 2) only a single tire was used, and 3) it was applied in a back-and-forth motion. Regardless, the research results indicated traffic is important and it seems appropriate to include some level of traffic simulation in this new laboratory experiment. A motorized system will most likely better simulate traffic than a manually pushed system. We do not anticipate a significant difference between a tire rolling over the substrate or the substrate moving under the rolling tire—it comes down to which is more feasible to design and construct. Initial testing of whether a back and forth motion produces a similar effect to a one-direction motion is highly recommended. Accelerated structural testing of concrete bridge decks has not been found to be sensitive to one-vs-two-direction load applications, but asphalt surfaces were shown to require one-direction motion (personal communication with Dr. Jerry Stephens, WTI). While this information is from tests for structural performance and did not include deicers, the fate and transport of deicers subject to trafficking could be different with one-vs-two direction loading, thus the need for preliminary tests. The speed of trafficking in the lab should match that in the field and ideally samples would be trafficked using multiple speeds (consider 5, 15, 30 mph). The lower speeds are reasonably feasible. For instance, if the test section is 4 ft long, a tire traveling at 5 mph would need to cross the section in about half a

second—reasonable for a motorized tester, but not possible with a manually-operated device. Additionally the effect of traffic volume on samples needs to be considered. As previously mentioned traffic is a difficult parameter to bring into the laboratory and the lack of data on this topic makes it difficult to make recommendations. For this reason extensive preliminary testing on trafficking samples in the laboratory is recommended and that the effects of traffic on samples should be investigated. Additional knowledge about the actual impact of traffic or the traffic parameters that are important (speed, vehicle weight, volume) can possibly be obtained by making observations during the next winter season on similarly treated roads with different traffic, such as low-speed versus high-speed roads and low-volume versus high-volume roads. This could help shed light on how to best incorporate traffic in the laboratory.

The two most common *pavement types* are asphalt and concrete, testing on both pavement types in the laboratory and field is recommended. Once the laboratory experiment is designed, built, and validated, ongoing testing using more specific pavement substrates can be conducted. For instance, samples should be able to be removed from actual roads and used in the laboratory test. This will allow testing on open-graded asphalt, dense-graded asphalt, tined concrete, old rough concrete, etc.

Melting rate of the deicers can be determined using the *SHRP Ice Melting Test* (H-205.1 and H-205.2) and/or the *DSC*. Previous work by Akin and Shi (2010) found that results from the SHRP Ice Melting Test correlate with DSC results. Using one or both methods would provide the necessary information for correlating laboratory and field deicer performance. The DSC is preferred because it provides the characteristic temperature of the deicer in addition to ice melting capacity. The characteristic temperature is the warmest temperature at which ice crystals begin to form in the presence of each deicer.

Uniformity of snow/ice on pavement surfaces may be difficult to achieve but is very important when comparing samples. Field testing of tire performance conducted in New Zealand required uniform winter driving conditions to be created in the field and was achieved using snow grooming equipment (personal communication with Dr. Jordy Hendrikx, NIWA). The SHRP Handbook provides a method for making uniform ice on a concrete mortar surface for the ice undercutting test. Using the information available it is reasonably possible to create a uniform snow/ice surface but taking the time to develop a standard method to create a uniform snow/ice surface prior to laboratory testing is strongly recommended. Additionally, testing should initially be conducted using fresh snow and aged snow to determine whether the changes that snow undergoes during storage are significant.

Identified Laboratory and Field Test Methods

Laboratory testing should be conducted in a cold room or environmental chamber of sufficient size to contain large equipment, and measurements of air and pavement temperatures, humidity, air speed (wind), and solar radiation at a minimum.

For evaluation of anti-icer performance, incorporation of a plowing mechanism into the laboratory test to better simulate the field operations is recommended. The knowledge gained from this work (particularly shear and ice disbondment tests) should be utilized to design such a plowing mechanism and possibly the sensing of plowing force in both the laboratory and field tests.

At least two devices to measure friction: the *Dynamic Friction Tester* (Figure 13, ASTM E 1911) (http://www.tics.hu/DFTester.htm) and the Vaisala Remote Road Surface State Sensor (DSC111) are recommended to try in laboratory and field testing. The *Dynamic Friction Tester* was selected based on recommendations from use in the field and the small required pavement surface area for testing, which will allow for testing in the laboratory and field using the same piece of equipment. This will also allow for direct correlations to be made between laboratory and field friction coefficient data collected. The small size will also allow several friction tests to be taken over the test surface. While several interviewees mentioned this device would be worth trying, an example of anyone using it on roads during winter conditions has not been found so preliminary testing should be performed on loose snow, compacted snow, ice, slush, etc. The estimated cost to purchase a new Dynamic Friction Tester would be $36,000 (quote provided by SHIMA TRADING CO, LTD, July 29, 2010). The DSC111 is a non-contact device that provides a measurement of grip based on a spectroscopic analysis of the road surface. This device can be used in the laboratory and field to provide direct correlation between the two environments. The estimated cost to purchase a new DSC111 would be $20,000 (quote provided by Vaisala, July 30, 2010). Because of the pervasiveness of friction trailers used in the field, it would be beneficial if one could also be used in the laboratory to provide a more spatially continuous measure of friction coefficient. However, the smaller space generally available in a laboratory could be a barrier. None of the interviewees, despite their extensive experience, were able to firmly recommend a friction trailer that would be appropriate for use in the laboratory. An additional recommendation is that a mathematical method for handling noisy data and for mining the friction data be determined prior to the start of any friction testing.

Field testing for deicer performance should be conducted in a controlled field environment so that the number of variables can be reduced and as much control as is possible can be applied to the existing conditions. The field testing location should have both concrete and asphalt

pavement surfaces, RWIS or the equivalent ability to monitor meteorological parameters, pavement temperature sensors (for both pavement types), the ability to create a uniform snow/ice surface, and traffic the snow/ice pavement surface.

Based on previous research budgets (Table 6) for similar research recommendations on the budgets for future phases of this research have been provided.

Suggested budget for Phase II: $275,000 (2-3 years)

Suggested budget for Phase III: $500,000 (3-5 years)

The suggested budgets will allow for method development, manufacturing of equipment, and testing. The budget for Phase III aims to capture the cost of field testing and reflects the high number of replicates required to correlate the laboratory and field data. All the cost numbers may change depending on the specific tasks and deliverables to be laid out in the work plan.

Conclusions

The literature review identified test methods that have been used to quantify deicer performance, shear and disbondment of snow and ice from pavement surfaces, and friction in the laboratory and field. Based on information gained from the literature review and interviews we have provided the following recommendations for developing a laboratory test method that quantifies deicer/anti-icer performance and correlates with field deicer performance.

The parameters identified as being important to evaluate include: air and pavement temperature, humidity, traffic, pavement type (asphalt and concrete), melting rate of deicers, and uniformity of snow/ice. While most of these parameters can be easily monitored in the laboratory and field, trafficking samples in the laboratory and creating uniform snow/ice in the laboratory and field will be the most difficult to simulate.

Recommendations for laboratory testing include using an environmental chamber that can control and monitor air temperature, humidity, air speed and solar radiation. For evaluation of anti-icer performance, we recommend the incorporation of a plowing mechanism into the laboratory test to better simulate the field operations. Two friction-measuring devices were recommended that can be used in both the laboratory and field: the Dynamic Friction Tester and the Vaisala Remote Road Surface State Sensor (DSC111). In addition to this we recommend using a friction trailer if the necessary laboratory space can be found. For field testing we recommend using a controlled field environment to conduct the field research. The suggested budgets for future phases based on previous research budgets are $275,000 for Phase II and $500,000 for Phase III.

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Appendix A: Interviews

Complete Interview Responses

Arlene Beisswenger, Anti-icing Materials International Laboratory (AMIL)

1. Did you look at any other experimental devices in the literature before designing yours? What factors led you to develop a new experimental setup?
    - AMIL specializes in testing aircraft deicing fluids, both aerodynamically and effectiveness. We routinely perform standard tests for aircraft deicers. We were contacted by Transport Canada to look at runway deicers.
    - We started by looking at the tests for aircraft deicers, such as the High Humidity Endurance Test and the Water Spray Endurance Test (WSET). Since these were for aircraft we needed to make changes to study runway deicers.
2. How did you end up with the experimental device and experimental design you used?
    - There was a lot of trial and error while developing the test. During preliminary tests we tried to visually see if the ice was bonded to the substrate, and then we tried to measure the percentage of ice melted. We decided scraping was an important phenomenon in the field and needed to be done in the lab, so first we manually scraped the ice before building a device with a scraper. The device also has a pad to measure friction after the scraping occurs.
3. How many samples/replications were required to validate your experimental device? Did you consider fractional design of experiment (DOE)?
    - We didn't officially do DOE, but we did many samples and replicates looking at various substrates, temperatures, precipitation intensities, and deicer application rates. The final test protocol involves six samples, three of which are used to verify the precipitation intensity. The other three are exposed to freezing rain for different durations.
4. Why/how did you choose the testing concentrations, temperature, and other factors at the levels you did?
    - With the deicer we started with the recommended application rate and tested both higher and lower rates
    - With temperature we started with the same temperature used in the WSET (23°F). We also did some tests at other temperatures (19.4 and 14°F), but ultimately ended up with an air temperature of 26.6°F and the substrate at 23°F.
    - We started with an aluminum substrate, but also tested other alternatives.
5. Why did you focus on the factors you did test?
    - Seemed the most important
6. Have you considered other factors, i.e. relative humidity, radiation?
    - Humidity is difficult to control, but we did measure it. There is also air circulation in the cold chamber.
7. What challenges do you foresee by incorporating other factors in your test method?
    - Humidity is difficult to control, but it would be important if you're trying to get frost.
8. What are the key factors/things that could have/can go wrong?

- Finding proper test substrate—concrete is very realistic, but there were reproducibility problems because of the porosity.
- Developing/building the test device—we wanted a scraper with stresses similar to plows.

9. What would you have done differently?
   - Probably make the test procedure more automated
10. What was the total cost of your project(s) to develop and standardize the test procedure?
    - don't remember
11. What was the total cost to develop your experimental device?
    - don't remember
12. What was the total cost to fabricate your experimental device?
    - don't remember
13. Do you still use the device? What is the cost per test?
    - Yes we still use the device, mostly with clients during product development stages. When a client contacts us we provide a quote for their desired testing program.
14. Do you use the frictional characteristic of visual assessment to determine pass/fail?
    - Yes, still note visual appearance as well as frictional characteristics
15. Do you have any suggestions for developing a standard laboratory test method for evaluating the undercutting and disbondment characteristics of deicers and anti-icers?
    - Be careful of scaling effects—laboratory tests are great for comparison testing, but you won't get the exact same results that would happen in the field, unless you do work specifically to determine the relationship between laboratory and field test results.
16. What other performance measures should we consider besides bond strength and friction?
    - Ice melting doesn't seem appropriate because that's not all that's going on in the field—if you did the math would calculate the need for much greater quantities of deicers than are actually used.
    - What's needed is a test that is more realistic.

George Comfort, BMT Fleet Technology, Inc

1. Can you tell me about some of your research involving laboratory tests with deicers or sand using snow or ice? Did you ever try to replicate traffic in a laboratory study?

- We have done quite a bit of research looking at deicers and sand, but we have never tried to replicate traffic in a laboratory study. We did have a slow speed track in the cold that we used full-size (aircraft) tires on, but not vehicles.

2. I understand you were involved in several projects that conducted field tests looking at the effectiveness of abrasives on icy roads by measuring friction. What friction measuring device(s) did you use and were you satisfied with it?

- For one project we used an electronic recording decelerometer (ERD) and a Findlay Ervine Grip Tester (a small trailer, continuous friction measuring device, used in summer for airport pavement friction) and we made some comparisons between the two. We have been working on writing a performance-based spec for the use of friction measurements.

3. There has been a lot of research and operational use of friction measurements in airport applications for winter conditions. Given the larger geographical responsibility state DOTs have versus individual airports, to what extent do you think DOTs can benefit from the advances the aviation industry has made regarding winter friction?

- We've actually done a lot more on airports than on roads and I think highway agencies *can* benefit. I think airports have a better understanding of the <u>limitations</u> of friction devices. We just finished a big study for the European Aviation Safety Agency to make recommendations about friction measuring equipment and what role it has and should have in the airport community.

4. I heard you were involved in some laboratory testing that utilized friction measuring devices for the Joint Winter Runway Friction Program. I heard the laboratory tests involved an indoor facility with a 30-yd road. Is this true? If so can you tell me about the tests, such as vehicles used, speeds involved, road conditions (asphalt or concrete, snow or ice covered), and temperatures.

- Yes, we were involved in this laboratory testing. We had a 10-meter long stretch (it's described in the reports). It all got started when there was an initiative for longer-lasting deicers, but there was concern about whether the friction would be reduced because of the residue. There were some tests with aircraft and friction testers and found the aircraft did not notice a drop in friction, but the CFME did. Wallops airfield (NASA Langley research center) study found that the difference between the aircraft and CFME could be due to a difference in tire pressure. The next question was what happens in cold weather, so we built the test strip where we could use the CFME and a loaded aircraft tire.

5. Can you draw any conclusions from your work or postulate on a possible relationship to friction coefficient between typical runway deicers (acetates, formates) versus chloride products?

- The most promising way to use friction is as a performance index. Basically a friction coefficient will help you determine if you have achieved bare pavement, which is the goal of deicing.

- When airports switched from urea to acetates/formates we were asked to come up with a scale so that if someone would normally put X amount of urea they could look on the chart to determine how much formate to use.

Sheldon Drobot, National Center for Atmospheric Research (NCAR)

1. Can you tell me about your work in using actual cars for data collection? Have you looked at measuring friction coefficients based on feedback from an ABS or TCS?

- We have funding from the USDOT Research and Innovative Technology Administration (RITA) and we also work closely with FHWA's Road Weather Management Program. We're looking at stock instruments on fleet vehicles, such as stability control, windshield wipers (the new automatic wipers that activate when precipitation is sensed), etc and developing an algorithm to determine weather conditions. The goal is to be able to be able to tell the driver the friction of the road surface. We do the testing at a test bed in Detroit.
- Also, in the past year we borrowed the Vaisala DSC111 road surface sensor—it's mobile and can be attached to a vehicle.

2. Have you used Vaisala's spectroscopy device that provides indication of "grip?" What can you tell me about the device?

- It's a non-contact, mobile or stationary device. We've done a couple control tests in a parking lot and we did notice that as road conditions got more slippery there was a difference in readings; so far it seems like a good device, but we have only done preliminary testing
- The device may be noisy or picking up micro scale variations in the road (although I don't think it's the latter)

Do you think the device would be sensitive to the vehicle's tires or handling, like some of the friction trailers can be?

- Probably not as long as it is installed at the proper height and orientation

3. The Clear Roads pooled fund is interested in developing a laboratory test that will indicate field performance of deicers, with friction as the primary performance measure. Do you know of any devices that would be appropriate for a laboratory setting where there are space (and speed) limitations?

- Well, you could try the Vaisala device for sure—they may even lend it to you if you tell them what you're doing.
- There's also the Halliday friction tester.
- Also, Minnesota (either the university or DOT or under a partnership) recently developed some kind of friction wheel, I don't know much about it, but you could talk to Curt Pape at MnDOT.

4. Are you familiar with any analytical techniques we should consider when analyzing friction data? Do you know of "data smoothing" techniques that you could refer me to?

- I don't have any first-hand knowledge of this really, but could be appropriate depending on the device. Perhaps someone with a statistics background could be of help.

5. Can you tell me about the test bed in Detroit where you're doing your studies?

- It's actually in Lebonia, a suburb of Detroit; there's a test bed environment on public roads, from interstates to side roads. It's instrumented to listen to vehicles—the vehicles just need a direct short range communication (DSRC) device.

Tim Kline- MnROAD Operations Engineer (pavement performance) MnDOT

1. Has MnROAD conducted any performance testing of deicers/anti-icers? If so what parameters were tested (friction, pavement temperature, etc.)?
   - No
2. Has MnDOT conducted any laboratory testing of deicer/anti-icer performance?
   - MnROAD- no
   - MnDOT- maybe in the Maintenance section
3. If yes to 1 and 2, has MnDOT tried to correlate laboratory and field results?
   - NA
4. How was MnROAD designed to be used?
   - MnROAD was built in the late 80's early 90's as a structural design experiment built to verify the AASHTO design methods. Over the years they figured out that the environment has more of an effect on the road than traffic. MnROAD currently has 55 different test cells.
5. Does MnROAD have a friction measuring device? If so who is the manufacturer and what is the model name?
   - MnROAD has used three friction testers, but does not own them per se, MnDOT owns or borrowed.
   1. Dynatest 1295 friction trailer is locked wheel skid tester, use about twice a year.
   2. Dynamic friction tester
   3. FHWA loaned MnROAD the Grip Tester (Virgina Tech design)- have used it once and would like to use it again.
6. How much does it cost to run a test on MnROAD? (cost sheet if available)
   - MnROAD charges $10,000 to $15,000 per test cell per year to do all the monitoring including but not limited to multiple friction measurements, structural strength, etc. MnROAD can build test cells and monitor them but this would increase the cost. For just friction measurements it would cost $1,000 to $2,000 per year per test cell for multiple measurements, so per measurement it cost approximately $500.
7. What parameters can MnROAD control? What parameters can MnROAD not control?
   - MnROAD can closely control materials used in the construction of the test cells and structural specifications on the test cells. The test sections are 500ft long and this short distance usually equates to good construction. MnROAD has a low volume road which they can control traffic on, they have a 80,000lb fully loaded truck that can run laps.
   - MnRoad cannot control the weather, but they do have two weather stations and they monitor all major parameters. MnROAD has a main line which is a section of live interstate so the traffic on this section cannot be controlled. The construction can also be a variable because they go with low bid contracts so work between test cells can be done by different companies.
8. What does MnROAD consider to be reasonable error in field data?
   - Haven't thought about it but he would consider 10-30% error reasonable and happy if all data came in under 10% error.
9. What type of research is currently and has been conducted at MnROAD?

- MnROAD currently has 20 different research projects. Research is funded or being conducted for MnDOT, local agencies/government, asphalt and concrete companies, universities and other private vendors. Most projects are material or construction related with a lot of green initiatives- reduce, reuse, recycle.
- Asked if they would be willing to have to have deicers tested on test sections? Yes. The mainline that is live interstate is taken care of (deiced) by the local MnDOT shed but the rest of MnROAD is deiced by MnROAD.

10. In your opinion, what do you think is the best way to quantify deicer/anti-icer performance in the field?

- Two ways- the amount of time it takes to get to bare pavement and by looking at accident rates.

Friction

1. With the three friction machines you have used do feel any of them could be used in laboratory testing?

1. Dynatest 1295 locked wheel trailer- No because it is a tow trailer and would require too much space.
2. Dynamic friction tester- yes only requires 2-3 square feet of pavement to conduct testing.
3. Grip test- No because it is also a tow unit like the Dyantest 1295.

2. What techniques do you use to analyze friction data?

- He only collects and stores data for processing does not do the actual processing/analysis. They run at least four tests and then take the average. They test multiple times a year for seasonal variation because they have found that temperature affects the results. They also measure the change over time due to traffic.

Tim Leggett and Gerald Sdoutz, Forensic Dynamics, Inc.

1. Regarding the drag sled you use to assess friction of anti-icers at different humidity levels, have you ever used it on snow-covered pavement or applied any correction factors to estimate the friction on a snow-covered surface? If so, what friction values were obtained or what correction factors were used?

- We (Forensic Dynamics Inc (FDi)) use a drag sled pulled at a constant speed in a climate controlled chamber that measures 4 ft by 4 ft by 8 ft. The tire is dragged back and forth and can be programmed to measure friction at any defined frequency (e.g., every 10 or 15 minutes). Some history: FHWA held a meeting in Minnesota to discuss the possible role anti-icers play in traffic accidents. Ideally, FDi would measure friction on the road immediately after the incident, but that is not realistic. Instead we engineered a laboratory experiment in which temperature and humidity could be controlled and friction measured. A very precise load cell was used (capacity of 100 pounds, but precise to the nearest 0.001 pound). We found that some chemicals do exhibit a slurry state during the transition phases, but this was not responsible for traffic incidents. Instead found that a period of dry weather followed by anti-icing would draw up oily contaminants on the road and lead to areas with reduced friction—the salts are excellent scrubbers, better even than just water. So, if too much time had passed without precipitation and the anti-icer is applied too far in advance of predicted precipitation, then unsafe conditions could develop.
- We have done experiments on ice, but not on snow. Friction on ice is temperature dependent—cold ice has higher friction. At warmer temperatures liquid can actually form on the surface of the ice and its lubricating effects lead to reduced friction. The friction of the iced surface is consistent with expectations from field data. The drag sled would have a tendency to "plow" snow from the surface because it is not a rolling tire. We have found it is hard to reproduce consistent ice and snow.
- We (technically Traction Technologies, a sister company of FDi) developed another friction tester that uses a small (model airplane size) rubber tire that rolls across a test sample's surface and provides friction. This sensor was intended to be deployed in the field at RWIS stations and caution motorists to reduce their speed during periods of low friction. This can be called the "In Road Friction Sensor." We conducted experiments using simulated snow (shaved ice from a Zamboni machine used at an ice rink) and found reasonable friction values *(around 0.31 according to the 2004 conference paper by Luker et al.)*.

2. It seems the only normal force is the weight of the tire (thus the need for only a 100-pound load cell); would the coefficient of friction change if the tire was loaded to several hundred pounds, like in a passenger vehicle?

- It could, depending on the surface, probably not for a dry surface or lightly wet asphalt surface, but with a lot of moisture (where hydroplaning should occur on the road) may not see the same friction with the drag sled. With snow or ice, a more heavily loaded tire could cause changes to the snow—such as melting, mixing, or even mechanical removal to some degree. The laboratory test we did showed that traffic is an important element that contributes to performance of deicers—traffic is the mechanical input that helps break up the ice.

- Look into work by George Comfort and Max Perchanok for more about trafficking

3. How well does the drag sled correlate to other friction measuring devices?

- The drag sled measures the static coefficient of friction, so it will be about 15% higher than the coefficient of friction determined from an accelerometer in a moving vehicle.

In the US some police departments use a "home-made" drag sled to measure friction at accident sites. Do you know what is used in Canada? You have a lot of experience with accident reconstruction—does friction come into play in your analyses, what sort of tool do you use in the field?

- The situation is similar in Canada and the two main devices used are: 1) a drag sled, and 2) an accelerometer mounted on the dash.
- There has been a lot of debate over static friction versus dynamic friction and what should we be measuring. The truth is each has its place. The way ABS systems work is it prevents brakes from locking up, so if had a vehicle that was exhibiting ABS brake marks from 50 mph then you should use the static (peak) coefficient of friction in calculations. Also, if you're doing calculations for a vehicle going around a corner that enters yaw, then it's also appropriate to use peak friction.

4. According to your reports, load measurements are collected at 10 Hz and about 30 data points are collected while dragging the tire across the surface. Did you report the average friction? What was the variability within the data?

- yes, reported average; we never looked at the variability in the data—the software averages the data points.

5. What was the cost of designing and proof-testing the drag sled device?

- The Insurance Corporation of British Columbia paid $25,000 and we probably spent another $25,000 or so—this was back in 1999. We built both the drag sled and the climate controlled chamber (had an HVAC guy to help with this).
- We have also changed the cooling system over the years and can now control the substrate temperature directly as well as the air temperature.
- Need to watch for tire wear so before every test do a dry test, then run test, then run wet (water) test; if see wet friction numbers drop then change out the tire.

6. What is the cost of testing the frictional characteristic of an anti-icer at various humidity levels, based on the protocol you have been using?

- We charge $1,000 per sample, which is exposed to the changing humidity levels; a 4-page report is provided after the test is complete
- We did not anticipate the drag sled and climate controlled chamber to be used this frequently when we built it, but it is used almost on a daily basis. We have worked with many manufacturers during both the product development stage and getting their products approved.
- We triple wash everything (drag sled and substrate) after each test and every 5 or 6 tests or so we wash it with dish soap.

7. If you had the opportunity to design another friction tester to assess performance of anti-icers and deicers with snow and/or ice in a laboratory, where would you start, what might it look like (would you design something similar to the drag sled or would it be completely different)?

- We built a trafficking device for a project that would traffic snow-covered pavement samples with a trailer-sized tire. We placed the samples periodically on the In Road Friction Sensor to measure the friction. If we had the opportunity to design a new friction tester we would want to start with the trafficking device and then instrument it to be able to measure friction. So, you could traffic samples for a while and then apply a braking force to the tire and calculate friction. The In Road Friction Sensor would have some scalability issues with solid deicers because of the small, smooth tire. It was also designed with the intention of field deployment. The specifics of the device (tilted arm, traveled in an arc, etc) were engineered for the sensor's designated purpose. What we took away from its operability is the importance of a rolling tire.
- Could also vary the slip speed of the tire during the friction measurements and get friction as a function of slip.
- Could also try to use an existing friction trailer by setting it up in the laboratory and creating a substrate that moves back and forth under the friction device.
- Whatever methodology you choose it would be good if it could be applied in such a way that it can be compared to other work that's been done.
- If laboratory tests are performed at slow speeds, then should also do some field tests with friction measurements at slow speeds to make sure the results are close.

8. Any other suggestions/thoughts for conducting a standard friction test in lab?

- Be sure to consider the tire (and tire wear over time), scale of the experiment, and humidity. Humidity is difficult to control and some chemicals are very sensitive to humidity (calcium chloride and magnesium chloride in particular are driven more by humidity than temperature). If you don't have any kind of humidity control, then it could be difficult to compare test results over different seasons.

9. What other performance measures do you think we might be able to consider besides friction?

- Friction is what matters, melting the snow or ice is really just the mechanism to improve the friction

10. Can you tell me anything else about the In Road Friction Sensor?

- It worked well, but small the sample could have scalability issues
- The Insurance Corporation of British Columbia paid FDi to develop it and at the end of the engineering phase it was sold to InTransTech, a public company that sold out to Cantronic Systems Inc. FDi probably still owns the patent on the device. Recently the friction sensor was rented out, but was damaged during shipping and no longer works. If the shipping company would pay for the damages the device could be rebuilt.

Jim McGraw and Allen Gallistel, Minnesota DOT

1. MnDOT has guidelines for deicer/anti-icer performance testing for practitioners on the web, are these results available to the public? Would you describe these results as qualitative or quantitative? How do you think these results could best be used? Why did MnDOT develop this protocol, what was the driving force behind it?
    - The guidelines posted on the web are there for public use and may provide qualitative and quantitative results. I suggest you talk to Sue Lodahl* with Maintenance Research for results on the field evaluations.

2. Does MnDOT conducted laboratory deicer/anti-icer performance testing? If so what test method(s) do you use?
    - Yeah we use the SHRP provisional standard ice melting capacity, freezing point, and skid resistance tests. We use the ice melting capacity test most frequently and we use it as a screening tool. If we get bad results from a product we consider it done in terms of using the product or further testing. We do this as an up front approval test. If the results look good then they will do field testing through Maintenance Research. We also do chemical analysis to look for active ingredients and corrosion inhibitors. We are not currently doing any corrosion testing but we have done the PNS corrosion test (dip test).

3. How would you design a laboratory experiment to quantify deicer/anti-icer performance to correlate with field testing? Is this even possible?
    - Without actually doing the field testing it may not work. Maintenance folks say the ice melting test results are similar between the laboratory results and what is seen in the field. We use the ice melting test to get effective temperature and we measure the dilution effect. The dilution effect is determined from the amount of brine generated in the ice melting test and whether or not it refreezes.

4. What parameters do you think are most important in quantifying deicer/anti-icer performance? (list in order of most to least important)
    - Effective temperature and ice melting capacity. You want to use something that works in your temperature range. When asked about other parameters such as humidity, air and pavement temperature and traffic they said they would consider these parameters if trying to correlate laboratory and field data.

5. Do you think it is possible to quantify each of these factors?
    - You can definitely quantify these parameters and you can get information from weather sites and get traffic volumes. When asked if there is an equivalent field test for ice melting capacity and effective temperature he responded that those are usually determined based on field experience.

6. Do you think it is possible to design a laboratory test that considers all of these factors?
    - Traffic would be difficult but all other parameters can be adjusted. An environmental chamber would work. When asked if he has thought about how to simulate traffic in the laboratory he responded that he has not thought about it enough.

7. Do you think it is possible to design a field test that considers all of these factors?
    - He suggests one way to get field data would be to survey the drivers during an application event, measure the times and collect the data then you can try and correlate that with the laboratory data. You would get a lot of anecdotal information but it will be useful information.

8. Why/how did you choose the testing parameters at the levels you did?
    - For the laboratory testing we follow the test protocols.

9. Why did you focus on the parameters you did test?
    - NA

10. What are the key factors/things that could have/can go wrong?
    - PNS uses Atomic-Absorption Spectroscopy (AA) to for analysis of $CaCl_2$ and $MgCl_2$ and we found that if you are not very careful with your dilutions you will get a lot of error. Your samples on the AA have to be really dilute so this presented a problem. We ended using the ASTM $CaCl_2$ titration test method that we modified with a buffer to test $MgCl_2$.
11. What would you have done differently?
    - See above.
12. What is the cost per sample for each test you run?
    - We have not had to track out costs on testing because it is part of the product evaluation process.
13. Has MnDOT tried to correlate laboratory and field performance of deicers/anti-icers data?
    - I would talk to Sue Lodahl* at Maintenance Research. As far as I know, no not other than anecdotal information from the drivers. The freezing point data provided by the vendors is no where near what you actually see.
14. In your opinion, what do you think is the best way to quantify deicer/anti-icer performance in the lab? In the field?
    - Ice melting capacity

*Due to time constraints we were unable to set up an interview.

Wilf Nixon, University of Iowa

1. Do you think the SHRP tests can correlate with a field test of deicer/anti-icer performance?
    - A qualified yes, the tests can test something about how chemicals perform. The definition of performance is important. For example if performance is defined as persistence on the road that is very different from melting ability. It depends, the tests can give us clues, but they won't tell us about persistence, traffic, etc. The information could be used to somehow correlate with the field.

2. How would you design a laboratory and a field test that would quantify deicer/anti-icer performance and correlate?
    - You need to know what is important and the how they are defining performance; persistence, relative performance, corrosion, etc. All three of these parameters would require a different laboratory test.
    - With laboratory tests you can control everything, and you may see a difference between parameters that ends up not being important or relevant in the field. In the field you cannot control anything.

3. In your opinion what are the most important factors when testing deicer/anti-icer performance? (most to least important)
    - Pavement temperature
    - Dilution of chemical during precipitation relative to time
    - Persistence in traffic; does the product stay where you put it, how long does it stay?
    - Corrosion

4. Do you think it is possible to quantify each of these factors?
    - Pavement Temperature- laboratory and field- yes
    - Dilution effect- lab- yes, field- no, or nobody has done it yet. For the field you would need snow density/ precipitation rate over time.
    - Persistence- lab- yes, field- at this point has only been done anecdotally.

How are you defining performance?
    - Bare pavement
    - How the pavement behaves- how does snow cover on a road change after treatment, you would need to instrument a road and testing each variable could be very costly.
    - Corrosion-lab- yes, field- the coupon test used by WashDOT where they mounted coupons on vehicles and guard rail. There are so many materials to test, different metal types, combinations of different metals and welds. He expressed concern with coupons and high corrosion rates from varying combinations of metals that create a cell that ends up increasing corrosion rates. Testing all possible metal types and all possible combinations of metals would be a huge number of samples to test. He suggested for a field test to consider setting up varying maintenance protocols where you change the types of cleaning maintenance vehicles (no washing, water power wash, soap and power wash, etc.) It will only give you qualitative data but it will be real world usable data.

5. Do you think it is possible to design a laboratory test that considers all of these factors?
    - See 4. above.

6. Do you think it is possible to design a field test that considers all of these factors?

- See 4. above.

7. Why/how did you choose the testing parameters at the levels you did?
   - NA
8. Why did you focus on the parameters you did test?
   - NA
9. What are the key factors/things that could have/can go wrong?
   - Getting the ice prepared uniformly in the SHRP tests was difficult. You have to consider how bubble free do you want the ice, are you using snow or ice, the variability in the ice or making it consistent was tough.
10. What would you have done differently?
    - Looking back would not do anything differently, because they eventually figured it out, but it did take a long time to get it down.
11. What was the total cost of your project(s)?
    - Estimated total project cost $100,000, will double check on this, contract with Iowa DOT.
12. What was the cost per sample?
    - Because the testing was experimental he could not give a useful answer here. His laboratory is/was not set up as a testing laboratory. He recommended using a commercial laboratory if this testing was going to be done more routinely.

Shear and Disbondment

1. Why did you develop a new experimental device and why did you not use a model previously developed in literature?
   - Originally they tried to use a low rate (slow moving) disbondment test but saw significant effect in the results due to the rate changes (speed changes). The maximum rate (speed) they could get was $^{1}/_{10}$ mph and they were trying to compare these laboratory results to field speeds of 30+ mph. Basically they decided that the laboratory test was not realistic and highly variable.
   - Instead they had a sit-down brainstorming session and came up the idea of using a ram so that they could match the 30 mph speed seen in the field. He stated that because of the short timeline and the need to get this project done quickly they used a brute force method.
2. How did you end up with the experimental device and experimental design you used?
   - Brainstormed with the laboratory folks on how they could get higher speeds so that the test was more realistic for speeds seen in the field. The experimental design looked at different cutting edge shapes under the SHRP program.
3. How many samples/replications were required to validate your experimental device? Did you considered fractional design of experiment (DOE)?
   - In the beginning they were running up to 10 tests for a given condition but with time and experience the results got better and repeatability increased and they were able to go down to running samples in triplicate. Some conditions were highly variable such as bong strength vs time after chemical application and for these they ran extra samples.
   - They used a factorial approach and a plot of the axis of variability to quickly come up with a working design.

4. Why/how did you choose the testing concentrations, temperature, and other factors at the levels you did?
    - The pavement temperature range used was based on temperature seen in Iowa from 0-30° F. The product concentrations were based on Iowa DOT application rates for the highway but these may have been increased for more consistent results (double check in paper).
5. Why did you focus on the factors you did test?
    - Focused on application rate, temperature and ice thickness because these were identified as key parameters.
6. Have you considered other factors, i.e. relative humidity, radiation?
    - See above.
7. What challenges do you foresee by incorporating other factors in your test method?
    - He would not necessarily see a problem with incorporating other variables in the test method but one thing to consider was that the device they developed was 30 x 5 x 5 ft, so it was very large and all testing was done in an environmental chamber.
8. What are the key factors/things that could have/can go wrong?
    - One issue they had was that the ram was a 6 ft by 1 in steel and required a lot of pressure to travel at 30 mph so the machine jumped (had a "kick-back"). It was a brute force method and was not further finessed due to the time crunch of the project but he highly recommends that if this method were to be used that it be refined, housed in cold room. He is nervous about saying this could be a standard test method because it may not be practical and it was expensive to make, and get up and running.
9. What would you have done differently?
    - Nothing given situation.
10. What was the total cost of your project related to shear/disbondment test?
    - Not sure
11. What was the total cost to develop your experimental device?
    - $50,000 (1990 dollars) to fabricate/manufacture and develop the method in the cold room.
12. What was the total cost to fabricate your experimental device?
    - See above.
13. What was the cost per sample?
    - NA
14. Any suggestions for developing a standard laboratory test method for evaluating the undercutting and disbondment characteristics of deicers and anti-icers?
    - If Clear Roads wants to use this experimental design they should focus on the redesign process. In terms of developing a standard laboratory test he does not have any suggestions beyond what other have tried. He suggests we get a group of folks together and chew through it. He also questions whether undercutting is the right thing to test. He is skeptical that one test can be developed to adequately test all parameters/variables to predict field performance.

Other Recommendations

- For field testing always have two ways to measure each parameter.

Max Perchanok, Ontario Ministry of Transportation

1. You have a lot of experience using friction measurements in winter research field tests. Field tests can be expensive and conditions can be too variable to compare effectiveness of various deicers/anti-icers. The Clear Roads pooled fund is interested in developing a laboratory test that will indicate field performance of deicers, with friction as the primary performance measure. There are so many friction measuring devices that can be used in the field. Are there any devices that would be appropriate for a laboratory setting where there are space (and speed) limitations? What about the Vaisala spectroscopy non-contact device?

- Here is some background on practices in Ontario. After snow accumulates on the road we plow. We then treat whatever snow is left with deicer, usually sodium chloride, and assess the time until bare pavement is achieved. Thus, our primary performance measure is time until we have bare (wet) pavement, which is associated with higher friction. With anti-icing when chemical is applied before the storm, can develop wet roads at the beginning when the snow contacts the chemicals. We are also interested in the friction on the road after anti-icing before the storm.
- I'm not familiar with laboratory devices other than the British Pendulum Tester. You want to use a device that shows friction similar to what a car would experience.
- We have three different friction testers, a Pon-cat (Traction Watcher One), SCRIM, and Halliday unit and we have looked at the sensitivity and repeatability of them. You'll want the same sensitivity with a laboratory device. One thing I can say about the Halliday device is that the tire lasts much longer.
- George Comfort with BMT Fleet Technology did some laboratory testing of friction for the Joint Winter Runway Friction Testing Program. I think he had a 30-yard icy road indoors.
- Vaisala's device look at the depth of snow and/or water and uses an algorithm to estimate grip—not truly friction.

2. Did you nearly always see clear-cut differences between treated or untreated road sections (e.g., salted versus unsalted)? What about between different chemicals?

- Yes we always see a difference between treated and untreated sections. Normally we use NaCl, but we do use other chlorides for prewetting. In the laboratory you will see a difference in performance between different chemicals, but not necessarily in the field where there are other compounding factors.

3. What are some of your techniques to analyze friction data (just compute an average or do you do something more sophisticated)?

- There are simple and complicated ways to statistically look at the data. For starters, want to determine the minimum number of samples, which depends on the variance. The variance is low for a bare road and a completely snowpacked road, but once there is partial melt or partial snow cover the variance is much higher. Ideally would want similar variance in the laboratory friction device as the field device.

4. Future plans involve developing a laboratory test, followed by verification with field tests. How many field tests do you think we might need to conduct in order to validate a truly customizable laboratory test—with different options for pavement and meteorological conditions? What do you think the field testing component might cost?

- I can't provide a cost for field testing. It depends too much on how the experiment is carried out. Would you buy a friction tester, snowplow, deicers, etc or would the experiment be conducted as part of the department's response to a winter storm? One thing we did in the past is a researcher designed an experiment that was basically carried out by the highway operators, but they were also in the plow truck and were able to document everything and make on-the-spot decisions. Video cameras on poles can also capture a good record at a much lower cost these days than in the past.
- The key thing is to compare friction and sensitivity of different surface materials. If you are trying to see how a deicer reacts in the field then need to try to mimic everything (sunlight, temperature, humidity, traffic)

Charlie Pizino, Midwest Research Institute (MRI)

I was primarily involved with the development of deicer test methods, particularly evaluation of corrosive effects on metals, rapid evaluation of effects on concrete, scaling effects on concrete, and frictional characteristics. I have spoken recently with Robert Blackburn, a former MRI employee who was involved with the anti-icing program for a number of years. I think he collaborated with one of your colleagues in field test program development and implementation. He would be willing to talk with you about that aspect of the program (rrblackburn@cox.net). If you have not done so already, you might contact state or government laboratories or municipalities that may have used the SHRP tests.

1. Do you think the SHRP tests can correlate with a field test of deicer/anti-icer performance?
   - The intent of the SHRP deicer research program was to develop a set of standardized tests that would fully characterize a deicing chemical. The tests were developed under controlled laboratory conditions to measure specific aspects of deicer performance. The tests were designed to provide comparative data for evaluation of a given deicer against industry standards such as sodium chloride and calcium chloride. Although field performance aspects were kept in mind during test development, it was not a stated objective of the program to design tests that would directly correlate with field performance. As stated in the introduction to test handbook (SHRP-H-332), "After initial evaluation in the laboratory, field testing is ultimately required to determine acceptable deicer performance and compatibility". I do not think that the SHRP tests can directly correlate with field tests. The laboratory tests however may provide some guidance in developing and interpreting field tests.
2. How would you design a laboratory and a field test that would quantify deicer/anti-icer performance and correlate?
   - I don't think you can design a laboratory test that would directly correlate with a field test. A field test might involve actual deicer application in a real world weather event or it might be a more controlled test on a larger scale than in the laboratory. In the former instance it would be impossible to predict or take into account the effects of traffic, pavement type, temperature fluctuations, wind patterns, etc. in a corresponding laboratory study. The only approach I can think of that would more closely link laboratory and field testing to real world performance would be gradual scale up. For example, from the laboratory, one could move to a section of sidewalk, then to a parking lot, then to a street section. However, the uniformity of the ice/snow pack would become problematic as would the means of quantization. It seems that accumulated experience in various regions eventually determines what deicer and application strategy will be most successful. Initial decisions are usually guided by performance characteristics of a given formulation.
3. In your opinion what are the most important factors when testing deicer/anti-icer performance? (most to least important)
   - <u>Deicer</u>: 1) melt rate/capacity; 2) penetration rate/capacity; 3) undercutting rate/capacity; 4) effective temperature range; 5) frictional characteristics; 6) capacity to damage pavement and construction/automotive metals.

- Anti-icer: 1) capacity to prevent ice/pavement bond formation; 2) effective temperature range; 3) frictional characteristics; 4) capacity to damage pavement and construction/automotive metals.
- Of overriding concern in either case would be the acute and chronic human health effects (safety), and environmental fate and impact. These factors would have to be considered in advance of any proposed use or application of a formulation. The environmental fate and impact might vary from region to region.
- A cost/benefit analysis would have to balance immediate performance benefits against potential long term deleterious effects on infrastructure.

4. Do you think it is possible to quantify each of these factors?
   - Yes, in a relative way. The environmental impact/fate would be most difficult to quantify because it would require monitoring over several years and perhaps decades. Assessing risk to regional plant and animal species that would be potentially exposed due to runoff would be a first step. Exposure of infrastructure to chronic application would be the next most difficult to quantify.
5. Do you think it is possible to design a laboratory test that considers all of these factors?
   - I don't think you could design a single test that would address all of these factors. One test might be developed that could assess melting, penetration, and undercutting. Another might combine pavement degradation with rebar corrosion. Laboratory tests sometimes use accelerated cycling to mimic repeated application, freeze/thaw, etc.
6. Do you think it is possible to design a field test that considers all of these factors?
   - Same response as question 5. The closer the field test design gets to a real world storm scenario, the more difficult it will be to quantify results in a meaningful way.
7. Why/how did you choose the testing parameters at the levels you did?
   - I remember that we chose some test parameter levels based on application concentrations used in the field. Depending on the test design we had to modify some parameters based on the reduced scale of the laboratory test. Sometimes manufacturer's recommendations guided initial test levels.
8. Why did you focus on the parameters you did test?
   - We felt that the developed test methods would characterize the most important aspects of deicer performance and would be able to guide decisions in selecting an appropriate product. In addition we provided a list of supplementary test methods mainly from EPA and ASTM sources to complement and supplement the new tests. The idea was to provide an organized, comprehensive set of test procedures in one manual.
9. What are the key factors/things that could have/can go wrong?
   - For laboratory tests, substrates (corrosion test coupons, concrete test samples, pavement substrates, etc) may or may not have been representative. Assumptions about application rates and test conditions may or may not have been on target. Method of growing ice test substrates may or may not have resulted in ice that would be characteristic of a real world scenario.
10. What would you have done differently?
    - Given the stated objective of the SHRP test development program, I don't think we would have done anything differently.

11. What was the total cost of your project(s)?

    SHRP anti-icing/deicing funding summary

    Anti-icing field test program: $625 K

    Ice/pavement bond nature study $659 K

    Ice/pavement disbonding study $59 K

    Deicer evaluation test method development: $309 K

12. What was the cost per sample?
    - I have no idea.

James Wambold, PennState University and CDRM, Inc.

1. You have experience measuring friction in the field in airport and highway applications. Field tests can be expensive and conditions can be too variable to compare effectiveness of various deicers/anti-icers.

- I have conducted many tests under winter and summer to measure friction. We even did a set of skid tests to measure the effects of several deicers. I have been into friction research for 40 years.

The Clear Roads pooled fund is interested in developing a laboratory test that will indicate field performance of deicers, with friction as the primary performance measure. There are so many friction measuring devices that can be used in the field. Are there any devices that would be appropriate for a laboratory setting where there are space (and speed) limitations?

- I would find it hard to find a device for laboratory tests in general as when you talk about winter, tire contact pressure as wheel a tire properties play a major roll. Then there is slip speed as another variable. Sweden, VTI in Linkoping, had and may still have the only laboratory device where they can use a full size tire on a winter surface. The device had a very long tunnel were the surface was cooled and moved under the tire up to near 40 mph. The only other test might be to use the Dynamic Friction tester at freezing conditions using a wet mix of deicing chemical. This may give comparable results for the friction on the different chemicals?

2. Did you nearly always see clear-cut differences between treated or untreated road sections (e.g., salted versus unsalted)?

- Yes

What about between different chemicals?

- Of the tests we did for PennDOT, only urea was more slippery.

3. What are some of your techniques to analyze friction data (just compute an average and standard deviation, or do you do something more sophisticated)?

- We always look at the friction vs. slip speed and today you would particularly want to look at what the ABS does and traction control.

4. Future plans involve developing a laboratory test, followed by verification with field tests. How many field tests do you think we might need to conduct in order to validate a truly customizable laboratory test—with different options for pavement and meteorological conditions?

- In the JWRFP we tested for 15 years, several weeks each year, that data base is available from Transport Canada. Frozen water (ice, snow and slush) varies with temperature, pressure and age. Effect of chemicals is one study, but if you just want the friction of the chemical after the condition is melted, you should use some standard surface to eliminate the surface effect. Maybe one PCC and One ACC.

5. What do you think the field testing component might cost?

- That is not answerable without knowing a lot more. What equipment, who runs it, who supplies the chemicals, traffic control, opportunity of weather conditions you need (some we never got in 15 years)

Thomas Yager, NASA Langley Research Center

1. The Joint Winter Runway Friction Measurement Program involved extensive testing of dozens of friction-measuring devices in many scenarios. Since one objective was to harmonize the friction measurements for contaminated (snow- or ice-covered) runways and ASTM E2100 was published, has this objective been met or is work still ongoing?

- Yes, no more work is planned. Two ASTM standards: IRFI (from Joint winter runway friction program) and IFI.

2. How does the Canadian Runway Friction Index differ from the International Runway Friction Index? From my understanding the CRFI uses vehicles equipped with electronic decelerometers, but the IRFI can be determined from any friction device calibrated to the IRFI Reference Device. Is this accurate? Are US Airports using the IRFI?

- Yes, that describes the CRFI and IRFI. As far as whether US airports are using the IRFI…no, not really. There is a learning curve with the pilots, but really it's that airport operators aren't required to convert friction data to IRFI (FAA hasn't put it in an Advisory Circular).

3. According to a paper presented at the 2002 Pavement Evaluation Conference in Virginia, Canada's National Research Council provided a snow and ice tribology researcher at all test sites. Can you provide contact information for at least one person who fulfilled this role, or contact them on my behalf with a request to talk to me?

- talk to Dr. Nirmal Sinha at NRC in Ontario

4. I'm interested in the amount of variability you might have found within individual friction measuring devices. Did some devices clearly perform better than others (i.e., more clearly distinguish icy, snowy, slushy, wet, and dry conditions)?

- ±0.03 (standard deviation from IRFI)—quite acceptable. Even had 3 decelerometers (bowmont, tapley, and ERD) mounted in one vehicle and all were within that level

5. You have experience measuring friction in the field in airport and highway applications. Field tests can be expensive and conditions can be too variable to compare effectiveness of various deicers/anti-icers. The Clear Roads pooled fund is interested in developing a laboratory test that will indicate field performance of deicers, with friction as the primary performance measure. There are so many friction measuring devices that can be used in the field. Are there any devices that would be appropriate for a laboratory setting where there are space (and speed) limitations?

- see E1911 (Dynamic Friction Tester). It has a disc with three rubber pads on the bottom that starts spinning at 56 mph and is lowered to the pavement; it gives continuous readings until it stops. It is about 18 inches by 18 inches so can make pavement samples to use in the lab, but it can also be used on outside pavement. Can use it on wet pavement, may be able to use it on ice, but probably not snow.

6. You seem to have a lot of experience with friction measuring devices in airport applications for winter conditions. Given the larger geographical responsibility state DOTs have versus individual airports, to what extent do you think DOTs can benefit from the advances the aviation industry has made regarding winter friction?

- There are friction devices that can be mounted right on plows so can better determine appropriate salt application rate (can save a lot of money on salt). I suggest contacting

Sally Shoop at US Army's CRREL facility in New Hampshire and George Comfort at Fleet Technology in Ontario.

7. Can you draw any conclusions from your work or postulate on a possible relationship to friction coefficient between typical runway deicers (acetates, formates) versus chloride products?

- Talk to George or Sally…

CLEAR ROADS

research for winter highway maintenance

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