Evaluation of the Performance of Deicing and Anti-icing Using Organic Alternatives for Sustainable Winter Road Maintenance

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2017

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final versions, as accepted by my examiners.

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Abstract

Large amounts of salts are applied every winter to highways, streets, parking lots and sidewalks. Despite its effectiveness, the use of salt has increasingly become a public concern because of the detrimental effect it has on the environment and the corrosion it causes to infrastructure and vehicles. Transportation agencies therefore are actively seeking ways to reduce salt use while keeping their roads safe. As an alternative to regular salt, new chemicals and additives, mostly agriculture byproducts or agro-based organic alternatives, that have fewer environmental side effects than regular road salts, are being developed by the industry and are increasingly available in the market. However, information on the field performance of these new organic alternatives as compared to regular salts is still limited. Questions concerning optimal application rates, mixing ratios, and the role of weather and traffic conditions still need to be answered for some newly available products. In this study, two organic agro-based products, namely, Fusion and Geomelt, for deicing/anti-icing treatments, were selected and their performance was tested through a series of field tests. The goal of this research is to investigate how well they would perform in field as compared to regular salt brine.

A field test was conducted to collect performance data of these materials when used in prewetting and anti-icing operations. A total of nine snow events were covered in this experiment. The maintenance treatments that were tested followed the common maintenance operation protocols recommended by the two municipalities. Traction levels and visual conditions were used as the main performance metrics along with other road weather and pavement condition data. Three main findings were obtained from an analysis of the test data. First, salts prewetted with these organic compounds performed similarly to those using regular salt brine. In most cases, the performance differences were not statistically significant, indicating that there was little evidence supporting the superiority of the organic materials for a prewetting purpose. The test data also indicated that this was true under low temperatures (~-10 ℃), contrary to the common beliefs about the performance of these products. However, it should be noted that performance similarities

could also be influenced by the fact that the organic liquids were used for prewetting salt at a much lower ratio (5% vs. 20% for brine). Also, the dominant compound in these prewet mixes is still regular salt - sodium chloride (95% for organic treated salt and 85% for brine treated salt). When used for prewetting purposes, Geomelt and Fusion showed similar performance in terms of traction level. However, when used as additives to brines for Direct Liquid Application (DLA), both organic products largely outperformed pure salt brine despite being applied at a half its application rate. Field tests also showed that the tested compounds could help maintain up to 20% higher traction and could maintain safer friction levels for up to an hour longer. Fusion outperformed Geomelt by up to 10 % in terms of traction level. Lastly, in general the sections treated with DLA performed significantly better than the untreated sections, confirming the advantage of anti-icing strategy for snow and ice control.

The field data was further used to estimate a performance model that can be used by maintenance practitioners facing similar conditions. Two different models were explored, the first set of models focused on assessing the relative snow melting rate of Geomelt and Fusion as compared to regular brine. In its final form, the model suggests that the difference in the friction number on a surface maintained with Fusion or Geomelt and one maintained with Brine will increase at a rate of 1.76 per hour and 1.95 per hour respectively on identical test sections if no further maintenance actions are taken. The second set of models estimated were general purpose models that can be used to estimate the friction level on a roadway after maintenance has been conducted. In these models, the effects of weather, wind, and chemical type were found to be significant.

Acknowledgements

I would like to express sincere thanks and appreciation to my supervisor, Prof. Liping Fu, who has provided guidance, motivation and substantial help in the development of my research. Prof. Liping Fu's guidance and advice has been invaluable in this endeavor, and this thesis would not have been possible without his support.

And I would like to thank Alan Issac, Mark Covert from City of Burlington and Wayne Wuilleme, Enrico Scalers from Town of Oakville, Max Perchanok from MTO, Ken Lang, Richard Crosbie (Driver) from Steel & Evan Ltd., for their support in this research.

I would also like to thank the members of my family, including my wife Fang Xu, daughter Lei Jiang. Their support and understanding throughout my studies has been a strong motivational force.

I am also grateful for the friendship, advice and support of my colleagues at the iTSS lab, especially, Matthew Muresan, Lalita, Zhengyang Lu, Tae Kwon; Taimur Usman, Raqib Omer, Wenfu Wang, Sajad Shiravi, Michael Linton, and Grace Li, who made me to enjoy my research and personal life in Canada.

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List of Abbreviations

NaCl	sodium chloride
MgCl2	magnesium chloride
CaCl2	calcium chloride
KAc	potassium acetate
CMA	calcium magnesium acetate
DOT	Department of Transportation
DLA	Direct Liquid Application
EPA	Environmental Protection Agency
ANOVA	Analysis of Variance
BPRT	Bare Pavement Regain Time
RMSE	Root Mean Squared Error
MTO	Ministry of Transportation, Ontario
MDOT	Michigan Department of Transportation
NCHRP	National Cooperative Highway Research Program
WRM	Winter Road Maintenance
PM	Particulate Matter
WisDOT	Wisconsin Department of Transportation
AADT	Annual Average Daily Traffic
GPS	Global Positioning System
RWIS	Road Weather Information System
PPMCC	Pearson Production-Moment Correlation Coefficients

Chapter 1 Introduction

1.1 Background

Salts, both in solid and liquid forms, remain a primary component of the materials for winter road maintenance due to their effectiveness in breaking and preventing the bonding of snow and ice to road surfaces. Amounts of salts are applied every year on highways and streets, which has increasingly become a public concern due to their negative effects they have on the environment, infrastructure and vehicles. Transportation maintenance industries are actively seeking ways to reduce salt use while keeping their roads moving safely.

New anti-icing chemicals and additives, mostly organic or agro-based, are being developed by the industry which have the potential to deliver better snow and ice control performance with fewer environmental side effects than regular road salts. However, information on the field performance of these new organic materials as compared to regular salts is still very limited. What is their deicing/anti-icing performance in the field when compared to regular road salt? How is their performance related to the road weather conditions? What are the optimal mixing ratios and application rates when used in combination with regular salts and brines? These are examples of some questions that many transportation agencies such as Ministry of Transportation Ontario (MTO) and Burlington and Oakville road maintenance departments are interested to address through this research.

1.2 The Research Problem

There are several organic products that are marketed as additives to brine solutions for both pre-wetting and anti-icing operations. This research focuses on two of these products that are most commonly used by the maintenance industry in Canada, namely, Fusion 2330 from Eco Solutions Inc. and Geomelt S30 from Future Road Solutions Inc. Both products are derived from sugar beet juice and a detailed description of these products is provided in Appendix A.

When these organic materials are mixed with brine at a specific concentration, they decrease the amount of regular salts that would otherwise be used to treat snowy/icy road conditions. Although relatively expensive compared to brines, these products can be used to lower the amount of salt used thereby reducing chloride concentrations in the soil and water bodies (eg., rivers and lakes) surrounding salt-treated roads (Buso&Lickens, 2010). Salts mixed with these products are also promised to provide better ice melting performance than regular salts, especially, under low temperatures.

According to the manufacturers' claims, both Fusion and Geomelt are not only biodegradable with no additional effect on the environment, but also superior to the general deicers in terms of snow melting performance. The manufacturer of the Fusion 2330 anti-icing fluid claims that it can deliver a 30% increase in ice melting capacity and reduces brine usage by up to 30% (Eco Solutions, 2007). Likewise, the manufacturer of Geomelt S30 claims that it can reduce salt usage by 25%-30% (Future Road Solutions, 2009).

Few past studies have assessed the effectiveness or performance of the above two products in winter road maintenance, therefore, there are few evidence-based and defendable guidelines on the performance, costs, and benefits of these products. Given this lack of research, this study is designed to assess the performance of the two products by conducting field tests. However, this project does not assess the environmental implications of using these products for prewetting and anti-icing, rather only focuses on their field performance for deicing and anti-icing operations. This study also attempts to quantify the performance differences of these chemicals by developing a model to quantify the friction provided by surfaces maintained with each of these chemicals.

1.3 Objectives and Scope of Work

The main objective of this study is to evaluate the effectiveness of two organic products, Geomelt and Fusion, when used as either pre-wetting agents or additives to enhance the performance of regular rock salts or salt brines. The specific objectives pursued in the proposed research are as follows:

1. Conduct a field experiment to assess the performance of the selected organic materials for both deicing and anti-icing operations under a variety of road weather conditions.

2. Perform a analysis of the performance of the organic alternatives in comparison with the regular material – salts and brines and determine their relative effectiveness.

3. Explore the impact of various road weather factors on the relative effectiveness of the organic products through an in-depth statistical modelling analysis.

This research will focus on two specific products, namely, Fusion 2330 and Geomelt S30, that are currently being used by the partner city. While it is known that the effectiveness of these products depends on the proportion (or ratio) by which these products are mixed with salt or brine as well as the application rate of the end mixtures, this project considers only the ratios and application rates recommended by the product providers and used by the two municipalities.

1.4 Structure of this Document

The remainder of this thesis describes various aspects of deicing and anti-icing chemicals for snow and ice control in winter. The thesis is organized as follows:

- Chapter 2 describes existing literature and current research limitations on the subject.
- Chapter 3 proposes the experiment design including test site selection, test protocol, and data collection.
- Chapter 4 analyzes the data collected from the test site, and discusses their implications.
- Chapter 5 explores and validates estimation Models of the Organic Anti-icers Effectiveness in winter.
- Chapter 6 summarizes the research findings and proposes future research works.

Chapter 2 Literature Review

2.1 Introduction

This chapter provides an in-depth literature review of the existing winter maintenance methods, snow and ice control materials, and the snow melting performance of snow and ice control materials. The main focus of the review is to gain knowledge about the best practice of snow and ice control, experimental methodology and possible issues pertaining to field testing of deicers.

2.2 Winter Road Maintenance Methods

There are several common snow and ice removal methods used for winter road maintenance, including plowing, de-icing, sanding and anti-icing. This section provides an overview of these methods.

2.2.1 Mechanical Method - Plowing

Mechanical snow removal methods are one of the oldest and most common methods employed. In cold regions, snow plows are often deployed during and after snow events to clear the road and support other maintenance activities. Snow plows come in a variety of forms, and often consist of a snow plow blade mounted to a large vehicle such as a pick-up truck, skid steer, all-terrain vehicle, and other large vehicle. In general, snow plows can be divided into the following three categories based on their design and purpose.

Straight Plow. As their name suggest, straight plows use a single straight blade to push and clear snow. They are especially suited for parking lots and areas around building and are often mounted on vehicles such as pick-up trucks.

V-Plows. V-plows employ a v-shaped blade that can be used to in a straight or angles position. In its angled position, the v-shaped blade allows easier breaking of hard-packed snow.

Pushers/Box/Containment plows. Loaders or other special tractors can attach a pusher to move large volumes of snow qickly. Pushers contain snow without creating windrows, eliminating the needs for repeated plowing to remove spills.

Severe winter storms can create dangerous conditions, such as hard-packed snow or ice. These conditions can be difficult to deal with solely through mechanical means as snow plows are often unable to fully remove all surface contaminants. It is therefore crucial that agencies using snowplows select the appropriate equipment for the workload, and give proper consideration to vehicle maintenance needs and vehicles operator needs.

2.2.2 Reactive Chemical Strategy - De-icing

De-icing as a maintenance strategy is rarely employed by itself, but is often combined with mechanical methods. De-icing is particularly effective in situations where equipment alone is insufficient to meet maintenance needs, such as in cases with strong snow-pavement bonds. (Chappelow et al., 1992).

The first step of de-icing strategy is to prewet the deicing materials. Studies have shown that prewetting is effective at improving the effectiveness of solid salts for deicing treatment(Fitch, et al, 2012).

The last step before mechanical removal, is better to apply deicing materials on the top layer of the accumulated snow or ice. This strategy's effectiveness hinges on a large quantity of chemical freezing-point depressant. These materials create a brine solution between the ice and pavement surface, lowering the freezing point of water and weakening any snow-pavement bonds, allowing for easier removal. Chloride salts have been used widely for de-icing, among which sodium chloride is the most frequently used material for snow and ice control for its better performance-price ratio and convenience to store. However, if temperatures are colder, calcium chloride or magnesium chloride are often used instead. (MDOT, 1993; Ketcham, 1996; Williams and Lanebarger, 2000)

2.2.3 Abrasive - Sanding

Sand was one of the major winter road maintenance materials until 1970 when the use of deicers became wide spread (Nixon, 2001). Today sand is still used under low temperatures where traditional deicing materials lose their effectiveness to melt ice. Sand (or other abrasives) are mostly used on snow packed conditions to enhance traction levels.

Current maintenance practices often use dry sand for winter road maintenance. However, dry sand is susceptible to blow off the road due to vehicular traffic and in some instances would be blown away within few minutes (MTO, 1994). When dry sand is spread, studies have shown that 30 percent of it immediately scatters off the roadway (NCHRP 2004). To overcome this problem, maintenance operators frequently apply repeated applications of sanding to maintain a suitable level of traction. However, the use of sanding for WRM is associated with some negative environmental concerns, and is costly to clean up and may be more detrimental to the environment than salt. Sand runoff is also an environmental concern (Stantec Consult, 2012), as it can block catch basins and storm sewers, which requires cleaning on regular basis, increase sedimentation at downstream lakes/streams, which increase water turbidity, and create elevated concentrations of PM10 (Perchanok 1991; NCHRP, 2004).

Although sand is usually applied dry, pre-wetting strategies have been developed and have been used in North America for few decades now. Previous studies have found to generally be more effective when compared to conventional dry (WisDOT, 2011; Nixon 2001). Some research has found pre-wetting to reduce abrasive use by almost 50% in cold weather conditions (Williams 2003). In a study conducted in Ontario, Canada (MTO 1994), average effective time for dry sand was found to be 14 minutes compared to 25 minutes for pre-wetted sand. Moreover, pre-wetted sand was found effective even after 400 vehicles passed; but dry sand needed reapplication after 70 vehicles passed.

Sand that is not quickly removed after a storm can create air quality problems as moving vehicles generate dusty conditions and its removal is significant expense. FHWA does not recommend the use of abrasives in its guidance manual on anti-icing practices. (Hyman and Vary, 1996). Selecting a sand or aggregate that has been screened or washed to reduce the fine particle fraction can reduce dust generation. Material larger than 300 microns in diameter has been found to be most effective.

2.2.4 Proactive Method - Anti-icing

Anti-icing is a proactive method where snow and ice control materials are applied before a snow event. This strategy focuses on the preventing ice from bonding to the pavement as the applied chemicals will promote the formation of a brine layer on the pavement. Anti-icing makes plowing easier and a higher level of friction will be achieved after the snow event. Pre-applied anti-icers can melt small accumulations of snow, and clear pavement in a shorter time (Hossain, et at., 2014). Overall, the anti-icing approach requires less material and labor, thus lowering costs and decreasing the environmental impacts of salting operations (NCHRP-577, 2007).

Solid, liquid or prewetted anti-icers can be applied before a snow/ ice event. The application of dry anti-icers can be very efficient for pretreatment. However, adequate moisture in the air or precipitation on the surface must be required. Moisture prevents the scattering of anti-icers from the pavement surface and can enhance the effectiveness of the anti-icer by activating it. Solid anti-icers are usually applied by hopper spreaders or under tailgate spreader.

Direct liquid application (DLA) for anti-icing is particularly advantageous because liquid can be applied homogeneously. DLA is often considered only when pavement temperatures are higher than -5 ℃. In cases where lower temperatures are expected higher salt application rates should be used (Ketcham et al., 1996). Despite this, some studies shown that anti-icing with liquid may be effective for temperatures down to -7 ℃ (Druschel, 2012; NCHRP-577, 2007). Anti-icing is also not effective when precipitation consist of freezing rain (NCHRP 526, 2004).

Pre-wetting is also effective if the solid chemicals would remain inert after application. This can happen if there is insufficient moisture to activate them; pre-wetting helps by providing the moisture needed to activate the salt. Other advantages of prewetting include:

- Salt is spread homogeneously(FHWA-RD-95-202, 1996)
- Salt granules adhere to the surface better.
- Long lasting effect compared to solid chemicals.
- Spreading speed is faster and the spreader speed must be adjusted.

- Since lower application rate is used compared to solid chemicals, one truck load covers more lane miles resulting in reduction in resources.

Overall, liquid anti-icing is very effective and economical when used correctly and proper anti-icing techniques can lead to less chemical usage and improved environmental quality. Higher services levels are achieved with the anti-icing pre-treatment by preventing formation of the bond between the ice and the road; Anti-icing reduce time and manpower requirements.

2.3 Snow and Ice Control Materials

The most common solid and liquid materials used for winter maintenance are presented in Table 2.1. Generally, snow and ice control materials are classified into two groups: chloride salts and organic salts. All of them can melt the ice and snow by lowering the freezing point of water. (Amsler D., 2006; Zhang J et al. 2009; Rubin J., 2010). The different groups of snow and ice control materials are briefly summarized below.

Table 2.1 Common Solid and Liquid Snow and Ice Control Materials

Group	Chemical Formula (Most Common) or process	Chemical Name or Business Name
Chloride Salts	NaCl	sodium chloride
	$MgCl_2$	magnesium chloride
	$CaCl_2$	calcium chloride
	KCl	potassium chloride
Synthesizing Products	KAc	potassium acetate
	CMA	calcium magnesium acetate
Natural based. Aro-based	brewing, (beet juice)	GeoMelt , Fusion S30
	Winemaking(Alcoho)	methanol and ethanol
	Combine with.Glycos	ethylene and propylene glycol

2.3.1 Chloride Salts

Among the chloride salts, sodium chloride (NaCl), magnesium chloride (MgCl2), calcium chloride (CaCl2)) are commonly used both in solid and liquid treatments (Shi, 2005). They are popular due to their high availability (NCHRP-577, 2007), low economical cost, and convenience to store, handle and spread on the pavement (Fischel, 2001; Ramakrishna, et al., 2005). However when the temperature reaches a degree low enough to affect the materials performance, these chemical materials may be unreliable. For example, sodium chloride will become ineffective in certain colder temperatures, while calcium chloride and magnesium chloride can work on (Ketcham, et al., 1996).

2.3.2 Organic Salts

Organic salts have been considered as an environmentally friendly alternative to chloride salts when they are used alone or when combined with chloride salts. One type of organic salt come from synthesis, among which the most famous ones are calcium magnesium acetate (CMA) and potassium acetate (KAc) (NCHRP-577, 2007). The second group of organic materials for anti-icing and deicing are made from agricultural resources including by-products from grain processing, brewing, winemaking, etc (NCHRP-577, 2007). Both of them involve of less or no chloride content in their composition, thus less or no corrosive effects on soil, water, plants and infrastructure. They are considered as highly environment-friendly materials. However, since their production is energy intensive and expensive, they continue to have a smaller market share.

2.4 Snow Melting Performance of Snow and Ice Control Materials

The most common snow and ice control materials are sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), calcium magnesium acetate (CMA) and potassium acetate (KAc). In addition to these, a number of newer organic materials are also in common use. This section introduces their characteristics and functions in winter maintenance.

2.4.1 Properties of Anti-icing Chemicals

With consideration on the characteristics of the materials, the environment, and related equipment, several criteria have been proposed for judging snow and ice control products. The main criteria are summarized as follows (Nixion and Williams, 2001; Ikiz, 2008):

Freezing Point Depression(FPD)

The FPD of a chemical directly impacts the effectiveness of a particular materials. It is relatively easy to compare chemicals according to their FPD capability; those with lower the freezing point are generally considered as more effective. However, chemicals with higher FPD capability are more versatile and thus effective over a wider range of conditions.

Consistency

Consistency reflects the materials' specific gravity and viscosity. For stable effectiveness, the snow and ice control materials should be consistent to prevent changing in density or unwanted lubrication between the material and the pavement induced by high viscose.

Environmental Impact

Environmental impacts should be evaluated before choosing materials for treatment. Materials may have impacts on soil, air, plants, underground water, or other factors, so they should be evaluated on an individual basis. In cases where significant environmental effects are identified, strategies should be identified to protect the environment.

Stability

Stability is the inertia of a material to initiate interaction with other materials. It should neither be biologically active, nor degrade to the environment over time.

Corrosion

Snow and ice control materials should be evaluated for their potential corrosive effect on vehicles, reinforced steel in the concrete, and other metals in infrastructure.

Handling

Handling refers to the convenience of using the chemical, that is, the ability to move it easily, and to use it with less manpower or less complicated equipment. For example, the material which can be moved by gravity flow are easier to handle compared to the ones requiring special pumps.

Conductivity

Conductivity refers to a measure of a material's ability to conduct an electronic current. This point is important to consider because some materials (particularly those that are liquids) have a very high conductivity, which poses hazard when roadside electronics are used.

Documentation

Documentation in this case refers to data sheets that indicate how the anti-icers are combined with different ingredients, and typically gives the constituent components of the material as a percentage of the total composition. The less amount of "other uncertain elements" present in the given anti-icer, the more efficient the anti-icer is (Nixon and Williams, 2001).

2.4.2 Types of Anti-Icing Chemicals and Their Characteristics

The basic mechanism for anti-icing is to depress the freezing point. Four types of chemicals are widely used for this purpose: calcium magnesium acetate, magnesium chloride, calcium chloride, potassium acetate and sodium chloride in liquid form (Mergenmeier, 1995). Currently, calcium chloride has the best performance in very low temperatures among the commonly used material, it is recommended for the colder situations (Ketcham et al., 1996; Hosseini, 2015). In the following tables (Table 2.2, 2.3, 2.4, 2.5), some of the chemicals commonly used will be stated with their eutectic temperatures, concentrations, effective temperature, cost, melting capacity, ice penetration(Hosseini, 2015; Ikiz, 2008).

In the context of winter maintenance, eutectic concentration refers to concentration of the material in solution which decreases water's freezing temperature to the lowest point. Ice penetration is ability to penetrate ice vertically which affects its ability to break the ice-pavement bond. The melting capacity means the ice melting ability of snow and ice control materials at different temperatures.

Cost is a critical criterion for choosing snow and ice control materials. The cost in this case includes both direct and indirect costs. Direct costs, include material costs, labor and equipment, indirect costs include treatment that may be required to alleviate environmental problems including corrosion to soil, and infrastructure, all of which need further treatment.

Table 2.2 Eutectic and Effective Temperature of the Most Commonly Used Anti-Icers(Hosseini, 2015; Ikiz, 2008; Ketcham at al.,1996)

Anti-icing Chemical Name	Eutectic Temp (℃)	Effective Temp (℃)
Calcium chloride ($CaCl_2$)	-51	-29
Sodium chloride (NaCl)	-21	-9
Magnesium chloride ($MgCl_2$)	-33	-15
Calcium magnesium acetate(CMA)	-27.5	-7
Potassium acetate (KAc)	-60	-26

Table 2.3 Melting Capacity of the Most Commonly Used Anti-Icers (Hosseini, 2015; Ikiz, 2008; Ketcham at al.,1996)

Anti-icing Chemical Name	Melting Capacity at -1 ℃ (gr/hr)	Melting Capacity at -12 ℃ (gr/hr)
Calcium chloride ($CaCl_2$)	10.5	4.2
Sodium chloride (NaCl)	9	0.9
Magnesium chloride ($MgCl_2$)	10	3.2
Calcium magnesium acetate(CMA)	7	0
Potassium acetate (KAc)	9	1.9

Table 2.4 Ice Penetration of the Most Commonly Used Anti-Icers (Hosseini, 2015; Ikiz, 2008; Ketcham at al.,1996)

Anti-icing Chemical Name	Ice Penetration at -1 ℃ (mm/hr)	Ice Penetration at -12 ℃ (mm/hr)
Calcium chloride ($CaCl_2$)	4.1	1.5
Sodium chloride (NaCl)	3.5	1
Magnesium chloride ($MgCl_2$)	5.6	3.5
Calcium magnesium acetate(CMA)	2.7	0.6
Potassium acetate (KAc)	5.3	1.2

Table 2.5 Eutectic Concentration and Cost of the Most Commonly Used Anti-Icers

Anti-icing Chemical Name	Eutectic Concentra (%)	Cost in 2010 ($/ton)
Calcium chloride ($CaCl_2$)	29.8	111
Sodium chloride (NaCl)	23.3	42
Magnesium chloride ($MgCl_2$)	21.6	140
Calcium magnesium acetate(CMA)	32.5	1492
Potassium acetate (KAc)	49	1166

2.4.3 Application Rate

Application rate is the quantity of de-icing and anti-icing material applied per unit of area during the winter. As different snow events require different application rates, we therefore need to determine the proper application rate prior to taking action. Some researchers and government agencies have proposed recommended application rates, some of which are highlighted in the following tables. Table 2.6 shows the solid and liquid salts application rate for highway (NCHRP, 2004; Hosseini, 2015), Table 2.7 shows anti-icing solid application rates for parking lots (Hossain and Fu, 2014; Hosseini, 2015). Table 2.8 shows liquid anti-icing application rate guidelines for parking lots (Fortin Consulting Inc.2006; Hosseini, 2015).

In addition to performance considerations, the cost of the delivered materials is also a crucial factor for determining application rates. Shi (2009) conducted a survey in Colorado, United States, Table 2.9 shows deicers listed by CDOT respondents according to their region, the cost with delivery to the region, and typical application rates. (Report No. CDOT-2009-1, Shi, et al., 2009)

Table 2.6 Solid and Liquid salts application rates for highways (NCHRP, 2004; Hosseini, 2015)

	$NaCl$		$CaCl_2$		$MgCl_2$		KAc		CMA	
Tem ℃	Solid Lbs/ 1000ft^2	Liquid Gal/ 1000ft^2	Solid Lbs/ 1000ft^2	Liquid Gal/ 1000ft^2	Solid Lbs/ 1000ft^2	Liquid Gal/ 1000ft^2	Solid Lbs/ 1000ft^2	Liquid Gal/ 1000ft^2	Solid Lbs/ 1000ft^2	Liquid Gal/ 1000ft^2
0	1.6	0.7	1.7	0.5	1.4	0.5	2.5	0.5	2.5	1.1
-1	1.6	0.8	1.7	0.5	1.5	0.5	2.5	0.5	2.5	1.2
-2	1.6	0.8	1.7	0.5	1.4	0.5	2.4	0.5	2.4	1.3
-3	1.6	0.9	1.6	0.5	1.5	0.6	2.5	0.5	2.5	1.5
-4	1.6	1.0	1.7	0.6	1.6	0.6	2.6	0.6	2.6	1.8
-5	1.6	1.0	1.8	0.6	1.6	0.6	2.6	0.6	2.6	1.8
-6	1.6	1.1	1.7	0.6	1.6	0.7	2.4	0.6	2.4	2.0
-7	1.6	1.1	1.7	0.7	1.5	0.7	2.4	0.5	2.4	2.0
-9	1.6	1.4	1.6	0.7	1.5	0.7	2.2	0.5	2.2	2.7
-12	1.6	1.9	1.6	0.8	1.5	0.7	2.2	0.6	2.2	4.2
-15	1.6	2.6	1.6	0.9	1.5	0.8	2.2	0.6	2.2	9.9

Table 2.7 Anti-icing Solid Application Rates for Parking Lots

(Hossain and Fu, 2014; Hosseini, 2015)

(Snow Type= Regular snow with density of 100 kg/m^3)

Snow Depth (cm)	Average Pavement Temp (℃)	Precipitation Duration + Desired Bare Pavement Regain Time (hours)							
		1	2	3	4	5	6	7	8
0.5	-7	85	70	55	45	30	15	0	0
0.5	-5	70	60	45	30	15	0	0	0
0.5	-3	60	45	30	15	0	0	0	0
0.5	-1	45	30	15	0	0	0	0	0
0.5	0	40	25	10	0	0	0	0	0
1	-7	90	75	60	45	30	20	5	0
1	-5	75	60	50	35	20	5	0	0
1	-3	65	50	35	20	5	0	0	0
1	-1	50	35	20	5	0	0	0	0
1	0	40	30	15	0	0	0	0	0
1.5	-7	95	80	65	50	35	20	10	0
1.5	-5	80	65	50	35	25	10	0	0
1.5	-3	65	50	40	25	10	0	0	0
1.5	-1	55	40	25	10	0	0	0	0
1.5	0	45	30	15	5	0	0	0	0

Table 2.8 Table Liquid anti-icing application rate guidance for parking lots (Fortin Consulting Inc.2006; Hosseini, 2015)

Condition	Gallons/1000 sq.ft.	
Regularly schedule applications	$MgCl_2$	Salt Brine(NaCl)
	0.1-0.2	0.25-0.3
Prior to Frost or Black Ice Event	0.1-0.2	0.25-0.3
Prior to light or moderate snow	0.1-0.2	0.2-0.4

Table 2.9 Deicers listed by CDOT respondents according to their Region, the cost with delivery to the Region, and typical application rate (Shi, et al., 2009)

Deicer or Anti-icer	Region	Cost delivered	Application Rate
NaCl (Solid)	1	$42/ton	500 pounds per lane mile on average
	1		500 lbs per lane mile
	2	$30-35/ton	500 pounds per lane mile
	3	NA	300-500 lbs per lane mile
	3	$23.5 /ton	600 -900 lbs per lane mile
	4	$29 to 32/ton	200 lbs per lane mile
	4	NA	100-500 lbs per lane mile
	4	$29 to 32/ton	200 lbs per lane mile
	5	NA	200-60 lbs per lane mile
	5	$20-24/ton	300-400 lbs per lane mile
	6	NA	100-500 lbs per lane mile
$MgCl_2$ (Liquid)	1	$0.84/gallon	25-45 gallons per lane mile
	1	$0.7/gallon	40-80 gallons per lane mile
	3	NA	40-80 gallons per lane mile
	3	$0.55/gallon	40 gallons per lane mile
	4	$0.53/gallon	40gallons per lane mile
	4	NA	20-100 gallons per lane mile

	4	$0.57/gallon	40 gallons per lane mile
	5	NA	30-80 gallons per lane mile
	5	NA	40-80 gallons per lane mile
	6	NA	20-100 gallons per lane mile
$MgCl_2$ (Solid)	5	NA	300-400 lbs per lane mile
	1	NA	500 lbs per lane mile
IceBan 300 (Lliquid)	3	$0.69 -0.72/ga	40 gallons per lane mile
Apex (Liquid)	2	$0.69 -0.72/ga	25 gallons per lane mile
	3	NA	40-80 gallons per lane mile
	3	$0.76/gal	25-30 gallons per lane mile
	5	$0.86/gal	30-60 gallons per lane mile
Rapic Thaw (Solid)	6	NA	80-100 gallons per lane mile
M 1000 Cold Tem Chloride (Liquid)	6	NA	60-80 gallons per lane mile
IceSlicer (Solid)	2	$92/ton	180-220 gallons per lane mile
	3	NA	100-300 gallons per lane mile
	4	NA	100-350 gallons per lane mile
	6	NA	100-350 gallons per lane mile
Cold Tem.Modified Envirtech Caliber(Liquid)	4	$0.73	40 gallons per lane mile
	6	NA	20-100 gallons per lane mile

2.4.4 Organic Materials in Winter Maintenance

Organic and semi-organic materials are less widely used in winter road maintenance (Fay, 2008), partly because of limited researche and available information on the effectiveness of these materials. . Some earlier research indicated that in very cold temperatures, organic and semi-organic products were generally not as effective as chloride or regular brine for pre-wetting and anti-icing purposes. A For example, a test conducted by Nixon (2005) showed that most of semi-organic materials failed to work when temperature dropped below -18 ℃, or even -12 ℃ .

Fay and Shi (2011) conducted a series of lab tests on a number of alternative materials including organic or agro-based. Their results showed that agro-based (as well as other two alternatives - $MgCl_2$ and KAc) performed better than the other de-icing materials. However, a study by Fu *et al.* (2012) suggested that organic products could result in higher friction levels and for an longer period of time. Hossain (2014) also found that some the organic or semi-organic materials showed a similar effectiveness to brine for anti-icing under different weather situations.

Muthumani (2015) also explored the performance of agro-based and complex chloride/minerals (CCM) materials, and the results showed that agro-based products significantly lowered the freezing point of sodium chloride and significantly decreased the brine's corrosiveness to environment, while CCM improved the melting capacity very slightly.

2.5 Summary

An extensive literature search was conducted to find material relevant to performance evaluation of organic deicers in comparison to regular salt. It was however found that there are few studies done on field testing of organic agricultural based products. Most of the past studies have focused on identifying the environmental impact of deicing materials (e.g., Ramakrishna and Viraraghavan, 2005), user experience with organic materials, and experimental studies involving lab tests of various deicers.

Fay and Volkening (2008) conducted a comprehensive survey of user experience in North America and Europe with respect to different deicing materials. The survey consisted of four multipart questions and was developed to document the user-perceived ranking of the deicers in terms of performance and impacts. The survey included state and local Department of Transportation (DOT) professionals, researchers and private sector specialists in highway winter maintenance. A total of 24 different deicers were used covering a large spectrum of materials from sand and sodium chloride to Potassium and agricultural products. Approximately 50% of the survey groups have experienced with agricultural materials; however, only one of the respondents in the survey had used Geomelt (one of the materials being tested in this study). More popular materials included calcium chloride, magnesium chloride, sand and sodium chloride. Users rated agricultural products as being effective in low temperature situations and generally considered them as the kind of alternatives having a positive impact on winter road safety. On the other side their higher costs were considered as the main drawback, hindering their wide application.

Fay and Volkening (2009) also conducted a laboratory test for the ice melting capacity of different deicers. Their lab testing results show little differences between the ice melting capacity of chlorides and agricultural products. As the exact constituents and concentrations of the materials used are not reported, little can be concluded from the study.

Taylor and Verkade (2010) conducted an ice melting laboratory experiment to determine how well agricultural materials melt ice in comparison to regular salt. It was found that, in terms of ice melting, beet juice (combined with sodium chloride) products tended to be on the lower end of the spectrum when compared to glycerol (combined with sodium chloride). The experiments were conducted on measured samples of water frozen to -12 ℃ and the effect of traffic and other variables thus could not be considered. Skid resistance tests were also conducted using a portable skid tester.

These tests were conducted to determine the extent to which different materials change the skid resistance of a pavement. It was found that beet juice based liquids caused a larger decline in friction than sodium chloride based solutions. The skid resistance results however should not be confused with friction levels experienced by vehicles during an event.

To the best of our knowledge, no study has been published that evaluates the actual field performance of different organic deicers. This research is one of the first to evaluate the field performance of materials using friction and visual characteristics as measures of performance. As this work involves data from real world conditions, we believe that the results obtained can be of high significance to municipalities and winter maintenance practitioners looking towards economically achieving a high level of service while limiting the use of salt.

Chapter 3 Methodology

3.1 Introduction

As discussed in the literature review previously, to decrease the negative effects of chloride based chemicals on the vehicles, infrastructure and environment, many government and environmental agencies are seeking alternatives to common salts like organic and agriculture based snow and ice control material. Some studies evaluated the performance of organic materials for winter road maintenance; however, most of those studies were conducted in a laboratory environment, therefore they do not take into account external factors existing in real situations (Nixon, et al., 2005; Shi, et al., 2009).

In this study, three different liquids were evaluated for their field performance as pre-wetting and anti-icing agents for snow and ice control. Each material was assigned a specific section on a straight stretch of road with similar pavement, traffic and environmental conditions. Material application and road condition data were then collected for multiple snow events.

The three different materials used in the experiment were salt brine, beet sugar based organic deicers - Fussion 2330 and Geomelt S30. Table 3.1 elaborates the constituents of the three materials.

Table 3.1 Deicer Material Constituents

Material	Constituents	Comments
Salt Brine	23% NaCl+water	Regular salt brine commonly used for winter maintenance.
Fussion 2330	30% beet juice +70% salt brine	Fussion 2330 and Geomelt S30 are supplied by different manufacturers and have similar constituents.
Geomelt S30	30% beet juice +70% salt brine	

The methodology proposed in this chapter for assessing the performance of two agriculture based products that are currently being used by Burlington and Oakville, namely, Fussion 2330 from Eco Solutions Inc. and Geomelt S30 from Future Road Solutions Inc. Both products are derived from sugar beet juice. The field test is aimed at achieving the following two objectives.

- Evaluating the performance of the organic anti-icing products for winter road maintenance operations .

- Investigating the ratio by which these products are mixed with salt or brine as well as the application rate of the end mixture.

3.2 Test Site Description

A stretch of a multi-lane arterial street, starting as New Street in the Town of Oakville and turning into Rebecca Street in the City of Burlington, was selected as the test site for this project (Figure 3.1). This route was selected because it meets some of the important requirements for conducting a reasonably controlled field experiment, such as degree of representation in terms of climate conditions, uniformity in external conditions (e.g., surrounding build-ups and traffic volume), and convenience (it can be covered by a single test vehicle in each run). The AADT of the street sections are between 16000 and 18000.

Figure 3.1 Test Site and Zones (Note that New Street ends and Rebecca Street begins at the border of Oakville and Burlington)

The test route is approximately 6 km in length and is divided into six segments (or zones) of approximately equal length, three from each city, for testing different deicing and ant-icing materials: one as a control section (base condition) and other two for the two organic products. The three zones in Burlington (Zone 1-3) are designated for testing pre-wetting applications while the three zones (4-6) in Oakville for testing anti-icing operations.

3.3 Maintenance Operations and Treatments

The test route is comprised of two lanes in each direction. Both prewet salt and anti-icing liquid (DLA) were applied as to cover both lanes in a single pass.

For testing prewet salt:

- Liquid was applied to the salt right at the spinner while the material was put down;
- Epoke 3500 with rear spreaders were used for salt application (Appendix B);

- Salt spreaders were ground speed regulated;
- Material was spread evenly across the two lanes (compared to the practice of dropping more at the center and have traffic disperse material to the sides);
- Salt brine was prewet at 20% by weight; organic liquids were prewet at 5% by weight. Material application rates and composition details can be found in Appendix F.

For DLA:

- Epoke 3500 with rear spreader was used to apply Geomelt;
- Schmidt Stratos B60-30 units with rear spreaders were used to apply salt brine and Fusion (Appendix B);
- DLA equipment was ground speed regulated;
- Salt brine was applied at 100 Litres/lane-km, organic liquids were applied at 50Litres/lane-km.

As different snow events require different application rates, a set of predetermined application rates were used throughout the study. In order to maintain consistency, rates were not changed between test sections during a single application.

Pre-wetting application rates

Three different predetermined material application rates were used. Choice of the actual setting was left to the maintenance supervisor and was decided based on the severity of the event and short- term forecast. However, for a single application, the same rates were used for all sections. Table 3.2 elaborates on the pre-wet application rates of the three materials.

DLA application rates

As anti-icing using DLA was conducted prior to the start of the event, only one set of pre-determined application rates were used for this experiment. Fussion 2330 and Geomelt S30were applied at the manufacturer's recommended application rates, where as salt brine was applied at the rate commonly used by the municipalities where the experiment was conducted. Table 3.3

shows the DLA rates along with the % of organic material constituting the applied mix and the net solid equivalent of salt being applied with every application.

Table 3.2 Pre-wet Application Rates and Mixing Ratios for Salt Brine, Fussion 2330 and Geomelt S30

Setting	Total Material /lane km	Dry Salt /lane km	Liquid /lane km	Cost ($/lane km)
Salt Brine				
1	60 kg	48 kg	12 kg (10 litres)	3.6
2	85 kg	68 kg	17 kg (14.2 litres)	5.1
3	110 kg	88 kg	22 kg (18.5 litres)	6.6
Organic (Fussion 2330 and Geomelt S30)				
1	60 kg	57 kg	3 kg (2.5 litres)	4.02
2	85 kg	80.75 kg	4.25 kg (3.5 litres)	5.6
3	110 kg	104.5 kg	5.5 kg (4.5 litres)	7.37

Table 3.3 DLA (for anti-icing) Application Rates and Mixing Ratios for Salt Brine, Fussion 2330 and Geomelt S30

Material	Application Rate (Litres/lane-km)	% Organic	Total Salt (kg/lane-km)	Cost ($/lane-km)
Salt Brine	100	0	23	1.2
Fussion 2330	50	30	8	2.0
Geomelt S30	50	30	8	2.0

3.4 Test Protocol Definition

Data collection was conducted according to the following protocol:

- A maintenance worker was designated to coordinate all activities with the friction truck operator. This was achieved using an online callout sheet shared between the municipality staff and the driver.

- Data collection begins before anti-icing materials are applied and continues for several hours after the first anti-icing application.
- Data collection runs occur approximately every two hours if road and weather conditions are not changing and more frequently as weather and road surface conditions continually change.
- Data collection continues until bare pavement is achieved or further plowing is required.

Before the start of the tests, a baseline run was performed to determine road conditions at the test site with bare dry state. It was observed that the road surface condition for all sections of the site was very similar in terms of visual observation and friction values (Appendix E). Thus data from different sections was considered suitable for direct comparison without any adjustments due to different pavement characteristics.

3.5 Data Collection

In order to quantify how effective the new bio-based products can improve the performance of the target mixture (pre-wetted salt or DLA brine) for pre-wetting and anti-icing treatments, the following two performance metrics are used:

- Friction or skid resistance: a physical measure to represent the amount of frictional force available between a road surface and vehicle tires.
- Road surface state: a visual characterization of road surfaces to represent the surface condition that the driver would see and feel. It could include two aspects: a) type of road surface contaminants such as loose snow, packed snow, slush and solid ice; and b) extent of snow and ice coverage such as bare pavement, centerline bare and wheel path bare.

For evaluation purpose, other relevant data were also collected simultaneously, this includes:

- Air temperature and surface temperature
- Road surface condition reported by patrolling staff
- All anti-icing/deicing operations conducted during the test period including chemical type, application rates and time, and maintenance vehicle location

A set of data collection systems were used for this project. Friction data were collected using Halliday's RT3 - a continuous friction measuring equipment (CFME) from Ministry of

Transportation Ontario (MTO). This equipment uses a friction wheel mounted on a patrol truck owned by Steel and Evan Limited to collect data on friction levels of the test sections. The collected data is saved to an onboard laptop.

Halliday's RT3 system outputs friction measurements in the scale of Halliday Friction Number (HFN) with values ranging from 0 to 100. A value of 100 represents the friction reading generated on a good, dry pavement and 5 for a smooth ice rink surface. As a result, HFN reflects the slipperiness of a road surface.

Before the RT3 system can be used, it must be calibrated according to the local road conditions. During the calibration procedure, the friction wheel is run over a dry stretch of road for a few times. The frictional force experienced by the wheel on that road is recoded as the reference friction and assigned with a value of 100. Once the device is calibrated, all values are measured in reference to the calibration value. A value of greater than 100 would mean friction is more than that experienced on the calibration run where as a value of less than 100 would translate into a lower friction. Friction values of less than zero are considered as invalid readings and are discarded by the code validation scripts described above.

A GPS equipped video recording system is installed in the patrol truck to record road surface conditions for visual classification of the actual road surface conditions. Air and pavement temperatures are collected using the road watch SS sensor. A detailed description of these devices is provided as follows.

Friction data is collected using the RT3 continuous friction measuring system, manufactured by Halliday Technologies. The friction wheel is connected to a road maintenance truck driven by an maintenance operator. An interface box located inside the maintenance truck receives the data and stores it onto an on-board laptop connected via serial link. The output of this device is friction levels relative to a bare dry baseline calibration value of 100. Figure 3.2 shows the friction wheel attached to a trailer.

GPS-tagged video and vehicle location data are collected using a GPSequipped video recording system located on the inside of the front windshield of the maintenance truck (figure 3.3). The GPS begins collecting data when the driver turns the vehicle on recording the time and vehicle location throughout the run. This information is used along with video footage to classify the road surface state during the data processing.

The RoadWatch SS pavement and air temperature sensor (Figure 3.4) are also installed in the service vehicle. Temperature readings from the RoadWatch SS are available on a display installed inside the vehicle. Temperature readings are logged onto a data logging form provided to the driver.

A laptop computer (Figure 3.5) with solid state hard drive (no moving parts – specially purchased for the project) is used for data logging. All friction values recorded from the RT3 are recorded directly on to the laptop. The recorded data is then made remotely available to the researchers for analyses.

Figure 3.2: Friction Wheel RT3 (Mounted on an S&E Truck)

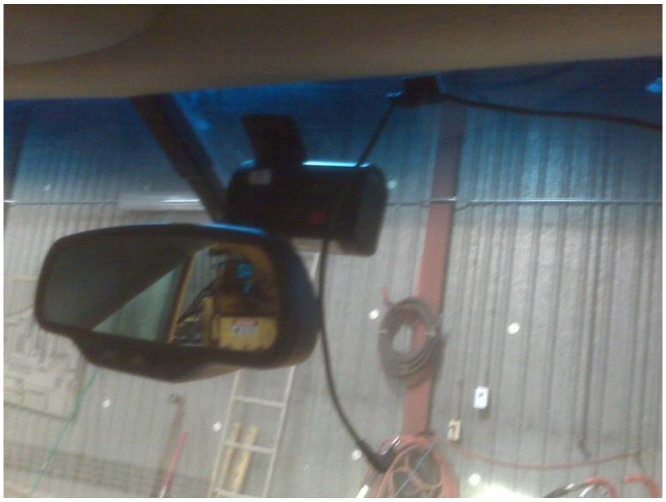


Figure 3.3: GPS and video recorder (Mounted inside an S&E Truck)

Figure 3.4: Roadwatch Air and Surface Thermometer (Mounted on an S&E Truck)

Figure 3.5: Laptop for Data Logging (Laptop with solid state hard drive, purchased specially for the purpose of in vehicle data logging)

Chapter 4 Performance Analysis and Evaluation

4.1 Introduction

Due to the mild winter season and delayed start of the project, the data collection effort was only able to cover one snow event in the 2009-2010 winter season (Feb. 22, 2010). A meaningful comparison between the three liquids required data from more events and thus data collection was extended to the 2010-2011 winter season.

DLA and prewetting performance data from a total of nine events were collected. The sample size can be considered sufficiently large for a meaningful performance comparison between the three materials. The 2010-2011 snow events that were covered in this study are summarized in Table 4.1. Material application rates and times were accordingly logged along and can be found in Appendix C. The variety of application rates and mixing ratios are summarized in Appendix C.

Table 4.1 Summary of Captured Events

Date	Number of Runs	Total Snow (cm)	Wind Speed (km/hr)	Air Temp		Pavement Temp		Pre-wetting	DLA
				Min	Max	Min	Max		
January 11, 2011	10	2.8	16	-2	1	-7	-3	Yes	Yes
January 15, 2011	7	5.8	17	-1	0	-8	-4	Yes	Yes
January 29, 2011	6	0.5	7	-2	0	-7	-2	Yes	Yes
February 1, 2011	4	1.6	21	-8	-7	-11	-8	Yes	Fusion &Geomelt *
February 2, 2011	4	12.8	41	-3	-2	-8	-7	Yes	Fusion &Geomelt *

February 20, 2011	14	4.6	12	0	2	-7	-1	Yes	Fusion &Geomelt *
February 25, 2011	13	0.6	28	2	4	-3	-1	Yes	Fusion &Geomelt *
March 5/6, 2011	26	5.2	20	-1	1	-6	-2	Yes	No DLA
March 22/23, 2011	16	12.6	23	0	7	-5	6	Yes	Yes

* No brine only DLA operation

As described previously, raw data on friction, location, video, material applications and temperature data were collected, assembled and subsequently processed. All the data were validated and fused into a single table for further analysis. A detailed description on the data processing procedure is provided as follows.

The data collected by the onboard system includes friction measurements (text format) and GPS-tagged videos. The raw friction files were processed and time-stamped based on the starting time of the run. Relevant information are extracted from the GPS log files (speed and position) while road conditions are visually observed and recorded based on the processed retrieved videos. This processed friction data are saved on separate tabs of the final time-synchronized spreadsheets.

1) Data Reduction

Data reduction is a process of transforming large volumes of data into a small number of summarized reports. This was an important part of the project as analyzing the results required a simple and easy way to read the collected information.

In order to determine which runs occurred at which times, the video retrieval software is used to determine when each run began by visual inspection. Since each run begins and ends at the same location, it is not difficult to pinpoint the beginning and end of each run using the GPS-tagged video. Once the continuous video is broken down into runs, they are further broken down into zones.

The raw friction files are composed of columns representing distance, friction and speed. The files are known to show two readings per second. A Python script of code has been developed to assign a time stamp to each reading based on user input of the beginning time of the run. The time when each run started is determined by watching the retrieved video and looking for a signal that the vehicle operator carried out. This indicated the time when the operator pressed a RESET button on the friction wheel interface box that set the recorded distance to zero. Figure 4.1 shows a video snapshot and its corresponding place in a raw friction file.

The python script then converted the speed values to kilometres per hour. Lastly the script averaged the dual readings per second to output one reading per second. The semi-processed friction data was then converted into a spreadsheet format to insert titles above each column. Figure 4.2 illustrates a reduced friction file.

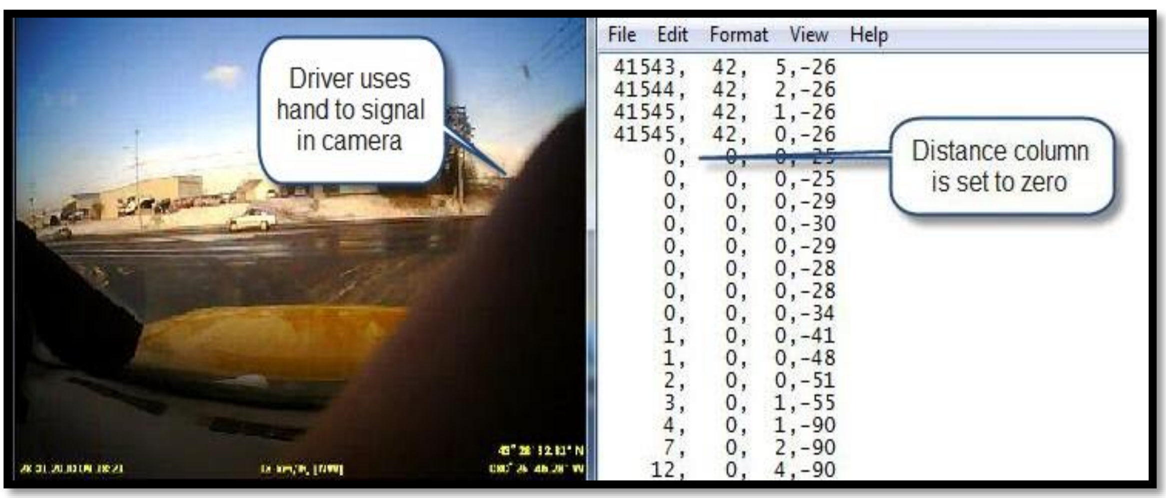


Figure 4.1: Raw Friction File and Video (the driver signaling in the camera when the reset button is pressed and the corresponding instant in the raw friction file)

	A	B	C	D	E
1	Distance	Friction	Speed	Tilt	Time
2	0	0	0	-25	9:18:21
3	0	0	0	-29.5	9:18:22
4	0	0	0	-28.5	9:18:23
5	0	0	0	-31	9:18:24
6	1	0	0	-44.5	9:18:25
7	2.5	0	0.8	-53	9:18:26
8	5.5	0	2.4	-90	9:18:27
9	15	0	8.8	-90	9:18:28
10	30	0	14.4	-90	9:18:29
11	48	0	18.4	-90	9:18:30
12	70	0	21.6	-90	9:18:31
13	97	56	27.2	-7.5	9:18:32
14	131.5	53	36.8	-3.5	9:18:33
15	173.5	54	46.4	13.5	9:18:34

Figure 4.2: Processed Friction Data (each entry in the spreadsheet corresponds to one second as opposed to Figure 1 where there are two entries per second)

Data associated with the GPS-tagged video was extracted from log files using a modified Python script. Extracted data include speed, time and GPS vehicle location. Once again these semi-processed text files are converted into a spreadsheet format. Each run had approximately 1-6 GPS log files as the files varied in the number of entries.

The videos are used to visually inspect the road surface conditions. The road surface conditions (RSC) had four criteria; longitudinal RSC, mid-lane RSC, wheel-track RSC and lane snow cover. For the first three criteria level of snow cover had a numerical value. Figure 4.3 illustrates the application used to enter the surface condition data.

A higher numerical value represented a more severe condition of road snow coverage than a lower value. The range of conditions goes from zero (bare dry) to five (mostly covered in snow). These values were assigned a timestamp for each entry with a new entry filled in whenever the conditions changed. The output is an excel file with the four criteria headings and the entries as rows.

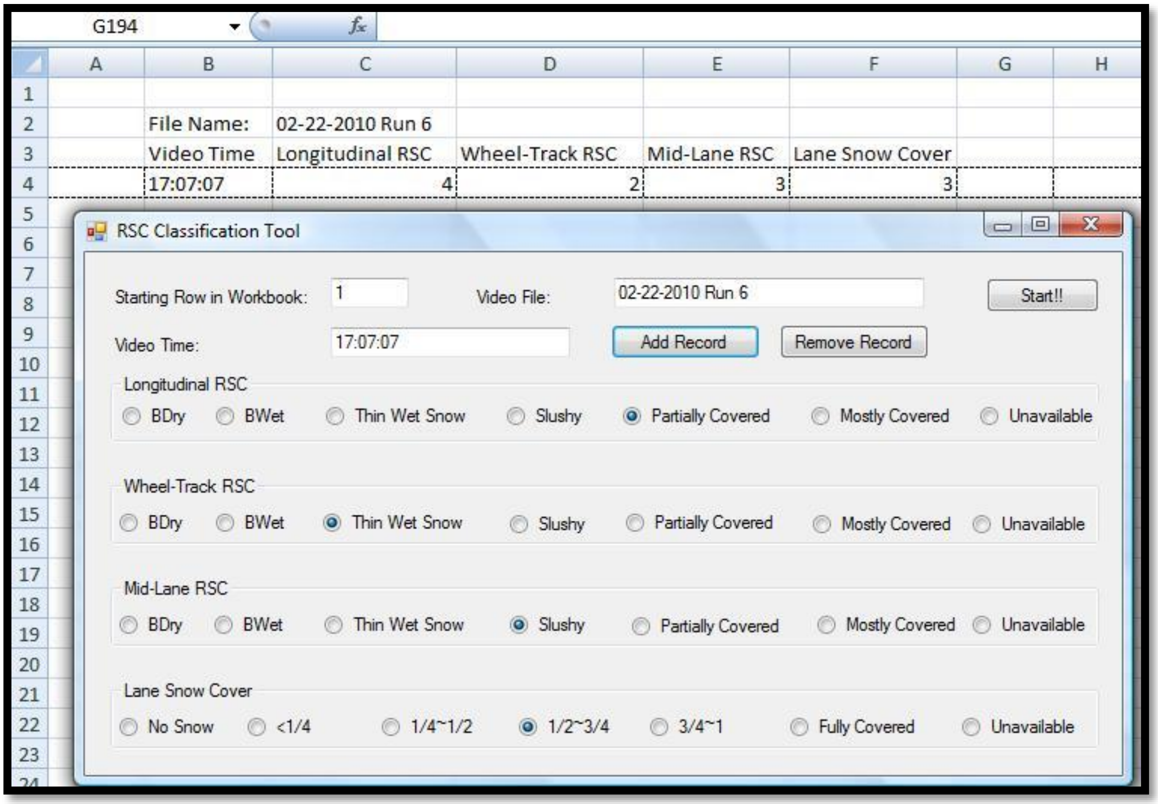


Figure 4.3: RSC Classification Tool (each choice assigned to a numerical value, starting from the left at zero and going up to five. The 'unavailable' option corresponds to the number 10)

2) Data Fusion

Each friction spreadsheet file was opened and the GPS data was pasted adjacent to the friction data columns. The times corresponding to the beginning of the forward and reverse runs were tagged. The RSC data was then pasted on the next several columns in the spreadsheet.

Once each spreadsheet was successfully time-synchronized with each form of data collected, the GPS-tagged video was re-watched to determine what time period corresponded to each zone. Each zone was located between two parallel streets and was approximately two kilometres in length. Once each zone's start and end time was determined, one last column was made in the final spreadsheet assigning a zone number from 4-6 and 0 for areas before the route or in the turn-around zone.

Once this was done, the final spreadsheet was put through another Python script that copied all the friction values to a new file, but omitted invalid friction entries associated with extremely low speeds and during sharp turns. This was done to ensure the accuracy of the friction values at the advice of the HallidayRT3 manufacturer. Friction values for each zone, going forward and returning, were graphed for analysis. Friction averages and standard deviation values were calculated for each graph.

For each test run, approximately 130 friction readings were obtained for each of the six test sections. This sample size is considered to be sufficiently large for obtaining statistically valid results for the specific conditions.

4.2 Data Comparison Methodology

Friction Readings and Road Images

Friction readings for all sections were manually compared to their respective road images to validate the recorded friction readings. A sample visual comparison between observed friction levels and actual road conditions is shown in Figure 4.4.

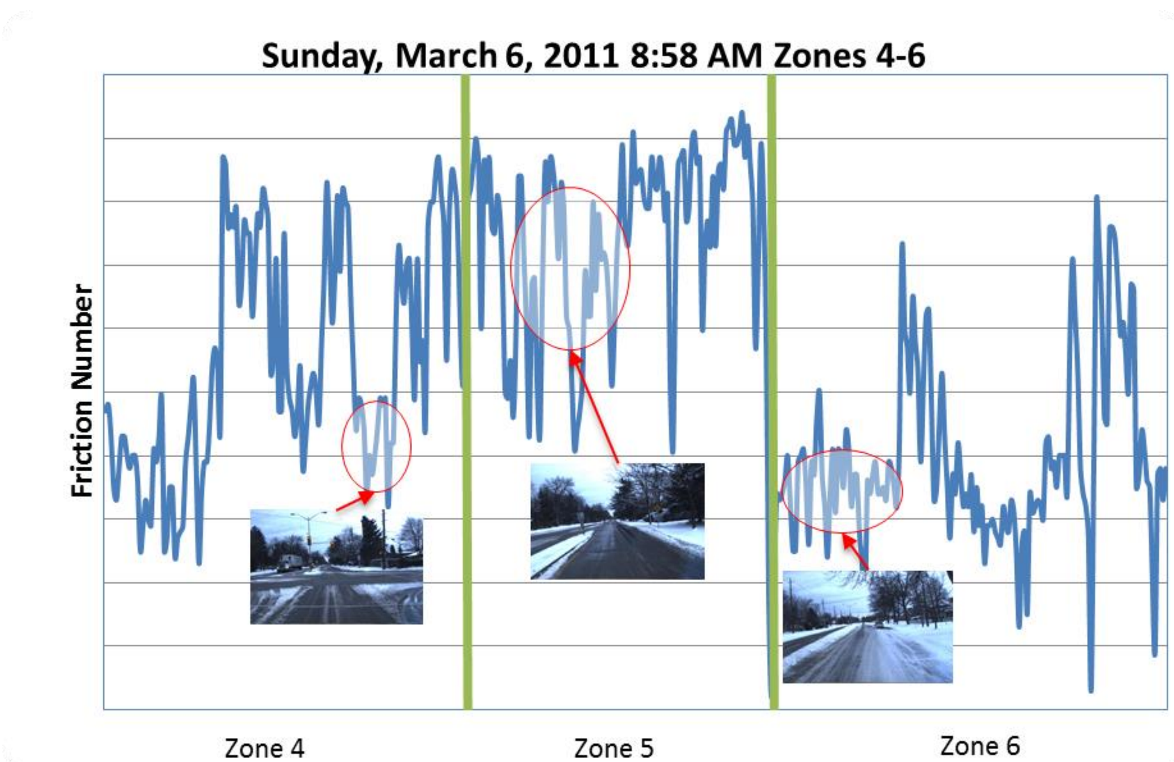


Figure 4.4 Sample friction measurements and road surface conditions

Figure 4.4 shows an example of the friction measurements along with several video snapshots at three selected locations. The processed data were subsequently analyzed for performance comparison as described in the following models.

Run-wise Comparison models

For each section, mean and standard deviation of friction values were calculated (see Equation 1 and 2). This operation was individually performed on all runs in a given storm. Average zonal friction levels throughout the event were compared to find performance differences between the three materials. Run-wise comparison of friction levels allowed comparison of material performance during different stages of the snow event. This analysis made it possible to identify materials that react faster and provide higher friction levels for a small period if time as compared to materials that react slower but remain affective for a longer period.

$$\bar{f}_k^A = \sum_{i=1}^{n} f_{k,j}^A \Big/ n_k^A \tag{1}$$

$$\bar{s}_k^A = \sqrt{\sum\nolimits_{i=1}^{n} \left(f_{k,i}^A - \bar{f}_k^A\right)^2 / (n_k^A - 1)} \tag{2}$$

Where: $\bar{f}_k^A$ =average friction number for zone A based on test run k;

$f_{k,j}^A = i^{th}$ friction reading in zone A from test run k;

n_k =total number of friction readings in a specific zone for test run k;

$\bar{s}_k^A =$ Average friction standard Error for zone A based on test run k.

Event Average Comparison Model

The daily friction sum (Equation 3) for each zone was also computed to compare the daily friction average between zones. As this computation takes friction into account friction values for an entire event, comparing daily averages gives a better estimate of the overall performance of a material.

$$\bar{f}^A = \sum\nolimits_{k=2}^{K} \left[\bar{f}_k^A \cdot (t_k - t_{k-1}) \times \left(\bar{f}_k^A - \bar{f}_{k-1}^A\right)/2\right] / (t_k - t_1) \tag{3}$$

Where: $\bar{f}^{A}$ = average friction level for zone A over the effect time window as defined later;

t_k = time when test run k started.

4.3 Performance as Pre-wetting Agent

Friction, video and temperature data from the three test zones (1-3) treated with pre-wet salts using brine, Geomelt and Fusion as the prewetting agent are used to compare the performance of the materials. Moreover, metrological data from a nearby RWIS station is also collected for each storm event.

The performance of the materials is gauged by their deicing ability as well as their ability to maintain safe friction levels over time. To perform a meaningful comparison between the three materials, the following methods are used:

- Zone-wise comparison of friction values over the duration of the event
- Visual comparison of road surface condition from image data
- Pair-wise t-tests (A form of ANONA statistics test)
- Comparison of metrological data to gauge the severity of the storm, precipitation and temperature range
- Material application and maintenance data

Figure 4.5 shows the average friction level of each section (material) as a function of the elapsed time after the first friction measurement over three different snow events for Feb 25, 2011 as example. The application time of the pre-wetted salts are noted in the same figure. Same methods can be used for the rest experiment days (Appendix G2 A).

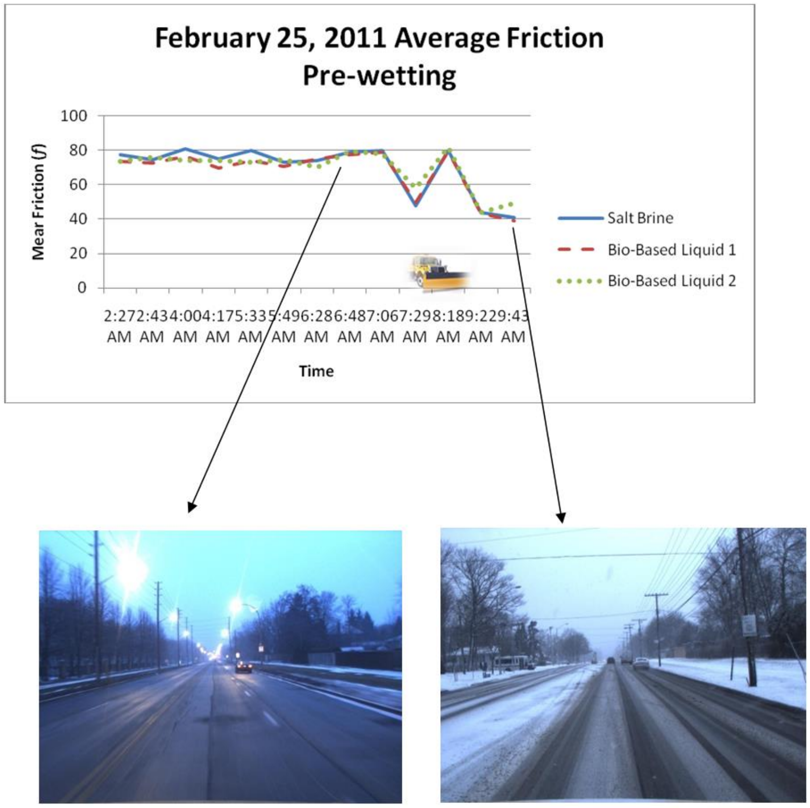


Figure 4.5 Performance of the Alternative Materials as Prewetting Agent (Feb 25, 2011)

Figure 4.5 also shows an example of typical friction readings of all tested compounds for data collected on February 25, 2011. While the figure shows that it initially performed slightly better than both Geomelt and Fusion, after the 7:06 am the situation changed and both Geomelt and Fusion performed slightly better than regular Brine instead. However, it is important to note that the differences were relatively small, and all the three materials exhibited similar pattern in terms of performance trend over time. It was observed that the recorded friction levels reflected road conditions as seen in the road images. A complete analysis of the data is presented in Table 4.2 for data collected on of February 25, 2011. This table shows the results of a statistical pair-wise t-test (a form of ANOVA statistical test) on differences in pre-wetting performance (Friction Level) of February 25, 2011.

Table 4.2 Statistic Test on Differences in Pre-wetting Performances

February 25, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	130	120	118	0.000	0.817	0.000
	x	77.542	73.339	73.580	Brine	Fusion	Brine
	s	7.292	7.810	8.312	Significant	Insignificant	Significant
0.25	n	124	117	121	0.080	0.001	0.058
	x	74.240	72.585	76.057	Brine	Fusion	Fusion
	s	7.116	7.532	7.873	Marginally Sig.	Significant	Marginally Sig.
1.5	n	114	126	118	0.000	0.006	0.000
	x	80.878	76.598	73.884	Brine	Geomelt	Brine
	s	7.512	8.708	8.257	Significant	Significant	Significant
1.75	n	118	135	97	0.000	0.000	0.839
	x	74.924	69.405	74.119	Brine	Fusion	Brine
	s	6.914	7.277	8.051	Significant	Significant	Insignificant
3	n	118	115	22	0.000	0.468	0.000
	x	79.950	74.026	73.228	Brine	Geomelt	Brine
	s	9.273	8.279	8.686	Significant	Insignificant	Significant
3.5	n	127	124	114	0.006	0.000	0.172
	x	72.961	70.339	74.313	Brine	Fusion	Brine
	s	6.770	8.098	8.408	Significant	Significant	Insignificant
4	n	193	180	160	0.069	0.000	0.000
	x	74.072	74.890	70.068	Similar	Geomelt	Brine
	s	11.638	7.173	9.431	Marginally Sig.	Significant	Significant
4.5	n	128	123	147	0.061	0.065	0.916
	x	79.023	77.145	79.128	Brine	Fusion	Similar

	s	7.339	8.487	9.152	Marginally Sig.	Marginally Sig.	Insignificant
4.5	n	116	116	118	0.319	0.321	0.042
	x	79.880	78.846	77.714	Brine	Geomelt	Brine
	s	7.238	8.537	8.936	Insignificant	Insignificant	Significant
5	n	228	190	146	0.000	0.000	0.000
	x	47.533	49.859	57.925	Geomelt	Fusion	Fusion
	s	5.355	5.007	11.760	Significant	Significant	Significant
6		127	149	135	0.604	0.035	0.181
		80.047	79.167	81.632	Brine	Fusion	Fusion
		8.388	8.777	10.730	Insignificant	Significant	Insignificant
7		132	136	149	0.330	0.260	0.741
		43.842	43.241	44.033	Similar	Fusion	Fusion
		3.812	6.075	5.794	Insignificant	Insignificant	Insignificant
7.25		130	139	134	0.001	0.000	0.000
		41.050	38.992	49.215	Brine	Fusion	Fusion
		4.734	4.957	7.146	Significant	Significant	Significant

From the Table 4.2, the t-test results show similar results with Figure 4.2. When compared with the regular brine, we can calculate the relative performance results of the three materials in terms of average friction over all experiment periods with nine snow events (Table 4.3). These results are plotted in the Figure 4.6.

Table 4.3 Difference in Performance for Prewetting

	Prewet(% difference)					
Date	Fusion vs Brine		Geomelt vs Brine		Fusion vs Geomelt	
Jan.11	1103.8	3.23	-779.1	-2.3	1882.88	5.6
Jan.15	-780.2	-4.7	-2414	-15	1633.56	12
Jan.29	-1225	-3.2	-5433	-14	4208.28	13
Feb.01	-1467	-6.3	-1148	-4.9	-318.94	-1

Feb.02	365.72	18.1	1370	67.6	-1004.3	-30
Feb.20	219.93	1.93	-156.3	-1.4	376.27	3.3
Feb.25	-958.9	-3.1	-188.4	-0.6	-770.57	-3
Mar.5&6	-572.7	-3.7	2018	13	-2590.7	-15
Mar.22&23	-610.1	-6.5	-2181	-23	1570.84	22
	Mostly indifferent		Mostly indifferent		Mostly indifferent	

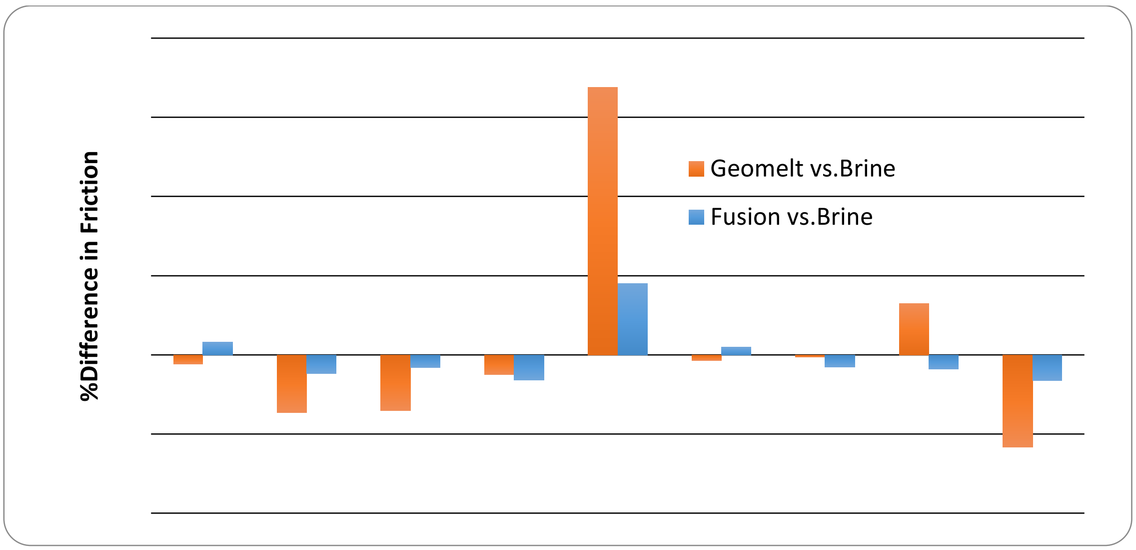


Figure 4.6 Relative Performance for Prewetting

From Table 4.3 and Figure 4.6, we can see that the results keep a high consistency. The main findings on the comparative performance of the three alternatives over the different snow events are summarized in Table 4.4.

Table 4.4 Summary of Findings on the Performance of the Alternative Products as Prewetting Agent

Date	Snow Pavement Temp. Duration	Summary of Maintenance Operations	Main Findings (Based on Video Data and Friction Measurements)
	2.8 cm		

January 11, 2011	-3 to -7 ℃ 11 am + 25 hrs	Prewet Salt @110 kg x 2	• Fusion performed marginally better than the other materials.
January 15, 2011	5.8 cm -4 to -8 ℃ 01am + 23 hrs	Prewet Salt @110 kg	• Brine performed marginally better than Fusion and much better than Geomelt.
January 29, 2011	0.5 cm -2 to -7 ℃ 08am +8hrs	Prewet Salt @110 kg	• Brine performed marginally better than Fusion and much better than Geomelt. However, there was only trace of precipitation and all sections had high traction.
February 1, 2011	1.6 cm -8 to -11 ℃ 2pm +21 hrs	Prewet Salt @110 kg	• Salt brine performed better. However, friction levels never fell to an unsafe level
February 2, 2011	12.8 cm -7 to -8 ℃ 11 am + 12hrs	Prewet Salt @110 kg	• Geomelt performed better than salt brine and Fusion. • As precipitation continued, friction levels in all three zones remained unsafe. • There was little visual difference in road surface conditions between the three zones.
February 20, 2011	4.6 cm -7 to -1 ℃ 11 am +11hrs	Prewet Salt @110 kg	• Fusion performed slightly better than brine at the beginning but their performance became similar as the event carried on.
February 25, 2011	0.6 cm -3 to 1 ℃ 8pm + 19 hrs	Prewet Salt @110 kg	• Brine performed slightly better than the other materials in terms of friction. There was little visual difference between the road surfaces.
	5.2 cm -6 to -2 ℃	Prewet Salt @110 kg x 2	

March 5/6, 2011	9pm + 12 hrs		• Geomelt performed better than Fusion and Brine in terms of friction. The difference can be seen visually
March 22/23, 2011	12.6 cm -5 to 6 ℃ March 05 11pm + 26 hrs	Prewet Salt @110 kg	• Brine performed better than Fusion and Geomelt.

4.4 Performance as Additive of Anti-icing Brine for DLA

Similar to the previous analysis, all data from the DLA test zones (4-6) are used to compare the performance of the three materials. Due to equipment malfunctioning, DLA operations using brine only had to be discontinued after four snow events (see Table 4.3). For the rest of the season, data were collected for DLA with Fusion, Geomelt and no material application in the third test section. This gave us the opportunity to compare the effectiveness of DLA operation in comparison to no DLA.

As shown in Figure 4.7, a cursory examination of the results showed that the friction level of the section treated with Fusion decreased in a much slow rate over time than the other two sections for most of tests conducted. Figure 4.4 plots the friction results for the day of Jan. 15, 2011 as an example. The application time of the anti-icing chemicals are noted in the same figure. Additional plots for other days are available in Appendix G2b.

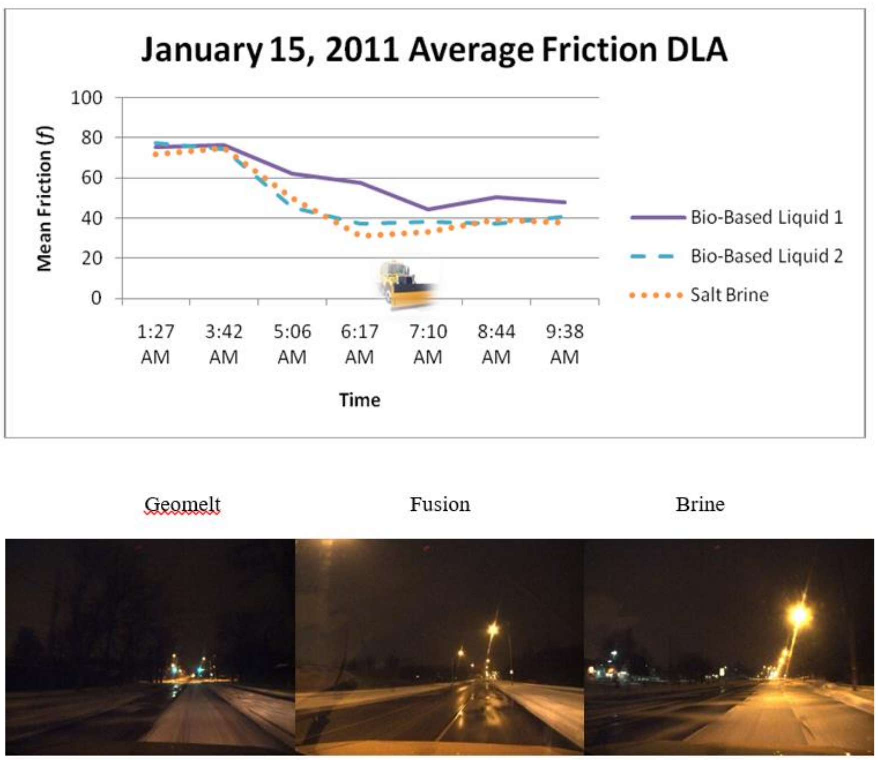


Figure 4.7 Performance of the Alternative Materials as Anti-icing Liquid Additive (Jan 15, 2011)

To verify these findings, a statistical analysis was conducted on all the data collected on January 15, 2011. The results of the statistical tests are shown in Table 4.5. For this data, statistical comparisons were made on differences in DLA & Anti-Icing performance (Friction Level) of January 15, 2011.

Table 4.5 Statistic T Test on difference in DLA & Anti-icing Performance

January 15, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	143	137	144	0.000	0.003	0.000
	x	75.510	77.431	71.701	Geomelt	Fusion	Fusion
	s	5.779	4.960	5.256	Significant	Significant	Significant
2.25	n	119	129	136	0.085	0.001	0.164
	x	76.395	74.147	75.132	Geomelt	Geomelt	Brine
	s	5.205	4.974	6.462	Marginally Sig.	Significant	Insignificant
3.5	n	125	122	126	0.000	0.000	0.000
	x	62.128	45.254	50.500	Geomelt	Geomelt	Brine
	s	17.100	4.127	9.577	Significant	Significant	Significant
4.75	n	135	135	150	0.000	0.000	0.000
	x	57.659	37.363	31.127	Geomelt	Geomelt	Fusion
	s	18.128	8.656	8.323	Significant	Significant	Significant
5.75	n	141	146	150	0.000	0.000	0.000
	x	44.461	38.212	33.027	Geomelt	Geomelt	Fusion
	s	8.526	6.0595	8.3134	Significant	Significant	Significant
7.25	n	196	162	183	0.000	0.000	0.110
	x	50.603	37.361	39.448	Geomelt	Geomelt	Brine
	s	12.445	9.6994	13.095	Significant	Significant	Insignificant

8	n	167	133	156	0.000	0.000	0.007
	x	48.048	40.602	37.763	Geomelt	Geomelt	Fusion
	s	8.937	9.245	8.451	Significant	Significant	Significant

As before, the relative performance results of the three materials in terms of average friction can be calculated for the nine events spanning the experiment period. These results are shown in Table 4.6.

Table 4.6 Difference in Performance for DLA

	DLA (% difference)					
Date	**Fusion vs Brine**		**Geomelt vs Brine**		**Fusion vs Geoment**	
Jan.11	565.856	1.7	249.53	0.8	-316.3	-0.9
Jan.15	4593.28	30	300.29	2	-4293	-22
Jan.29	2656.52	8	1164.2	3.5	-1492	-4.2
Feb.01	1968.81	9.3	698.09	3.3	-1271	-5.5
Feb.02	1014.86	31	631.96	20	-382.9	-9
Feb.20	3767.89	37	2046.7	20	-1721	-12
Feb.25	3883.36	15	3155	12	-728.4	-2.5
Mar.5&6	4434.26	23	3550.8	18	-883.5	-3.7
Mar.22&23	3734.27	35	2840	26	-894.3	-6.1
	Fusion Outperforms Brine		Geomelt Outperforms Brine		Fusion Outperforms Geomelt	

The results from the Table 4.6 can be plotted in the following Figure 4.8 and Figure 4.9.

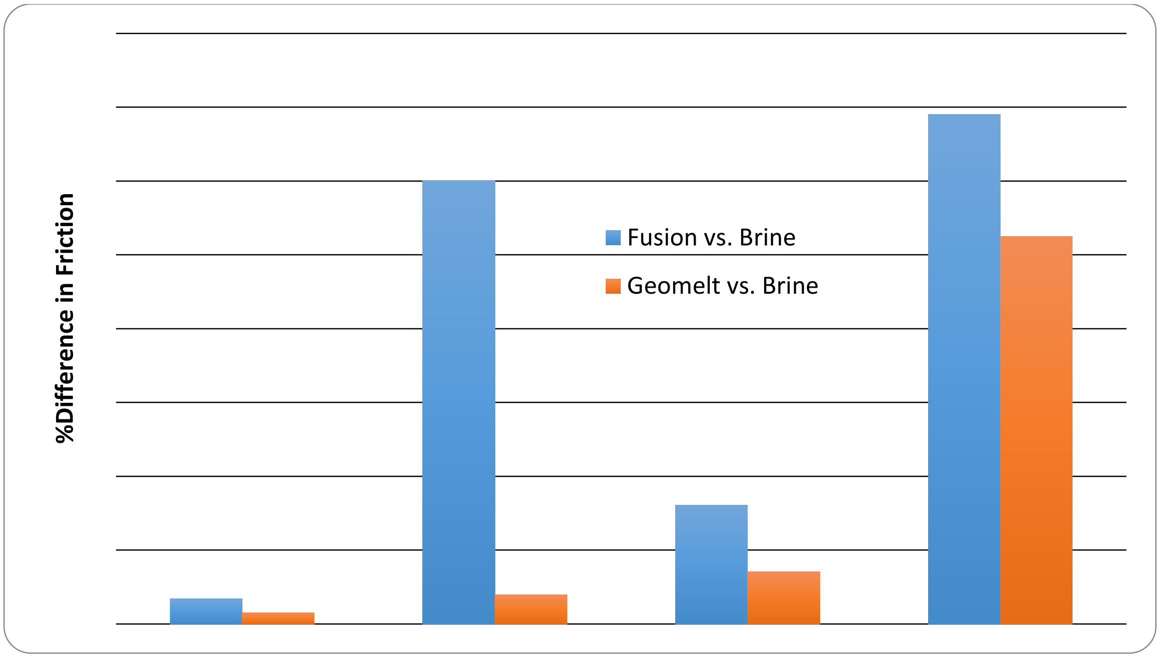


Figure 4.8 Relative Performance for DLA (1)

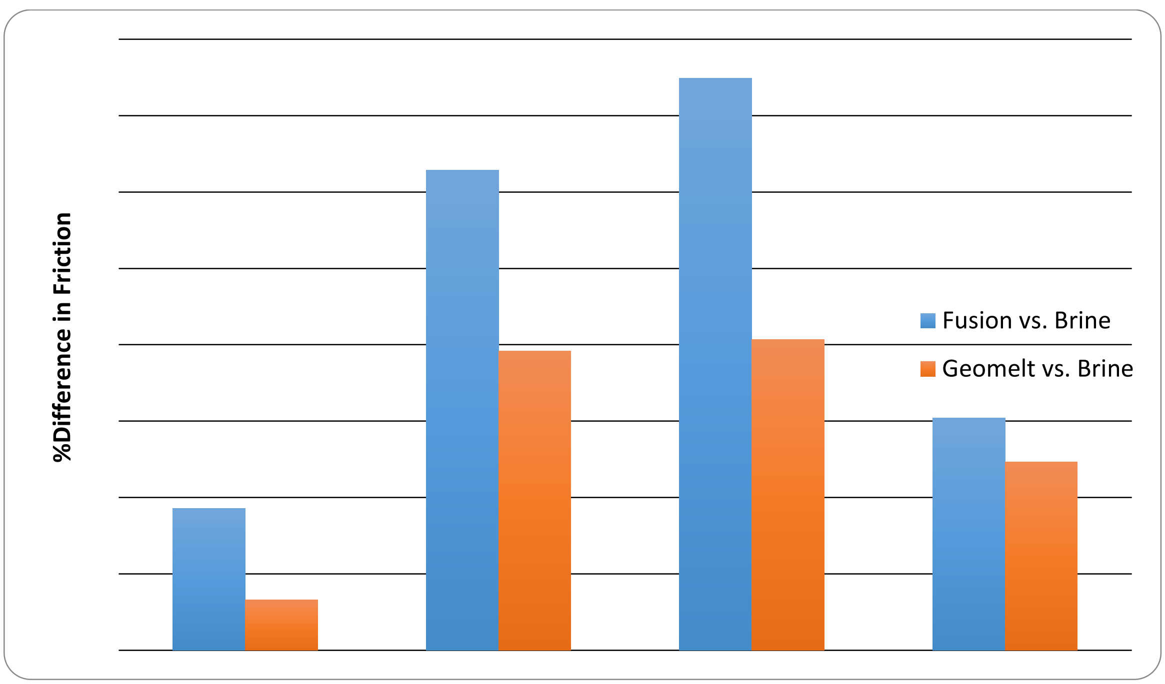


Figure 4.9 Relative Performance for DLA (2)

The results plotted in Figure 4.8 and Figure 4.9 show that Fusion and Geomelt always outperformed the regular Brine. Table 4.7 summarises the main findings on the comparative performance of the three alternatives.

Table 4.7 Summary of Findings on the Performance of the Alternative Products for DLA

Date	Snow Pavement Temp Duration	Summary of Maintenance Operations	Main Findings (Based on Video Data and Friction Measurements)
January 11, 2011	2.8 cm -3 to -7 ℃ 11 am + 25 hrs	DLA Salt brine 100L/km DLA Organic 50L/km	• Both Fusion and Geomelt performed better than Brine • Fusion performed marginally better than Geomelt
January 15, 2011	5.8 cm -4 to -8 ℃ 01am + 23 hrs	DLA Salt brine 100L/km DLA Organic 50L/km	• Fusion performed best. Friction levels were up to 20% higher than brine. • Geomelt performed slightly better than Brine • DLA with Fusion helped maintain safe friction levels for an hour longer than brine
January 29, 2011	0.5 cm -2 to -7 ℃ 8am +8hrs	DLA Salt brine 100L/km DLA Organic 50L/km	• Both Fusion and Geomelt evidently performed better than brine. • Fusion outperformed Geomelt
February 1, 2011	1.6 cm -8 to -11 ℃	DLA Organic 50L/km	

	Dec 31- 2pm +21 hrs		• Fusion outperformed Geomelt by approximately 5%. • DLA sections performed better than the untreated section.
February 2, 2011	12.8 cm -7 to -8 ℃ 11 am + 12hrs	DLA Organic 50L/km	• Fusion outperformed Brine by over 30% in terms of friction • Fusion outperformed Geomelt by up to 10%. • DLA sections performed better than the untreated section.
February 20, 2011	4.6 cm -7 to -1 ℃ 11 am +11hrs	DLA Organic 50L/km	• Fusion performed best. Friction levels were over 20% higher than brine. • DLA with Fusion helped maintain safe friction levels for an hour longer than brine
February 25, 2011	0.6 cm -3 to 1 ℃ 8pm + 19 hrs	DLA Organic 50L/km	• Both Fusion and Geomelt performed much better than Brine. However, there was little visual difference between the road surfaces.
March 5/6, 2011	5.2 cm -6 to -2 ℃ Mar 5 9pm + 12 hrs	NO DLA	• Despite no application, section with Fusion performed better than the previously untreated section. • The better performance could be due to residue material from previous applications.
March 22/23, 2011	12.6 cm -5 to 6 ℃ March 05 11pm + 26 hrs	DLA Salt brine 100L/km DLA Organic 50L/km	• Fusion and Geomelt performed much better than Brine. • Fusion outperformed Geomelt slightly.

4.5 Summary

This Chapter describes the results of the field experiments through an exploratory data analysis. The following findings can be concluded from the results of the tests with respect to pre-wetting treatment:

- In general, the three materials showed mixed performance with no material outperforms another in all events. The differences were mostly small (with one exception) (see Appendix C).
- Contrary to general belief, a significant increase in performance of organic materials for prewetting under low temperatures was not observed. However, as only one event with temperatures below -10 ℃ was captured, the limited data cannot be used to form conclusions about the performance of organic materials under low temperatures.
- Geomelt and Fusion showed similar performance and there is no clear evidence that one is superior to the other.
- Pair-wise t-tests are also performed on friction values from the three materials. The tests show similar results (See Appendix G for details).

For DLA and Anti-icing, the following can be concluded from the results of the various tests:.

- In general, organic materials showed better performance in comparison to salt brine. In some cases performance differences of up to 20% were observed. While it is possible that the observed difference in performance could be due to some external factors such as drifting snow and other local phenomena. However, given the consistency of results under a wide range of conditions, it is unlikely that traffic and other local phenomena played a dominating role in the experiments.
- Despite being applied at a lower application rate (See Appendix C for details) organic materials largely outperformed salt brine. It was observed that organic materials helped maintain higher traction as well as buy more time for the maintenance personnel before friction levels on treated sections fell to dangerously low levels (See Figure 4.9);

- Fusion outperformed Geomelt by up to 15 %. The collected data can be used to establish superiority of Fusion in comparison to Geomelt (given the tested range of conditions);
- In general section treated with DLA performed significantly better than untreated sections, warranting the use of DLA for snow and ice control;
- Pair-wise t-tests are also performed on friction values from the three materials. The tests show superior performance by Fusion in comparison to other materials (See Appendix G for details).

Chapter 5 Regression Analysis of the Performance of Organic Materials

5.1 Introduction

The main purpose of this study is to evaluate the two of new organic or bio-based chemicals and additives, namely, Fusion 2330 and Geomelt S30 that are most commonly used for both pre-wetting and anti-icing operations under a wide range of weather conditions in a stretch of a multi-lane arterial street, starting as New Street in the Town of Oakville and turning into Rebecca Street in the City of Burlington with the AADT of the traffic between 16000 and 18000. In Chapter 3 and 4, using the field data collected, the performance of the above two organic products was evaluated and compared to the regular brine under the observed weather conditions. The results of the analysis conducted in Chapter 4 suggested that the friction levels provided by the various chemicals were different in a statistically meaningful way. In order to quantify the effect of the chemical type on the friction levels while controlling the effects of other factors, a regression analysis was conducted to link the friction level to material type as well as other environmental and maintenance factors. In addition to quantifying the effect of the tested chemicals, such a model would also be useful to maintenance practitioners as it may be used to identify the conditions under which this types of materials would be most effective. The following sections provide a detail discussion on the data used for this modeling analysis and the main findings.

5.2 Data Sources and Pre-Processing

As discussed in previous sections, field data collected at the test site includes total daily precipitation, air temperature, road temperature, and wind speed. To support the modelling process, the aggregated raw data discussed in Chapter 4 was further processed. Records were divided into rows containing records for individual test sections, and an additional column containing the time since material was last applied was added. Furthermore, additional data sources were also identified, including archival weather data from Environment Canada. These data provided additional details on prevailing weather conditions that were not collected during field tests. Weather data was obtained for all months where data collection occurred, and is available from

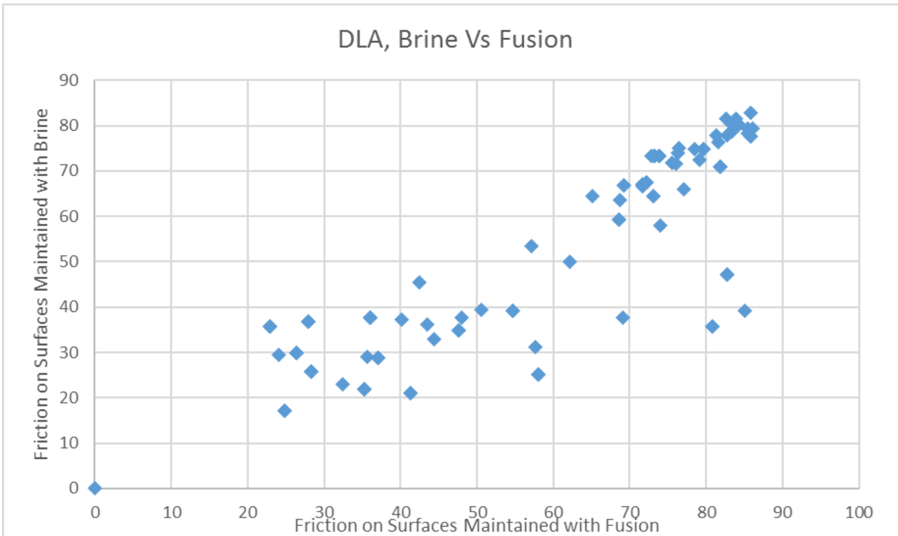
Environment Canada on an hourly basis. These data were collected from an aviation weather station located at Toronto's Pearson International Airport (about 30kilometres away). A full description of the data available, including a sample data table, is available in **Appendix H.** The weather data provided at this location contains some overlap with data collected at the test sites, including temperature and wind levels. In addition to this, however, the data also includes a qualitative variable describing current weather conditions, including such categories such as cloudy, mostly cloudy, rain, snow, snow showers that was not contained in the original field data. A full description of the categories and definitions are available in **Appendix H.**

Supplemental weather data from Environment Canada was then merged with the field dataset by matching records from the closest hour. The qualitative variables for weather condition were converted into various Boolean (True or False) condition state variables for use in the modelling process. Inclusion of these variables allows consideration of recent and current weather conditions.

For this analysis individual hourly data records were divided into two groups using a random process. Following the common practice for modeling, a subset containing 15% of the records was retained for subsequent validation, and 85% of the records were then used to estimate the model. Over the entire testing period, a total of 300 individual records each for tests on pre-wet and DLA sections (for a total of 600 records) were available, resulting in 255 records from each being used for model estimation and the remaining 45 for validation.

5.3 Model Development

Preliminary exploration of the data was conducted by visualizing the relationship between the friction levels provided and the time since maintenance was conducted, as it is expected to be one of the key factors affecting the level of service delivered on roadway . Since the analysis detailed in Chapter 4 suggests that there is a statistically difference in the friction levels between the chemicals on the DLA test sections, the initial analysis focussed on determining if this difference is time dependant. Put another way, we wished to determine if there was a difference in the *melting rate* or *friction recovery rate* of the different chemicals. The potential of this relationship is highlighted in Figure 5.1 and 5.2 which plot the respective measurements of friction taken at similar times across the different test sections against each other. The figures suggest lower correlation between the friction provided by sections maintained with brine and those maintained with the alternatives on DLA test sections, suggesting that the various chemicals have different performance. This gives motivation for the development of a model that can consider these differences. The figures suggest that the pre-wet sections have similar performance between the various test sections (less apparent variability), suggesting that there is not much in the way of observable difference between their estimates.



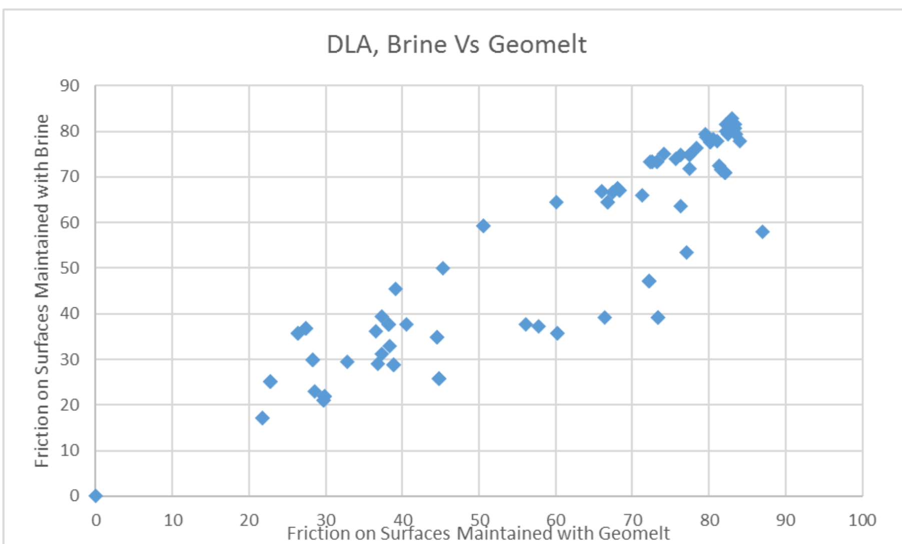


Figure 5.1 Observed Frictions on Sections Treated with Different Materials (DLA Sections)

Figure 5.2 Observed Frictions on Sections Treated with Different Materials (Pre Wet Sections)

The potential of this relationship is highlighted further in Figure 5.3 and 5.4, which plots the differences in the friction levels provided on surfaces maintained with brine from those maintained with one of the other two chemicals as it varies with time.

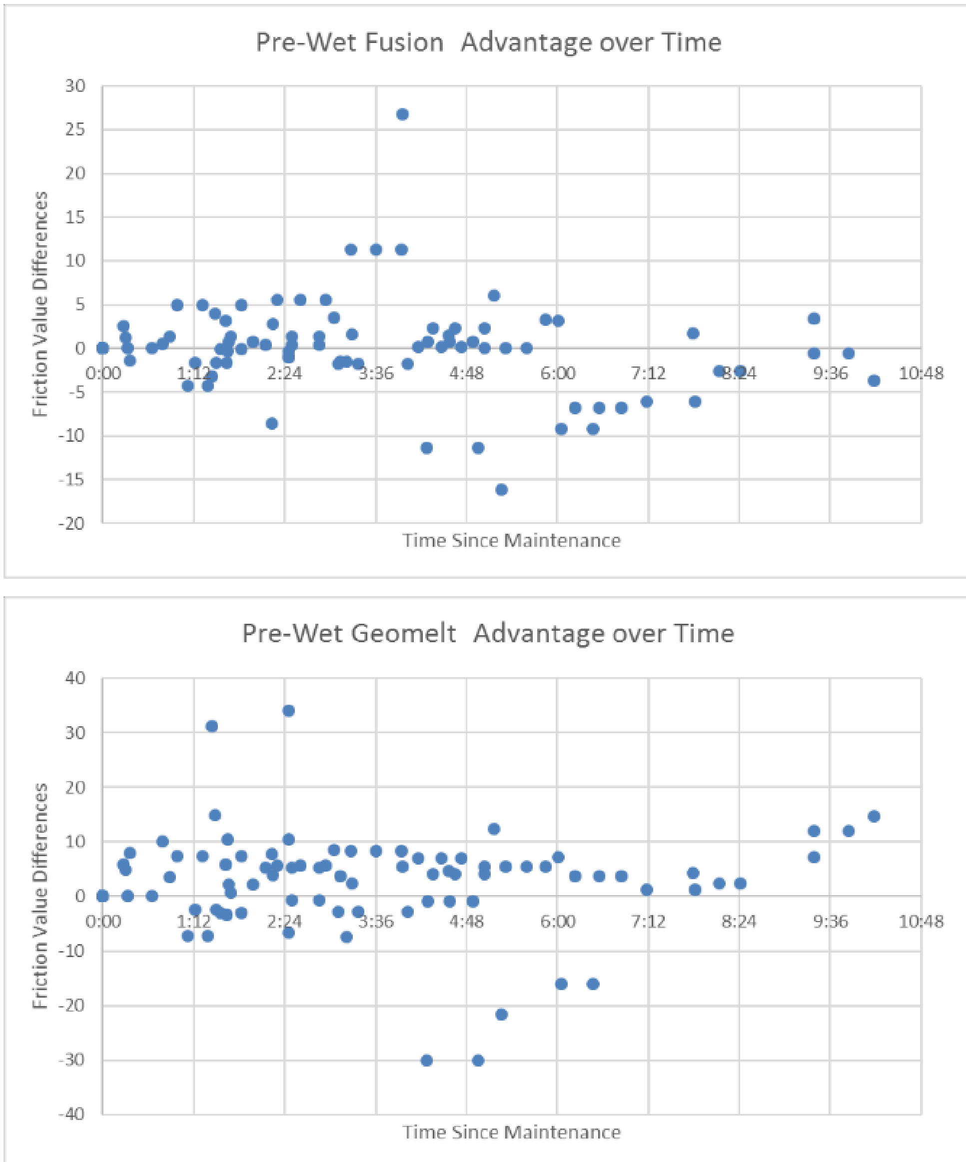


Figure 5.3 Overview of the Differences in Friction Values (Pre-Wet Sections)

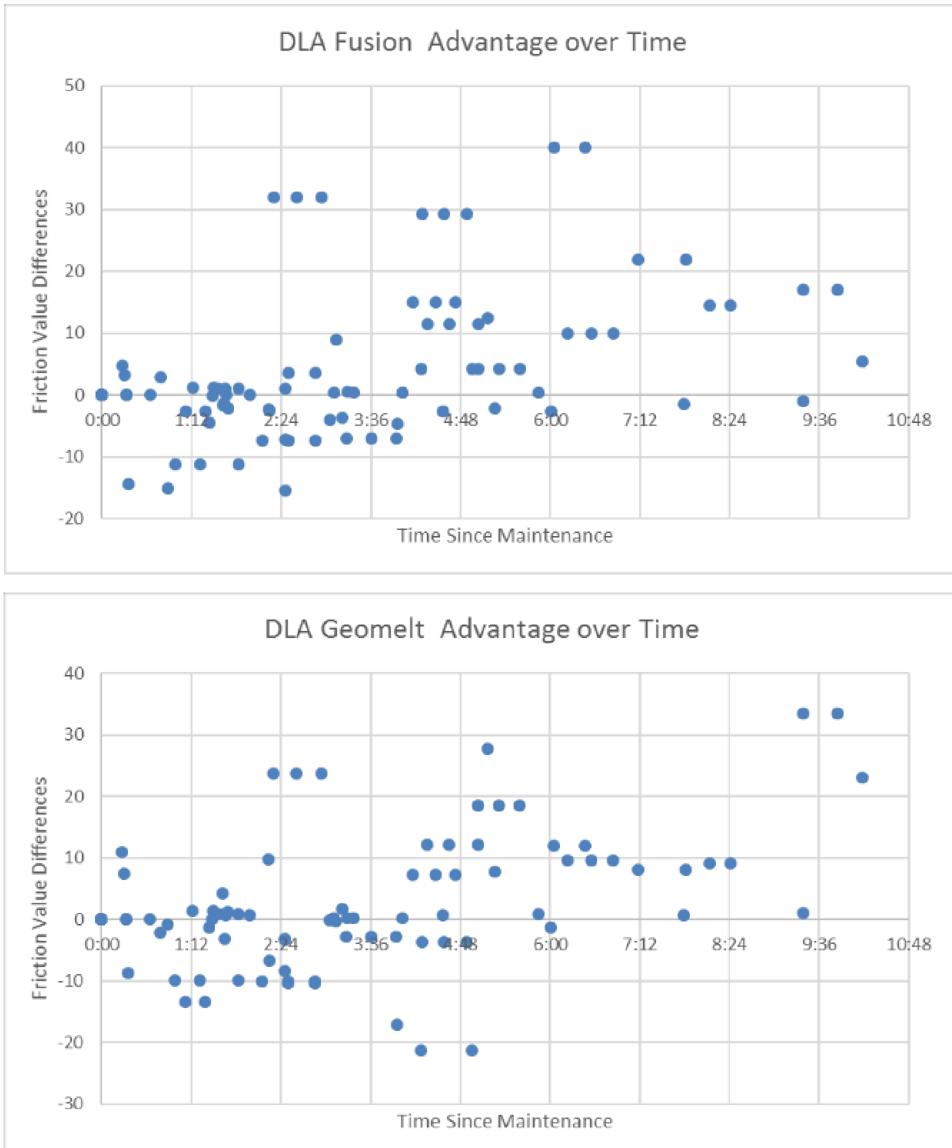


Figure 5.4 Overview of the Differences in Friction Values (DLA Sections_

A key observation that can be made is the apparent random scattering of the pre-wet test section results. These scatter points again suggest that there may be no linear time dependant pattern to the effect of pre-wetting, which was expected given the results of the analysis done in Chapter 4. However, a cursory examination of scatter plots for DLA show some evidence of pattern, with the friction spread appearing to increase as time progressed. The modelling effort conducted in the next sections focusses on understanding the scale of this performance difference in the context of broader maintenance actions.

5.4 Regression Results – Time Dependant Advantage of Fusion and Geomelt

To investigate the effects identified in the previous section, a regression analysis was conducted to identify which of the collected data appear to influence the friction level. In particular, the effect of application rate, time since maintenance, and weather over the test days was considered. Although data from both pre-wet and DLA tests sites were examined in the modelling effort, results were only statistically significant for the case of the DLA test sections. This was expected as the exploratory analysis conducted in Chapter 4 on the pre-wet showed no statistically significant differences between the materials.

Using the DLA data, the factor-dependant performance of the two chemicals was analysed separately for each of the two chemicals. The performance advantage is measured as the difference in friction values and the results are shown below.

Table 5.1 Regression Results on the Advantage of DLA Fusion over Brine

Regression Statistics (FUSION)	
Multiple R	0.516044
R Square	0.266301
Adjusted R Square	0.251173
Standard Error	8.816036
Observations	100

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	2736.361	1368.181	17.6034	3E-07
Residual	97	7539.082	77.7225		
Total	99	10275.44			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3.0657	1.347643	-2.27486	0.025116	-5.7404	-0.39101	-5.7404	-0.39101
(DLA) Time Since Maintenance	42.28391	8.048605	5.25357	8.84E-07	26.30965	58.25816	26.30965	58.25816
(DLA) Application Rate Difference	-0.05655	0.020519	-2.75578	0.006995	-0.09727	-0.01582	-0.09727	-0.01582

Table 5.2 Regress Results on the Advantage of DLA Geomelt over Brine

Regression Statistics (GEOMELT)	
Multiple R	0.505744
R Square	0.255777
Adjusted R Square	0.240432
Standard Error	9.845597
Observations	100

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3231.574	1615.787	16.66863	5.99E-07
Residual	97	9402.772	96.93579		
Total	99	12634.35			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.99124	1.505024	-1.32306	0.188924	-4.9783	0.995813	-4.9783	0.995813
(DLA) Time Since Maintenance	46.91484	8.988543	5.219404	1.02E-06	29.07507	64.75461	29.07507	64.75461
(DLA) Application Rate Difference	-0.05652	0.022915	-2.46657	0.015396	-0.102	-0.01104	-0.102	-0.01104

In both cases the same set of variables were found to be significant. Weather and temperature were not found to affect the performance difference. The friction advantage of Fusion and Geomelt was found to be dependent on the amount of time since maintenance was conducted, and in the difference between application rates. Represented with an equation, the model based on the coefficients would be:

$$F_{adv,fusion} = \frac{42.3}{24} h_e - 0.057 b_e \tag{5-1}$$

$$F_{adv,geo} = \frac{46.9}{24} h_e - 0.057 b_e \tag{5-2}$$

In this equation, F_{adv} is the additional friction level (difference in the expected HFN value) provided on surfaces maintained with fusion or geomelt, h_e is the hours since maintenance was conducted, and b_e is the difference in application rate between DLA and Brine in kg/lane-km ($\mathrm{App_{brine}} - \mathrm{App_{fusion/geo}}$)

The positive coefficient on h_e suggests that Fusion and Geomelt both provide surfaces with higher friction (at least in the window of the data), and that this difference increases as time passes. This suggests that these chemicals remain effective for longer after being applied, or are better able to remain on the surface. The negative coefficient on b_e suggests that the advantage of Geomelt or Fusion can be mitigated by applying extra brine (hence the negative coefficient on the second term).

Although these two models representing interesting findings, the estimated model was only able to account for around 25% of the variance. This suggests that there are many other confounding factors, and further research may be needed to identify them. This may also be due to inaccuracies in data collection, or due to the data resolution which may be too high (often in excess of 1.5 hours). As Fusion and Geomelt tend to exhibit higher friction values overall, more frequent data may be necessary to obtain accurate estimates of their time-dependant correlation.

5.5 Predictive Model of Friction Levels

The models explored in the first section focussed on the factor-dependant relationship of the friction advantage provided by the alternative chemicals, and aimed to quantify the performance differences of each of the chemicals with respect to time. However, as the many confounding factors may interfere with accurate quantification of these benefits, a more general approach was also considered. In this approach, two models representing the factors that affect friction were sought for both DLA and PW separately that could estimate the friction of the roadway given current weather.

5.5.1 DLA Model

For tests conducted using DLA, The final estimated model takes the following form:

$$F = \beta_0 + \beta_1 T + \beta_2 S_{state} + \beta_3 A_{fus} + \beta_4 A_{geo} + \beta_5 W + \beta_6 S_{daily,total} \qquad (5\text{-}3)$$

Where β_x is the estimated coefficient, with β_0 as the intercept. T is the time since maintenance, in hours. S_{state} is a Boolean flag variable indicating if it has been snowing in the last hour, while $S_{daily,total}$ is the total expected snowfall for that day. A_{geo} and A_{fus} are adjustment factors to account for the effect of adding Geomelt and Fusion respectively. Finally W is the wind speed.

The results of the regression yielded the following estimates for the beta parameters.

Table 5.3 Single Model (DLA) Estimates for the Beta Parameters

	Coefficients	*Std. Err.*	*t Stat*	*P-value*
β_0	90.384	3.502	25.810	0.000
β_1	-38.382	9.336	-4.111	0.000
β_2	-25.222	2.032	-12.414	0.000
β_3	6.680	2.463	2.712	0.007
β_4	5.292	2.483	2.132	0.034
β_5	-0.869	0.131	-6.634	0.000
β_6	-0.804	0.266	-3.021	0.003
$R^2 = 0.487$				

The results show that both Fusion and Geomelt have a positive effect on friction, with fusion performing slightly better than Geomelt. The coefficient in this model represents a single, average effect of these chemicals.

5.5.2 Discussion - DLA-Model

All the variables considered in our regression analysis were found to be statistically significant. The results show that both Fusion and Geomelt have a positive effect on friction. Although the results show a slight advantage for Fusion when compared to Geomelt (increases friction number by 6.67 as compared to 5.29), it is important to note that additional data would be required to substantiate any advantage as the confidence intervals of the coefficient estimates overlap substantially.

The effect of maintenance time was found to be negative, with each passing hour resulting in lower friction levels. As much of the data was collected during periods with ongoing weather events, this effect is expected as chemicals are diluted and leave the road. As expected, the effect of snow during the hour in question and overall daily values of snow was also found to be negative.

In the analysis conducted, wind was found to have a negative effect on road friction values. This effect likely arises from the tendency of wind to blow chemicals off the roadway after they are applied.

5.5.3 Pre-Wetting Model

For tests conducted on pre-wetted sections, the final estimated model takes the following form:

$$F = \beta_0 + \beta_1 T + \beta_2 S_{state} + \beta_5 W + \beta_6 S_{daily,total} \qquad (5\text{-}4)$$

Unlike the DLA model, here in the case of pre-wetting, the difference between using Fusion or Geomelt was found to not be statistically significant.

Table 5.4 Single Model (PW) Estimates for the Beta Parameters

	Coefficients	*Std. Err.*	*t Stat*	*P-value*
β_0	101.609	3.615	28.105	0.000
β_1	-71.412	10.599	-6.737	0.000
β_2	-27.941	2.305	-12.121	0.000
β_5	-0.849	0.149	-5.707	0.000
β_6	-1.623	0.302	-5.371	0.000
$R^2 = 0.512$				

As was the case in previous sections, no statistically significant difference was observed between test sections based on the material used, and consequently no factors accounting for Fusion or Geomelt were found.

5.5.4 Discussion on PW-Model

Unlike the DLA model, here in the case of pre-wetting, the difference between using Fusion or Geomelt was found to not be statistically significant. These results agree with the exploratory analysis conducted during the ANOVA. This suggests that, as far as pre-wetted chemicals are concerned, there is no performance advantage in using any of the tested organic materials from the perspective friction levels.

Much like the results of the DLA analysis, the coefficient values all have similar signs and values. As in the DLA model, each of the coefficients that consider the effect of maintenance time, wind and snowfall was found to be negative. Of particular note is the increased negative effect of the

Wind level parameter. This result is expected to some extent, as Pre-wet materials still contain solid material that is more susceptible to removal by strong winds.

5.6 Model Validation and Limitations

5.6.1 Model Validation

Model validation was conducted by using the estimated model to predict friction at the 15% holdout dataset. The difference between the predictions and the measured values was used to calculate the Root Mean Squared Error (RMSE). A similar process was repeated for data used to estimate the model.

Table 5.5 DLA and PW Models Selected Validation RMSE

Model	RMSE, Validation (PPMCC)	RMSE, Model Data (PPMCC)
DLA	18.42 (0.25)	13.05 (0.49)
Pre-Wetting	16.22 (0.62)	15.23 (0.51)

Although cursory comparison of the RMSE values reveal similarities, a comparison of the Pearson product-moment correlation coefficients (PPMCC) suggests less correlation in the estimates of the DLA values on the Validation data set. This suggests some unreliability in their estimates which means that further factors influencing the friction values have not all been accounted for. Further research would therefore be required to obtain more accurate estimates.

5.6.2 Limitations

Although other weather variables were also considered in all the models developed, including both roadway and air temperature, these were found to be insignificant over the analysis period. Further more conclusive analyses will be required to include the effect of these factors and increase the predictive power of these models. It is also important to note that the analysis period considered in this study is biased to days and time periods that have some snowfall expected, and as such these models should only be applied in the context of maintenance under continuous weather conditions.

It is also important to note that since the field data collected did not contain enough variation between application rates, the models estimated in Section 5.5 do not have a coefficient for application rate. As a field study conducted on a real-world roadway, the opportunities for testing a variety of application rates was limited. These models are therefore only valid for the application rates tested in this study, and more research would be needed to consider the effect of application rate.

Chapter 6 Conclusions and Recommendations

In this research, we have conducted a field study to evaluate the performance of two organic products, namely, Geomelt and Fusion, as compared to regular salt brines for snow and ice control. Both products can be used as either pre-wetting agents or additives to regular brines to enhance their deicing/anti-icing performance. A field test was conducted on an arterial road in the City of Burlington and Oakville to investigate the performance of these materials when being used in prewetting and anti-icing operations over nine snow events in the 2010-2011 winter seasons. The materials were applied at a given set of rates recommended by the product providers and used by the two municipalities. Two main performance metrics were used in the subsequent comparative analysis, including friction levels and visual characteristics (e.g. snow cover). The following section summarizes the main findings, followed by a set of recommendations for future research.

6.1 Main Findings

For Prewetting:

- Salts prewet with organic materials performed similar to those using salt brine. In most cases, the performance differences were not statistically significant, indicating that there was little evidence supporting the superiority of the organic materials for the prewetting purpose. Our limited data also indicated that this was true in conditions of low temperature (~-10 ℃), contrary to the common belief about these products. However, it should be noted that this indifference in performance could be due to the fact that the dominant amount of materials in these prewet mixes is still the regular salt - sodium chloride (95%).
- When used for prewetting purposes, Geomelt and Fusion showed similar performance with no statistically significant differences. This was further confirmed through the subsequent exploratory data analysis and regression modelling, as in all the models estimated the material type was not found significant.

For DLA:

- Despite being applied at a half application rate of the regular salt brine in DLA treatments, the Fusion-brine mixture largely outperformed pure salt brine. It was observed that Fusion could help maintain up to 20% higher traction and up to an hour longer before road conditions fell to an unsafe level.

- Fusion outperformed Geomelt by up to 15 % in terms of traction level. The difference between performance of Geomelt and brine was not significantly significant. Again it should be noted that the Geomelt liquid was applied at a half application rate of the regular brine.
- In general the sections treated with DLA performed significantly better than untreated sections, confirming the advantage of the anti-icing strategy for snow and ice control (see Table 5.1).
- Subsequent modelling estimated a factor for the average effect of Fusion and Geomelt. These factors were estimated at 6.68 and 5.29, respectively, representing the average friction advantage expected in Newton Metres (Nm).
- The modelling effort has shown that DLA and Pre-wetting were both negatively affected by strong winds in a similar manner.
- Initial modelling efforts suggest that there was a time-dependant relationship in the performance advantage of Fusion and Geomelt, with each additional hour after material was applied increasing the advantage by 1.67 Nm and 1.95 Nm, respectively.

6.2 Recommendations for Future Work

It must be emphasized that the generality of the results from this study is limited to the tested application rates and the observed winter conditions. Literature has suggested that organic materials perform better under temperatures where regular salt would fail. It has also been claimed that these materials can help reduce scattering and activate salt faster. The following is a list of specific recommendations for future research:

1. As an initial effort, fixed mixing ratios and application rates for both prewet salts and anti-icing liquids were considered in this project. It is understood that these rates were recommended by the manufacturers and considered to be the best based on the knowledge of the cities for their maintenance operations. However, it is possible that other mixing ratios and application rates may be more cost-effective for certain road weather conditions. A more extensive field experiment is required in order to identify the optimal, weather sensitive mixing

ratios and application ratios (refer to Appendix H for suggested application rates to be evaluated).

2. More tests should be conducted to cover a wider range of external conditions, including pavement types, traffic, and temperatures (e.g., below -10 ℃). For example, this study did not cover explicitly account the effect of traffic on the performance of a deicing material. In future studies, traffic data should be collected as part of the test and treatments should be randomized among the test sections. Also, tests should be conducted at other locations with different pavement types (e.g. asphalt vs. Portland cement concrete), road geometry and surrounding conditions.

3. Organic materials are generally more expensive than regular brine, but less detrimental to the environment and infrastructure. As a result, a comprehensive cost benefit analysis is warranted in order to arrive at the best decision in terms of material selection.

4. To verify the claim that bio based liquids help reduce scatter and activate salt faster, it would be worth testing if a lower amount of salt prewetted with a larger % of organic material can give similar performance to conventional prewet rates. Moreover, in order for the use of bio based material to make economic sense, their cost has to be in similar range as to that of the conventional salt-brine mix. In each case, the quantity of salt is reduced and the prewetting liquid is increased while keeping the price equal to that of a regular salt brine prewetting application.

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Appendix A: Product Sheets

A.1 Fusion 2330 (Eco Solutions Inc)

Product Specification	
Unit of Measure	EA
Brand Name	ECO SOLUTIONS
Colour	Brown
Contains	Degraded Sugar Beef Juice, Sodium Chloride, Natural Corrosion Inhibitors
Effective Temp	-24 ℃
Item	Liquid Ice Melt
Net Weight	2.3 lbs
Package Type	Bulk
Size	**1 L**

A2. GeoMelt S30 (Future Road Solutions Inc)

Appearance	Brown	Wt./Liter	1.270kg/liter
Dry Solids	30%	Freeze Point	-34.4 ℃
Specific Gravity	1.275	pH	6.0-9.0
Wt./Gal	10.6 pounds/gal	Water Solubility	Complete

Appendix B: Prewetting and DLA Anti-icing Operations

B.1 Prewetting Equipment

Epoke 3500

B.2 Anti-icing Equipment

Schmidt Stratos

Appendix C: Maintenance Activities

January 11, 2011

Time	Pre-wetted Salt (kg/lane-km)			Time	DLA for Anti-Icing (L/lane-km)		
	1 (Brine)	2 (Fusion)	3 (Geomelt)		4 (Fusion)	5 (Geomelt)	6 (Brine)
7:45 PM	110	110	110	Prior to event, time unknown	50	50	100
10:00 PM	110	110	110	5:30 PM	Pre-wet Salt with Brine at 70 kg/lane-km		
				9:40 PM	Pre-wet Salt with Brine at 105 kg/lane-km		
Total Precipitation (mm): 2.4 Total Snow (cm): 2.8							

January 15, 2011

Time	Pre-wetted Salt (kg/lane-km)			Time	DLA for Anti-Icing (L/lane-km)		
	1 (Brine)	2 (Fusion)	3 (Geomelt)		4 (Fusion)	5 (Geomelt)	6 (Brine)
4:45 AM	110		110	Prior to event, time unknown	50	50	100
6:10 AM		110		5:30 AM	Pre-wet Salt with Brine at 70 kg/lane-km		
12~1 PM	Ploughed	Ploughed	Ploughed	7:00 AM	Ploughed and Pre-wet Salt with Brine at 105kg/lane-km		
Total Precipitation (mm): 5.4 Total Snow(cm): 5.8							

January 29, 2011

Time	Pre-wetted Salt (kg/lane-km)			Time	DLA for Anti-Icing (L/lane-km)		
	1 (Brine)	2 (Fusion)	3 (Geomelt)		4 (Fusion)	5 (Geomelt)	6 (Brine)
10:30 AM	110	110	110	Prior to event, time unknown	50	50	100
				11:15 AM	Pre-wet Salt with Brine at 70 kg/lane-km		
Total Precipitation (mm): Trace Total Snow (cm): Trace							

February 1, 2011

Time	Pre-wetted Salt (kg/lane-km)			Time	DLA for Anti-Icing (L/lane-km)		
	1 (Brine)	2 (Fusion)	3 (Geomelt)		4 (Fusion)	5 (Geomelt)	6 (Brine)
10:40 PM	110	110	110	Prior to event, time unknown	50	50	**0**
Total Precipitation (mm): 1.0 Total Snow (cm): 1.6							

February 2, 2011

Time	Pre-wetted Salt (kg/lane-km)			Time	DLA for Anti-Icing (L/lane-km)		
	1 (Brine)	2 (Fusion)	3 (Geomelt)		4 (Fusion)	5 (Geomelt)	6 (Brine)
3:30 AM	110 and ploughed	110 and ploughed	110 and ploughed	Prior to event, time unknown	50	50	**0**
Total Precipitation (mm): 9.4 Total Snow (cm): 12.8							

February 20, 2011

<table>
<tr><td rowspan="2">Time</td><td colspan="3">Pre-wetted Salt
(kg/lane-km)</td><td rowspan="2">Time</td><td colspan="3">DLA for Anti-Icing
(L/lane-km)</td></tr>
<tr><td>1
(Brine)</td><td>2
(Fusion)</td><td>3
(Geomelt)</td><td>4
(Fusion)</td><td>5
(Geomelt)</td><td>6
(Brine)</td></tr>
<tr><td>9:10 PM</td><td>110</td><td>110</td><td>110</td><td rowspan="2">Prior to event, time unknown</td><td rowspan="2">50</td><td rowspan="2">50</td><td rowspan="2">0</td></tr>
<tr><td>1:00 AM
(Feb. 21)</td><td>Ploughed</td><td>Ploughed</td><td>Ploughed</td></tr>
<tr><td colspan="8">Total Precipitation (mm): 4.2
Total Snow (cm): 4.6</td></tr>
</table>

February 25, 2011

<table>
<tr><td rowspan="2">Time</td><td colspan="3">Pre-wetted Salt
(kg/lane-km)</td><td rowspan="2">Time</td><td colspan="3">DLA for Anti-Icing
(L/lane-km)</td></tr>
<tr><td>1
(Brine)</td><td>2
(Fusion)</td><td>3
(Geomelt)</td><td>4
(Fusion)</td><td>5
(Geomelt)</td><td>6
(Brine)</td></tr>
<tr><td>7:40 AM</td><td>110 and ploughed</td><td>110 and ploughed</td><td>110 and ploughed</td><td>Prior to event, time unknown</td><td>50</td><td>50</td><td>0</td></tr>
<tr><td colspan="8">Total Precipitation (mm): 0.4
Total Snow (cm): 0.6</td></tr>
</table>

March 6, 2011

<table>
<tr><td rowspan="2">Time</td><td colspan="3">Pre-wetted Salt
(kg/lane-km)</td><td rowspan="2">Time</td><td colspan="3">DLA for Anti-Icing
(L/lane-km)</td></tr>
<tr><td>1
(Brine)</td><td>2
(Fusion)</td><td>3
(Geomelt)</td><td>4
(Fusion)</td><td>5
(Geomelt)</td><td>6
(Brine)</td></tr>
<tr><td>2:00 AM</td><td>110</td><td>110</td><td>110</td><td colspan="4" rowspan="2">Unexpected event. No DLA Prior to Event</td></tr>
<tr><td>7:00 AM</td><td>Ploughed and 110</td><td>Ploughed and 110</td><td>Ploughed and 110</td></tr>
<tr><td colspan="8">*Total Precipitation (mm): 2.0
*Total Snow (cm): 2.0</td></tr>
</table>

* There was a significant amount of precipitation on March 5:
Total Precipitation (mm): 21.6
Total Snow (cm): 3.2

March 23, 2011

Time	Pre-wetted Salt (kg/lane-km)			Time	DLA for Anti-Icing (L/lane-km)		
	1 (Brine)	2 (Fusion)	3 (Geomelt)		4 (Fusion)	5 (Geomelt)	6 (Brine)
3:25 AM	110	110	110	1:15 PM	50	50	100
Total Precipitation (mm): 11.8 Total Snow (cm): 12.6							

Appendix D: Base Runs

Prior to the start of the tests, baseline data were collected to ensure uniform road conditions on all test sections. Figure E1 shows friction values on all six test sections. It can be seen that the road conditions in terms of friction level are very similar and thus comparison can be carried out without any scaling between zones.

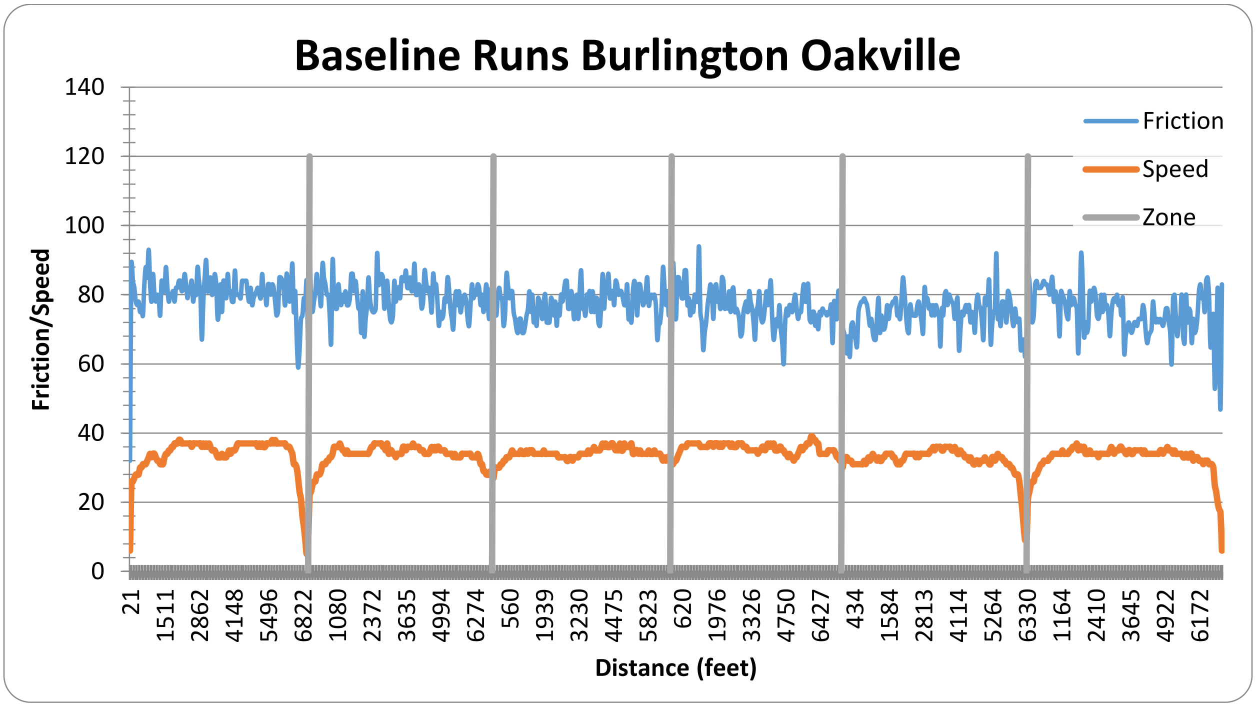


Figure: E1 Baseline Friction Values

Appendix E: Statistical Test Results

E1. Statistical Test on Differences in Pre-wetting and Anti-icing Performance

March 22 & 23, 2011 Pre-wet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0 (1st run)	n	140	116	117	0.000	0.343	0.000
	x	72.411	68.904	68.186	Brine	Similar	Brine
	s	6.432	6.433	6.847	Significant	Insignificant	Significant
0.5	n	117	17	121	0.000	0.000	0.476
	x	68.254	65.559	68.844	Brine	Fusion	Same
	s	5.446	8.688	7.265	Significant	Significant	Insignificant
1.5	n	118	109	110	0.002	0.376	0.032
	x	73.118	70.309	71.136	Brine	Fusion	Brine
	s	6.943	6.873	6.966	Significant	Insignificant	Significant
2	n	121	117	116	0.012	0.001	0.246
	x	68.402	66.331	69.402	Brine	Fusion	Fusion
	s	5.743	6.808	7.933	Significant	Significant	Insignificant
3	n	103	106	100	0.064	0.986	0.085
	x	71.716	69.785	69.802	Brine	Similar	Brine
	s	8.343	6.460	7.169	Marginally Sig.	Insignificant	Marginally Sig.
3.5	n	113	115	111	0.208	0.002	0.019
	x	66.439	65.353	68.423	Brine	Fusion	Fusion
	s	5.526	7.389	7.424	Insignificant	Significant	Significant
4.5	n	114	113	105	0.000	1.000	0.000
	x	74.820	69.500	69.500	Brine	Similar	Brine

	s	9.182	7.204	6.755	Significant	Insignificant	Significant
5	n	117	119	115	0.000	0.142	0.055
	x	69.907	66.967	68.226	Brine	Fusion	Brine
	s	5.569	6.535	7.189	Significant	Insignificant	Marginally Sig.
6	n	112	111	103	0.769	0.330	0.168
	x	72.912	73.205	74.269	Geomelt	Fusion	Fusion
	s	6.645	8.279	7.727	Insignificant	Insignificant	Insignificant
6.5	n	118	115	117	0.265	0.052	0.558
	x	70.025	68.828	70.940	Brine	Fusion	Similar
	s	6.864	9.357	7.829	Insignificant	Marginally Sig.	Insignificant
7.5	n	144	144	137	0.000	0.000	0.000
	x	23.993	49.655	31.399	Geomelt	Geomelt	Fusion
	s	5.942	12.090	8.999	Significant	Significant	Significant
8	n	132	136	134	0.000	0.000	0.000
	x	54.195	41.745	26.022	Brine	Geomelt	Brine
	s	16.883	13.867	11.323	Significant	Significant	Significant
8.5	n	132	142	142	0.000	0.000	0.000
	x	43.180	34.098	27.448	Brine	Geomelt	Brine
	s	5.548	4.749	7.876	Significant	Significant	Significant
9	n	172	158	157	0.000	0.043	0.000
	x	32.919	15.610	13.247	Brine	Geomelt	Brine
	s	11.104	11.393	9.193	Significant	Significant	Significant
10	n	151	171	163	0.000	0.004	0.000
	x	42.460	32.221	28.462	Brine	Geomelt	Brine
	s	6.182	3.520	6.027	Significant	Significant	Significant
10.5	n	125	171	183	0.000	0.000	0.000
	x	39.316	33.285	34.872	Brine	Fusion	Brine
	s	5.639	8.078	8.336	Significant	Significant	Significant

March 22 & 23, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0 (1st run)	n	130	130	135	0.000	0.000	0.459
	x	72.153	68.115	67.522	Geomelt	Geomelt	Fusion
	s	6.651	6.970	6.041	Significant	Significant	Insignificant
0.5	n	153	124	130	0.000	0.000	0.000
	x	69.604	74.792	65.229	Geomelt	Fusion	Fusion
	s	6.980	5.362	6.007	Significant	Significant	Significant
1.5	n	128	128	125	0.000	0.126	0.126
	x	71.643	68.310	66.992	Geomelt	Geomelt	Fusion
	s	6.709	6.957	6.765	Significant	Insignificant	Insignificant
2	n	28	312	135	0.000	0.018	0.000
	x	69.287	75.310	64.897	Geomelt	Fusion	Fusion
	s	7.406	6.959	4.740	Significant	Significant	Significant
3	n	129	125	130	0.000	0.000	0.304
	x	71.715	67.468	66.600	Geomelt	Geomelt	Fusion
	s	6.585	7.126	6.565	Significant	Significant	Insignificant
3.5	n	119	118	136	0.000	0.000	0.000
	x	68.752	76.286	63.620	Geomelt	Fusion	Fusion
	s	6.778	5.862	7.499	Significant	Significant	Significant
4.5	n	118	128	134	0.006	0.000	0.380
	x	69.244	66.047	66.844	Geomelt	Geomelt	Similar
	s	6.638	7.457	7.261	Significant	Significant	Insignificant
5	n	123	113	140	0.000	0.000	0.000
	x	67.912	74.868	64.560	Geomelt	Fusion	Fusion
	s	7.130	6.043	7.894	Significant	Significant	Significant
6	n	114	112	124	0.000	0.000	0.015

	x	73.096	66.770	64.440	Geomelt	Geomelt	Fusion
	s	8.034	7.843	6.730	Significant	Significant	Significant
6.5	n	211	111	133	0.000	0.000	0.000
	x	69.814	77.455	63.164	Geomelt	Fusion	Fusion
	s	8.880	10.607	7.919	Significant	Significant	Significant
7.5	n	130	126	134	0.676	0.000	0.000
	x	65.061	60.148	64.552	Geomelt	Geomelt	Brine
	s	9.762	10.847	9.378	Insignificant	Significant	Significant
8	n	125	115	134	0.000	0.000	0.000
	x	68.548	50.569	59.185	Geomelt	Geomelt	Brine
	s	17.616	11.647	13.075	Significant	Significant	Significant
8.5	n	156	120	148	0.000	0.176	0.000
	x	74.038	72.331	40.423	Geomelt	Geomelt	Fusion
	s	10.784	10.092	4.672	Significant	Insignificant	Significant
9	n	133	150	161	0.020	0.000	0.000
	x	40.119	57.722	37.216	Geomelt	Fusion	Fusion
	s	12.596	8.711	7.459	Significant	Significant	Significant
10	n	129	137	163	0.000	0.000	0.000
	x	80.809	60.280	35.645	Geomelt	Geomelt	Fusion
	s	12.012	12.812	3.890	Significant	Significant	Significant
10.5	n	229	163	250	0.000	0.000	0.000
	x	77.962	62.848	39.388	Geomelt	Geomelt	Fusion
	s	11.590	10.078	5.976	Significant	Significant	Significant

January 11, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	125	129	127	0.000	0.000	0.000
(1^{st} run)	x	87.816	83.837	80.622	Brine	Geomelt	Brine

	s	9.224	6.132	6.638	Significant	Significant	Significant
1.5	n	136	152	159	0.231	0.431	0.059
	x	81.588	80.704	80.195	Brine	Geomelt	Brine
	s	6.725	5.652	5.742	Insignificant	Insignificant	Marginally Sig.
3	n	137	138	135	0.515	0.011	0.116
	x	80.613	80.123	81.933	Brine	Fusion	Fusion
	s	7.258	5.003	6.526	Insignificant	Significant	Insignificant
4.5	n	132	139	127	0.005	0.980	0.007
	x	81.674	79.144	79.165	Brine	Fusion	Brine
	s	7.634	7.003	7.271	Significant	Insignificant	Significant
6	n	121	132	131	0.350	0.325	0.942
	x	82.843	82.015	82.779	Brine	Fusion	Brine
	s	7.616	6.306	6.249	Insignificant	Insignificant	Insignificant
7.75	n	120	126	145	0.021	0.395	0.004
	x	85.350	83.111	82.497	Brine	Geomelt	Brine
	s	9.005	5.667	6.216	Significant	Insignificant	Significant
9.5	n	141	137	153	0.495	0.471	0.927
	x	83.014	82.423	82.948	Brine	Fusion	Brine
	s	7.279	7.126	4.893	Insignificant	Insignificant	Insignificant
13	n	130	137	140	0.023	0.766	0.047
	x	87.485	85.453	85.679	Brine	Fusion	Brine
	s	8.203	6.077	6.530	Significant	Insignificant	Significant
13.75	n	169	157	141	0.000	0.000	0.000
	x	55.053	68.274	49.362	Geomelt	Geomelt	Brine
	s	12.991	13.967	8.027	Significant	Significant	Significant
16	n	174	188	158	0.000	0.033	0.027
	x	14.201	18.819	16.354	Geomelt	Geomelt	Fusion
	s	9.575	13.168	8.037	Significant	Significant	Significant

January 11, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0 (1st run)	n	138	129	147	0.000	0.000	0.008
	x	81.536	78.364	76.347	Geomelt	Geomelt	Fusion
	s	6.535	6.281	6.258	Significant	Significant	Significant
1.5	n	147	128	142	0.000	0.000	0.000
	x	81.306	84.016	77.824	Geomelt	Geomelt	Fusion
	s	6.387	6.092	6.402	Significant	Significant	Significant
3	n	149	138	173	0.092	0.374	0.004
	x	82.644	83.370	N/A	N/A	Fusion	N/A
	s	7.367	6.415	4.996	Marginally Sig.	Insignificant	Significant
4.5	n	115	120	157	0.002	0.777	0.000
	x	83.104	83.350	80.618	Geomelt	Similar	Fusion
	s	7.210	5.994	5.236	Significant	Insignificant	Significant
6	n	135	125	144	0.002	0.038	0.341
	x	83.933	82.176	81.424	Geomelt	Geomelt	Fusion
	s	7.099	6.481	6.405	Significant	Significant	Insignificant
7.75	n	131	129	148	0.000	0.165	0.000
	x	84.130	83.124	80.345	Geomelt	Geomelt	Fusion
	s	5.946	5.713	5.500	Significant	Insignificant	Significant
9.5	n	129	131	141	0.000	0.168	0.000
	x	83.659	82.542	79.461	Geomelt	Geomelt	Fusion
	s	7.569	5.207	4.642	Significant	Insignificant	Significant
13	n	137	131	152	0.000	0.001	0.842
	x	85.824	83.038	82.895	Geomelt	Geomelt	Fusion
	s	7.006	6.360	5.649	Significant	Significant	Insignificant

13.75	n	188	138	171	0.002	0.000	0.000
	x	42.500	39.094	45.398	Brine	Geomelt	Brine
	s	7.879	7.072	9.467	Significant	Significant	Significant
16	n	179	159	171	0.000	0.000	0.001
	x	24.112	32.874	29.404	Brine	Fusion	Fusion
	s	7.431	8.943	9.366	Significant	Significant	Significant

January 15, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	115	139	152	0.000	0.000	0.000
	x	84.243	80.928	77.750	Brine	Geomelt	Brine
	s	5.327	5.335	5.276	Significant	Significant	Significant
2.25	n	125	128	124	0.480	0.000	0.000
	x	80.136	79.625	77.581	Brine	Geomelt	Brine
	s	6.557	4.764	4.386	Insignificant	Significant	Significant
3.5	n	131	128	128	0.000	0.000	0.000
	x	62.336	44.367	49.773	Brine	Fusion	Brine
	s	15.171	3.236	8.884	Significant	Significant	Significant
4.75	n	145	136	129	0.061	0.000	0.001
	x	43.703	46.228	39.279	Geomelt	Geomelt	Brine
	s	11.533	10.974	9.502	Marginally Sig.	Significant	Significant
5.75	n	159	135	139	0.000	0.000	0.244
	x	27.019	30.859	26.052	Geomelt	Geomelt	Brine
	s	5.383	5.892	8.239	Significant	Significant	Insignificant
7.25	n	184	170	143	0.122	0.000	0.000
	x	32.524	34.132	21.520	Geomelt	Geomelt	Brine

	s	8.353	9.950	12.190	Insignificant	Significant	Significant
8	n	150	127	140	0.085	0.000	0.000
	x	47.033	49.882	40.621	Geomelt	Geomelt	Brine
	s	18.408	7.516	8.838	Marginally Sig.	Significant	Significant

January 15, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	143	137	144	0.000	0.003	0.000
	x	75.510	77.431	71.701	Geomelt	Fusion	Fusion
	s	5.779	4.960	5.256	Significant	Significant	Significant
2.25	n	119	129	136	0.085	0.001	0.164
	x	76.395	74.147	75.132	Geomelt	Geomelt	Brine
	s	5.205	4.974	6.462	Marginally Sig.	Significant	Insignificant
3.5	n	125	122	126	0.000	0.000	0.000
	x	62.128	45.254	50.500	Geomelt	Geomelt	Brine
	s	17.100	4.127	9.577	Significant	Significant	Significant
4.75	n	135	135	150	0.000	0.000	0.000
	x	57.659	37.363	31.127	Geomelt	Geomelt	Fusion
	s	18.128	8.656	8.323	Significant	Significant	Significant
5.75	n	141	146	150	0.000	0.000	0.000
	x	44.461	38.212	33.027	Geomelt	Geomelt	Fusion
	s	8.526	6.0595	8.3134	Significant	Significant	Significant
7.25	n	196	162	183	0.000	0.000	0.110
	x	50.603	37.361	39.448	Geomelt	Geomelt	Brine
	s	12.445	9.6994	13.095	Significant	Significant	Insignificant

8	n	167	133	156	0.000	0.000	0.007
	x	48.048	40.602	37.763	Geomelt	Geomelt	Fusion
	s	8.937	9.245	8.451	Significant	Significant	Significant

January 29, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	140	136	127	0.001	0.695	0.000
	x	85.157	82.956	82.661	Brine	Geomelt	Brine
	s	5.064	6.070	6.100	Significant	Insignificant	Significant
1.5	n	136	128	125	0.000	0.014	0.000
	x	87.000	83.180	81.160	Brine	Geomelt	Brine
	s	6.866	6.024	6.924	Significant	Significant	Significant
2.5	n	120	126	124	0.000	0.000	0.000
	x	88.592	84.817	78.653	Brine	Geomelt	Brine
	s	7.351	7.631	7.092	Significant	Significant	Significant
4	n	132	118	131	0.633	0.000	0.000
	x	87.674	87.092	51.438	Brine	Geomelt	Brine
	s	9.322	8.197	9.287	Insignificant	Significant	Significant
5.25	n	113	129	123	0.000	0.182	0.000
	x	89.186	85.411	84.203	Brine	Geomelt	Brine
	s	8.084	6.829	7.449	Significant	Insignificant	Significant
7.25	n	113	125	119	0.032	0.610	0.017
	x	85.903	84.224	83.756	Brine	Geomelt	Brine
	s	5.636	6.399	7.785	Significant	Insignificant	Significant

January 29, 2011 DLA & Anti-Icing					
Hrs		Geomelt	Fusion	Brine	p-value

Elapsed					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	129	131	153	0.000	0.000	0.806
	x	85.411	79.466	79.275	Geomelt	Geomelt	Similar
	s	5.618	5.707	7.400	Significant	Significant	Insignificant
1.5	n	118	124	142	0.000	0.000	0.279
	x	83.407	79.649	78.630	Geomelt	Geomelt	Fusion
	s	6.047	5.278	7.721	Significant	Significant	Insignificant
2.5	n	136	136	143	0.002	0.468	0.012
	x	76.312	75.721	73.874	Geomelt	Geomelt	Fusion
	s	6.405	5.754	6.370	Significant	Insignificant	Significant
4	n	139	147	151	0.000	0.000	0.000
	x	77.122	71.343	65.887	Geomelt	Geomelt	Fusion
	s	10.902	8.989	9.901	Significant	Significant	Significant
5.25	n	123	138	153	0.000	0.002	0.000
	x	86.049	83.514	79.322	Geomelt	Geomelt	Fusion
	s	6.089	7.031	8.389	Significant	Significant	Significant
7.25	n	133	121	126	0.000	0.003	0.010
	x	84.147	82.174	80.056	Geomelt	Geomelt	Fusion
	s	7.282	6.037	6.734	Significant	Significant	Significant

February 1, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	118	134	128	0.000	0.000	0.000
	x	86.864	78.694	73.852	Brine	Geomelt	Brine
	s	7.630	8.766	7.519	Significant	Significant	Significant
1.5	n	123	130	128	0.000	0.243	0.001
	x	83.943	79.777	85.846	Brine	Fusion	

	s	7.426	6.740	7.290	Significant	Insignificant	Significant
3	n	127	119	111	0.000	0.702	0.000
	x	86.795	81.067	81.432	Brine	Fusion	Brine
	s	7.188	7.231	7.232	Significant	Insignificant	Significant
4.5	n	133	129	139	0.000	0.641	0.000
	x	85.331	80.915	80.561	Brine	Geomelt	Brine
	s	6.446	6.178	6.206	Significant	Insignificant	Significant

February 1, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	119	133	147	0.000	0.000	0.001
	x	85.891	80.195	77.612	Geomelt	Geomelt	Fusion
	s	7.148	6.253	6.232	Significant	Significant	Significant
1.5	n	123	126	139	0.000	0.000	0.002
	x	85.846	80.206	77.633	Geomelt	Geomelt	Fusion
	s	5.462	6.854	6.367	Significant	Significant	Significant
3	n	133	123	139	0.000	0.000	0.009
	x	85.466	80.520	78.367	Geomelt	Geomelt	Fusion
	s	7.394	6.279	6.929	Significant	Significant	Significant
4.5	n	167	109	176	0.000	0.044	0.000
	x	82.754	81.119	77.830	Geomelt	Geomelt	Fusion
	s	7.417	5.936	5.578	Significant	Significant	Significant

February 1, 2011 Prewet					
Hrs		Brine	Geomelt	Fusion	p-value

Elapsed					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	187	137	158	0.000	0.000	
	x	23.824	26.328	24.780	Geomelt	Geomelt	Fusion
	s	5.001	4.494	6.774	Significant	Significant	
0.75	n	140	142	131	0.000	0.000	0.000
	x	15.979	19.007	27.031	Geomelt	Fusion	Fusion
	s	4.554	3.528	10.025	Significant	Significant	Significant
1.75	n	141	136	137	0.000	0.000	0.000
	x	9.603	11.794	20.942	Geomelt	Fusion	Fusion
	s	3.897	3.499	10.787	Significant	Significant	Significant
2.5	n	157	126	133	0.000	0.000	0.000
	x	8.121	10.095	17.850	Geomelt	Fusion	Getomelt
	s	4.503	3.467	11.864	Significant	Significant	Significant

February 1, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	140	138	139	0.000	0.186	0.000
	x	35.650	36.870	29.064	Geomelt	Fusion	Fusion
	s	9.073	5.955	4.834	Significant	Insignificant	Significant
0.75	n	131	134	138	0.000	0.005	0.000
	x	32.433	28.604	23.021	Geomelt	Geomelt	Fusion
	s	12.841	8.708	4.937	Significant	Significant	Significant
1.75	n	143	147	148	0.000	0.046	0.000
	x	24.811	21.714	17.108	Geomelt	Geomelt	Fusion
	s	15.609	9.943	4.588	Significant	Significant	Significant
2.5	n	136	129	139	0.724	0.003	0.005
	x	23.273	20.473	22.896	Geomelt	Geomelt	Brine

	s	7.979	7.358	7.057	Insignificant	Significant	Significant

February 20, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	116	118	110	0.007	0.017	0.000
	x	80.552	77.864	75.673	Brine	Geomelt	Brine
	s	8.406	6.516	7.230	Significant	Significant	Significant
0.25	n	131	118	126	0.065	0.123	0.968
	x	76.702	75.203	76.667	Brine	Fusion	Brine
	s	6.100	6.589	8.138	Marginally Sig.	Insignificant	Insignificant
1.25	n	123	129	119	0.000	0.004	0.000
	x	83.282	78.907	76.032	Brine	Geomelt	Brine
	s	7.201	7.312	7.203	Significant	Significant	Significant
1.5	n	122	126	120	0.099	0.398	0.506
	x	83.282	78.907	76.032	Brine	Geomelt	Brine
	s	6.327	6.995	7.721	Marginally Sig.	Insignificant	Insignificant
2.25	n	122	122	116	0.000	0.000	0.519
	x	76.855	79.678	77.690	Geomelt	Geomelt	Fusion
	s	10.441	8.218	8.255	Significant	Significant	Insignificant
2.5	n	136	135	128	0.000	0.000	0.000
	x	32.669	34.704	41.891	Geomelt	Fusion	Fusion
	s	2.274	3.793	3.044	Significant	Significant	Significant
3	n	174	152	154	0.230	0.000	0.000
	x	28.713	28.013	32.545	Brine	Fusion	Fusion
	s	4.310	5.937	3.892	Insignificant	Significant	Significant

3.25	n	199	144	152	0.000	0.000	0.000
	x	19.774	28.438	23.276	Geomelt	Geomelt	Fusion
	s	10.056	17.351	8.083	Significant	Significant	Significant
3.5	n	140	146	141	0.000	0.000	0.933
	x	26.564	37.842	26.709	Geomelt	Geomelt	Fusion
	s	17.532	8.476	10.689	Significant	Significant	Insignificant
4	n	155	147	161	0.642	0.000	0.000
	x	33.465	33.728	41.398	Geomelt	Fusion	Fusion
	s	13.637	13.940	9.602	Insignificant	Significant	Significant
4.25	n	132	124	124	0.117	0.000	0.000
	x	36.742	34.823	30.927	Brine	Geomelt	Brine
	s	12.083	6.847	8.632	Insignificant	Significant	Significant
4.5	n	123	166	148	0.003	0.852	0.015
	x	44.854	40.633	40.351	Brine	Geomelt	Brine
	s	13.716	8.370	16.575	Significant	Insignificant	Significant
5	n	125	127	127	0.022	0.000	0.000
	x	47.976	45.591	34.236	Brine	Geomelt	Brine
	s	8.660	7.800	14.383	Significant	Significant	Significant
5.25	n	124	129	122	0.000	0.000	0.000
	x	34.298	37.620	41.713	Geomelt	Fusion	Fusion
	s	6.536	5.446	9.748	Significant	Significant	Significant
February 20, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	125	130	140	0.000	0.009	0.092
	x	78.472	76.262	74.886	Geomelt	Geomelt	Fusion
	s	6.415	6.953	6.387	Significant	Significant	Marginally Sig.
0.25	n	141	125	134	0.000	0.002	0.000

	x	79.193	81.270	72.437	Geomelt	Fusion	Fusion
	s	5.684	5.342	5.982	Significant	Significant	Significant
1.25	n	126	133	136	0.000	0.000	0.017
	x	79.600	77.508	74.738	Geomelt	Geomelt	Fusion
	s	6.036	6.997	6.931	Significant	Significant	Significant
1.5	n	141	122	142	0.000	0.000	0.000
	x	79.600	77.508	74.738	Geomelt	Geomelt	Fusion
	s	6.313	6.068	7.059	Significant	Significant	Significant
2.25	n	131	123	136	0.000	0.000	0.000
	x	82.721	72.238	47.209	Geomelt	Geomelt	Fusion
	s	6.761	10.708	11.569	Significant	Significant	Significant
2.5	n	159	124	139	0.000	0.014	0.000
	x	46.170	48.419	40.345	Geomelt	Fusion	Fusion
	s	9.532	5.611	4.462	Significant	Significant	Significant
3	n	164	140	156	0.000	0.000	0.462
	x	34.872	31.679	31.320	Geomelt	Geomelt	Similar
	s	4.096	4.171	4.103	Significant	Significant	Insignificant
3.25	n	160	157	147	0.000	0.000	0.001
	x	26.400	28.344	29.830	Brine	Fusion	Brine
	s	3.757	4.770	3.028	Significant	Significant	Significant
3.5	n	185	147	154	0.000	0.000	0.212
	x	27.697	24.864	24.273	Geomelt	Geomelt	Similar
	s	6.267	4.064	4.137	Significant	Significant	Insignificant
4	n	170	167	147	0.000	0.000	0.000
	x	51.012	25.359	21.340	Geomelt	Geomelt	Fusion
	s	18.419	5.525	4.594	Significant	Significant	Significant
4.25	n	136	137	136	0.114	0.000	0.088
	x	27.441	22.825	25.154	Geomelt	Geomelt	Brine
	s	7.906	5.492	14.840	Insignificant	Significant	Marginally Sig.

4.5	n	144	122	156	0.000	0.000	0.000
	x	65.028	55.959	38.609	Geomelt	Geomelt	Fusion
	s	15.190	21.365	13.547	Significant	Significant	Significant
5	n	141	118	142	0.000	0.000	0.000
	x	36.596	69.525	48.345	Brine	Fusion	Fusion
	s	22.749	14.163	16.682	Significant	Significant	Significant
5.25	n	126	119	134	0.000	0.000	0.000
	x	73.968	86.983	57.881	Geomelt	Fusion	Fusion
	s	15.260	10.888	17.946	Significant	Significant	Significant

February 25, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	130	120	118	0.000	0.817	0.000
	x	77.542	73.339	73.580	Brine	Fusion	Brine
	s	7.292	7.810	8.312	Significant	Insignificant	Significant
0.25	n	124	117	121	0.080	0.001	0.058
	x	74.240	72.585	76.057	Brine	Fusion	Fusion
	s	7.116	7.532	7.873	Marginally Sig.	Significant	Marginally Sig.
1.5	n	114	126	118	0.000	0.006	0.000
	x	80.878	76.598	73.884	Brine	Geomelt	Brine
	s	7.512	8.708	8.257	Significant	Significant	Significant
1.75	n	118	135	97	0.000	0.000	0.839
	x	74.924	69.405	74.119	Brine	Fusion	Brine
	s	6.914	7.277	8.051	Significant	Significant	Insignificant
3	n	118	115	22	0.000	0.468	0.000
	x	79.950	74.026	73.228	Brine	Geomelt	Brine

	s	9.273	8.279	8.686	Significant	Insignificant	Significant
3.5	n	127	124	114	0.006	0.000	0.172
	x	72.961	70.339	74.313	Brine	Fusion	Brine
	s	6.770	8.098	8.408	Significant	Significant	Insignificant
4	n	193	180	160	0.069	0.000	0.000
	x	74.072	74.890	70.068	Similar	Geomelt	Brine
	s	11.638	7.173	9.431	Marginally Sig.	Significant	Significant
4.5	n	128	123	147	0.061	0.065	0.916
	x	79.023	77.145	79.128	Brine	Fusion	Similar
	s	7.339	8.487	9.152	Marginally Sig.	Marginally Sig.	Insignificant
4.5	n	116	116	118	0.319	0.321	0.042
	x	79.880	78.846	77.714	Brine	Geomelt	Brine
	s	7.238	8.537	8.936	Insignificant	Insignificant	Significant
5	n	228	190	146	0.000	0.000	0.000
	x	47.533	49.859	57.925	Geomelt	Fusion	Fusion
	s	5.355	5.007	11.760	Significant	Significant	Significant
6		127	149	135	0.604	0.035	0.181
		80.047	79.167	81.632	Brine	Fusion	Fusion
		8.388	8.777	10.730	Insignificant	Significant	Insignificant
7		132	136	149	0.330	0.260	0.741
		43.842	43.241	44.033	Similar	Fusion	Fusion
		3.812	6.075	5.794	Insignificant	Insignificant	Insignificant
7.25		130	139	134	0.001	0.000	0.000
		41.050	38.992	49.215	Brine	Fusion	Fusion
		4.734	4.957	7.146	Significant	Significant	Significant

February 25, 2011 DLA & Anti-Icing					
Hrs		Geomelt	Fusion	Brine	p-value

Elapsed					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	126	132	143	0.659	0.546	0.265
	x	72.874	72.338	73.257	Brine	Similar	Brine
	s	7.387	6.870	6.814	Insignificant	Insignificant	Insignificant
0.25	n	125	127	138	0.000	0.000	0.000
	x	76.016	81.633	71.655	Geomelt	Fusion	Fusion
	s	7.590	5.917	7.659	Significant	Significant	Significant
1.5	n	123	127	136	0.449	0.407	0.980
	x	73.895	73.188	73.248	Similar	Similar	Similar
	s	6.255	7.014	7.524	Insignificant	Insignificant	Insignificant
1.75	n	133	124	142	0.000	0.120	0.000
	x	75.731	78.936	71.392	Geomeltg	Fusion	Fusion
	s	7.006	5.606	10.487	Significant	Insignificant	Significant
3	n	132	128	142	0.977	0.382	0.977
	x	73.241	72.531	73.229	Similar	Geomelt	Brine
	s	6.488	6.261	7.374	Insignificant	Insignificant	Insignificant
3.5	n	128	122	135	0.000	0.000	0.000
	x	73.240	77.878	70.353	Geomelt	Fusion	Fusion
	s	6.998	5.063	9.047	Significant	Significant	Significant
4	n	204	128	139	0.007	0.000	0.055
	x	74.16098	70.08527	71.73571	Geomelt	Geomelt	Brine
	s	9.28463	6.770837	7.296999	Significant	Significant	Marginally Sig
4.5	n	144	176	178	0.000	0.775	0.000
	x	81.86897	82.10169	70.83237	Geomelt	Fusion	Fusion
	s	7.440743	7.001692	14.67062	Significant	Insignificant	Significant
4.5	n	203	130	139	0.000	0.007	0.000
	x	82.60294	80.00763	74.15	Geomelt	Geomelt	Fusion
	s	8.767056	8.354176	10.60604	Significant	Significant	Significant

5	n	136	187	148	0.000	0.000	0.000
	x	88.07299	85.29255	70.24161	Geomelt	Geomelt	Fusion
	s	9.161649	8.479894	16.01842	Significant	Significant	Significant
6		N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A			
		N/A	N/A	N/A			
7		140	128	180	0.000	0.000	0.000
		85.035	66.442	39.265	Geomelt	Geomelt	Fusion
		10.479	13.145	5.323	Significant	Significant	Significant
7.25		138	128	143	0.000	0.000	0.000
		69.076	56.064	37.667	Geomelt	Geomelt	Fusion
		14.981	7.044	6.673	Significant	Significant	Significant

March 5 & 6, 2011 Prewet							
Hrs Elapsed		Brine	Geomelt	Fusion	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	135	151	128	0.001	0.000	0.000
	x	36.348	34.980	33.403	Brine	Geomelt	Brine
	s	3.373	2.839	2.830	Significant	Significant	Significant
0.33	n	147	142	131	0.817	0.000	0.000
	x	27.993	27.853	30.235	Similar	Fusion	Fusion
	s	5.615	4.693	4.615	Insignificant	Significant	Significant
0.66	n	130	150	149	0.154	0.024	0.627
	x	24.473	25.603	24.113	Geomelt	Geomelt	Similar
	s	6.975	6.177	5.123	Insignificant	Significant	Insignificant
1	n	175	144	171	0.000	0.004	0.000
	x	20.670	24.218	25.105	Geomelt	Fusion	Fusion
	s	5.816	4.967	6.919	Significant	Significant	Significant

1.33	n	131	146	126	0.039	0.296	0.005
	x	24.000	22.381	21.512	Brine	Geomelt	Brine
	s	6.771	6.181	7.377	Significant	Insignificant	Significant
1.66	n	163	140	143	0.357	0.000	0.001
	x	22.793	23.624	19.393	Geomelt	Geomelt	Brine
	s	6.771	8.676	9.916	Insignificant	Significant	Significant
2	n	144	189	173	0.359	0.000	0.002
	x	21.544	20.605	23.822	Brine	Fusion	Fusion
	s	6.026	7.179	8.597	Insignificant	Significant	Significant
2.33	n	132	128	117	0.000	0.000	0.000
	x	20.699	33.930	24.203	Geomelt	Geomelt	Fusion
	s	5.714	6.671	8.251	Significant	Significant	Significant
2.66	n	126	121	118	0.000	0.000	0.000
	x	19.672	32.852	35.487	Geomelt	Fusion	Fusion
	s	7.686	5.511	4.737	Significant	Significant	Significant
3	n	148	129	116	0.000	0.000	0.244
	x	28.832	25.954	29.701	Brine	Fusion	Fusion
	s	6.218	6.171	5.862	Significant	Significant	Insignificant
4	n	136	144	120	0.214	0.000	0.000
	x	19.569	18.372	23.686	Brine	Fusion	Fusion
	s	7.944	8.176	7.353	Insignificant	Significant	Significant
4.33	n	127	130	114	0.035	0.042	0.000
	x	14.508	16.176	18.087	Geomelt	Fusion	Fusion
	s	6.604	6.061	8.244	Significant	Significant	Significant
4.33	n	128	143	117	0.308	0.018	0.003
	x	19.109	19.556	22.466	Similar	Fusion	Fusion
	s	8.273	6.776	11.728	Insignificant	Significant	Significant
4.66	n	132	137	125	0.118	0.000	0.016
	x	17.880	16.565	20.389	Brine	Fusion	Fusion
	s	7.688	5.983	8.851	Insignificant	Significant	Significant

5	n	130	152	128	0.000	0.000	0.000
	x	21.427	17.307	31.132	Brine	Fusion	Fusion
	s	7.990	8.272	7.388	Significant	Significant	Significant
5.33	n	131	128	122	0.000	0.000	0.019
	x	17.955	13.527	20.309	Brine	Fusion	Fusion
	s	6.315	4.667	9.265	Significant	Significant	Significant
6	n	139	125	136	0.000	0.000	0.406
	x	25.079	16.952	25.912	Brine	Fusion	Fusion
	s	7.563	6.404	9.015	Significant	Significant	Insignificant
6.33	n	137	132	133	0.000	0.000	0.002
	x	23.691	19.451	25.888	Brine	Fusion	Fusion
	s	5.540	6.324	5.996	Significant	Significant	Significant
6.66	n	249	142	123	0.000	0.000	0.000
	x	27.856	27.035	44.924	Similar	Fusion	Fusion
	s	7.851	5.786	8.156	Significant	Significant	Significant
7	n	186	144	127	0.000	0.000	0.065
	x	26.337	18.917	24.633	Brine	Fusion	Brine
	s	7.548	6.766	8.343	Significant	Significant	Marginally Sig.
7.33	n	148	135	134	0.000	0.000	0.000
	x	26.268	17.581	22.452	Brine	Fusion	Brine
	s	7.341	9.144	10.182	Significant	Significant	Significant
7.66	n	128	132	136	0.000	0.000	0.699
	x	28.775	21.774	28.540	Brine	Fusion	Similar
	s	6.871	11.111	10.997	Significant	Significant	Insignificant
8	n	140	129	163	0.000	0.040	0.683
	x	30.787	26.822	30.189	Brine	Fusion	Similar
	s	5.634	9.791	15.565	Significant	Significant	Insignificant
8.33	n	151	127	132	0.007	0.045	0.872
	x	27.539	30.016	27.414	Geomelt	Geomelt	Similar

	s	8.033	6.473	13.323	Significant	Significant	Insignificant
9.33	n	175	144	155	0.016	0.000	0.000
	x	35.040	33.145	44.115	Brine	Fusion	Fusion
	s	8.241	5.652	12.446	Significant	Significant	Significant
10	n	130	146	145	0.018	0.000	0.000
	x	33.237	35.442	43.027	Geomelt	Fusion	Fusion
	s	10.857	7.472	18.046	Significant	Significant	Significant
10.33	n	170	150	154	0.001	0.000	0.000
	x	42.690	37.642	54.490	Brine	Fusion	Fusion
	s	15.942	9.698	17.204	Significant	Significant	Significant

March 5 & 6, 2011 DLA & Anti-Icing							
Hrs Elapsed		Geomelt	Fusion	Brine	p-value		
					Geomelt vs. Brine	Geomelt vs. Fusion	Brine vs. Fusion
0	n	154	129	141	0.008	0.000	0.082
	x	36.058	38.285	37.676	Brine	Fusion	Fusion
	s	6.768	2.671	3.077	Significant	Significant	Marginally Sig.
0.33	n	155	138	147	0.087	0.000	0.035
	x	32.987	35.540	34.133	Brine	Fusion	Fusion
	s	3.447	3.084	7.480	Marginally Sig.	Significant	Significant
0.66	n	170	122	147	0.055	0.603	0.039
	x	26.228	26.579	27.615	Brine	Similar	Brine
	s	7.855	3.532	4.793	Marginally Sig.	Insignificant	Significant
1	n	113	126	144	0.000	0.000	0.000
	x	22.947	26.362	35.710	Brine	Fusion	Brine

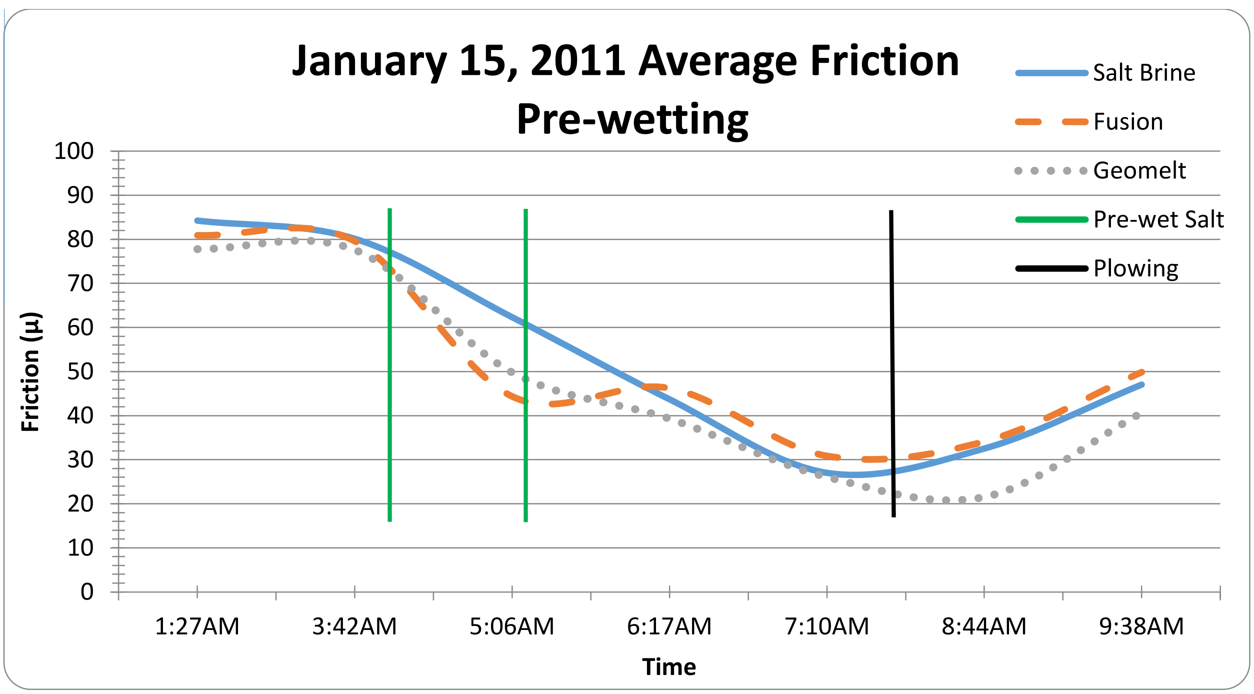
	s	6.878	5.100	7.509	Significant	Significant	Significant
1.33	n	145	164	159	0.039	0.296	0.005
	x	25.322	24.891	46.491	Brine	Geomelt	Brine
	s	8.780	7.080	11.869	Significant	Insignificant	Significant
1.66	n	157	128	135	0.001	0.219	0.006
	x	28.443	29.775	33.132	Brine	Fusion	Brine
	s	10.933	7.303	11.985	Significant	Insignificant	Significant
2	n	176	174	164	0.000	0.549	0.000
	x	27.938	27.389	36.855	Brine	Similar	Brine
	s	10.628	5.933	10.922	Significant	Insignificant	Significant
2.33	n	149	117	132	0.000	0.000	0.707
	x	49.293	39.178	39.759	Geomelt	Geomelt	Similar
	s	20.162	11.653	12.825	Significant	Significant	Insignificant
2.66	n	143	122	133	0.224	0.001	0.000
	x	31.076	26.504	32.642	Brine	Geomelt	Brine
	s	12.766	9.995	8.326	Insignificant	Significant	Significant
3	n	141	128	132	0.000	0.000	0.954
	x	43.486	36.488	36.216	Geomelt	Geomelt	Similar
	s	14.978	14.465	9.365	Significant	Significant	Insignificant
4	n	138	118	132	0.000	0.000	0.000
	x	35.288	29.882	22.000	Geomelt	Geomelt	Fusion
	s	12.086	7.069	10.221	Significant	Significant	Significant
4.33	n	135	112	130	0.000	0.055	0.000
	x	33.625	38.018	21.847	Geomelt	Fusion	Fusion
	s	11.753	21.613	9.669	Significant	Marginally Sig.	Significant
4.33	n	138	115	132	0.000	0.016	0.000
	x	31.748	28.422	17.203	Geomelt	Geomelt	Fusion
	s	10.584	11.140	10.923	Significant	Significant	Significant
4.66	n	125	123	140	0.058	0.000	0.000

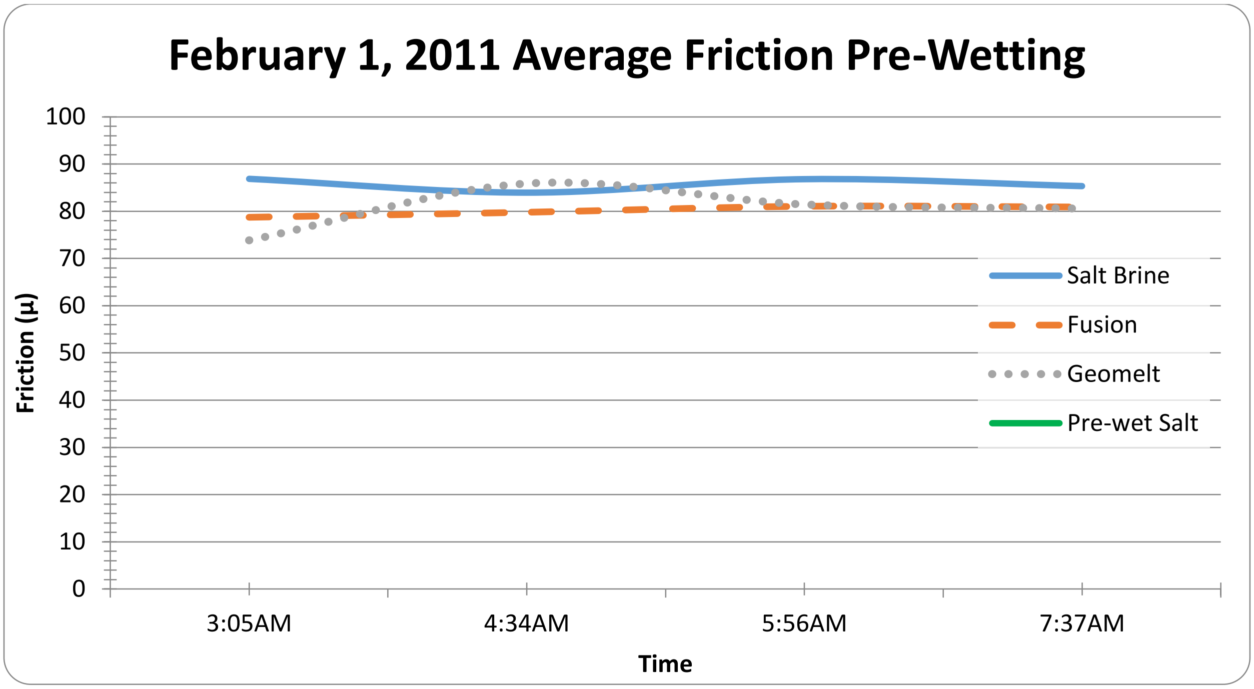
	x	28.357	44.806	25.723	Geomelt	Fusion	Fusion
	s	10.595	14.640	12.002	Marginally Sig.	Significant	Significant
5	n	135	137	142	0.000	0.000	0.733
	x	38.559	27.348	26.916	Geomelt	Geomelt	Fusion
	s	11.821	11.680	9.345	Significant	Significant	Insignificant
5.33	n	132	120	138	0.527	0.787	0.000
	x	32.571	46.240	31.460	Geomelt	Fusion	Fusion
	s	11.605	12.106	16.907	Insignificant	Insignificant	Significant
6	n	133	130	136	0.000	0.000	0.000
	x	37.090	38.916	28.752	Geomelt	Fusion	Fusion
	s	14.760	13.567	15.552	Significant	Significant	Significant
6.33	n	166	132	136	0.000	0.000	0.000
	x	48.072	28.617	23.730	Geomelt	Geomelt	Fusion
	s	16.273	10.439	8.240	Significant	Significant	Significant
6.66	n	130	131	133	0.000	0.000	0.000
	x	44.924	37.492	29.179	Geomelt	Geomelt	Fusion
	s	14.763	12.354	11.626	Significant	Significant	Significant
7	n	167	137	135	0.000	0.000	0.000
	x	41.345	29.746	21.103	Geomelt	Geomelt	Fusion
	s	12.475	10.060	10.661	Significant	Significant	Significant
7.33	n	129	136	132	0.000	0.000	0.000
	x	44.908	36.905	29.278	Geomelt	Geomelt	Fusion
	s	15.652	12.337	16.338	Significant	Significant	Significant
7.66	n	176	146	135	0.000	0.000	0.001
	x	47.263	28.687	24.404	Geomelt	Geomelt	Fusion
	s	13.324	9.617	11.362	Significant	Significant	Significant
8	n	137	127	136	0.000	0.153	0.000
	x	47.565	44.547	34.766	Geomelt	Geomelt	Fusion
	s	16.556	17.668	11.332	Significant	Insignificant	Significant

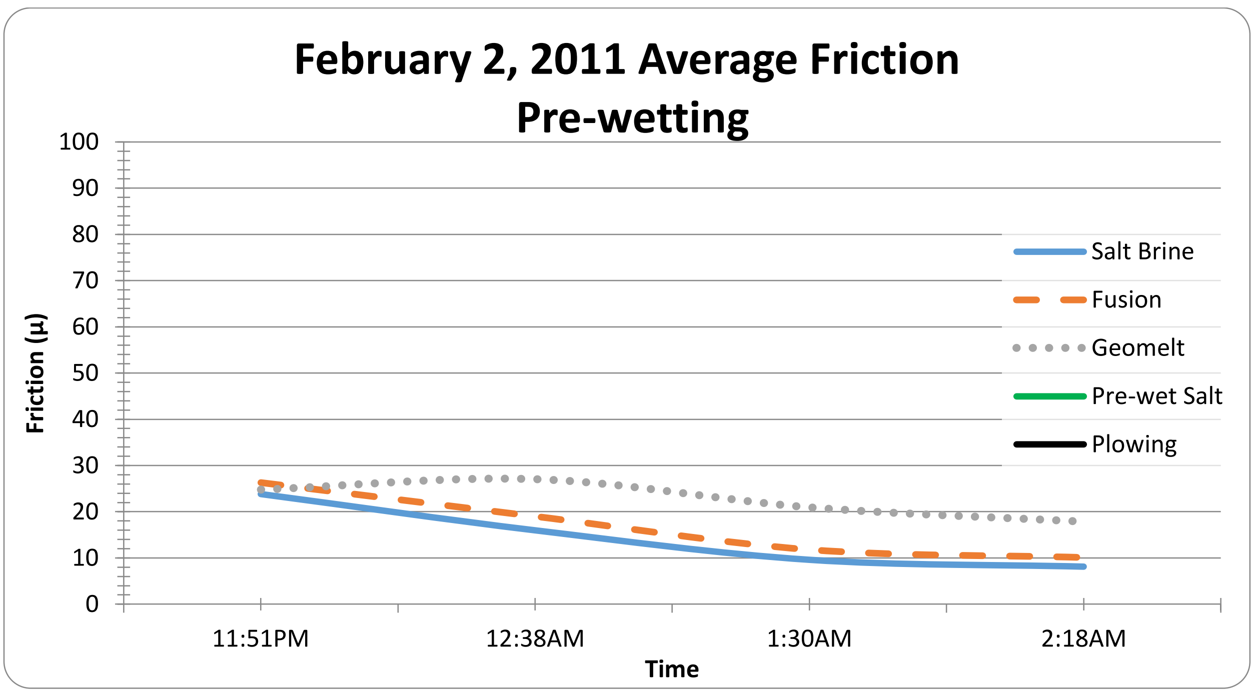
8.33	n	189	152	152	0.000	0.000	0.000
	x	47.445	40.928	28.693	Geomelt	Geomelt	Fusion
	s	15.620	12.044	10.867	Significant	Significant	Significant
9.33	n	135	114	147	0.000	0.000	0.000
	x	54.699	73.365	39.236	Geomelt	Fusion	Fusion
	s	17.655	16.239	13.756	Significant	Significant	Significant
10	n	148	141	137	0.700	0.005	0.013
	x	56.188	50.796	55.457	Geomelt	Geomelt	Brine
	s	16.681	15.810	15.483	Insignificant	Significant	Significant
10.33	n	133	117	141	0.069	0.069	0.000
	x	57.134	77.025	53.366	Geomelt	Fusion	Fusion
	s	19.161	10.113	14.629	Marginally Sig.	Marginally Sig.	Significant

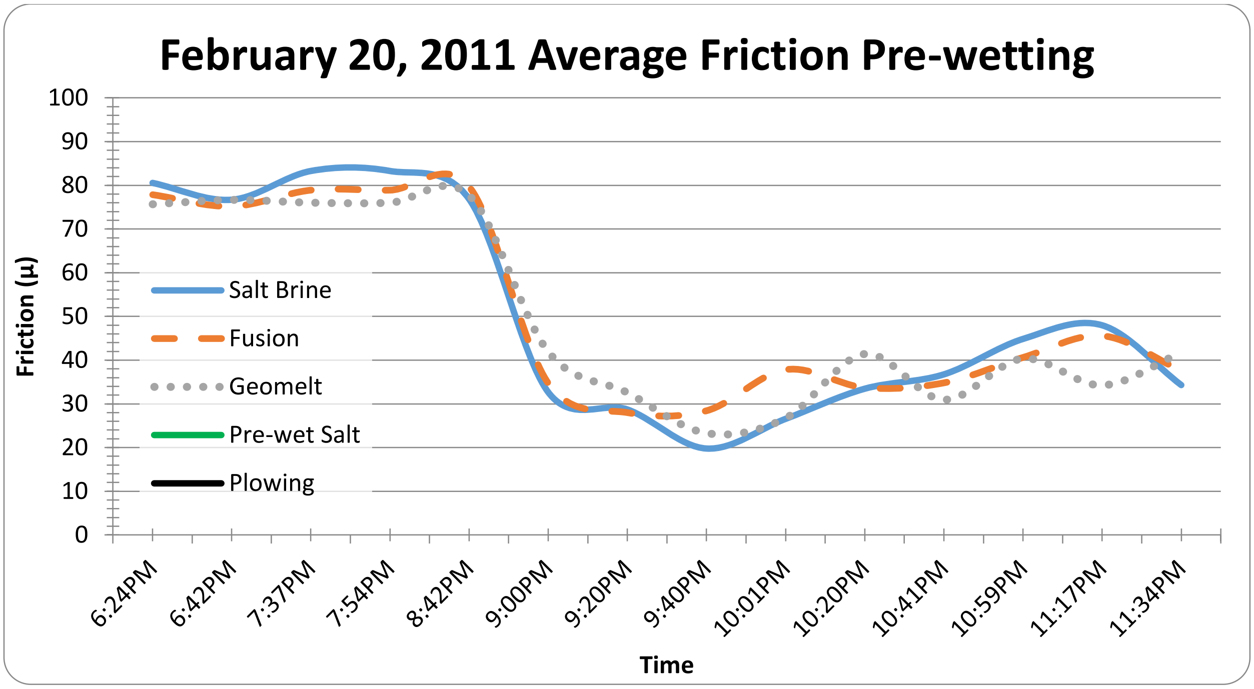
*The product performed better than the other at a confidence level of 95%.

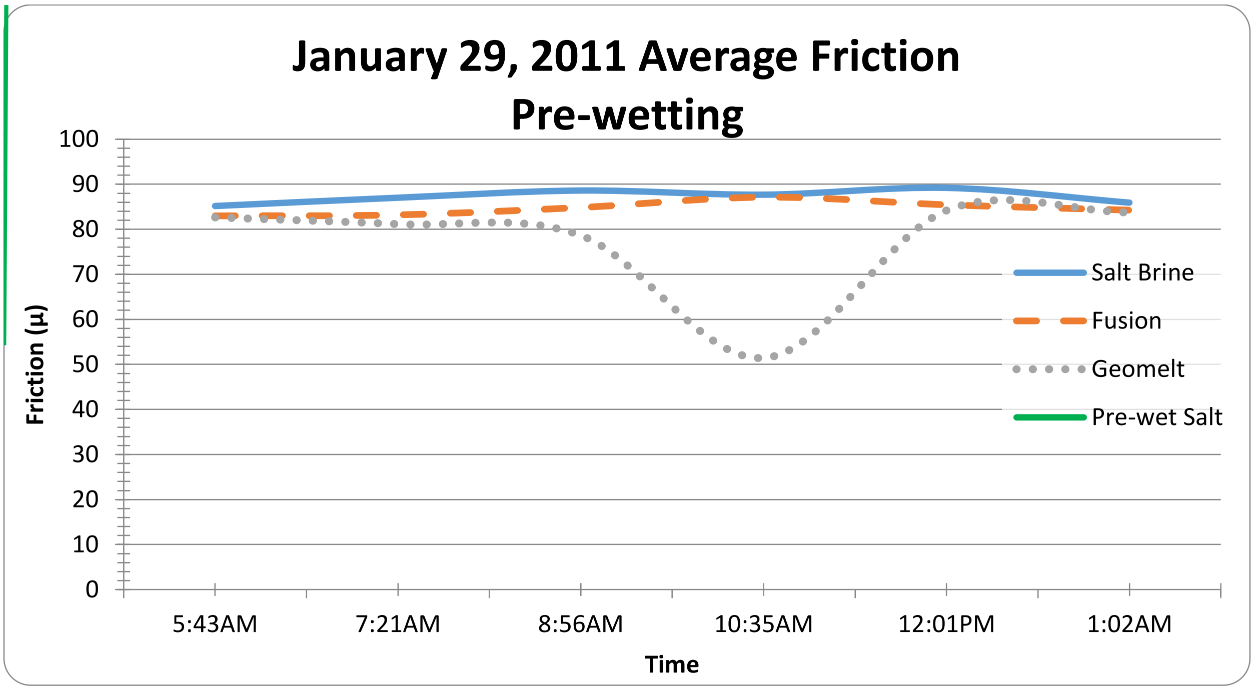
E2-A: Daily Average friction curves for Prewetting

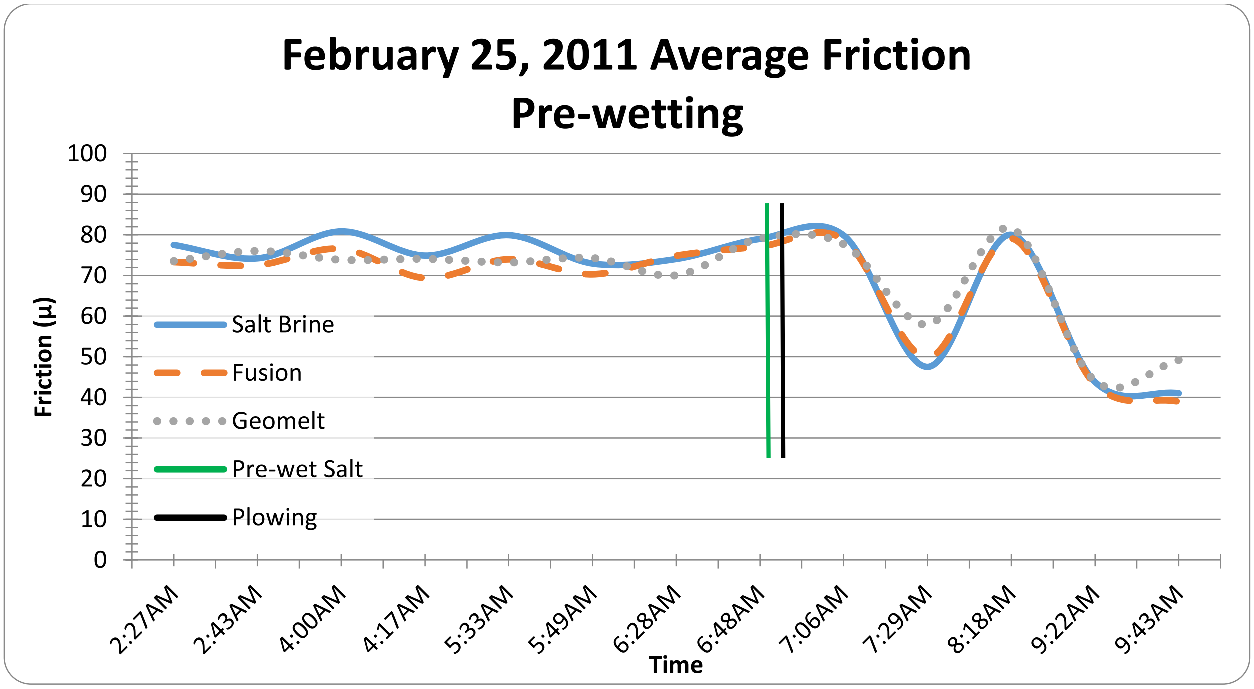


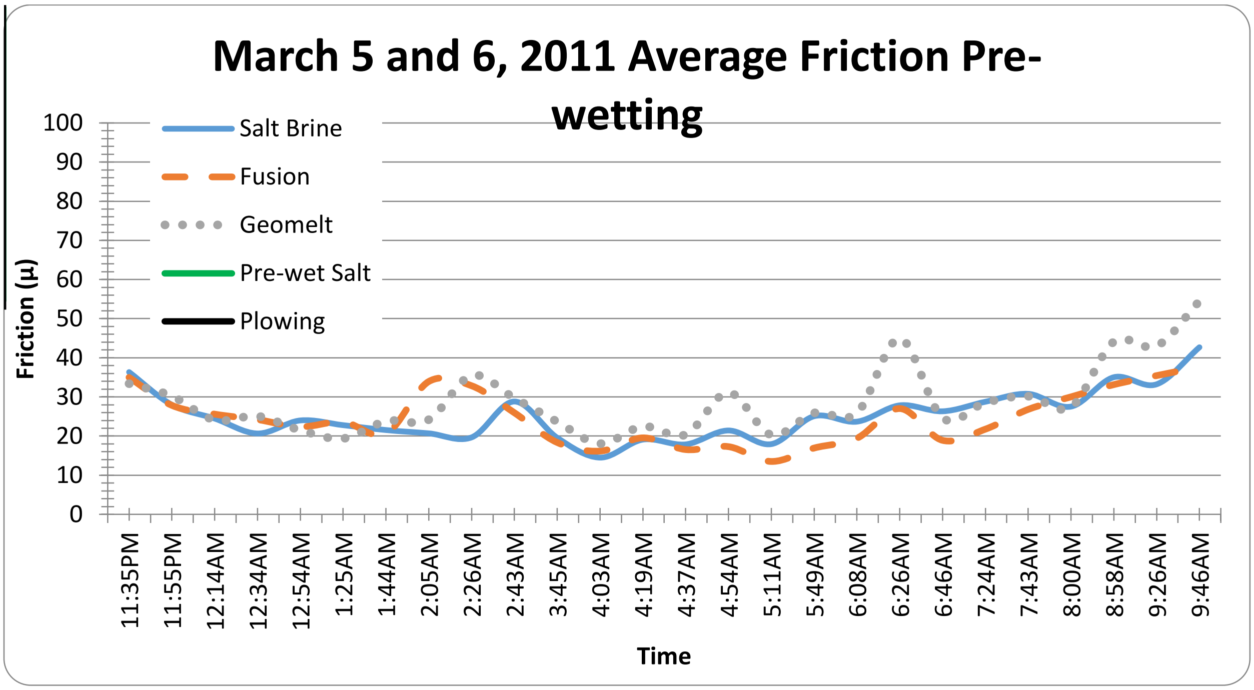

February 1, 2011 Average Friction Pre-Wetting
100
90
80
70
60
50
40
30
20
10
0
Friction (µ)
3:05AM
4:34AM
5:56AM
7:37AM
Time
Salt Brine
Fusion
Geomelt
Pre-wet Salt

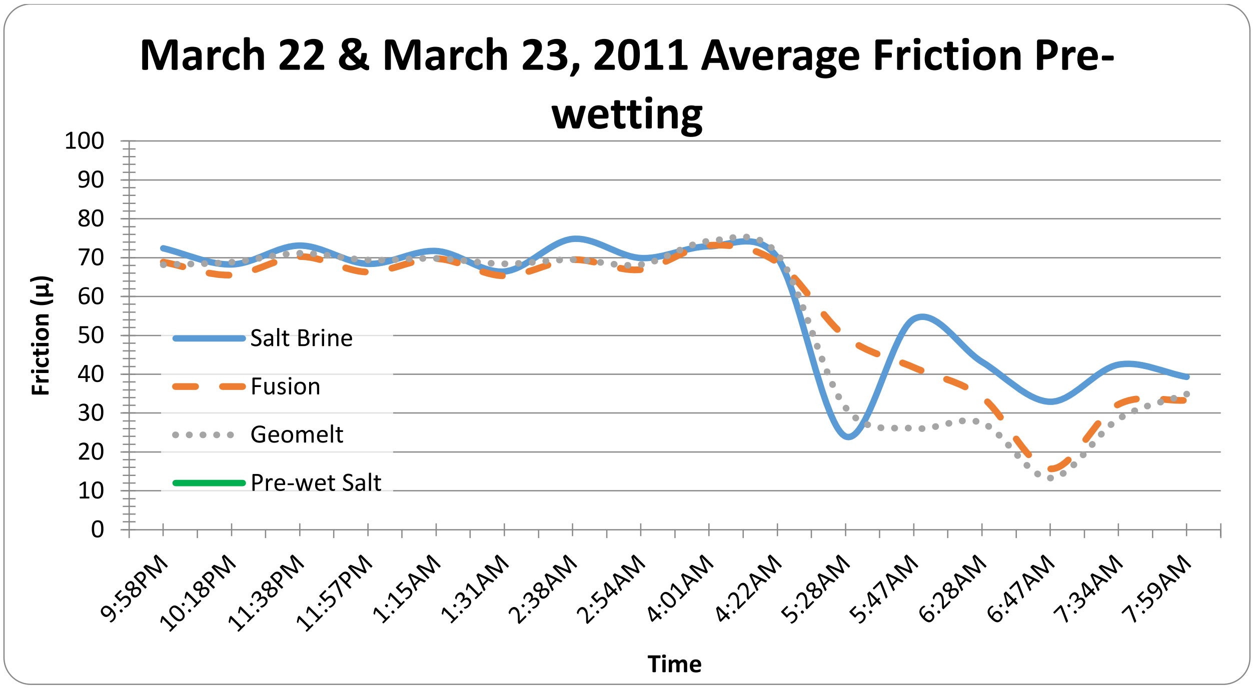

February 2, 2011 Average Friction Pre-wetting
100
90
80
70
60
50
40
30
20
10
0
Friction (µ)
11:51PM
12:38AM
1:30AM
2:18AM
Time
Salt Brine
Fusion
Geomelt
Pre-wet Salt
Plowing


February 20, 2011 Average Friction Pre-wetting
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt
Plowing
6:24PM
6:42PM
7:37PM
7:54PM
8:42PM
9:00PM
9:20PM
9:40PM
10:01PM
10:20PM
10:41PM
10:59PM
11:17PM
11:34PM
Time

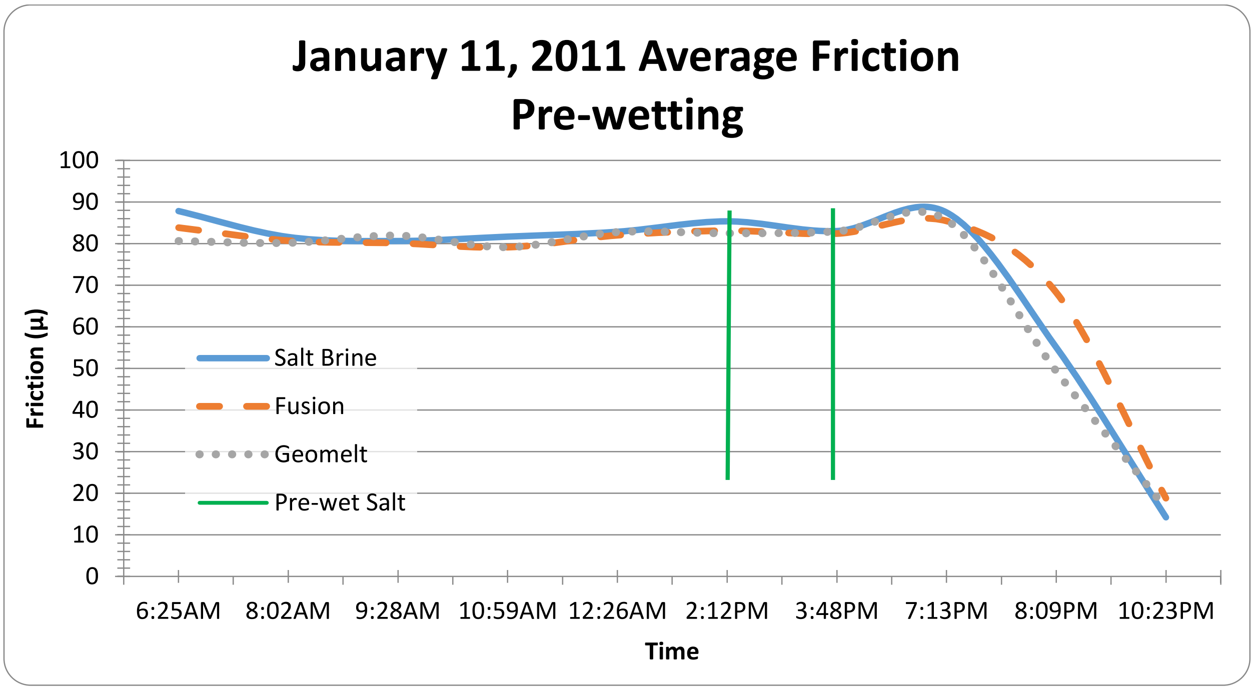

January 29, 2011 Average Friction Pre-wetting
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt
5:43AM
7:21AM
8:56AM
10:35AM
12:01PM
1:02AM
Time


February 25, 2011 Average Friction
Pre-wetting
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt
Plowing
2:27AM
2:43AM
4:00AM
4:17AM
5:33AM
5:49AM
6:28AM
6:48AM
7:06AM
7:29AM
8:18AM
9:22AM
9:43AM
Time


March 5 and 6, 2011 Average Friction Pre-wetting
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt
Plowing
11:35PM
11:55PM
12:14AM
12:34AM
12:54AM
1:25AM
1:44AM
2:05AM
2:26AM
2:43AM
3:45AM
4:03AM
4:19AM
4:37AM
4:54AM
5:11AM
5:49AM
6:08AM
6:26AM
6:46AM
7:24AM
7:43AM
8:00AM
8:58AM
9:26AM
9:46AM
Time

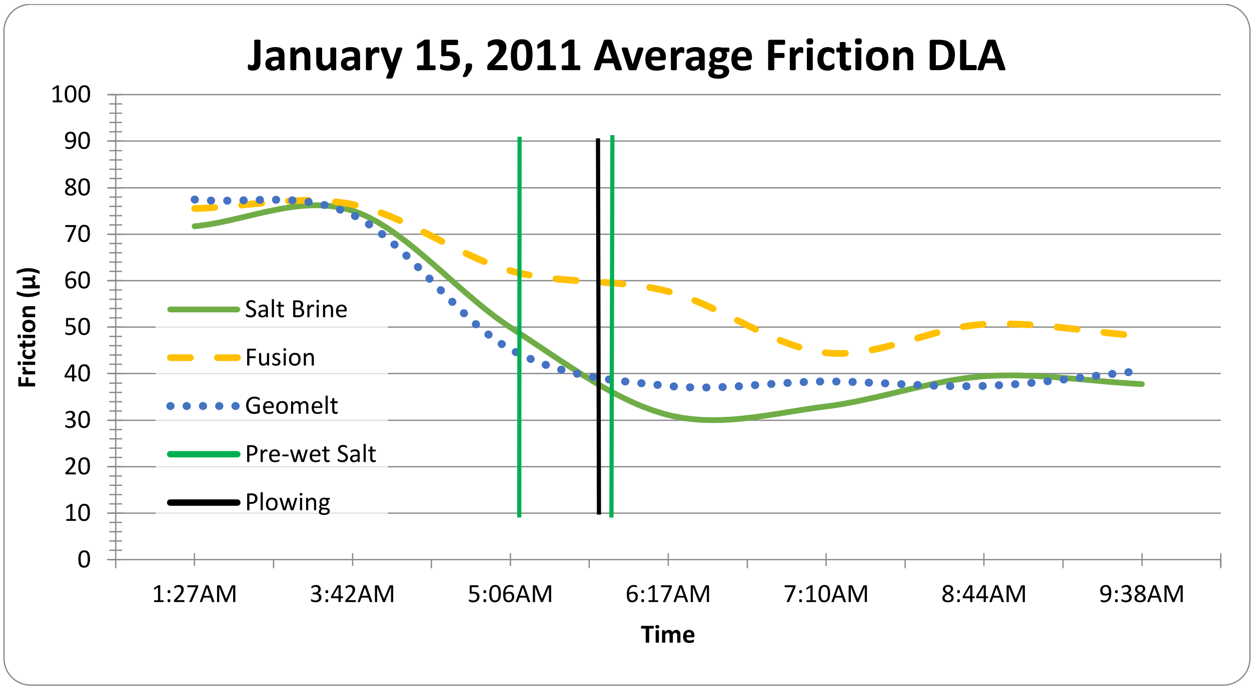


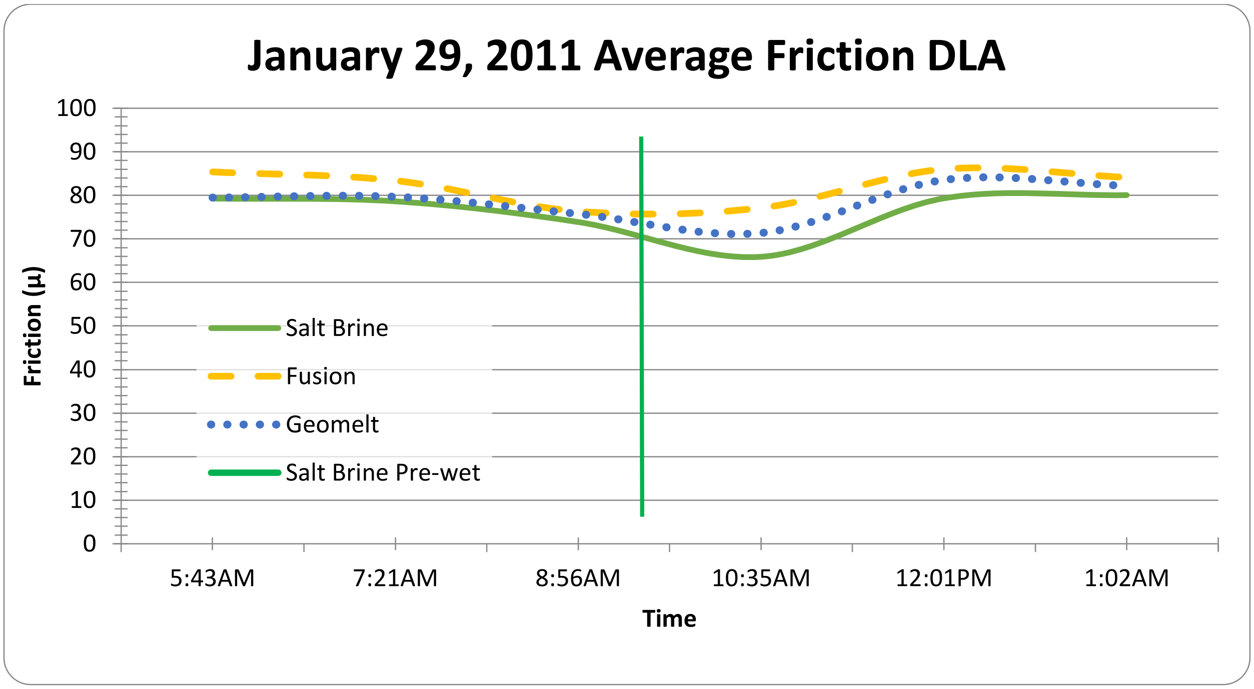
March 22 & March 23, 2011 Average Friction Pre-wetting
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt
9:58PM
10:18PM
11:38PM
11:57PM
1:15AM
1:31AM
2:38AM
2:54AM
4:01AM
4:22AM
5:28AM
5:47AM
6:28AM
6:47AM
7:34AM
7:59AM
Time

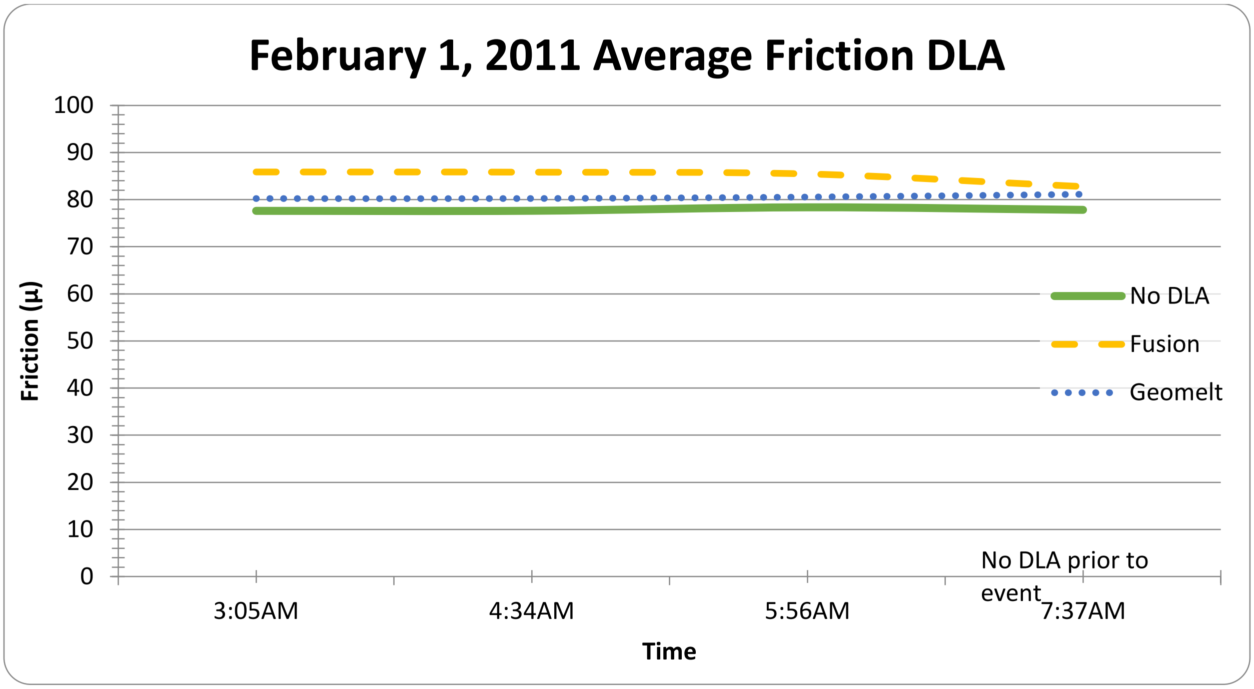


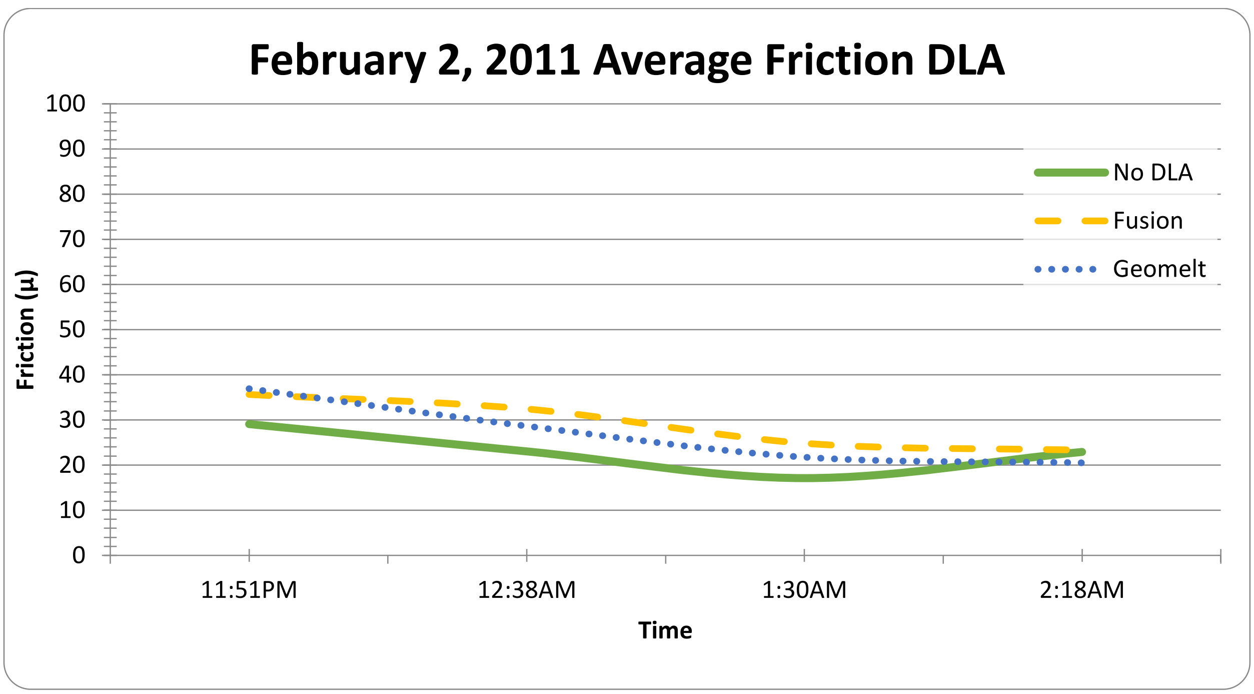
January 11, 2011 Average Friction Pre-wetting
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt
6:25AM
8:02AM
9:28AM
10:59AM
12:26AM
2:12PM
3:48PM
7:13PM
8:09PM
10:23PM
Time

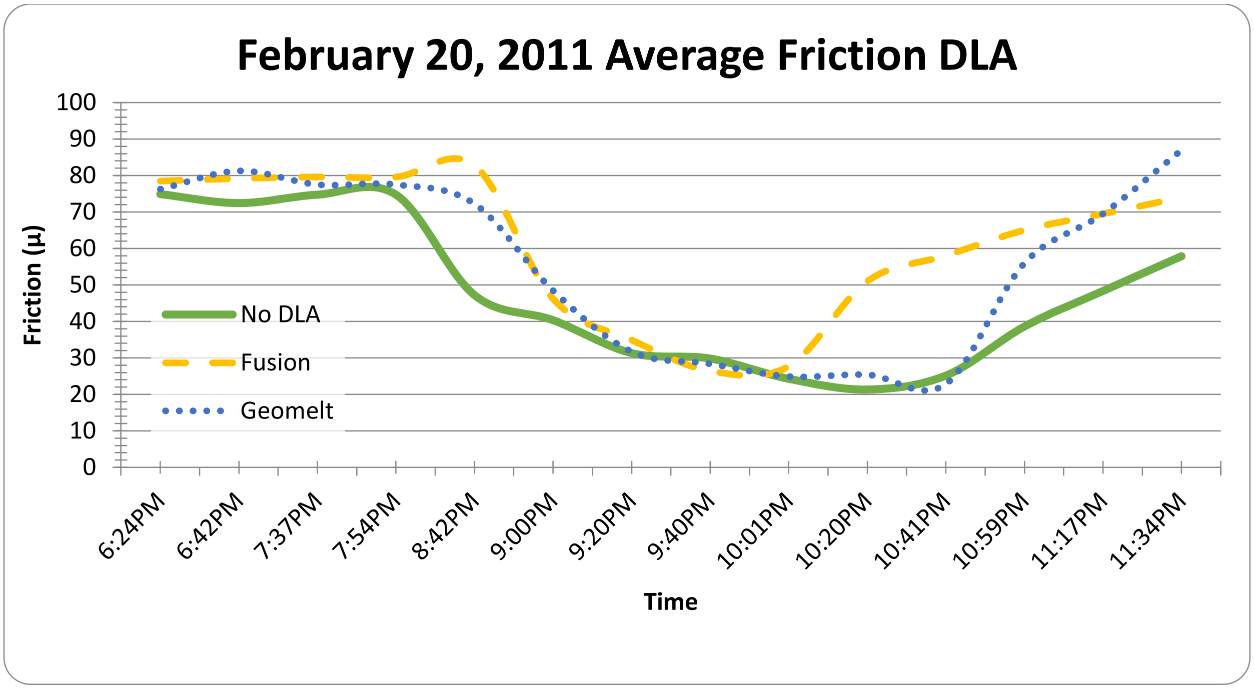
E2-B: Daily Average friction curves for DLA

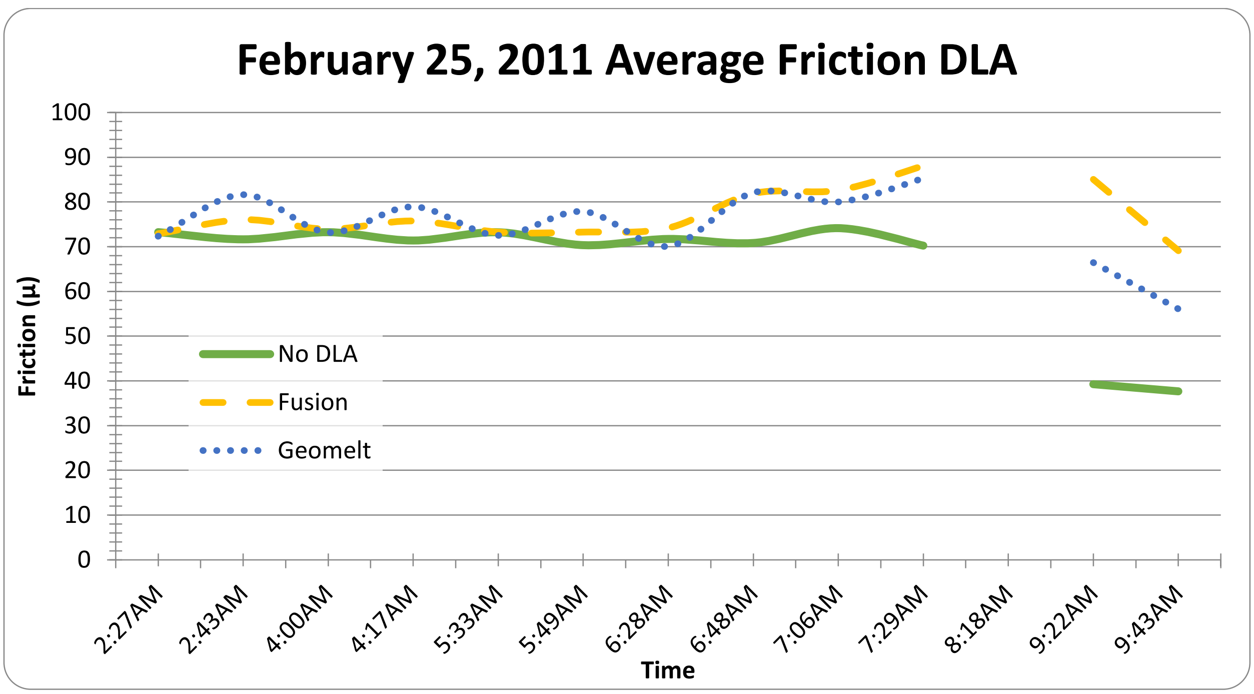


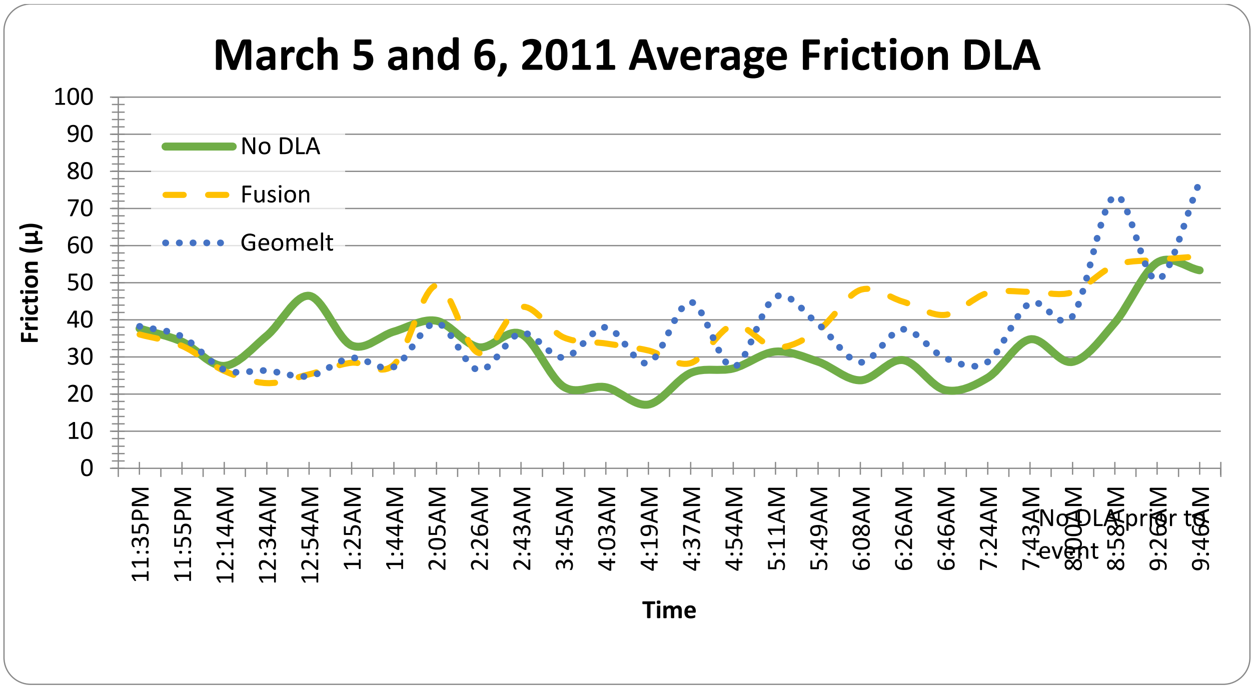


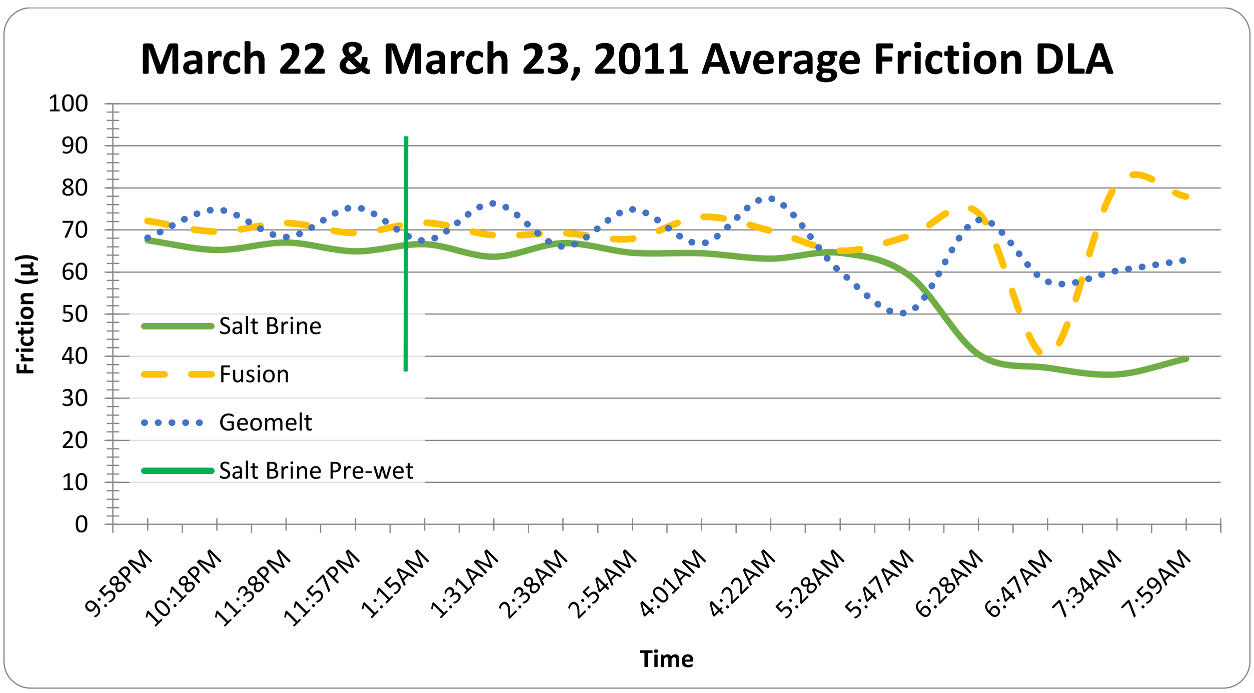

February 1, 2011 Average Friction DLA
100
90
80
70
60
50
40
30
20
10
0
Friction (µ)
3:05AM
4:34AM
5:56AM
7:37AM
Time
No DLA
Fusion
Geomelt
No DLA prior to event

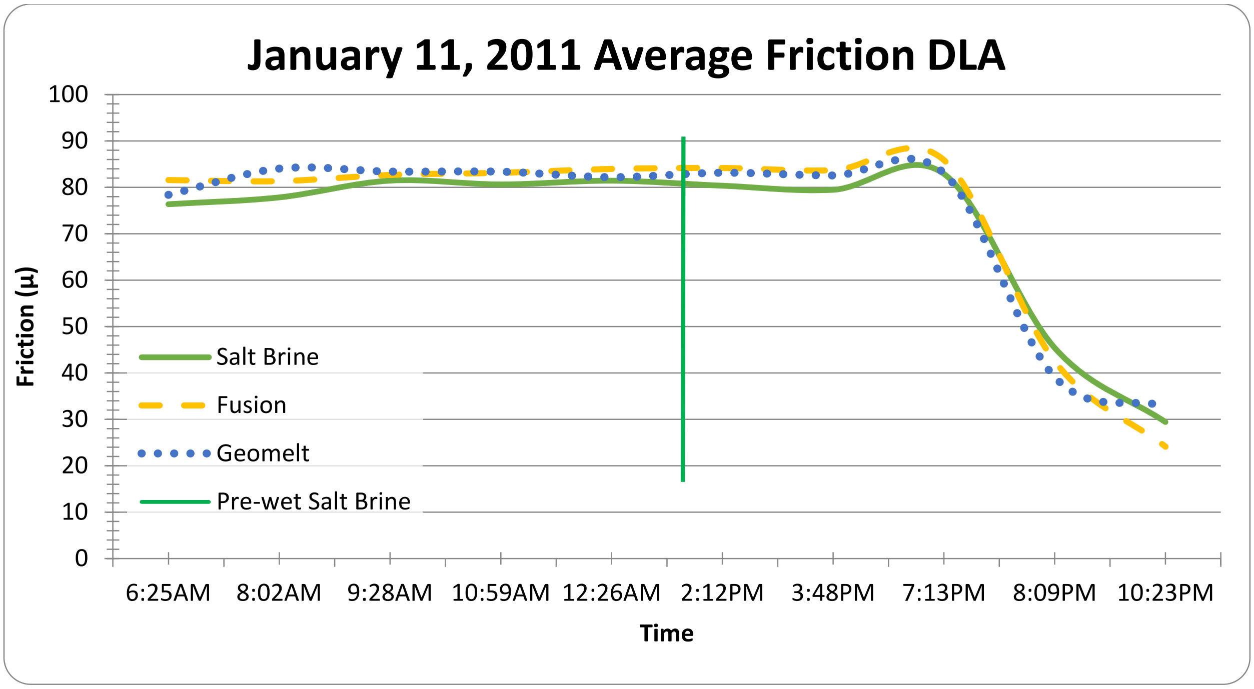

February 2, 2011 Average Friction DLA
100
90
80
70
60
50
40
30
20
10
0
Friction (µ)
11:51PM
12:38AM
1:30AM
2:18AM
Time
No DLA
Fusion
Geomelt


February 20, 2011 Average Friction DLA
100
90
80
70
60
50
40
30
20
10
0
Friction (µ)
No DLA
Fusion
Geomelt
6:24PM
6:42PM
7:37PM
7:54PM
8:42PM
9:00PM
9:20PM
9:40PM
10:01PM
10:20PM
10:41PM
10:59PM
11:17PM
11:34PM
Time


February 25, 2011 Average Friction DLA
100
90
80
70
60
50
40
30
20
10
0
Friction (µ)
No DLA
Fusion
Geomelt
2:27AM
2:43AM
4:00AM
4:17AM
5:33AM
5:49AM
6:28AM
6:48AM
7:06AM
7:29AM
8:18AM
9:22AM
9:43AM
Time


March 5 and 6, 2011 Average Friction DLA
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
No DLA
Fusion
Geomelt
11:35PM
11:55PM
12:14AM
12:34AM
12:54AM
1:25AM
1:44AM
2:05AM
2:26AM
2:43AM
3:45AM
4:03AM
4:19AM
4:37AM
4:54AM
5:11AM
5:49AM
6:08AM
6:26AM
6:46AM
7:24AM
7:43AM
8:00AM
8:58AM
9:26AM
9:46AM
No DLA prior to event
Time


March 22 & March 23, 2011 Average Friction DLA
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Salt Brine Pre-wet
9:58PM
10:18PM
11:38PM
11:57PM
1:15AM
1:31AM
2:38AM
2:54AM
4:01AM
4:22AM
5:28AM
5:47AM
6:28AM
6:47AM
7:34AM
7:59AM
Time



January 11, 2011 Average Friction DLA
Friction (µ)
100
90
80
70
60
50
40
30
20
10
0
Salt Brine
Fusion
Geomelt
Pre-wet Salt Brine
6:25AM
8:02AM
9:28AM
10:59AM
12:26AM
2:12PM
3:48PM
7:13PM
8:09PM
10:23PM
Time

Appendix F: Cost Analysis and Application Rates

Pre-wet- Salt Brine

Setting	Total Material/lane km	Salt/lane km	Liquid/lane km	Cost ($/lane km)
1	60 kg	48 kg	12 kg (10 litres)	3.6
2	85 kg	68 kg	17 kg (14.2 litres)	5.1
3	110 kg	88 kg	22 kg (18.5 litres)	6.6

Pre-wet: Fusion and Geomelt

Setting	Total Material/lane km	Salt/lane km	Liquid/lane km	Cost($/lane km)
1	60 kg	57 kg	3 kg (2.5 litres)	4.02
2	85 kg	80.75 kg	4.25 kg (3.5 litres)	5.6
3	110 kg	104.5 kg	5.5 kg (4.5 litres)	7.37

Direct Liquid Application for Anti-icing

Material	Application Rate (Litres/lane-km)	% Organic	Total Salt (kg/lane-km)	Cost ($/lane-km)
Salt Brine	100	0	23	1.2
Fusion	50	30	8	2.0
Geomelt	50	30	8	2.0

Appendix G: Difference in Performance for Prewetting and DLA.

	Prewet(% difference)						DLA(% difference)					
Date	Fusion vs Brine		Geomelt vs Brine		Fusion vs Geomelt		Fusion vs Brine		Geomelt vs Brine		Fusion vs Geoment	
Jan.11	1103.8	3.23	-779.1	-2.3	1882.88	5.6	565.856	1.7	249.53	0.8	-316.3	-0.9
Jan.15	-780.2	-4.7	-2414	-15	1633.56	12	4593.28	30	300.29	2	-4293	-22
Jan.29	-1225	-3.2	-5433	-14	4208.28	13	2656.52	8	1164.2	3.5	-1492	-4.2
Feb.01	-1467	-6.3	-1148	-4.9	-318.94	-1	1968.81	9.3	698.09	3.3	-1271	-5.5
Feb.02	365.72	18.1	1370	67.6	-1004.3	-30	1014.86	31	631.96	20	-382.9	-9
Feb.20	219.93	1.93	-156.3	-1.4	376.27	3.3	3767.89	37	2046.7	20	-1721	-12
Feb.25	-958.9	-3.1	-188.4	-0.6	-770.57	-3	3883.36	15	3155	12	-728.4	-2.5
Mar.5&6	-572.7	-3.7	2018	13	-2590.7	-15	4434.26	23	3550.8	18	-883.5	-3.7
Mar.22&23	-610.1	-6.5	-2181	-23	1570.84	22	3734.27	35	2840	26	-894.3	-6.1
Comments												
	Mostly indifferent		Mostly indifferent		Mostly indifferent		Fusion Outperforms Brine		Geomelt Outperforms Brine		Fusion Outperforms Geomelt	

Appendix H: Sample Weather Data from Environment Canada.

Sample of Environment Canada Data Available at Pearson Airport

Hourly Data Report for January 11, 2011										
	Temp °C	Dew Point Temp °C	Rel Hum %	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Hmdx	Wind Chill	Weather
TIME										
00:00	-8.5	-11.9	76	1	13	24.1	100.64		-14	Mostly Cloudy
01:00	-8.3	-11.8	76	36	15	24.1	100.60		-15	Mostly Cloudy
02:00	-8.8	-11.7	79	2	13	24.1	100.56		-15	Mostly Cloudy
03:00	-9.2	-11.6	83	2	11	24.1	100.60		-15	Mostly Cloudy
04:00	-9.5	-11.8	83	36	13	24.1	100.54		-16	Mostly Cloudy
05:00	-9.1	-11.5	83	1	11	24.1	100.52		-15	Cloudy
06:00	-8.8	-11.2	83	1	9	24.1	100.49		-13	Cloudy
07:00	-8.2	-10.7	82	2	15	24.1	100.43		-15	Cloudy
08:00	-7.3	-10.0	81	4	13	24.1	100.41		-13	Cloudy
09:00	-6.9	-9.6	81	7	15	24.1	100.39		-13	Cloudy
10:00	-6.4	-8.7	84	6	15	24.1	100.36		-12	Mostly Cloudy

Weather phenomena reported include:

- Tornado
- Waterspout
- Funnel Cloud
- Thunderstorms
- Heavy Thunderstorms
- Rain*
- Rain Showers*
- Drizzle*
- Freezing Rain*
- Freezing Drizzle*
- Snow*
- Snow Grains*
- Ice Crystals
- Ice Pellets*
- Ice Pellet Showers*
- Snow Showers*
- Snow Pellets*
- Hail*
- Fog
- Ice Fog
- Smoke
- Haze
- Blowing Snow
- Blowing Sand
- Blowing Dust
- Dust
- Freezing Fog
- Virga

Precipitation types marked with an asterisk (*) are observed in three intensities: light, moderate and heavy. If the precipitation is listed in the WEATHER column without a modifier then the intensity is light. Otherwise it will appear with a modifier of moderate or heavy.

See http://climate.weather.gc.ca/glossary_e.html#weather for more information.