Optimum Deicing and Anti-icing for Snow and Ice Control of Parking Lots and Sidewalks

by

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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 revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

ABSTRACT

Snow and ice cause pavement surfaces to become slippery and unsafe for both foot and vehicular traffic. To alleviate the hazards of pedestrians slipping and vehicular accidents, various forms of maintenance operations such as, deicing and anti-icing are conducted to control snow and ice from transportation facilities including roadways, parking lots and sidewalks. These efforts use a significant amount of resources every winter season. For instance, over $1 billion is spent annually for snow and ice control in Canada. This large cost includes the use over 5 million tons of salts (TAC, 2013). The application of excessive amount of salts has, however, raised concerns among environmental and regulatory agencies as well as the public about their detrimental effects on the environment and corrosive effects to the infrastructure (e.g., pavement, roadside structures) and vehicles. A sensible and optimal salting strategy is therefore necessary in order to reduce the harmful effects of salt while keeping the various transportation facilities safe.

To realize an optimal salting strategy, one of the first steps is developing salting guidelines that specify salt application rates and treatment options for the conditions of any given snow event. A significant amount of research has been conducted in the past to develop such guidelines; however, most of these efforts focused on roadway maintenance with little concern about parking lots and sidewalks. The salt application rates developed for roadways are not applicable for the latter due to differences in traffic characteristics (vehicular vs. pedestrian) and service requirements (i.e., desirable bare pavement regain time). The main goal of this research is to develop a quantitative understanding of the snow melting performance of common snow control materials and methods, through a systematic field study, so that optimal application rates can be determined for parking lots or sidewalks under any specific weather events; this will ultimately lead to the development of a comprehensive winter maintenance guideline for parking lots and sidewalks.

The field tests were conducted over the winter seasons of 2011-2012, 2012-2013 and 2013-2014 in Waterloo, Ontario, Canada. In these testing seasons, there were about 100 snow events in total with pavement surface temperatures ranging from about -20°C to 3°C, and snow precipitation from about 0.2cm to 22cm. Approximately 5000 tests were conducted using different salts (e.g., regular rock salt, alternative solid salts-semi to full organic, pre-wetted salts, liquid organic salts) and treatment methods (i.e., deicing and anti-icing), including tests with plowed and unplowed snow, with and without traffic, and in both stall areas, driveways and sidewalks. In order to closely simulate the way parking lot maintenance is performed in the real world, 60 to 70% of the test operations started between 3am and 7am.

The field tests have resulted in a unique database covering the field performance of various winter maintenance materials and techniques. This performance data has then been rigorously analyzed using statistical tools to develop a quantitative understanding of the conditions that influence the effectiveness of

various maintenance treatment options and to facilitate the establishment of a set of recommended treatment options and application rates for a wide variety of winter events. A majority of the tests covered deicing application of different salts. The performance of a given treatment has been measured as the time needed to reach 80% bare pavement status from the time salt was applied on top of snow. With the performance data from the deicing operations, an extensive exploratory data analysis has been conducted to investigate the factors that influence the performance of salt as a deicer. From this analysis, it was found that salt application rate, pavement temperature, snow depth, snow density and traffic are highly correlated with the snow melting performance of salt. A multivariate regression analysis was then conducted for a more rigorous analysis, quantitative information of effect, and statistical reliability of the influencing factors. The results of the regression has confirmed that all the initial factors suspected are statistically significant on the snow melting performance of salt at a 95% confidence level. With the understanding gained on physical behavior of the snow melting of salt and from the collected empirical data, a physical-empirical model has been developed. This model was then used to determine minimum application rate for a given snow event. Factors to adjust the base application rate have also been developed for some facility or treatment specific conditions such as different traffic patterns, pavement types, or using alternative salt as a deicer.

In addition to deicing treatments, a significant amount of anti-icing tests have been conducted using various common and emerging anti-icers. Since, the main objective of anti-icing is to prevent bonding between snow and the pavement's surface form occurring, the co-efficient of friction was measured on treated sections and control sections using a friction tester after the end of a snow event. The friction data and event conditions data were then rigorously analyzed using various statistical tools to determine the optimal application rate for anti-icing purposes.

In summary, this research first investigated the direct link between the snow melting performance of salt and weather characteristics. The results derived from this work were based on impressive amount of field testing data that reflected real-world conditions. With the collected performance and weather data, a snow melting model has been developed that is the first of its kind based on the literature reviewed. The model was then used to determine minimum salt application rates for a number of given scenarios. The performance model has also been used to prescribe adjustments to the recommended application rates based on some external or site specific factors (e.g., traffic, pavement type). This research is also the first to conduct an in-depth analysis on the investigation of the effectiveness of anti-icing operations and tested both common and emerging anti-icers. Based on a significant amount of data, an analysis of variance on the friction data has been conducted to determine the effectiveness of treatment and determine optimal application rates with statistical reliability. The field test results and insight that have been gained from this research have been used to develop a decision support tool for snow and ice control in the real world. These tools are the first of their kind and are currently in use among a number of winter maintenance contractor for parking lots and sidewalks. This research also provides deep insights on the optimal winter maintenance of other types of transportation facilities, such as roadway winter maintenance operations.

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To

Dalia (my wife)

Afik (son)

Abha (daughter)

Malia (daughter)

And

All Snow Fighters

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LIST OF ACRONYMS

AC	Asphalt Concrete
BPRT	Bare Pavement Regain Time
BP	Bare Pavement
CMA	Calcium Magnesium Acetate
COF	Coefficient of Friction
DOT	Department of Transportation
EDA	Exploratory Data Analysis
IC	Interlocking Concrete Pavers
LOS	Level of Service
MOE	Ministry of Environment
PCC	Portland Cement Concrete
P/U	Proprietary/Unknown
TRCA	Toronto Region and Conservation Authority

CHAPTER 1
INTRODUCTION

1.1. Background

Safe and efficient surface transportation systems are essential for the economic vitality of any country. As a critical part of the total transportation system, parking lots and sidewalks are used by trip-makers in their day-to-day business. It is imperative, therefore, that the safety of pedestrian and vehicular traffic in these facilities be maintained at all times. Maintaining a high safety standard can be challenging, especially in northern countries where the entire transportation system can be negatively affected by adverse winter weather.

In northern countries such as Canada, the winter climate generates a unique set of challenges to the transportation system. During the winter months, the accumulation of contaminants such as snow, slush and ice is very common. These snow and ice contaminants deteriorate the surface conditions of any paved surface, which in turn affects the mobility and safety of pedestrians and vehicular traffic. For example, surfaces covered with snow and ice have been shown to increase a pedestrian's risk of slipping and falling by reducing the average level of traction (friction) of the pavement surface (Lin et al. 1995, Bakken et al. 2002).

Fundamentally, slips and falls are caused by a loss of traction or friction between the pedestrian's shoes and the surface being walked on. A study conducted by Berggard (2010) in Sweden indicated that the risks of slipping on slippery surfaces, such as icy or snowy surfaces, are higher than on other surfaces. Furthermore, as one would intuitively expect, the study noted that that slipping rates have a negative relationship with friction; that is as friction decreased the slipping rates increased. In addition to the increased risk of slipping, the study also reported that pedestrian injuries on slippery surfaces are more severe than those on non-slippery surfaces.

Therefore, maintaining safe traction or friction on these surfaces is critical to the safety of pedestrian and vehicular traffic during the winter months. In order to maintain safe traction levels and ensure the safety and mobility of transportation facilities in winter conditions, snow and ice control operations such as plowing and salting are performed. However, the costs of these winter maintenances are substantial. For example, North American transportation agencies spend more than $3 billion annually on winter maintenance activities such as snow removal and salt application (TAC 2013, Highway Statistics Publications, 2005). In Canada specifically, Environment Canada (2004) reported that Canadian agencies spend over $1 billion annually to clear snow and ice on various transportation facilities. This includes the use of over 5 million tonnes of salts for deicing and anti-icing operations.

Due to its effectiveness in sub-freezing conditions and low costs, regular rock salt has become the chemical of choice for many transportation agencies and has been used extensively as the dominant material for snow and ice control. While the use of salts is essential to ensure public safety, maintain mobility and assure the nation's economic vitality, the release of such large quantities of salts has been shown to cause significant environmental side effects, such as damage to the soil, water, vegetation and wildlife (Andrey and Knapper, 2003; NCHRP 577-2007). Salt is also a significant factor contributing to the corrosion of bridges, buildings and vehicles, increasing their maintenance costs by billions of dollars (Shi et al 2010, Fay et al 2011).

Environment Canada (2012) reported that about 20 to 40% of the total salt used in winter maintenance goes towards the maintenance of parking lots and sidewalks, though these numbers can be even higher for densely populated areas (Omer et al. 2013). Therefore, a sensible salting strategy that keeps the various transportation facilities safe but reduces the impact of its harmful effects is necessary and should be considered by the transposition agencies of cities and municipalities faced with austere winter weather.

Developing a sensible salting strategy is a multi-step process; but one of the first steps is the development of facility-specific snow and ice control guidelines that prescribe the best methods, materials and salt application rates for a given winter event condition. A significant amount of effort has been made in the past to develop such winter maintenance guidelines (Perchanok et al., 1991; Chang et al., 1994; Ketcham et al., 1996; NCHRP-526, 2004); however, most of these efforts focused on highway maintenance strategies, with few on parking lots and footways such as sidewalks and platforms. The salt application rates developed for roadways are not applicable for the latter due to drastic differences in traffic characteristics (vehicular vs. pedestrian) and service requirements (e.g., desirable bare pavement regain time and pavement traction needs). It is generally understood that developing the best guideline for a specific type of facility, such as a parking lot or sidewalk, requires a quantitative understanding of the snow melting performance of the materials being used and application rates within the usage environment of these facilities. This research addresses this need.

1.2. Snow and Ice Control Operations

As indicated above, a significant amount of effort has been made to improve the efficiency and effectiveness of various winter maintenance methods. The most common methods include deicing (i.e., application of salts on top of snow or ice contaminants after a weather event), anti-icing (i.e., pre-application of salts before a weather event), sanding and plowing. Deicing has been used to control snow and ice since the early nineteenth century (Blackburn et al. 1992). On the other hand, a comparatively newer and promising method is anti-icing; a method which involves the application of a freezing point depressant, such as salt, prior to a snow event in order to prevent the formation of a snow or ice bond with the pavement surface (Ketcham et al., 1996; NCHRP-526, 2004). Anti-icing has been recognized to have several significant benefits; however, the benefits have mostly been demonstrated in the context of highway maintenance, with very few studies focusing on the effectiveness of this strategy or in determining its best practice when it is applied for snow and ice control of parking lots and sidewalks. As mentioned earlier, the operating conditions of parking lots and sidewalks are significantly different from roadways, which means materials and rates that are ideal for roadway anti-icing treatments may not be suitable for parking lots and sidewalks. For instance, liquid salt is more effective for roadway maintenance when compared to solid salt, as the latter can be easily dispersed by vehicular traffic; however, the effects of vehicular traffic within parking lots is substantially lower than on roadways and thus the application of solid salts may be more suitable.

Past studies have shown that regular salt is only effective until certain temperatures, which means they are of little effect or use for snow and ice control when the temperature drops to values below their practical eutectic point (e.g., Blackburn et al., 2004). Therefore, the maintenance industry has a significant interest in finding alternative materials to regular road salt that can either be used at a lower temperature range and application rate or have lower effects on the environment and infrastructure.

In summary, snow and ice control operations are critical for ensuring the safety and mobility of vehicular and pedestrian traffic; however, this could entail not only significant financial costs, but potential environmental and infrastructural damages as well. To reduce the costs, damages and chemical use, transportation agencies and stakeholders are seeking ways to optimize their winter maintenance operations while improving safety and mobility on every component of the transportation system. To realize this goal, there should be clear facility-specific guidelines for snow and ice controls. These guidelines should address the following questions: What is the right snow and ice control method for a given weather event? What is the right snow and ice control chemical? What is the right application rate for the selected chemical? How can the performance of snow control methods and materials be measured effectively? Questions such as these can only be addressed through a systematic and comprehensive field study that properly assess and quantifies the snow melting performance of the chemicals and methods currently available.

1.3. The Research Problem

As indicated in the previous section, selecting the right snow and ice control method, the right chemical and the right application rate is a challenging yet indispensable task that governs winter maintenance operations. In general, about 65% of winter maintenance contractors follow the conventional method of controlling snow, i.e., applying road salt as a deicing treatment (post salting). The salt application rate varies from contractor to contractor and also on the type of snow storm and maintenance site in question. Maintenance personal also often use personal experience or the application rate suggested for roads as their primary guide. The industry as a whole, however, is just beginning to realize the importance of developing defendable guidelines for the selection of application rates and salt spreading methods.

To obtain additional insight on current practices, two online surveys were conducted as part of this research project; one survey polled winter maintenance contractors (Omer et al., 2012) while the other polled cities and municipalities (Hossain et al., 2013). The main objective of the surveys was to investigate and document the current state of practice in regards to the winter maintenance of parking lots and sidewalks, with the eventual goal of using this information to develop guidelines that are easy to adopt and address common issues faced by field practitioners.

The first survey was conducted over 600 maintenance contractors and included questions on the various dimensions of snow and ice control practices in parking lots and sidewalks. The survey questionnaire was sent out via email by Landscape Ontario, an Ontario based association representing over 2000 horticultural professionals such as landscape contractors, maintenance and snow management contractors, and landscape designers. More than 100 complete responses were received. This survey revealed the following key elements prevalent in current practice:

- Most of the contractors deice using regular salt.
- For application rates, respondents were asked to choose typical values for low, medium and high application rates for salt that would normally be applied. The application rates reported by the contractors had large variations, indicating that maintenance contractors are unsure of the amount of material needed for a given set of conditions. A summary of the application rates has been presented in Table 1-1. It should be noted here that, unlike most other questions on the survey, these questions were only answered by 75% of the respondents, indicating that a number of respondents were unsure of the amount of material that went down in every application. Regarding unit of application rates, most of the contractors used both tonnes/acre and lbs/1000sqft.
- From the perspective of adopting newer technologies, despite their proven effectiveness under certain conditions, only about 25% of contractors indicated that they have used anti-icing, pre-wet salt or direct liquid application for parking lot maintenance. While high initial cost is one of the major hurdles for adopting some new methods and technologies (e.g. pre-wetting equipment) another reason for the low adoption rate is the lack of formal studies and guidelines that explain the correct use and potential savings that their use would have in parking lots and sidewalks.
- A majority of the contractors surveyed reported over applying salt to avoid slips and falls, as they often lead to litigations and increases in insurance premiums. Given the relatively low price of salt and minimal penalties for over application, it can be expected that this trend for over application of salt will continue. A large proportion of the respondents (75%) believe that 10% or more salt could be saved if litigations and insurance premiums were not a concern.

The second survey investigated the current winter maintenance practices used by the cities and municipalities. These government bodies are both generally responsible for ensuring the safety of the internal streets, sidewalks and parking lots of their various establishments and office buildings. The online survey was sent to 222 cities and municipalities in Canada and the United Sates that were selected based on differences in winter severity. Of those cities, over 25% of them responded, providing information that will be useful in developing practical guidelines and improving the overall efficiency of the industry. The major findings from this effort are summarized as follows:

- The majority of respondents mentioned that they generally perform deicing. Specifically, for light to medium events, approximately 65% of cities reported that they used deicing (either plowing and salting or salting only), whereas only 5% of respondents reported that they performed anti-icing. Although anti-icing has been shown to be more promising for minimizing salt application rates and improving efficiency in maintenance operations, these results clearly show that this method has not been adopted for maintaining parking lots and sidewalks. To prevent snow-pavement bonding, most contractors reported performing plowing operations before a snow accumulation of 5 cm. This technique can be improved by anti-icing using a low application rate.
- For salt application rates, respondents were presented with two cases: one case was given to determine their typical application rates in response to a light event or when snow accumulation on the pavement is minimal, and the other case was given to determine the application rate that would normally be applied for heavy snow accumulation on the pavement. The question was intentionally made open-ended and respondents were requested to express the rates used in their preferred units (lbs/1000sqft, gm/m2, etc.). During analysis, a set of interesting responses/comments were observed. These include expression of application rates and units in typical road rates (kg/lane-km or lbs/lane-mile) or a mixture of unusual units (Kg Per Minute, Kgs/Sqm, lbs/sqyds etc.); many respondents also reported not knowing or being unsure of the application rates used, including comments like "whatever is needed", "road standards in Ontario", "we have no standard" etc. Responses that contained application rates were converted to a common unit (lbs/1000sqft) and subdivided into two categories: low rates (less than 10lbs/1000sqft) and high rates (10 to 30lbs/1000sqft), as shown in Figure 1-1. Note that while processing the data, responses indicated that the rates used were generally adopted from the road rates, resulting in lower application rates than those reported by the contractors in general (Fu et al., 2013).
- Despite pressure to adopt environmentally friendly winter maintenance strategies from concerned groups, almost all cities reported using ordinary chloride salts. No mention was found regarding the usage of organic salts. When asked regarding which snow control chemicals are used, 65% of

cities used regular sodium chloride, while 35% reported using other materials in addition to sodium chloride (e.g., magnesium chloride).

- 64% of the cities indicated that regular dry sodium chloride was used for snow control while 36% used pre-wetted salts. 60% of the respondents who used pre-wetted salts reported using regular brine as a pre-wetting agent, while 30% use other chloride solutions (e.g., magnesium products).

Table 1-1: Application Rates Reported by Maintenance Contractors for Parking Lots and Sidewalks

Snow Event Type	Mean Application Rate (lbs/1000sqft)	Mode	Standard Deviation
Light	12.0	5 to 10	10.5
Medium	20.0	10 to 20	15.5
Heavy	30.0	30 to 40	18.0

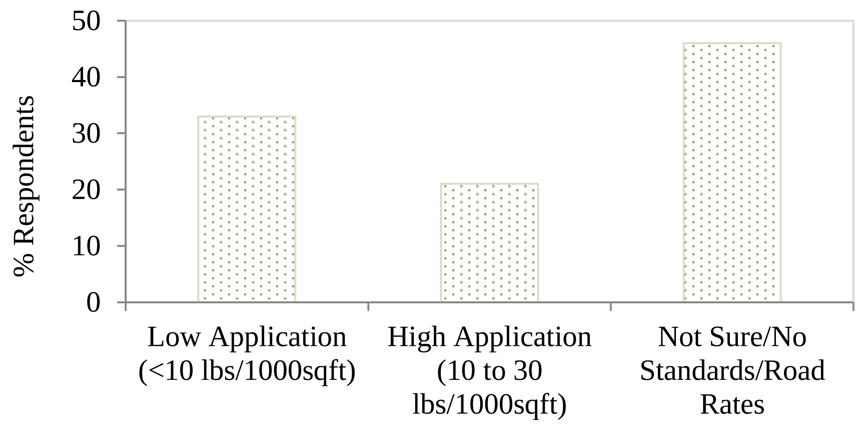


Figure 1-1: Distribution of Application Rates Obtained from Survey Conducted over Canadian and American Municipalities

To assess the performance of various snow and ice melting chemicals (e.g., regular salt/sodium chloride, magnesium and calcium products, etc.) for use in deicing and anti-icing treatment, a number of efforts have been undertaken in the past; however, most of the studies were conducted in a laboratory setting. For instance, Chappelow et al. (1992) conducted a study to assess the performance of various snow and ice melting chemicals. Similar and more recent research has further explored the issues examined by Chappelow et al. including studies by Shi et al. (2009) and Druschel et al (2012). The study included snow and ice melting performance tests for over twenty deicing solids, liquids, and their blends such as regular salt, treated salts (e.g., IceSlicer, Thawrox), and dyed magnesium chloride. Shi et al. (2009) and Druschel (2012) both report that the regular road salt performed similar to the individual deicer at temperature ranges that fell between -15°C to 0°C. The study conducted by Druschel (2012) also included a few field tests for evaluating the bouncing and undercutting characteristics of solid deicers on roadways; however, the ice melting capacities of these salts were not considered in any part of the field investigation. The study additionally indicated that the ice thickness, pavement material, and sun-condition had a higher potential contribution to the snow melting performance than the traffic, truck proportion, wind condition, roadway shade, and pavement surface age. While laboratory tests such as these are useful in obtaining the basic characteristics of deicers and developing material specifications (PNS/Clear Roads, 2010), they have limitations such as poor generalization and weak correlation to field performance.

To develop guidelines for road sectors, Blackburn et al. (2004) conducted a field study for three winter seasons to evaluate the performances of different snow control methods currently in use at 24 highway agencies in the United States. The study included the evaluation of different snow control strategies, tactics and materials, including deicing and anti-icing with solid and liquid chemicals, plowing only, and abrasive-use strategy. The measure of effectiveness to evaluate the methods used was the visual pavement snow and ice condition level. The winter pavement condition levels were classified into seven groups. The first condition level describes a pavement surface that remains in a bare/wet condition at all times, whereas a pavement surface that is exposed to drifting and excessive unplowed snow up to the point of warranting a temporary closure is classified with a condition level of seven. However, the study indicated that the snow and ice control strategy is level of service (LOS) driven, and that the treatment decision should depend on specific weather events, material characteristics, traffic volume, and cycle time considerations. Based on field observations, the study recommended a salting guideline for event-specific snow control as well as the use of a six step method in certain cases to determine application rates. Again, these guidelines, however, were developed exclusively for highway maintenance.

Based on empirical data, Amsler D. (2004) suggested that the salt applications amount can be adjusted for various dilution factors, such as precipitation type and amount, traffic volume and pavement bonding conditions. For highway operations, the study also recommended the salting rates for five chemicals: sodium chloride, calcium chloride, magnesium chloride, potassium acetate and calcium magnesium acetate. However, these guidelines were not derived directly from the snow melting performance of chemical agents in real operations or on statistically reliable data.

To compare the different treatment methods, Blackburn et al. (1991) conducted a two year study to investigate the effectiveness of anti-icing over deicing for highway operations. They found that anti-icing can be effective at a temperature above -9°C with a solid salt application rate of 100 lbs/lane-mile (1.57 lbs/1000 sqft), using saturated brine for pre-wetting at a rate between 0.021 and 0.025 L/kg. The study also found that anti-icing is not effective during prolonged snow fall or freezing rain. Additionally, compared to brine, magnesium chloride was found to be more successful in the prevention of bonding at relatively lower temperature. Based on a few case studies, they also indicated that an anti-icing operation saves costs for both maintenance organizations and road-users. For maintenance organizations, the cost savings came from lower application rates, while for road-users improvements in pavement conditions led to cost savings in the form of fewer accidents. In addition to this study, several others have also reported end benefits in anti-icing over the conventional method of deicing (Amsler D., 2006; O'Keefe and Shi, 2005).

In addition to evaluating deicing and anti-icing methods, past studies have also examined the relative performance of alternative snow control chemicals and additives, such as regular dry salt, pre-wet salt, chloride and organic blends etc. For example, Fonnesbech J. (2007) conducted a study to evaluate the anti-icing performance of pre-wetted salt and brine. They compared pre-wetted salt (salt and brine ratio of 70:30 by weight) at an application rate of 10 g/m2 (2.05 lbs/1000 sqft) to 20% brine applied at 20 ml/m2 (6.10 L/1000 sqft). Ultimately, the study demonstrated that anti-icing with brine is more effective than pre-wetted salt due to its more even distribution and the longer retention time of brine in the solution. In a separate study, Fu et al. (2012) examined the effectiveness of anti-icing using different liquids and pre-wetted solid salt. The study evaluated the performance of regular brine compared to an organic blend that is a mixture of beet juice and brine (30:70 mixture). The effectiveness of each anti-icing material was measured by comparing the friction data obtained from the test sections treated with these compounds. The materials were each evaluated as both pre-wetting liquids and separately in direct applications. Their study revealed that the brine and the beet juice mixture both performed similarly when used as pre-wetting liquids, achieving the same range of friction coefficients. The beet juice mixture, however, outperformed brine when they were applied alone as an anti-icing treatment on roadways.

Growing concern over the environmental damage caused by rock salt has stimulated numerous efforts, both in the present and the past, to develop a more sustainable and environmentally friendly alternative. According to TRB Special Report-235 (1991), one of the most promising alternatives for rock salt is calcium magnesium acetate (CMA). The report noted that laboratory tests have shown that CMA, in addition to having lower adverse impacts on human health and the environment, does not corrode materials in motor vehicles, bridges and highways as readily as rock salt does. Despite these advantages, CMA generally becomes ineffective when the temperature drops below -5°C, a fact that can limit its applicability.

In 2006, Fu et al. undertook a study to evaluate the effectiveness of some blends of snow control chemicals. The study compared the snow melting performance of rock salt mixed with less corrosive chemicals such as, calcium chloride, magnesium chloride to both dry rock salt only and rock salt pre-wetted by sodium chloride. The study revealed that, in general, the regular rock salt was outperformed by these blends of rock salt with less corrosive salts. Moreover, the dry rock salt mixed with calcium chloride outperformed the mixture of rock salt with magnesium chloride by 9.5% to 71.4% in reducing average snow cover. However, this study was conducted for only one winter season and only compared blends of chloride salts applied on highways.

In summary, few studies have been conducted that assess the snow melting performance factors of various salts and various snow control methods within a field environment. Furthermore, to the best of our knowledge, no studies that report on the effectiveness of various snow and ice control methods (e.g., deicing vs. anti-icing) and materials (e.g. salt vs. organic) for parking lots and sidewalks. Therefore, there are few defendable and uniform guidelines on snow and ice control methods, materials, and application rates that could be adopted for parking lots and sidewalks. The few available guidelines either stop short of recommending application rates (Environment Canada, 2004) or derive rates directly from those specifically for roads. This lack of uniform guidelines, combined with the maintenance contractors' desire to minimize their business risk and legal exposures, results in excessive quantities of salts being applied in these areas.

1.4. Research Objectives

Many efforts have been made in the past to evaluate alternative snow and ice control methods and materials for roadway winter maintenance operations, including those discussed previously. However, few have focused on quantifying the snow melting performance of chemicals through systematic field testing. Moreover, these studies exclusively focus on high-volume roadways and, consequently, their recommendations are not suitable for maintenance and decision-making in parking lots, sidewalks and platforms. In response to these significant gaps, the primary goal of this research is to develop a better understanding of the conditions that influence the effectiveness of commonly used treatment operations (deicing and anti-icing) for parking lots and sidewalks, and develop guidelines for the optimum selection of materials, application rates and techniques. The specific objectives of this study include:

- Create a comprehensive snow and ice control operational database covering both deicing and anti-icing treatments with regular and alternative salts through a systematic field study;
- Determine the condition variables, such as precipitation types and amounts, chemical types and concentrations, temperatures, and traffic volumes that affect the deicing performance of snow and ice melting chemicals;

- Compare the relative performance of alternative materials (e.g., regular dry salt vs. pre-wetted salt or regular salt vs. alternative salts);
- Develop snow and ice melting performance models that can be used to determine the optimum application rates based on event and site characteristics such as, pavement surface conditions, precipitation amount, temperature and the level of service to be achieved;
- Investigate the factors that govern the adjustment of application rates for facility specific snow and ice control operations;
- Investigate the effectiveness of anti-icing treatment and determine optimal application rate;
- Develop user-friendly snow and ice control guidelines and decision support tools for parking lots, sidewalks and platforms. This will include, but not be limited to, material selection guides, salt application rates and treatment strategies.

1.5. Organization of the Thesis

This thesis consists of seven chapters. The first chapter introduced the motivation of this study and gave a brief overview of current winter maintenance practices, the research problem, and the specific objectives of this research. The second chapter provides an extensive literature review on current practices and snow control methods, including deicing and anti-icing, the snow and ice melting capacity of snow control chemicals, the factors that affect this ice melting capacity, alternative chemicals, and past studies on the measuring effectiveness for snow and ice control operations. The third chapter describes the field tests that were conducted to collect the snow and ice control operational data of various snow control methods and materials. The fourth and fifth chapters provide the results of the deicing performance of salt and alternatives with recommendations for optimum application rates and adjustments, followed by performance of anti-icing in sixth chapter. The seventh and final chapter provides the conclusion of this doctoral research and outlines the future areas of research.

CHAPTER 2
LITERATURE REVIEW

Winter-based snow and ice control has been studied from varying perspectives since the early nineteenth century. However, most of the work done in this area was aimed at the generation of a maintenance manual, handbook or guideline and was conducted through interviews of maintenance personnel, evaluating general experience, or through irregular field observations. As indicated previously, very little work has been done to quantify the snow melting performances of chemical agents or in evaluating the various methods of deicing and anti-icing; and even fewer studies have examined these elements in parking lot and sidewalk applications.

This chapter therefore aims to provide an in-depth literature review on the current winter maintenance practices of roadways, as the underlying principles of snow and ice control should not vary from facility to facility. Maintenance methods for snow and ice control can be divided into three different categories: deicing, anti-icing or mechanical removal (Blackburn et al., 2004). As this research is focused primarily on quantifying the snow melting performance of snow control chemicals for deicing and anti-icing treatments, most of the literature reviews in the following sections is related to deicing and anti-icing treatments. This chapter is divided into three parts; the first section details previous research that has been done on alternative current treatment methods as used for snow and ice controls. The second section details a thorough review on the ice melting capacity of chemicals and the factors that influence this capacity. Next, the third section provides a critical review on existing research in alternative chemicals, including organic salts, and then summarizes the measures of effectiveness currently used in snow control operations. Finally, the chapter ends with some concluding remarks summarizing the basis for this study.

2.1. Current Practices for Snow and Ice Controls

Countries, provinces and states that experience any amount of snowfall during their winter months have all adapted various methods of snow and ice control. These methods can sometimes vary according to winter behavior for that specific geographic area, and may include methods such as plowing, salting, sanding, etc. Minsk (1998) classified winter maintenance operations through three distinct categories: chemical, mechanical and thermal. Applying a snow control chemical (e.g., sodium chloride) as freezing-point depressant on a pavement or integrating the freezing-point depressant into the pavement is an example of a chemical method. Methods such as plowing, scraping, or using high velocity air to blow snow are all classified as mechanical. Finally, thermal methods include those that control or prevent the formation of snow through the application of heat, either from above or below the pavement surface.

Among conventional methods, plowing-only has always been a staple form of winter maintenance practice, especially when mass amounts of accumulated snow need to be removed from pavement surfaces. This method, however, has a few drawbacks, as snow missed by the plow often bonds itself to the pavement surface due to compaction from the plow's tires and blade. Consequently, salting is usually applied to contaminated pavement to break the snow-pavement bond, as has been the case since 1941 (Blackburn et al. 1991). When salt is applied, it produces a layer of a dissolved brine solution; it is the layer that enables the salt to break the bond. After this bond is broken, it becomes easier to remove the snow; however, breaking this bond can be challenging as the quantity of salt needed to break a bond increases proportionally with the bond strength.

Recent technological and logistical developments have allowed a higher level of diversification in snow and ice control. Many different types of winter operations are currently in use, including deicing (e.g., post-salting only, plowing and salting after), anti-icing (e.g., pre-salting only, pre-salting and plowing after), pre-wetting, direct liquid application or even combinations of those two methods. The distribution of the major winter maintenance methods used obtained from surveys conducted for this project is shown in Figure 2-1 (Hossain et al. 2013, Fu et al., 2012). With these various types of snow control methods comes the ultimate question: Which method is more ideal under specific conditions? There are many angles one can use to approach this question; such as, the effectiveness of the method, the cost of the method with respect to money and time, and assessing how environmentally friendly the method is. Answering this question will help contractors optimize their maintenance practices to combat snow and ice contamination during the winter. For now, it is important to gain a comprehensive understanding of the various snow and ice control methods available, and so a brief review of these methods has been given in the following sections.

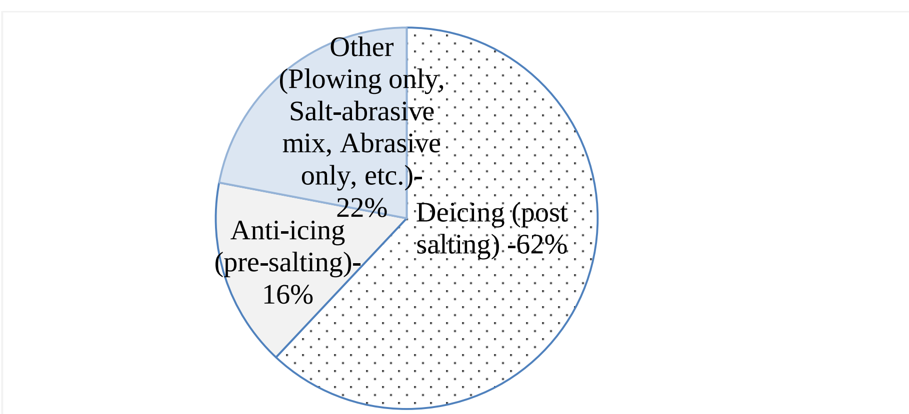


Figure 2-1: Distribution of Respondents by Winter Maintenance Methods of Parking Lots and Sidewalks

2.1.1. Deicing Treatment

Since the use of a plowing-only method is generally unsuccessful at clearing snow completely, to prevent bonding and provide safe friction levels chemical agents are often applied. These agents are able to melt snow and ice, usually by lowering the freezing point of water or by breaking the previously formed bond between snow and pavement. Accomplishing these essential end-results can be done in two ways: deicing or anti-icing. Deicing is a method of snow control in which salts are applied to melt snow and ice (Blackburn et al. 2004). The salt is applied on top of the snow after a snowfall has occurred; or, they can be applied on left-over snow after initial accumulations of snow have plowed off. The most common type of salt for this application is rock salt; and, depending on the types and amounts of salts being used, these deicing methods can be effective at temperatures ranging from -9°C to -25°C. Of note, however, is that if the temperature drops below the effective range of a deicing agent, then that salt will have little to no effect.

Past studies have indicated that deicing methods are the most popular due to their flexibility in terms of the window of the application time and the fact that they enable maintenance personnel to clear compacted snow by breaking the formed bond between snow and pavement (Cussler E. et al., 1987; MDOT 1993; Ketcham 1996). According to Williams and Linebarger (2000) deicing methods have become more popular for most transportation agencies due to their high effectiveness, easy operation, and low initial costs. The effectiveness of deicing depends on the chemical materials, application rates, and mechanical equipment used for deicing (Chappelow et al., 1992). According to NCHRP-526 Report (2004), deicing is a suitable strategy for most weather conditions, sites, and traffic conditions, except when pavement temperatures drop below -7°C.

In the deicing process, as mentioned, the chemical agent is deployed on top of the snow. The deployed chemical first melts the snow that is immediately underneath the deployed particles. The snow melted solution (i.e. brine) then penetrates through the snow layers and is deposited on the pavement surface. The resulting brine helps break bonding and ease further snow plowing for future recurring events.

However, if maintenance operations depend exclusively on deicing treatment, then they will require relatively higher application rates and more time to reach a desired level of service (Ketcham 1996). The typical range of application rates for deicing in the road sector varies from 1.57 lbs/1000 sqft (100 lbs/lane-mile) to 7.89lbs/1000 sqft (500 lbs/lane-mile) and the final application depends on different external conditions (Perchanok et al. 1991; Yehia S. et al, 1998; Lewis M. 2004; Blackburn et al. 2004, Jiang W., 2011). Past studies have also indicated that, compared to anti-icing, deicing needs more material to achieve the same level of service than anti-icing does (Jahan K. et al., 2012).

Amsler D. (2006) indicated that a deicing strategy can become more effective if it is performed with a coarse, graded solid on the snow surface. Based on laboratory tests, Druschel S. (2012) found that the grain size can affect the snow melting performance significantly. The larger solid can not only ‘melt’ the surface of the snow but also ‘melt’ the interface of the snow and pavement (Blackburn et al.2004).

However, the deicing operation has several unavoidable issues. Firstly, the most common deicing chemical used is sodium chloride, and its application has the potential to cause substantial problems including contamination of drinking water and sub-soil layers and corrosion of concrete pavement and motor vehicles (Mcelory A. et al., 1988; Adkins D. et al., 1989; Mehta K., 1996; Burtwell, 2001). Secondly, because of poor roadway conditions, both prior to and during maintenance, the potential for accidents may be increased when deicing operations are conducted. Additionally, it is important to note that deicing may also consume large amounts of snow control materials and labour to achieve a desired level of service (Eaton R., 2004; O’Keefe and Shi, 2005).

2.1.2. Anti-icing Treatment

Anti-icing is a strategy which applies snow and ice control materials before or immediately after a snow event starts. The objective of anti-icing is to prevent an ice to pavement bond and ease plow operations (Mergenmeier A., 1995; Blackburn, 2004; Wisconsin Transportation Bulletin, 2005; Amsler D., 2006). Blackburn et al. (1991) were among the first to conduct comprehensive research on the development of anti-icing technology in the context of North American weather and winter maintenance. To meet this end, they first conducted an in-depth literature review on prevailing anti-icing strategies in Europe and United States. The literature reviews aimed to assess the limitations of previous anti-icing practices and determine why anti-icing is not prevalent in North America. They then conducted a two year field study to evaluate the different kinds of anti-icing methods in order to determine the best method available under various conditions. The study reported that, for an anti-icing treatment, if the salts are applied at an appropriate time and not under severe storm conditions or on an extremely cold pavement surface (i.e. colder than -5ºC), an application rate of 7.7g/m2 (100lb/lane-mile) will be adequate. The study also found that anti-icing operations can contribute to cost savings for both highway agencies and motorists by reducing the use of materials and by reducing the occurrence of accidents respectively.

Since then, due to the advantages inherent in an anti-icing strategy, it has become one of the most popular methods to respond to the issues of winter events. (Wyant D., 1998; Stidger, 2002 and Evans M., 2008). Studies have also shown that, in addition to its benefits against regular winter weather, anti-icing is particularly effective in dealing with heavy frosts and freezing fogs (LRRB, 2005; Smith D., 2006; Evans M., 2008).

Field tests of anti-icing have shown that, it can decrease the needed amount of ice control materials and that, when applied correctly, can reduce the time that would be spent clearing the roadways (Barrett M. et al., 2001; Fonnesbech, 2001; Shi X. et al., 2005, Evans M., 2008, Fu et al., 2011). Consequently, reductions in the cost of winter maintenance can be realized, and its use gives more time for maintenance crew to response (Wyant D., 1998; Boselly, 2001 and Salt Insittute, 2007). Anti-icing can also provide a high level of service due to its ability to prevent the formation of an ice-pavement bond on the roadways. In this way, it makes plowing and blowing operations more easy (Roosevelt D., 1997; Boselly, 2001 and Shi X., 2005). All of these factors contribute to ensure safer road conditions, a fact that has been confirmed by a substantial quantity of tests and surveys conducted on transpiration agencies (Shi X., 2005 and Zinke S., 2006).

In applying an anti-icing strategy, both solid and liquid chemicals are used. Solid chemicals specifically have been in use for many years in anti-icing operations. If dry anti-icing agents are applied, the moisture in the air must be sufficient (Mitchell G. et al., 2003; Blackburn R.R., 2004), as moisture reduces the ability of an anti-icing agent to be blown off the road by causing it to stick to the pavement. In addition to this, moisture has also been shown to improve the performance of applied chemicals ('Anti-icing Use Increases at state and country levels', 2001). However, despite the presence of moisture, solid chemicals may still be lost through blowing by traffic and particle bouncing (Mitchell G. et al, 2003).

Despite the fact that sodium chloride (road salt) is the most commonly used solid chemical for anti-icing operations, some agencies may still use a mix of several solid chemicals. Based on a series of workshops with the maintenance personnel, Amsler D. (2006) reported that anti-icing operations can be effective with solid salts if they are properly applied and remain on the pavement after application.

However, for roads, solid salt with water or another liquid chemical is recommended in order to minimize the bounce and scatter tendencies of salts and reduce the loss of particles from wind-blow caused by vehicular traffic. This fact is confirmed in studies done by Blackburn et al. (2004) and Evans M. (2005). They indicate that, when compared with solid chemicals, liquid chemicals are generally more effective when the pavement temperature is above -5°C (23°F), but should not be applied at temperatures below -6.67°C (20°F) or when the road is covered by thick ice or snow (Blackburn et al., 2004). However, Ketcham et al. (1996) indicates that liquid chemicals can be applied at -9.44°C (15°F) when the temperature is forecasted to rise quickly. In current winter maintenance, there are five chemicals that are used frequently for anti-icing by liquids: sodium chloride (NaCl), magnesium chloride (MgCl2), calcium chloride (CaCl2), calcium magnesium acetate (CMA), and potassium acetate (KAc) (Ketcham et al., 1996). NaCl mixed with CaCl2 and MgCl2 is highly recommended because of their low cost and low-temperature feasibility (Mitchell G. et al, 2003; Zhang J. et al, 2007; Salt and Highway Deicing Newsletter, 2007).

Despite the advantages of liquid chemicals, the NCHRP-526 report (2004) states that dry solid salt can still be effective as an anti-icing agent when it is applied at traffic speeds under 45km/h, and when the traffic volume is less than 100 vehicles per hour. The report also indicated that parking areas present a unique potential for anti-icing operations with solid salt, as less dispersion effects would be expected.

2.1.3. Pre-wetting

In deicing/anti-icing operations, pre-wetting of solid dry salts with liquid chemical is a relatively newer maintenance strategy for improving snow melting performance of applied chemicals on the pavement, and retaining solid salts on the road surface. (Shi X.,2005 and Fonnesbech J., 2005, Fu L., et al. 2012). As in subzero temperatures there is little to no moisture present in the air to help activate the salt, pre-wetting the salt immediately before application ensures that moisture is present to facilitate its chemical activation process. Pre-wetting has been proven as an effective method to provide a higher LOS for the following two reasons: First, wet salt is adhered to the ground, resulting in less scatter and less material usage, and second, to be an effective deicing agent, salt requires moisture (Ketcham et al.1996; Roosevelt D.1997, Fu et al. 2012).

Pre-wetting is commonly done with salt brine (Pesti G., 2003; Fu L. et al, 2012); however, it is likely that other liquid chemicals could also be used to pre-wet solid chemicals, abrasives and abrasive/solid chemical mixtures (Blackburn, 2004 and Wisconsin Transportation Bulletin, 2005). By pre-wetting, the loss of salts can be reduced substantially and can provide adequate chemical concentrations on the pavement surface to prevent the formation of black ice. According to Wisconsin Transportation Bulletin (2005), pre-wetting reduces salt loss by up to 30%. For instance, Figure 2-2 shows that, in this specific instance, an additional 25% of the total salt could be retrieved from the center strip of a 24 ft pavement after a comparative treatment operation with dry salt and pre-wetted salt under same application rates.

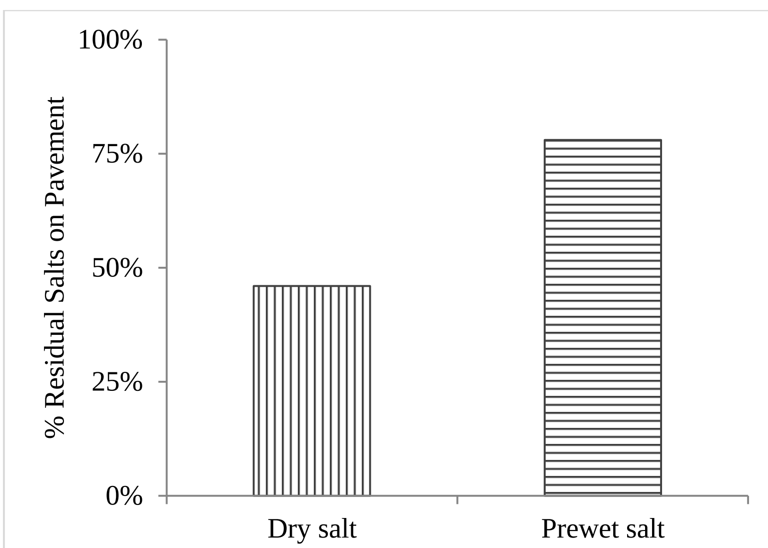


Figure 2-2: Salt Retrieved from Pavement Surface (Wisconsin Transportation Bulletin, 2005)

As with other methods, several studies (Martinelli T., 2001; Perchanok M. 2001; Sooklall R., 2006) confirmed that the performance of pre-wetted salt depends on the grain size of the salt, the application rate of pre-wetting, the type of the existing road, and the current weather conditions. Another factor which affects the performance of pre-wetted salt is the rate and type of the liquid used for pre-wetting. In a study conducted by Fu L. et al. (2006), different liquids for pre-wetting dry salt were compared, including mixtures of sodium chloride, calcium chloride, magnesium chloride, and pure water. They found that calcium chloride, as a pre-wetting agent, was more effective than other agents, and generally provided a higher LOS.

2.1.4. Abrasive Use

According to Nixon A. (2001) and Blackburn et al. (2004), the main function of abrasives is to provide improved traction on ice-covered roadways, especially when it is too cold for other chemicals to work effectively; this generally occurs at temperatures below 12°F (-11°C) (Technology Transfer Center, 1996; Shi et al., 2004; Blackburn et al., 2004 and Environmental Canada, 2005). Amsler D. (2006) detailed several kinds of abrasives which can be used for snow and ice control, including natural sands, finely crushed rocks or gravels, bottom ashes, slags, ore tailings and cinders. The application rate for abrasives varies among the different winter maintenance agencies due to the diverse weather conditions present in each of their individual locations. However, based on several laboratory tests and researches, Blackburn et al. (2004) observed that most agencies apply the abrasives within a range from 500lb/lane-mile to 1500lb/lane-mile while the average application rate is 800lb/lane-mile for roadways. Nixon A. (2001) also mentioned that the application rate of abrasives is 1200lb/lane-mile on the road.

Despite the purported benefits of this practice, mixing sand with salt for snow and ice control has been questioned by several other researchers (e.g., Nixon, et al, 2001), especially in applications on highways under non-extreme cold conditions. One of the major problems with abrasive use is determining a means to keep them on the road (Nixon A., 2001 and Wisconsin Transportation Bulletin, 2005). As detailed by Nixon A. (2001), there are three currently utilized methods: pre-wetting abrasives, heating abrasives, and mixing abrasives with water just prior to application. It is important to note, however, that since most of the abrasives used are inert substances (e.g., sand), they will not help melt snow and ice. Studies have confirmed this fact, including a field study conducted by Fu et al. (2011) in which the snow melting performances of salts and sand-salt mixes were compared. The study clearly demonstrated that the performance in terms of both amount of snow melted and friction level is quite similar between the two application scenarios, suggesting that the benefit of adding sand to salt is minimal. Moreover, abrasives can be expensive when the total costs of handling, cleaning, drainage and environmental costs are considered (NCHRP-577, 2007, Nixon et al 2004).

2.1.5. Mechanical Strategy

As mentioned previously, mechanical removal of snow and ice (i.e., plowing) is the most basic form of snow control in parking lots and sidewalks that exists today; approximately 15% contractors use the plowing-only method to control snow and ice in parking lots and sidewalks (Hossain and Fu 2012). However, the exclusive use of plowing is often the only feasible way to treat snow at some establishments, especially those with low LOS requirements. Despite this, a plowing only method can still be effective even when a higher level of service is needed, if snow does not bond to pavement (Blackburn, 2004). Where the exclusive use of plowing is not sufficient, it can be made more effective if it is conducted in conjunction with anti-icing (Asmler D. and Blackburn,2004 and Ito Y.,2004). Indeed, a large quantity of surveys have indicated that crash rates decrease significantly after plowing (The Salt Institute, 1999; Cuelho E.,2002).

Plowing operations are generally done by machines, though sometimes, depending on snow events and LOS strategy, manual plowing is done in addition to a machine plowing. Plowing by manual power (i.e, shoveling) is one of the oldest forms of snow control, and is a very common choice of snow control for homeowners and small business owners, especially for small areas such as walkways or sidewalks (Blackburrn et al. 1991). However, generally most winter maintenance contractors will plow parking lots and other areas for their customers with the aid of a machine because of its effectiveness at removing large amounts of snow in a small amount of time. There are two sub-methods of plowing snow with the aid of a machine. The first involves removing snow by pushing it with a plow-blade driven by a truck. This method became popular in the 1920's with the dawn of bigger plow-blades as well as heavier and faster trucks (Blackburrn et al. 1991). The second is an emerging method of plowing snow, and utilizes the aid of a machine with a device called a snow-blower. This method has become very popular for homeowners and small business places and other small-scale applications. The snow blower clears snow by throwing it off of the parking lot, accomplishing this feat by scooping up snow into a chute and directing that snow out, off of the ground, and off the parking lot.

Although plowing with machines is the main choice of contractors due to its superior efficiency with respect to both time and labour, there is an unavoidable downside to plowing with a plow-truck: a reduction in the friction level to one lower than the original due to the plow blade compacting freshly fallen snow (Epps and Ardila-Coulson, 1997; Ketcham et al., 1996). To avoid this hazard, subsequent salting is needed to melt the compacted left over snow by the plow blade.

2.1.6. New technology: Snowmelt System

To melt the snow in real time, or close to real time, another technology has recently been added. This technology utilizes an underground heating system to avoid snow accumulation; specifically, a snowmelt system melts snow and ice through the use of electric cables or hydronic tubing that is embedded in the pavement (The City of Hamilton website; The Heatizon System website). The system can be installed during the construction phase of a parking lot, or it can be retrofitted into existing parking lots. Snowmelt systems that operate with electric cables function by using three components: a heating cable, a control unit and an activation device. The activation device will turn the system on and off, based on weather conditions while the electric cables embedded in the pavement heats up and melt snow, preventing the accumulation of new snow. Snowmelt systems operating through hydronic tubing function by using a heating element to heat up a mixture of water and propylene glycol and then circulate it through flexible polymer tubes in a closed loop system. This system utilizes a control unit and activation device to control its operation. While this system has no direct and initial environment effect, the high initial costs and year round maintenance costs makes it more impractical for wide implantation to control snow and ice in parking lots and sidewalks.

2.1.7. Combined Maintenance Strategies

Because winter weather events in different areas present a variety of weather and pavement conditions, a combination of strategies is almost always used. According to Lewis M. (2007), one of the most popular strategies is a mix of abrasives and salt. This strategy, however, is not as effective as using chemicals only. Despite this, the benefits of this strategy are still open for debate, with some studies, such as one by Kuemmel and Bari (1996), concluding that a salt/abrasive mixture can be beneficial in colder regions. Due to different LOS and priorities, various combinations of maintenance methods exist, such as using abrasive and chemical mixes, using mechanical and anti-icing methods at the same time, or applying mechanical and abrasives. The Table 2-1 below indicates the expected LOS levels that can be achieved from various snow and ice control strategies and tactics during and after a winter weather event (Blackburn, 2004).

Table 2-1: Strategies and Tactics and LOS Expectations (Blackburn et al., 2004)

Strategies and Tactics	Within-event LOS			After-event LOS		
	Low	Medium	High	Low	Medium	High
Anti-icing			X			X
Deicing	X	X			X	
Mechanical	X					
Mechanical and Abrasives	X					
Mechanical and Anti-icing	X		X			X
Mechanical and Deicing	X	X			X	
Mechanical and Prewetted Abrasives	X					
Anti-icing for Frost/Black Ice/ Icing Protection	X					X
Mechanical and Abrasives Containing>100lb/LM of chemical	X	X	X		X	X
Chemical Treatment Before or Early in Event, Mechanical Removal During Event, and Deicing at End of Event	X		X		X	

2.2. Ice Melting Capacity of Chemicals Agents

A quantitative understanding of the snow and ice melting performance of chemical agents in a real field environment is a critical step in developing a suitable rate for any given precipitation amount. Many studies in the past were conducted under laboratory environments, and were aimed at quantifying the various dimensions of performances such as, the melting capacity, the speed, and the ability to break or prevent the bond between ice and the pavement (e.g., McElroy et al. 1988; Chappelow and Darwin, 1992; Ketcham et al., 1996; Fischel, 2001; Nixon, et al., 2005; Fay et al, 2008).

Dickinson (1959) was among the first who attempted to quantify the ice melting capacity of different winter maintenance chemicals. Again, based on a review of the laboratory tests results, the study reported that the ice melting capacity of calcium chloride was higher than that of sodium chloride, and attributed the differences to their respective chemical properties, such as moisture-attracting ability. In recent years, Chappelow et al. (1992), Nixon et al. (2004), and Shi et al. (2009) have conducted similar studies to investigate the ice melting performance of different chemicals. For example, Nixon et al. (2005) and Shi et al. (2009) conducted laboratory studies to evaluate the ice melting performance of various snow melting chemicals as measured by ice penetration, ice undercutting potential and the amount of brine produced for a given chemical under controlled environments. Nixon et al. (2005) compared the ice melting capacity among seven liquid salts and found that temperature had a positive relationship with the ice melting capacity of the material; though they also noticed that the performance of the tested materials varied. Shi et al. (2009) compared the ice melting performance of regular solid salt and six different liquid salts (e.g., magnesium chloride, calcium chloride), and several solid-liquid blends (e.g., sodium acetate, calcium magnesium acetate). Their study revealed that the road salt outperformed all other solids and liquids at three temperatures (0°C, -5°C, and -18°C).

Other studies undertaken include one by Gerbino-Bevins (2011) where the ice melting capacity of different chemicals was investigated. Within their study, liquids and two solid salts were tested. The solid salts tested were regular road salt and pink salt, which is a treated salt. Despite its name, the pink salt tested was an orange coloured, finely graded salt made mostly of sodium chloride with small amounts of magnesium chloride and calcium chloride. In addition to the laboratory test method mentioned in the SHRP handbook (1992), the study also introduced a new method, the shaker test, to evaluate the ice melting capacity. For this test, an insulated and modified shaker (container) was used to simulate the effect of traffic on the roadway while evaluating the ice melting capacity of the salts. The test results revealed that both salts have identical ice melting capacity at two distinct temperatures (-12°C, -6°C); but, at a temperature of -18°C, the pink salt outperformed the regular salt.

Koefod et al. (2012) also conducted a study to measure the ice-melting capacity of regular road salt, and used test methods that were different than those specified in the SHRP handbook (1992). Their study claimed that the amount of ice melted for a given salt was underestimated by the SHRP test method for low application rates. While laboratory tests are useful in obtaining the basic characteristics of deicers, translating these results to real-world conditions can be very challenging. Laboratory tests are usually conducted in controlled environments, and often do not account for the myriad of conditions experienced in the real world. This fact limits their applicability, and the results of these tests often show weak correlation to actual field performance as a result. While these laboratory tests are useful in obtaining the basic characteristics of deicers, they have limitations such as poor generalization and weak correlation to the field performance.

It is clear, therefore, that while a number of studies are focused on determining application rates for deicing and anti-icing, they have almost always been done in the context of a high volume roadway and consequently lack the ability to clearly assess the performance of these chemical agents in parking lots and sidewalks.

2.3. Factors Affecting Ice Melting Capacity

An understanding of the factors which may affect the ice melting capacity of a given chemical is necessary, as it enables the quantification of that chemical's snow melting performance; this is essential in the determination of optimal application rates for any specified weather event. Many past studies on different chemicals have investigated the effect of various factors on snow melting performance, including factors such as salt application rate, pavement temperature, traffic, snow thickness, solar radiation, chemical type, and dilution potential (e.g., Raukola et al. 2001, Blackburn et al., 2004; Fu et al., 2012). From field investigations and the experiences of winter maintenance personnel, Blackburn et al. (2004) and Drushel (2012) indicate that factors such as application rate, pavement temperature, precipitation type and amount, chemical concentration, prevailing weather conditions, timing of application, and traffic action may affect the ice melting capacity of chemical agents in snow and ice control operations. As such, a brief note about each factor is presented in the following subsections.

2.3.1. Application Rates

Application rate is the most important factor and has a direct effect on the amount of snow and ice that can be melted and the speed at which they melt (Blackburn et al. 1991, Perchanok 1991, Ketcham et al. 1996, Fu et al. 2011). However, there is no common consensus among winter maintenance personnel on the optimum application rate, or even the range that the application rate should fall in with respect to the different treatment methods, salts, and weather conditions. Consequently, each agency tends to use different application rates.

Blackburn et al. (2004) developed a method for determining the recommended application rates for controlling snow and ice on roadways for some specific winter scenarios. These rates were developed through consideration of the main dilution factors, such as, precipitation type and rate, precipitation trend, road wheel path conditions, treatment cycle time, and traffic speed and volume. This method includes a six-step procedure with six different Tables for adjusting the application rates for these different factors. Table 2-2 shows the recommended application rates for different types of application scenarios.

Table 2-2: Recommended Application Rates for Salts (Adapted, Source: Blackburn et al. 2004)

Pavement Temperature (°F)	Adjusted Dilution Potential	Ice Pavement Bond	Application Rate	
			Solid (1) lb/lane-mile	Liquid (2) gal/lane-mile
Over 32° F	Low	No	90	40
		Yes	200	NR
	Medium	No	100	44
		Yes	225	NR
	High	No	110	48
		Yes	250	NR
32 to 30	Low	No	130	57
		Yes	275	NR
	Medium	No	150	66
		Yes	300	NR
	High	No	160	70
		Yes	325	NR
30 to 25	Low	No	170	74
		Yes	350	NR
	Medium	No	180	79
		Yes	375	NR
	High	No	190	83
		Yes	400	NR
25 to 20	Low	No	200	87
		Yes	425	NR
	Medium	No	210	92
		Yes	450	NR
	High	No	220	96
		Yes	475	NR
20 to 15	Low	No	230	NR
		Yes	500	NR
	Medium	No	240	NR
		Yes	525	NR
	High	No	250	NR
		Yes	550	NR
15 to 10	Low	No	260	NR
		Yes	575	NR
	Medium	No	270	NR
		Yes	600	NR
	High	No	280	NR
		Yes	625	NR
Below 10° F	A. If unbonded, try mechanical removal B. If bonded, apply chemical at 700lb/lane mile. Plow when slushy. Repeat as necessary. C. Apply abrasives as necessary			

Based on previous studies, Ketcham et al (1996) developed an anti-icing application guideline including recommended application rates for different winter scenarios and precipitations types. In contrast to Blackburn et al. (2004), the application rates recommended were based on the differing storm types, namely, a light storm, medium storm and heavy storm, and also with consideration to the pavement temperature. The suggested rates vary according to treatments types (dry app. vs. liquid app.) and list five temperature scenarios, specifically, above 0°C and rising; above 0°C and falling; -4 to -1°C; -10 to -4°C, and below -10°C. Table 2-3 shows the application rates and methods for fighting a moderate to heavy snow storm.

Table 2-3: Application Rates and Methods (Source: Ketcham et al., 1996)

Pavement Temperature Range and Trend	Initial Operation				Subsequent Operation			Comments
	Pavement Surface at Time of Initial Application	Maintenance Action	Dry Chemical Spread Rate, Kg/Lane-km (lb/lane-mile)		Maintenacne Action	Dry Chemical Spread Rate, Kg/Lane-km (lb/lane-mile)		
			Liquid	Solid or Prewetted Solid		Liquid	Prewetted Solid	
Above 0 degree C, Steady or Rising	Dry, Wet, Slush or Light Snow Cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward O C (32 F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100lb/lane-mi), plow if needed
Above 0 degree C or below is imminent, also -1 to 0 degree C, remaining in range	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow accummulation and reapply liquid or solid chemical as needed	28 (100)	28 (100)	1) If the desired plowing treatment frequency can not ne maintained, the spread rate can be increased to 55kg/lane-km (200lb/lane0mile) to accommodate longer operational cycles 2) Do not apply liquid chemical onto heavy snow accummulation ir packed snow
	Wet, Slush or Light Snow Cover	Apply liquid or solid chemical	28 (100)	28 (100)				
-4 to -1C (25 to 30F), remaining in range	Dry	Apply liquid or prewetted solid chemical	55 (200)	42-55 (150-200)	Plow accummulation and reapply liquid or solid chemical as needed	55 (200)	55 (200)	1) If the desired plowing treatment frequency can not ne maintained, the spread rate can be increased to 110 kg/lane-km (400lb/lane-mile) to accommodate longer operational cycles 2) Do not apply liquid chemical onto heavy snow accummulation ir packed snow
-10 to -4C, remaining in range	Dry, Wet, Slush or Light Snow Cover	Apply liquid or prewetted solid chemical		55 (200)	Plow accummulation and reapply liquid or solid chemical as needed		70 (250)	1) If the desired plowing treatment frequency can not ne maintained, the spread rate can be increased to 140 kg/lane-km (500lb/lane-mile) to accommodate longer operational cycles 2) If sufficient moisture is present, solid chemical without prewetting can be applied
Below -10C, Steady or Fallinng	Dry, or Light Snow Cover	Plow as needed		55 (200)	Plow accummulation as needed		70 (250)	1) It is not recommended that chemicals be applied in this tempeature range 2) Abrasives can be applied to enhance traction

The Finland National Road Administration (2001) has a recommended salting rate matrix for controlling ice contamination on roadways and for meeting the bare pavement policy while giving consideration to the ice thickness, road temperature and moisture amount on the road. This ice-specific guideline exists because in Finland it is more common to experience an icy hazard than to experience accumulated snow. This method is applied in three steps: First, a surface signal sensor is used to measure the thickness of the water film on the road; then the characteristics of the surface (dry, moist, wet, and icy) are determined; and, finally, the prevailing freezing point temperature is measured after consideration of the dissolved salt levels on the pavement and the precipitation amount. Table 2-4 shows the final recommended application rates table for their road system.

Table 2-4: Application Rate (Source, Raukola 2001)

Temperature on the Road °C/°F	Brine Application Rate (g/m^2) by Road Moisture Determination (For pre-wet salt, see rate in parenthesis)		
	Moist	Wet	Very Wet
-0.5 (31.1)	5	5	15(5)
-1 (30.2)	5	10	25 5)
-2 (28.4)	5	20(5)	(10)
-3 (26.6)	10	30(10)	(15)
-4 (24.8)	15	(10)	(20)
-5 (23)	15	(10)	(25)
-6 (21.2)	5	(10)	(30)
-7 (19.4)	5	(15)	(35)

In the North America, the range of application rates for road salt varies from 100 lbs/lane-mile (1.57 lbs/1000 sqft) to 500 lbs/lane-mile (7.89 lbs/1000 sqft), and final application depends on different external conditions (Perchanok et al. 1991; Yehia S. et al, 1998; Lewis M. 2004; Blackburn et al. 2004, Jiang W., 2011). In the United Kingdom, road salt is applied at rates from 30 to 70 lbs/lane-mile (2~4 lbs/1000 sqft) for light to medium events, and 100 lbs/lane-mile (5 lbs/1000 sqft) for heavy snowfalls or severe conditions. Pre-wetting of salt is usually done at a 30% pre-wetting ratio with brine (Burtwell, 2001). No published guideline found for the parking lots and sidewalks through a systematic study. Consequently, a wide range of application rates is reported by the contractors and cities during the surveys that were conducted by Fu et al. (2013) and Hossain at al. (2013).

2.3.2. Pavement Temperature

Another well-known factor that affects a given chemical's snow melting performance is the temperature. Keyser (1973) points out that pavement temperature is more important than the air temperature on deicer performance. The study indicated that, while air temperature affects the formation of different types of precipitations, pavement temperature affects the performance of snow melting chemicals. The pavement temperature dictates the amount and type of chemical agent that should be used to combat a snow event, as low temperatures can reduce the ice melting capacity and speed (Fay, 2010). As temperature decreases, the amount of salt needed to achieve same level of service increases. Moreover, some salts become ineffective below their eutectic temperatures and are unable to melt snow and ice. Table 2-5 shows the lowest practical and theoretical eutectic temperatures of various snow and ice control chemicals used in Canada. Although each of the chemicals listed act by depressing the freezing temperature of water, they differ in pace according to their chemical abilities. Figure 2-4 demonstrates the relationship between the theoretical eutectic temperature and concentration of commonly used chemicals.

Table 2-5: Practical Effective Temperature vs. Theoretical Eutectic Temperatures (Sooklall, 2006)

Chemicals	Lowest Effective Temperature (C)	Eutectic Temperature (C)	Eutectic Concentration (%)
Calcium chloride ($CaCl_2$)	-29.0	-51.0	29.8
Calcium magnesium acetate (CMA)	-7.0	-27.5	32.5
Magnesium chloride ($MgCl_2$)	-23.0	-33.0	21.6
Potasium acetate (Kac)	-25.0	-60.0	50.0
Sodium chloride (NaCl)	-7.0	-21.0	23.3
Urea	-4.0	-11.7	32.6

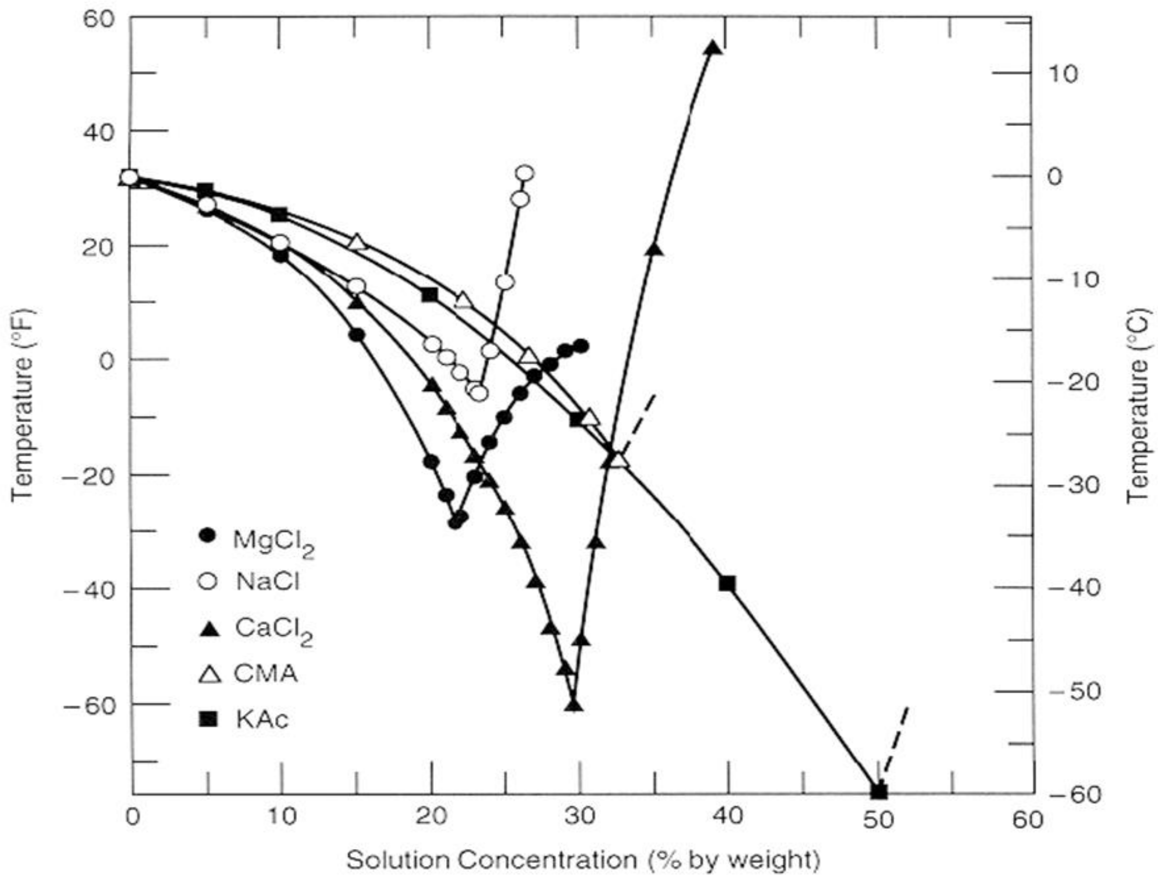


Figure 2-3: Eutectic Temperature and Eutectic Concentration of Five Chemicals (Zhang J. et al 2009)

From this figure, it is clear that regular road salt is theoretically ineffective for snow and ice control at temperatures less than -20°C; however, salt is found to be practically ineffective as temperatures approach -7ºC (Blackburn et al. 1991). As a result, other alternatives and premium additives such as, calcium chloride, magnesium chloride, glycol or their blends may be required directly or to supplement rock salt as a mixture; in some cases, abrasives may also have to be applied to provide immediate traction (Ketcham, 1996).

McElroy et al. (1988) evaluated the ice melting capacity of some solid chemical agents in temperatures ranging from -3.9°C to -15°C in a laboratory environment. The study revealed that melting speed decreases as the surface temperatures decreases. Nixon et al. (2005) conducted a study to compare the ice melting capacity of several liquid salts under a temperatures ranging from -17.8°C to -1.1°C. Similar to McElory (1988), the study found a similar trend for snow melting rates, namely that the amount of ice melted decreased with surface temperature.

2.3.3. Precipitation Amount and Type

The precipitation amount and type is one of the most influential factors that dictate the treatment methods at the final decision level. The treatment should be varied according to snow/precipitation type (e.g. dry snow, wet snow, frost or freezing rain). For instance, DLA and pre-wetted salt are expected to be more effective than dry rock salt on bonded ice or compacted dry snow due to the initial moisture present in each. While the former helps to ease plow efforts, the latter helps in melting snow. However, if frost or light snow is predicted a direct liquid application before the event could be the most effective solution to slick conditions (Ketcham et al., 1996). The moisture content of the precipitation type also has an impact on chemical dilution (Amsler 2006).

2.3.4. Residual Salt on Pavement

It is obvious that an improper winter maintenance activity (e.g. incorrect salting rates or non-uniform distribution) for a given snowstorm could result in residual salt on the pavement. As such, salts should be applied at an appropriate rate so that excessive application can be avoided while still meeting the required LOS standard. If there is a sufficient residual salt on the pavement surface from previous treatment, it may not even be necessary to apply further salts at a frost event, or a reduced amount of salt could be applied to achieve the desired end-results (Ketcham et al., 1996). However, extra caution is always important, and therefore it is also essential to monitor the dilution of chemical concentrations during continuous or intense precipitation and when the snow type possesses a high water content (e.g. wet snow, freezing rain, etc.). Insufficient chemical concentration could lead to the refreezing of the water film present on the pavement's top surface.

2.3.5. Traffic

Traffic action has both positive and negative effects in winter maintenance operations. Heat from tire frictional resistance, engine, and exhaust system can help to maintain and even improve road surface temperature (Ketcham 1996). This increase in the road surface temperature can positively impact the effectiveness of chemical agents for snow and ice control. However, traffic actions can also remove chemicals from the road surface through turbulence and wind-blow (Ketcham 1996; Amsler 1998; Manning and Perchanok, 1993; Burtwell, 2001), which will reduce the chemical concentration and effectiveness.

2.3.6. Sky Conditions

It is not counterintuitive to note that a sunny day will have a strong positive effect on a surface treated with a chemical agent, and will increase the snow and ice melt rate. In contrast, a surface where the sky is mostly covered in cloud will not realize the same positive benefits, as the sun's heat that would warm the pavement on a sunny day is now obscured. It is equally important to note that the sun can have different effects on each type of pavement, as the amount of heat stored depends on the pavement type and depth, and since heat is released differentially, varying according to thermal properties. Past studies (e.g., Sato N. 2004) indicated that since Portland cement concrete gives up heat more rapidly than asphalt, snow and ice may melt faster on it than on asphalt; however, the latter absorbs heat faster than the former.

2.3.7. Salt Spreading

Uniform spreading is essential to melt snow and ice efficiently for a given chemical. Therefore, chemical spreaders need to be calibrated to ensure uniformity in spreading and that their actual application rates are the same as or close to what is desired. This is important because if the application rate is lower than the designed rate, the treatment will be less effective in melting snow or ice. Similarly, the excessive application of deicers will have a negative impact on the operational cost and the environment. In their survey, Fu et al. (2012) asked contractors for information concerning typical rates for a low, medium or high application of salt as well as information on how these application rates were calculated. The survey revealed that a number of respondents were unsure of the amount of material they put in every application, and that the majority of the contractors only estimate their application rates based on truck or hopper loads, or by using the amount of salt purchased during the season. Only 25% of the contractors surveyed used scales or automated rate controllers to measure the amount of salt being put down at specific sites.

2.4. Alternative Chemical Agents

A number of solid and liquid chemicals are used for winter maintenance, and some of the most widely used chemicals include sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), potassium chloride (KCl), potassium acetate (KAc), urea and calcium magnesium acetate (CMA). All of these chemicals melt ice and snow through the same underlying principle of depressing the freezing point of water which then breaks the bond between ice and pavement (Trost B., 1987; Amsler D., 2006; Zhang J et al. 2009; Rubin J., 2010).

Amsler (1998) has recommended the use of solid chemicals in deicing operations and liquid chemicals for use in anti-icing operations. Other studies make similar recommendations, including one that suggests that solid salts which have larger particles be applied specifically for deicing operations (Blackburn et al., 2004). The Minnesota Department of Transpiration (2009)/CTC & Associates LLC. (2009) also report that a coarse grained solid deicers can be more effective when the precipitation rate is higher than 0.5 inch/hr. However, Blackburn et al. (2004) indicated that solid deicers with finer gradations may work faster for snow melting, though they may also refreeze more quickly. However, solid chemicals may not be suitable in colder weather conditions due to their slow melting action (Environmental Canada, 2005; Amsler D, 2006). Essentially, they should not be applied when temperatures fall below -11^{o}C /12°F (Ketcham et al., 1996; Li J., 1999; Shi et al., 2004; Blackburn et al., 2004).

In recent times, liquid chemicals have become more popular with highway agencies. They can be used in both pre-wetting and anti-icing operations (Wisconsin Transportation Bulletin, 2005); though they should be applied before or during the early stages of the snow event (MDOT, 2006). They can provide high LOS and work effectively in anti-icing operations (Nixon A., 2001; Blackburn et al., 2004). From an anti-icing perspective, the stratum of crystallized chemicals left on the roadways when water evaporates makes them an ideal choice for these types of applications (Alger et al., 1994). Compared with solid chemicals, liquid chemicals can adhere to the pavement better and need lower application rates (Wisconsin Transportation Bulletin, 2005).

Various laboratory tests and research indicates that liquid chemicals can work well in temperatures above 28 °F (-2.22 °C), but are probably not a good choice when temperatures fall below 20 °F (-6.67 °C) due to their tendency to freeze (Blackburn et al., 2004; Peterson et al., 2010). Liquid chemicals are not suitable for deicing operations, and, if they are applied on thick snow or ice, a more slippery condition may occur (Amsler D., 2006). Despite this, the Illinois Department of Transportation has reported success in conducting a deicing operation using about 250lb/lane-mile of dry salt on the top of compacted snow followed by an application 30 to 50 gal/lane-mile of liquid salt immediately, this application occurred when air temperatures were 10 °F (-12.22 °C) with sunny conditions.

Woodham D. (1994) conducted a study to investigate the performance of alternative solid salts, including rock salt, calcium chloride, magnesium chloride, CMA, S. Dakota salt (combination of sodium acetate and sodium format, patented by the North Dakota DOT), and their blends. Although a limited number of field tests and laboratory tests were conducted, the study showed that, based on skid resistance, the mixture of magnesium chloride and sand outperformed all other alternatives. The laboratory tests showed that calcium chloride and S. Dakota salt had higher ice melting capacities than rock salt, which had a higher ice melting capacity than CMA. Shi et al. (2009) compared the ice melting performance of regular solid salt, six liquid salts, such as magnesium chloride and calcium chloride, alongside several solid-liquid blends, including NAAC and CMA. Their study revealed that, at the three temperatures they tested (0°C, -5°C, and -18°C), the rock salt outperformed all other solids and liquids.

2.5. Measures of Effectiveness of Snow Control Treatment

As mentioned in the first chapter, the evaluation of the effectiveness of different snow control methods and alternative materials is critical for establishing a comprehensive and objective oriented service standard. The service standard should be made such that it can be used to gauge the performance of the maintenance work being completed, and assess the surface conditions from an agency's or user's perspective. As winter maintenances are level of service (LOS) driven, a number of different methods are available to assess the status of a roadway and the effectiveness of a snow control method; these include the pavement condition index, bare pavement and snow cover status, and coefficient of friction. More specifically, according to Blackburn et al. (2004), the effectiveness of a snow control method can be measured by bare/wet pavement status after certain time after end of a snow event, pavement friction number a certain number of hours after the end of an event, maximum accumulation of snow during a snow storm, and absence of a snow pavement bond during a storm. As such, the current measures of effectiveness can be summarized as bare pavement status, bare pavement regain time and coefficient of friction. A brief overview of each measure is given below:

2.5.1. Bare Pavement Status (% Snow Melted)

Bare pavement status is a simple visual indicator to describe the pavement conditions. It is expressed as a percentage of bare area out of the total pavement area. Other indicators used to describe the condition of a pavement include: dry, damp, wet, depth and percentage cover of slush, depth and percentage cover of loose snow, depth and percentage cover of packed snow, frost covered, percentage cover of thin ice or black ice, and percentage cover of thick ice usually from freezing rain (Blackburn et al., 2004).

2.5.2. Bare Pavement Regain Time (BPRT):

BPRT is used as a surrogate for the level of service (LOS) achieved by snow control treatment. BPRT is estimated as the elapsed time from salt application to the time when the bare pavement reaches 80% - a threshold value decided on the basis of a survey of user expectations. For example, MTO's Maintenance Quality Standards (MQS) designates that all Class I highways must reach bare pavement within 8 hours for 90% of the events over a season, i.e., LOS requirement for Class I highway is 8 hrs (Class I Highways: BPRT- 8hrs).

2.5.3. Coefficient of Friction:

The friction level is calculated by the ratio of horizontal force to vertical force that exerted by vehicle tire or footwear of the pedestrian. This is often represented by a value called the coefficient of friction (COF) and may be more objective way to measure the performance of snow control methods of parking lots and sidewalks (TAC, 2009). However, it should be noted that, the coefficient friction is measured along a line on the road lane or pavement surface that does not capture the condition of road surface across the lane.

2.6. Snow Melting Science and Models

A review was also conducted to enhance our understanding of the fundamental processes that govern the snow melting characteristics of a given chemical. This knowledge is critical for the development of a robust snow melting model. The following sub-sections present a summary of the information related to the science of snow melting mechanisms and related models.

2.6.1. Thermodynamics of Snow Melting

To model the process of melting snow with a given chemical, the concepts that govern the melting of pure snow must first be understood. Melting is a physical process in which a phase transition from solid to liquid occurs. Phase transitions involve the creation or breaking of bonds between molecules. Phase transitions such as melting, where bonds are broken, are endothermic processes; this means they require the addition of energy to the system to occur. Thus, the melting of pure snow involves the transfer of heat to the snow from its surroundings (Potapova, 2012).

The energy lost or absorbed when snow melts can be calculated using the concepts of specific and latent heat. The heat transferred to or from an object when it experiences a change in temperature is known as specific heat. This quantity of heat, Q_s , is equal to the product of the mass of the object, m ,the specific heat capacity of the object, C_p , and the change in temperature of the object, ΔT, as displayed in Equation 2-1:

$$Q_s = C_p * m * \Delta T \quad (2\text{-}1)$$

In contrast, the heat transferred when an object goes through a change in phase is called latent heat. The energy transferred when freezing or melting an object, Q_l, can be quantified as the product of the object's mass and its specific latent heat of fusion or vaporization, L (Fukusako, 1990).

$$Q_l = m * L \quad (2\text{-}2)$$

Water has relatively high specific and latent heat capacities when compared to many other common substances. As such, a great deal of energy would be required to heat and melt a given amount of ice. Such a method would be costly and impractical for snow maintenance. Therefore, for typical winter maintenance, snow is usually plowed off an area. Any remaining snow is then melted by the application of salt through the process of freezing point depression, which is explained in the following sub-section.

2.6.2. Freezing Point Depression Concept

Solutions are affected by four properties known as colligative properties; these properties are vapour pressure, osmotic pressure, boiling point elevation, and freezing point depression. When mixing salt with water, a solution is formed in which salt is the solute and water is the solvent. Thus, the effects of colligative properties, namely, freezing point depression, will be induced in the solution system. Furthermore, the magnitude of these effects is dependent on the concentration of the solute as well as the properties of the solute (snow control chemical types) and the solvent (e.g., precipitation forms).

Freezing point depression describes the decrease in freezing point when a solute is dissolved in a solution. For an ideal solution, freezing point depression is proportional to the amount of solute dissolved in a given amount of solvent (Potapova, 2012). Thus, the change in freezing point for an ideal solution can be predicted using Blagden's Law:

$$\Delta T_{\mathrm{F}} = K_F \; * b * i \qquad (2\text{-}3)$$

where

ΔT_{F} is the freezing point depression, defined as the difference between the freezing point of the pure solvent and freezing point of the solution.

K_F is the freezing point depression constant, also known as the cryoscopic constant. Note that this constant is dependent on the properties of the solvent. (eg. For water, K_F = 1.853°C·kg/mol)

b is the molality of solution, defined as moles of solute per kilogram of solvent.

i is the van't Hoff factor, which is the number of ions present per molecule of solute dissolved.

In this study, applying salt onto snow and ice implies that we are obtaining an aqueous solution containing sodium chloride as the solute. When mixing salt with water, the van't Hoff factor (i) will be equal to 2-2, as a sodium chloride molecule will dissolve in water as one sodium ion and one chloride ion. As the amount of salt dissolved increases, the molality (b) of the solution will also be increased. The freezing point depression constant for water (K_F) is 1.853°C·kg/mol. With this information, the change in freezing point for an ideal solution of water and salt can be calculated.

When analyzing the freezing point depression of non-ideal solutions, solute and solvent interactions need to be taken into consideration. To account for these interactions, a curve fitting technique can be implemented. This method involves plotting the ratio of the mass of the solvent to the solute against the inverse of the change in temperature. When the slope and the intercept are extracted from the resulting linear plot, we can obtain the corresponding molecular weight and a parameter describing the interactions. This value ranges from 0.12 to 3.67 and can be used to describe the non-ideality of a solution when calculating freezing point depression (Zimmerman, 1992).

Because many solutions are non-ideal, the freezing point of a solution with many different concentrations can be determined experimentally. Once this has been done, the concentration of the solute can be plotted against the freezing point of the solution, creating a phase diagram. Using linear interpolation between these points, the phase diagram can be used to estimate the freezing temperature of a solution with any solute concentration. The phase diagram for a solution of salt in water is displayed in Figure 2-4 (Zhang et al, 2009).

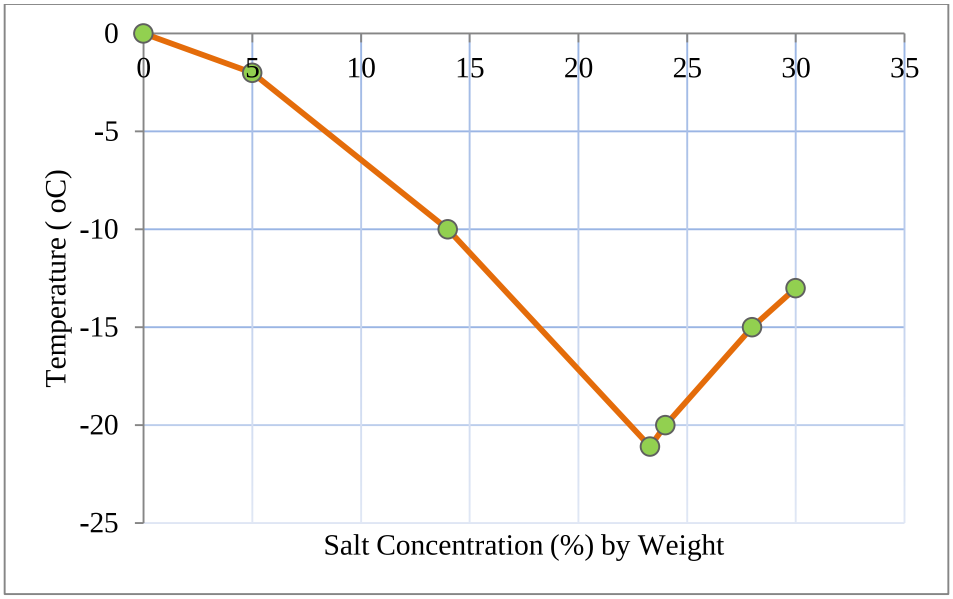


Figure 2-4: Phase Diagram of Aqueous Salt Binary Solution

2.6.3. Eutectic Concentration and Temperature

Eutectic systems are systems that contain a mixture of chemical compounds in certain proportions (usually expressed in mass percent) such that any system with the same compounds in different proportions would freeze at a higher temperature than the eutectic system. The composition of such a system is known as the eutectic composition. Binary solutions, including aqueous salt solutions, have eutectic compositions. Using the concepts of thermodynamics for ideal systems, melting curves for binary systems can be calculated. Assuming that the two components do not form crystals, and the difference in heat capacities of the pure components is small, the freezing temperature for a binary mixture at a given composition can be calculated using the following equation (Demus et al, 1972):

$$T_i = \frac{\Delta H_{fi}}{\frac{\Delta H_{fi}}{T_{fi}} - R * \ln(x_i)} \quad (2\text{-}4)$$

where

T_i is the upper freezing temperature of a binary eutectic system, in K.

ΔH_{fi} is the molar heat of fusion of pure component *i*, in J/mol.

T_{fi} is the freezing point of pure component *i*, in K.

R is the universal gas constant, in J/(mol·K).

x_i is the mole fraction of pure component *i*.

Given a phase diagram, the eutectic composition and eutectic temperature can be determined. Again, for non-ideal solutions, these values can be determined from an experimentally constructed phase diagram such as the one displayed in Figure 2-5. Using this strategy, the eutectic temperature of a solution of sodium chloride and water can be estimated as -21.1°C.

2.6.4. First-Order Reaction Rate Kinetics

As the process of snow melting occurs over a period of time, it can be viewed as a reaction which follows reaction kinetics. In reaction kinetics, a first-order reaction is a reaction in which the rate of the reaction is dependent only on the concentration of a single reactant (Connors, 1990). As a result, the snow melting rate can be determined as follows:

$$Reaction\ Rate\ (Melting\ Rate) = -\frac{d\{A]}{dt} = B[A] \quad 2\text{-}5$$

where $[A]$ is the initial amount of reactant (in our case, snow-salt solution amount), t is the time, and B is the reaction rate (i.e., melting speed) constant, in units of 1/time.

It can be shown that rearranging and integrating Equation 2-5 yields the following expression:

$$ln[A]_t - ln[A]_o = -Bt \quad 2\text{-}6$$

This can be further rearranged:

$$\ln(\frac{[A]_t}{[A]_o}) = -Bt \quad 2\text{-}7$$

$$Q_R = \frac{[A]_t}{[A]_o} = e^{-Bt} \quad 2\text{-}8$$

$$Q_R = e^{-Bt} \quad 2\text{-}9$$

Q_R is the fraction of the snow amount remaining at time t, and

$Q_t = (1 - Q_R)$ is the fraction of snow melted over time t

2.7. Summary of the Chapter

As discussed above, a wide range of snow controls methods, materials, application rates and guidelines are being used in current winter practices. The existing guidelines are not uniformly accepted as most of them are based on little to no knowledge of the effectiveness of these methods; this is especially true of the guidelines and material recommended for use on parking lots and sidewalks. The major limitations of existing research are:

- The performance of a treatment method (i.e., deicing/anti-icing) or snow control material (e.g., regular salt or alternative salt) has been mostly investigated in laboratory settings. Therefore, the real world factors (e.g., snow amount, type, pavement surface temperature etc.) that can affect this performance were not captured and quantified. The few studies attempted in field conditions have been conducted in very loosely controlled environments and often eventually concluded with a qualitative evaluation rather than a quantitative one. Moreover, none of these studies investigated the problem using a statistically sound approach.

- Most of the past studies do not provide reliable application rates for a given winter scenario. More importantly, the application rates that are provided do not reflect the projection of the pavement condition levels, since these application rates are not determined from a study that considered achieving a certain level of service for a given treatment. Some guidelines that provide application rates give amounts that are not statistically reliable and are derived from qualitative judgments and considerations. Furthermore, no studies have ever attempted to develop a snow melting performance model for a chemical agent for use in maintenance, and no study has attempted to generate a model to forecast the pavement condition level for treatment operations.
- The most common material used for snow and ice control is chloride salt, specifically, sodium chloride. However, as this salt becomes less effective below -8°C, other chloride salts or alternative products (i.e., blend of chloride salts and organic products, organic products alone) are also used in some regions. Very few studies have been conducted to evaluate the performance of these alternative salts, and few have recommended any guideline on the conditions under which these materials are more beneficial or what application rate is optimal for that condition.

CHAPTER 3
DESCRIPTION OF FIELD TESTS

To address the objectives of this doctoral research, an integrated empirical and analytical approach is applied. This chapter details the field tests that were conducted to collect the performance data for each treatment method evaluated including deicing, anti-icing or a specific material, such as regular salt or organic salt. This chapter also provides an overview of the collected data that were used to analyze and model the performance of a given treatment option or compare the performance of two snow control materials.

3.1. Field Tests

A series of field experiments in semi-controlled environments were conducted during three winter seasons to determine how various factors influence the deicing or anti-icing performance of a chemical. As discussed in Chapter 2, past studies have indicated that a large number of factors affect the performance of any given chemical or method; despite this, it is generally understood that the determination of a single causative factor (e.g., X) that has an influence in the effects/results (e.g., Y) of an ongoing experiment is critical in experimental research. However, it is equally important to note that there could be another factor (e.g., Z) that simultaneously influences the results (Y) in the field experiment; consequently, it is possible that the factor identified in the experiment (X) might not be the true causative factor at all. Therefore, the effect of various factors can be spurious, intervening or anteceding. In our case, it should be noted that, due to the uncontrolled nature of the field testing environment, it was not possible to evaluate the effects of a given factor while controlling the levels of other factors; instead, a statistical analysis of the observational data was employed to determine the joint effect of multiple factors. The following sections discuss the components of the field tests that were considered in this research. These field tests ultimately aimed to capture all the reasonable factors in the context of the intended application environment: parking lots and sidewalks.

3.1.1. Test Sections

All tests were performed in a systematic way such that the factors affecting the performance of various treatments and materials were accounted for under a wide range of winter conditions. Furthermore, for any given snow event, each field test consisted of multiple test sections (e.g., 10’x20’) possessing similar external conditions such as similar pavement types, similar initial snow type and depth, and similar traffic conditions. To meet these constraints while still retaining convenience for tests operations, a parking lot at the University of Waterloo was selected for field testing in parking lots; sidewalks test sections were also selected from areas around the university’s campus.

The parking lot selected for the test site is approximately 25540 m^2 (6.31 acres) and includes about 900 parking stalls and 8 driveways (Figure 3-1). The pavement's composition is asphalt concrete which is the most common composition for parking lots in North America.

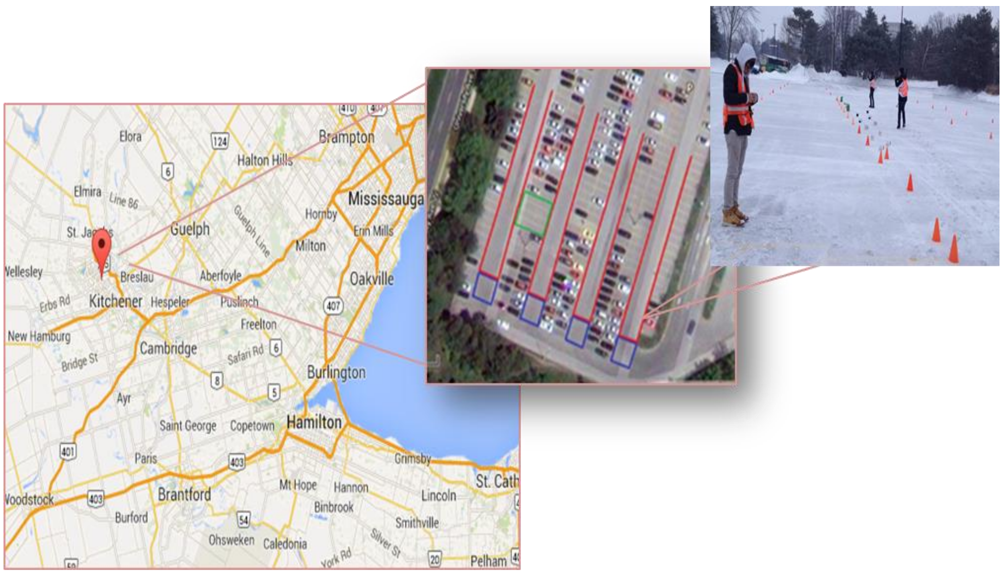


Figure 3-1: Test Site: Parking Lot C at the University of Waterloo, Ontario, Canada

To simulate the real word scenarios that a parking lot experiences in the winter months, different combinations of test scenarios were created. These included, for instance, groups of parking stalls with traffic vs. without traffic, plowed vs. unplowed snow conditions, and groups with different treatments such as deicing or anti-icing with applications of either solid salts or liquid salts. The chemicals used included organic, semi-organic and inorganic salts. Similarly, multiple sets of driveway sections with plowed vs. unplowed snow were tested to investigate traffic actions on snow melting. The combinations of the test sections tested in this research project are shown in Figure 3-2.

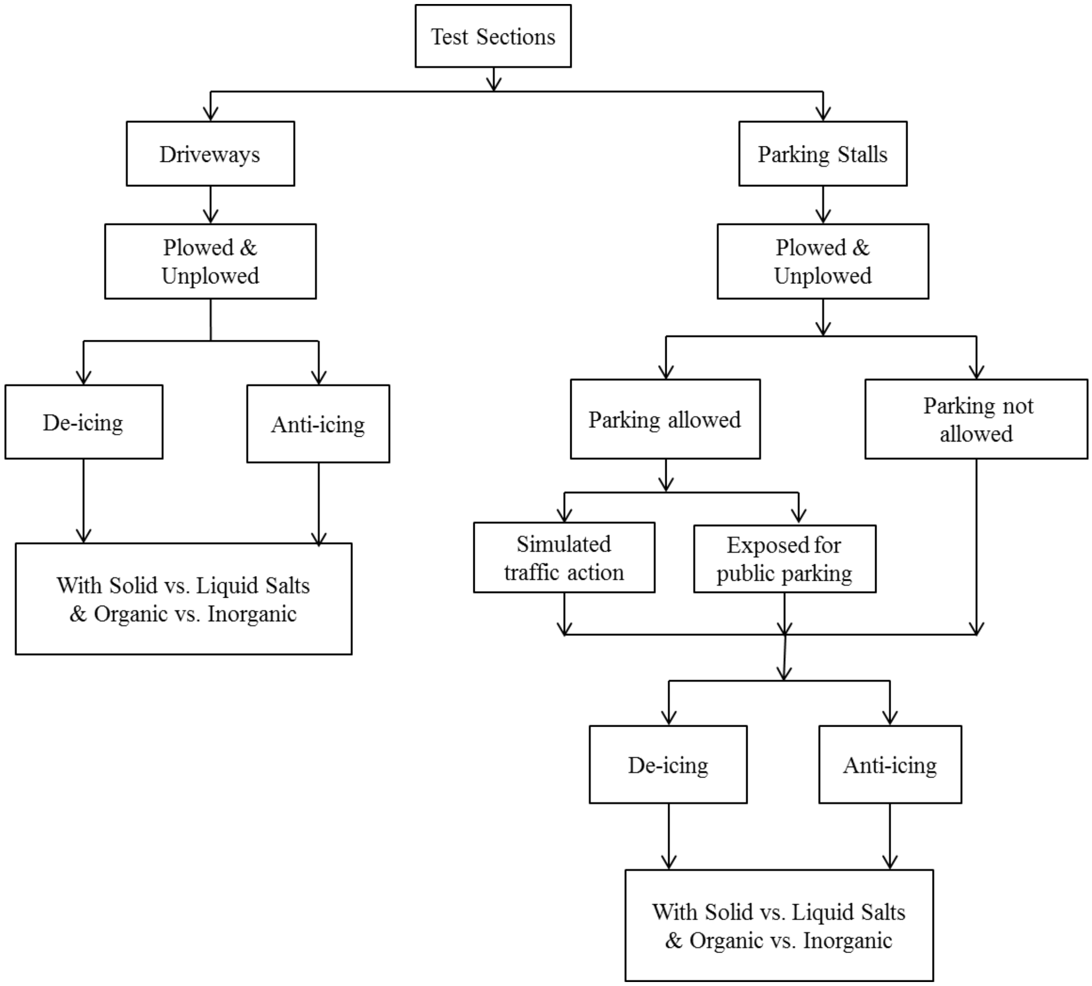


Figure 3-2: Combination of Test Sections for Parking Lot

3.1.2. Parking Stalls

Tests were conducted in parking stalls under various initial snow contaminations and treatment conditions. For parking stalls that were open to the public for parking, after tests commenced (i.e., after salting) all traffic controlling equipment (e.g., on-test signage and traffic cone) was removed and cars were permitted to park in them. The stalls closest to the University were selected to act as test sections, since the exact time a car spent in these tests sections (i.e., parking stalls) was not known. This selection regime maximized the probability that a selected stall was occupied for the duration of the test. To allow comparison to the results of these sections, separate control sections with the same salt application rate and no traffic was also prepared.

In addition to the above real world test scenarios, a number of tests were conducted to simulate the effects of parking frequency (i.e., effect of heat from car exhaust or blocking of sun) on snow melting. It is generally understood that, the movement of cars in a parking stall varies according to the type of business (e.g., a convenience store vs. fast-food place vs. an office space). This type of test involved salting in different sections with varied salting rates (Figure 3-3); cars were then parked in these sections for varying lengths of time (e.g., 15 mins, 60 mins). After the selected time period had passed, the cars were driven out of the spot, and then parked back in the spot. This cycle was continued until the end of test.

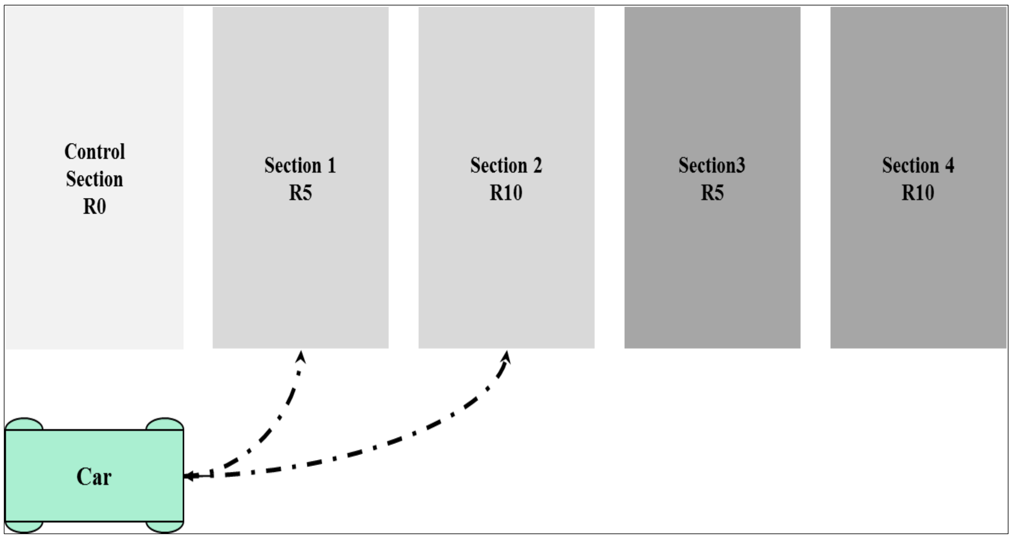


Figure 3-3: Sample Test Sections for Investigating Parking Effects on Deicing Performance in Parking Stalls (R0: the control section, Parking stalls (1, 2) and (3,4) will experience parking at 15 and 30mins and applications rates of 5 and 10lbs/1000sft respectively)

3.1.3. Driveways

To investigate the effects of the dynamic action of traffic (i.e. the rolling actions of tire on snow melting) a number of different tests were conducted in the driveways. For these tests, micro sections (e.g., 10’x20’) were created based on the uniformity of the initial snow/ice conditions present. Consecutive test sections were separated substantially to minimize the effect of the transportation of salt and solutions containing salt due to slope and traffic.

Because it can be assumed that the traffic volume on a particular driveway is relatively uniform, different test sections with different salt application rates on the same driveway can provide a comparative picture of traffic and salting effects on snow melting. This concept is illustrated in Figure 3-4, which shows an example of driveway test sections with different application rates (e.g., 10, 20 and 30lbs/1000 sqft). The traffic count data were manually collected during the testing time. In addition to manual counting, a web-camera was installed to count traffic during the initial stages of the test season; however, this camera eventually became non-functional due to the low ambient temperature of its surroundings.

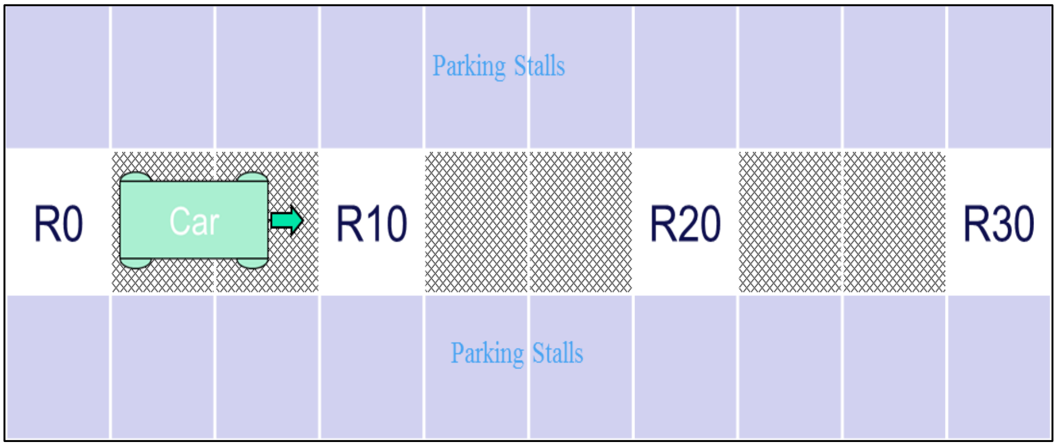


Figure 3-4: Test Sections for Investigating Traffic Effects on Snow Melting on Driveways

(R0= Control section; Sections R10, R20 and R30-Applicationn rate will be 10, 20 and 30lbs/1000sqft)

3.1.4. Sidewalks

In addition to the tests in parking lots, a large numbers of field tests were also performed on the sidewalks and walkways around the University Waterloo. The sidewalk sections included regular concrete pavement, interlocking pavers and asphalt pavement. To maintain similar weather conditions, test areas were selected such that they were within 500 m of the parking lot. Figure 3-5 shows the setup for test area selection on a day when tests were conducted on concrete pavement and interlocking concrete pavers.

The sidewalks test segments chosen were heavily used by pedestrians, cyclists, and maintenance vehicles. To obtain an overview of the usage of these facilities, pedestrian traffic was manually counted during the AM and PM peak hours for a week at the locations where most of the tests were conducted. The average AM pedestrian volume recorded was 374 pedestrians/hr across test areas. The asphalt pavement at tests sites was regular-grade asphalt concrete, while the concrete pavement at test sites was regular Portland cement concrete. Lastly, the interlocking concrete pavement at test sites was made from grey colored Portland cement concrete paver tiles (6”x6”).

Figure 3-5: Test site: Sidewalks at Ring Road and University Ave West, Waterloo, ON

3.2. Test Protocols

3.2.1. Deicing

Deicing was performed after a snow event occurred. Salts were applied at rates based on the depth of the snow present, prevailing pavement surface temperature, and forecasted air temperature. Refer to Figure 3-6 for the deicing treatment process. To compare the performance between materials or methods, tests were conducted in a side-by-side set up so other factors could be kept constant. An illustration of this set-up and the common test activities conducted is shown in Figure 3-7 and Figure 3-8 respectively.

3.2.2. Anti-icing

For anti-icing, salts were applied prior to a snow event to prevent bonding from occurring. In general, an anti-icing treatment is performed 2 to 12 hours in advance of snow events. Figure 3-6 shows the anti-icing process.

Figure 3-6: Field Test Procedure (Deicing and Anti-icing)

Data Collection

(Pavement Condition)

Test Site Selection

(Side by side)

Salts Application

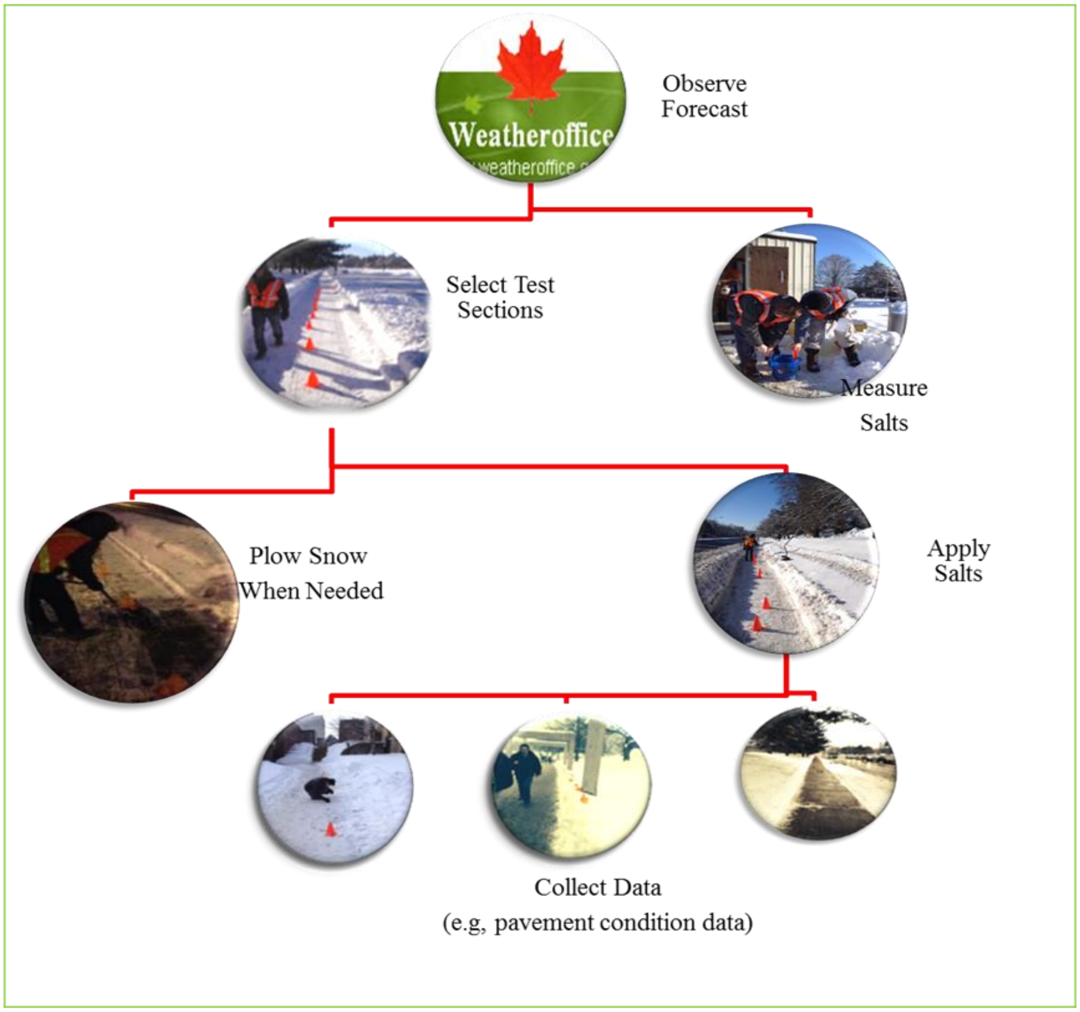
(Material A and Material B)

a) Set-up for Comparing Methods (Dry salts vs Pre-wetted salts)

b) Set-up for Testing Organic Salts (e.g., Green salts)

Figure 3-7: Setup of Test Site while Comparing Two Materials or Methods (e.g., Regular salt vs Alternative salts, or Pre-wetted salt vs. Dry salt)

a) Test Activities: Parking Lot



b) Test Activities: Sidewalks

Figure 3-8: Parking Lot and Sidewalk Test Activities

3.2.3. Chemicals Tested

Regular road salt (i.e., rock salt) was the major solid material tested in this study; however, complex blends of rock salts as well as other compounds with low percentages of chloride constituents (i.e., organic salts) were tested as an alternative to road salt. Additionally, the study also tested a variety of liquid salts. After consulting with the Toronto Region Conservation Authority (TRCA) and Metrolinx (A Provincial Transit Authority), a review was conducted to select the materials for testing; the selection criteria used included the percentage of organic contents in the composition, the product's current usage, availability, and price, and the performance of the product under low temperatures. Table 3-1 and Table 3-2 show the list of materials tested in this study.

The solid materials selected for testing were supplied by the respective suppliers, named as Green Salt, Blue Salt, Slicer and Jet Blue. The ingredients and composition of these salts were provided by the supplier.

However, to the best of our knowledge no independent research has been conducted to verify this information. Most of these salts contain chloride, however, Green Salt is claimed to be a fully organic salt with no chloride constituent in the composition. As discussed in Chapter 2, it has been shown that there is a benefit in the usage of pre-wetted salt, though that benefit is still not quantified. To fill this gap, our test scheme included conducting a series of tests using pre-wetted salt.

The liquid salts tested included brine, Snowmelt (organic), Fusion (organic and chloride content) and, Caliber M1000 (organic and chloride content). In addition, Snowmelt was tested at two concentration levels: 100% concentrated Snowmelt (full organic), and Snowmelt diluted with brine at a ratio of 30:70 (snowmelt to brine). This ratio was used for majority of the tests as recommended by the supplier. The brine used in the tests was regular brine (23% sodium chloride by mass) and was supplied by the City of Kitchener. It should be noted that the City of Kitchener filled the brine containers with an injecting pipe system, which was also used to provide other types of anti-icing materials (e.g., Fusion, Beet juice). While there was a potential for cross contamination of the brine, the degree of this effect was considered to be relatively small.

Table 3-1: Solid Salts Tested

Salt Name	Composition*	Cost* ($/ton)	Physical look
Rock Salt (also called regular salt/road salt)	Sodium Chloride	80	
Blue Salt	Sodium Chloride Treated with Magnesium Chloride (Proportion not known)	100	
Slicer	78% NaCl 9.4% $MgCl_2$ 2-3% proprietary ingredients	358	

Green Salt	Sodium Formate Treated with GEN3 runway deicing fluid (Proportion not known)	950	
Jet Blue	Sodium Chloride Treated with proprietary polyol (Proportion not known)	495	

Table 3-2: Liquid Salts Tested

Trade Name	Composition*	Cost ($/L)*	Physical Look
Brine	23% NaCl 77% Water	0.15	
Fusion 2350	12% NaCl 50% Degraded Beet Juice 38% P/U	0.30	
Snowmelt	15-20% Gylcerine 10-20% Polyether Polymer 3-8% Lactic Acid 2-4% Sorbitol 1-3% Formic Acid 1-3% Acetic Acid 1-2% 1,2-Butanediol Balanced with Water	0.29	

Caliber M1000	27% $MgCl_2$ 6% Carbohydrate 67% Water and P/U	0.40	

*Note: The compositions are based on information provided by the supplier or found in the literature/material information sheet. The unit rates reported is very general and provided by the materials suppliers. P/U stands for Proprietary /Unknown.

3.2.4. Application Rates and Spreading

When determining the appropriate rate of salt to apply, a variety of factors were taken into consideration. Figure 3-9 below lists the different factors that are driving forces for deciding the application rate required to reach a desired pavement condition. The test plan included conducting a fractional factorial experiment (i.e., investigating the response of some major influencing factors at their different levels) to check the sensitivity of the major influencing factors, e.g., the effect of the material's application rates on the response factors (i.e., the performance measure - %BP or CoF).

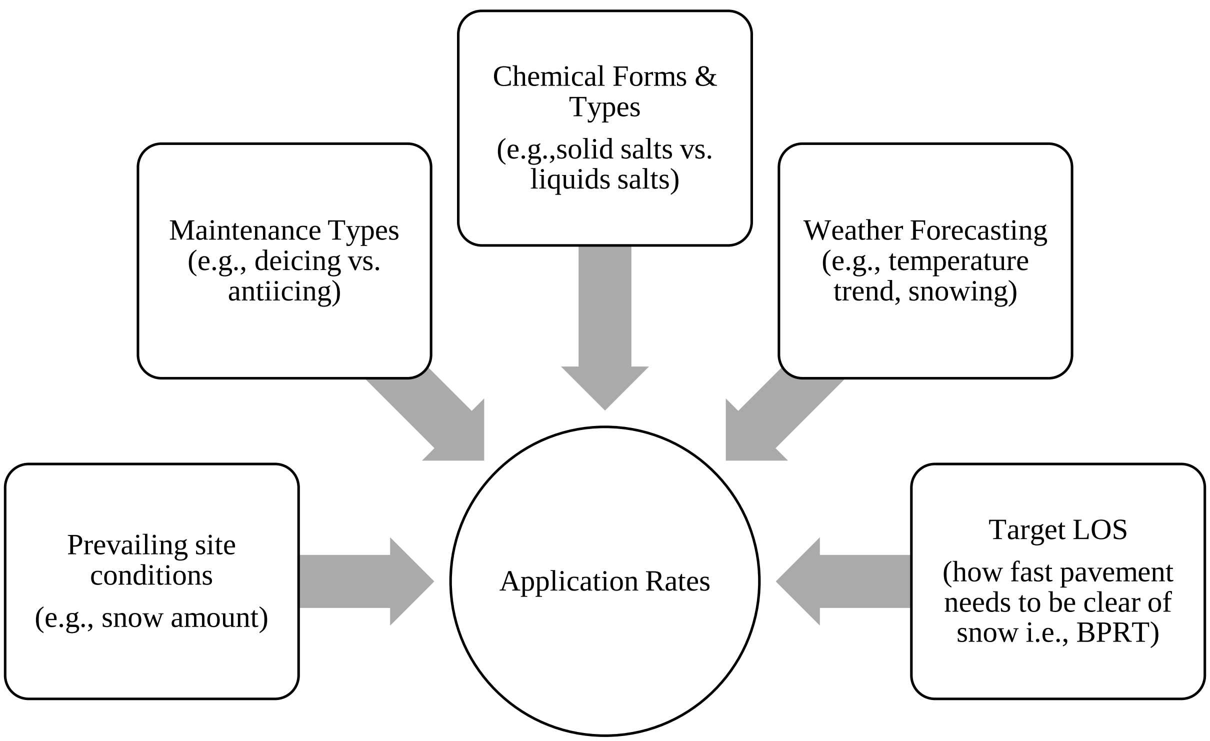


Figure 3-9: Application Rates Decision Factors

This study employed a variety of different salt application rates, simulating the wide spectrum of application rates observed in a recent survey of current practices. Currently, typical salt application rates vary from 5 to 200 lbs/1000 sqft for parking lots, sidewalks and transit platforms. However, application rates between 5 to 50 lbs/1000 sqft seem to be common for parking lots and sidewalks.

The application of liquids is not common for snow and ice control in parking lots and sidewalks. Trial rates were thus initially set based on recommendations from manufacturers and were then adjusted as tests proceed over the testing period according to snow conditions, pavement temperatures, and other variables. As a part of our experimental design process and based on the recommendations provided by the suppliers, three application rates for each product were tested (i.e., 3, 6 and 9 L/1000 sqft). Note that the application rates in the road industry vary from 3 to 10 L/1000 sqft, while 4 L/1000 sqft is the most common application rate being used and recommended for parking lots. To ensure uniformity and mimic practical salt application in each case, solid salts were salted manually (i.e., salts were spread by hand-spreading) while liquid salts were applied by liquid sprayers.

3.3. Description of the Collected Data

To quantify the treatment performance and compare the effectiveness of alternative methods and chemicals in field experiments, the result (i.e., effect) of a treatment was evaluated through direct measurements of performance on pavement surface conditions (e.g., pavement contaminant condition, percentage of bare pavement gained over time and the surface’s friction level). These measurements were collected manually, through observations, and with friction equipment. Within each experiment, the variables (predictors) influencing the performance of the treatment were controlled, including treatments types, application rates, initial pavement conditions, and some of the external factors (e.g., traffic). The data collected and used in this research is discussed in following section.

3.3.1. Test specific data

Data related to each test includes:

- Test section identification number
- Test date: month/day/year
- Weather event type (light vs. heavy)
- Precipitation form (Snow/rain/freezing rain)
- Treatment type (deicing vs. anti-icing)
- Testing site (parking stalls or driveways or sidewalks)
- Chemical forms used in the test (dry or liquids)
- Ranges of application rates tested (low vs. medium vs. high rates)

- Event start time and end time
- Total number of observations in the test
- Test site team
- Duty roaster of the test team

Data collected during each observation run includes:

- Field observation number and time of observation
- Prevailing pavement contaminant type (e.g., snow, slush, ice)
- Pavement scenarios to be tested on (plowed section vs. unplowed section)
- Material type: dry solid salt, alternative salts, winter sand, and liquid brine or organic products
- Mixing ratio (%) of the liquid salt applied
- Plowing method (manual or truck)
- Plow quality (uniform vs. non-uniform)
- Salt application forms (manual, salting truck, liquid sprayer)
- Application rate
- Surface temperatures (pavement surface and snow surface)
- Snow coverage percentage
- Snow-pavement bonding state (bonded vs. not bonded)
- Total snow depth before and after plow
- Snow density
- Slipperiness level (qualitative: very slippery, slippery or not slippery)
- Friction level by friction tester
- Solid Residual salt visual level (qualitative- highly, moderately or not visible)
- Dissolved residual salt on pavement
- Unsafe incidents (pedestrian slips and falls, accidents)
- Traffic data (e.g., pedestrian traffic, vehicular traffic, volume)

3.3.2. Weather data

Weather data were collected from Environment Canada's website.

- Air Temperature
- Humidity
- Prevailing sky-view condition (sunny vs. others (cloudy, overcast))
- Prevailing weather state (e.g., snowing, raining, or no precipitation)
- Visibility

- Wind-chill
- Dew-point
- Wind speed, direction and wind gust
- Wind directions
- Air pressure

3.4. Performance Metrics and Data

3.4.1. Bare Pavement Regain Time (BPRT)

Pavement surface state is the visual characterization of winter pavement surfaces that represents a driver or pedestrian's perception of condition of a parking lot or sidewalk's surface. It includes two aspects: the type of road surface contaminants, such as loose snow, packed snow, slush or solid ice; and the extent of snow and ice coverage (i.e., the fraction of bare pavement over the fraction of pavement covered by snow).

After application of salt on top of snow as a deicing treatment, the change (% of bare area in a test section) in pavement surface condition over time was recorded through visual observation and with a digital camera. To clarify, estimating the extent of snow coverage on a test section (i.e. percent of bare area in a test section) was done by field observers collecting hourly data, with the estimate made by the most observers becoming the recorded value. Bare Pavement Regain Time (BPRT) is the elapsed time (hrs.) from salt application to the time when the percentage of bare pavement reaches 80%, a threshold value decided on the basis of a survey of user expectations (note that the results of this study will not be restricted to this BP LOS threshold). Bare pavement regain time (BPRT) is used as a surrogate for the level of service (LOS) achieved by each particular chemical application treatment; accordingly, this means that a lower value of BPRT can be translated as a higher LOS experienced by users. Therefore, BPRT has been used as response variable (i.e., performance indicator for deicing treatment) in the statistical analysis of the tests results.

However, it should be noted that there were quite a few instances where following a deicing treatment bare pavement status (at least 80%) was not reached by a majority of test sections, or tests ended with a bare pavement status of just 40 to 60%. This likely occurred as a result of cold temperatures, compacted snow or low application rates. In this case, the snow melting speed (i.e., percentage bare pavement/hour) for a treated section was used to compare the snow melting performance of salt on different test sections. By dividing the observed percentage of bare pavement by the time between that observation and the initial time of salting, the average percentage of pavement cleared per hour (i.e., percentage bare pavement/hour) can be estimated.

3.4.2. Coefficient of Friction

Friction is a physical measurement that represents the amount of force available between a vehicle's tires or a pedestrian's shoes and the road surface. The friction data were collected in anti-icing treated sections and control sections using a portable friction-measuring device, the ASFT T2-GO.

3.5. Highlights of the Chapter

- A series of field tests, including deicing and anti-icing treatments, were conducted in the winter seasons of 2011-2012, 2012-2013 and 2013-2014. The tests compared different treatment schemes and covered a wide variety of external conditions (e.g. dry salt vs pre wetted salt; with traffic vs without traffic).
- Deicing treatment was conducted at the end of a snow event, whereas anti-icing was conducted before the snow event began. A total of five solid salts and four liquid salts were tested.
- In addition to the five solid salts, deicing tests also included pre-wetted rock salt.
- When comparing two materials or methods, tests were conducted in a side-by-side set up so factors other than material types or methods that might influence treatment performance can be kept constant.
- Deicing performance was measured by estimating the bare pavement regain time (BPRT, in hours) which is the time elapsed from salt application to the time 80% bare pavement status is reached. This measure was used commonly in the analysis of the performance of the various deicing treatments. In addition, melting speed (%BP/hr) was also considered to compare the snow melting performance for certain cases, such as when snow melting was significantly low for some external condition (e.g., days with very low temperatures).
- After application of salt, time series performance and weather data were collected and processed for subsequent analysis.

CHAPTER 4

PERFORMANCE OF DEICING TREATMENT USING REGULAR SALTS[1]

This chapter presents the results of the analysis of data obtained from deicing tests using regular salts. The dataset consists of time series observations on weather, maintenance information, and performance data obtained through the three winter seasons of this project. An overview of the deicing tests, data collected (including detailed results), and the major findings are presented in the following sections.

4.1. Test Overview and Data

The primary goal of this study, as indicated in previous sections, was an investigation into the performance of deicing treatments, particularly regular salt; consequently, deicing tests were conducted on almost every weather event during the testing seasons of 2011-2012, 2012-2013 and 2013-2014. In these testing seasons, there were about 100 snow events in total; pavement surface temperatures during tests ranged from about -20°C to 3°C and snow precipitation from about 0.2cm to 22cm, as shown in Figure 4-1. Interestingly, these three winter seasons had different sets of weather conditions: the first season was very mild and contained a limited number of events (14 events in total); the second season contained average winter conditions for the region; and the last winter was extremely heavy, especially when the number of colder days is considered (over 15 events with temperatures below -15°C), main features of the weather event is also provided in Figure 4-1. A total of 1167 tests were conducted using regular road salt, including tests with plowed and unplowed snow, with and without traffic, and in both stall areas and driveways. To closely simulate the way parking lot maintenance is performed in the real world, about 60% of the test operations started between 3am and 7am. For each snow event, salt was applied to a set of test sections according to the test protocols described in Chapter 3; time series performance and condition data were also collected during tests.

At the start of each test, important information about the event was entered into a master event form. This information included the starting and ending times of the snowfall, initial snow depth, snow type, snow density, and prevailing temperatures. To measuring density, a 1m x 1m area was sectioned off. Snow was then collected from this section and weighed to determine the snow density. An hourly data form was filled

[1]This chapter is based on three papers: a) Deicing Performance of Salt: Modeling and Applications, 2014, Transportation Research Record, Journal of the Transportation Research Board of National Academics. b) Modeling the Effects of Traffic on Snow Melting, 2015, TRB Conference, 94th Annual General Meeting, Washington DC c) Snow Melting Performance of Salt: Effects of Pavement Types, 2015, TRB Conference, 94th Annual General Meeting, Washington, DC

out at a fixed time interval with weather data, performance data (i.e., percentage of bare pavement over snow covered area) and the contaminant type.

The weather data included, but were not restricted to, air temperature, sky-view condition, humidity, wind speed, dew-point, and wind chill. Temperatures of the pavement and snow surfaces were taken after removing patches of snow, and on top of the snow surface, respectively, using an infrared surface temperature reader. The event based data collection form was used to record the initial and final conditions of the tests, and total snowfall over the event. The form was also used to record some processed data from the day, such as, average temperatures for the event and pavement condition. The data collection process continued until every test section achieved 80 percent or higher bare pavement.

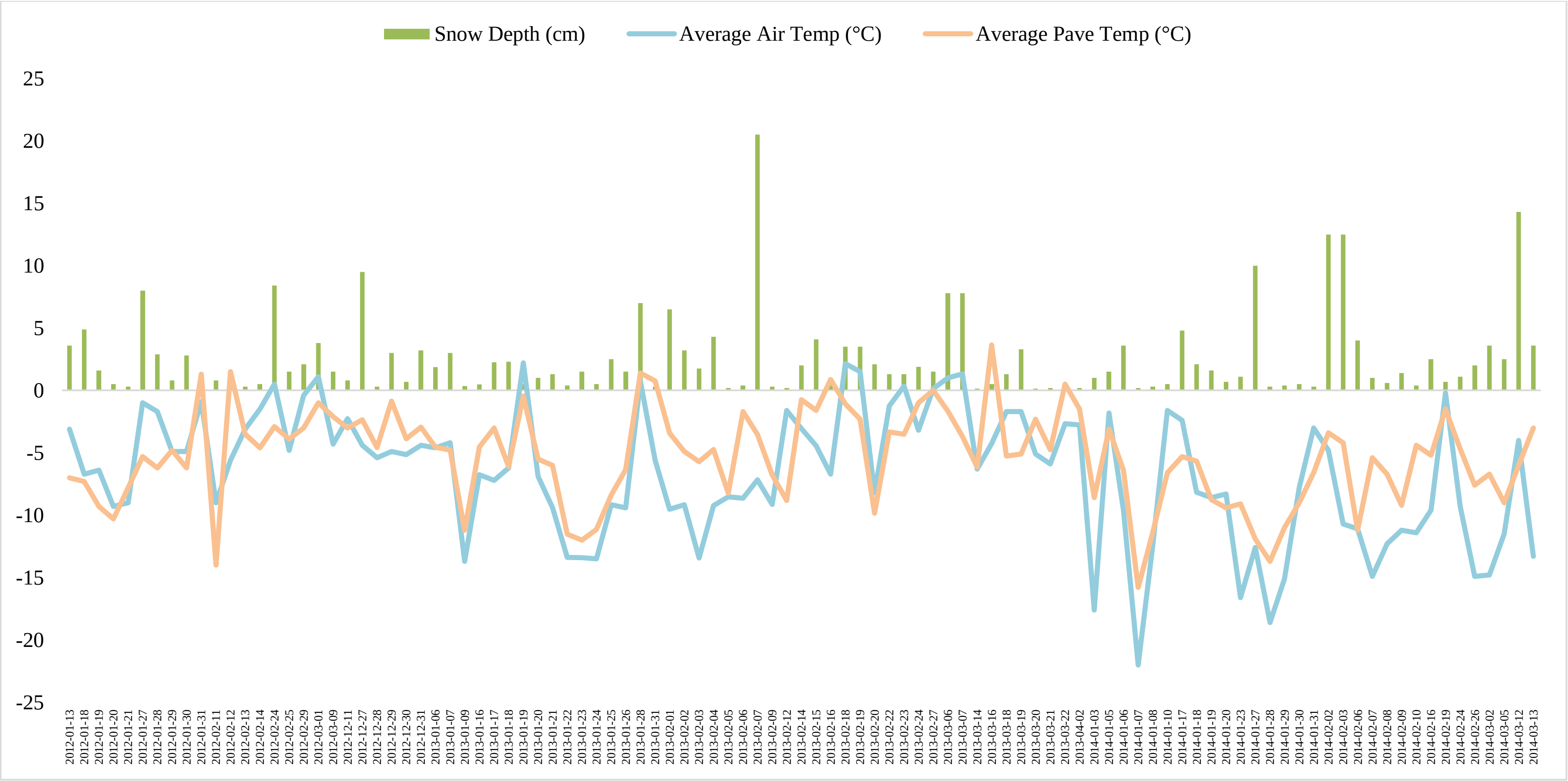
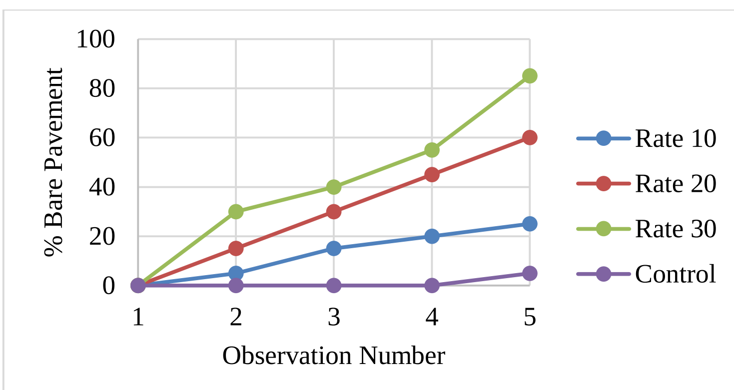


Figure 4-1: Snow Events in Winter Season 2012, 2013 and 2014

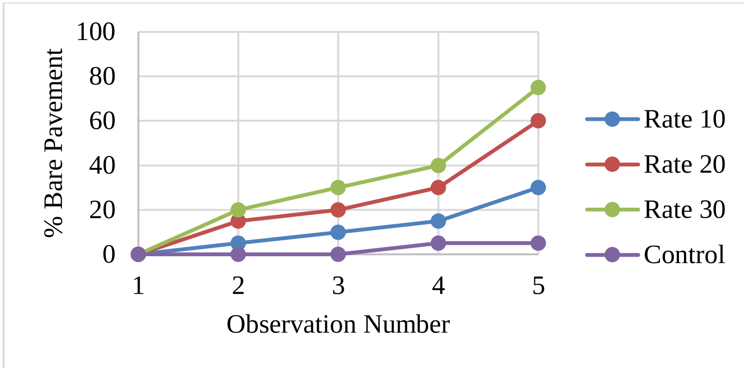
4.1.1. Test Results – An Example

This section discusses the results from a typical day of tests conducted over the data collection period as an example. This particular snow event started at 6:00 pm and ended at 8:00 pm on February 25, 2014. All deicing treatments in the parking stalls (control sections and those open to the public) and driveways started on the following morning at 8:30am. The total snow amount on the pavement surface was about 1 cm. Road salt was applied at rates of 10, 20 and 30lbs/1000sqft in three groups of test sections and data collection started immediately after the salt application. The test lasted for five hours with an average air temperature and pavement temperature of -14.6°C and -8.8°C, respectively. As the surface temperature was lower than where salt is typically effective, the melting speed (change in bare pavement percentage) was also low (Figure 4-2). This was true for stall areas with and without traffic. However, the snow melting trend observed in the driveway sections seemed much faster than in stall areas. For example, a salt application rate 20lbs/1000sqft was able to reach 80% bare pavement in the driveway, whereas the final bare pavement percentage was only 60% in stall areas for this application rates.

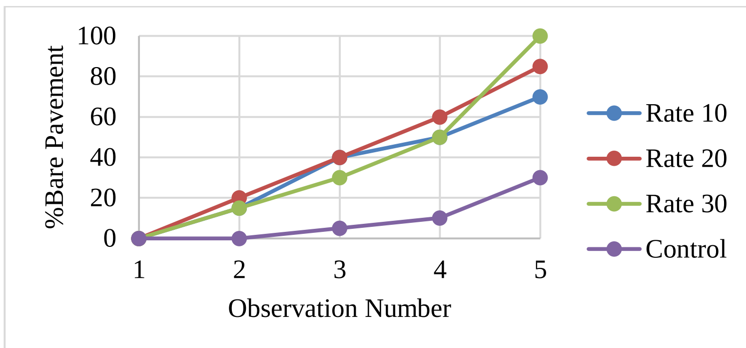
As expected, it can also be observed that the bare pavement percentages for the parking stalls varied when application rates varied (i.e., the high percentages were observed for the high application rates), whereas using higher amounts of salt results in smaller differences in performance in the driveway test sections.



a) Stall Areas without Traffic - Percent Bare Pavement over Time



b) Stall Areas with Traffic- Percent Bare Pavement over Time



c) Driveways- Percent Bare Pavement over Time

Figure 4-2: Deicing Test Results from a Typical Day

Table 4-1 shows the summary of raw data obtained from a sample day of testing on 17 January 2013. On this day, a number of application rates (5 to 50lbs/1000sqft) were tested. As indicated previously, after the application of salt on top of snow, time series weather data and performance data (% BP) were recorded each hour, including general notes of the testing day; samples of these data are presented in Table 4-1. These data were then further processed and bare pavement regain time has been estimated for a test section for a given application rate. A sample of a processed dataset from three days of testing is shown in Table 4-2.

Table 4-1: Sample Raw Data (Treatment, Weather and Performance)

Date	Time from Salting (hrs)	Section Ids	App. Rate (lbs/1000	Obs. Air Temp	[illegible]	%BP over Time	Snow Density (kg/m^3)	Initial Snow depth (cm)	Change in depth (cm)	Total Snow depth (cm)
17/01/2013	0	D1	10	-6.0	-3.0	0	112.9	0.75	0.75	1.5
17/01/2013	1	D1	10	-7.0	-3.5	40	112.9	0.75	0.75	1.5
17/01/2013	2	D1	10	-8.0	-3.0	70	112.9	0.75	0.75	1.5
17/01/2013	3	D1	10	-8.0	-3.0	90	112.9	0.75	0.75	1.5
17/01/2013	0	D2	20	-6.0	-3.0	0	112.9	0.75	0.75	1.5
17/01/2013	1	D2	20	-7.0	-3.5	60	112.9	0.75	0.75	1.5
17/01/2013	2	D2	20	-8.0	-3.0	85	112.9	0.75	0.75	1.5
17/01/2013	0	D3	30	-6.0	-3.0	0	112.9	0.75	0.75	1.5
17/01/2013	1	D3	30	-7.0	-3.5	90	112.9	0.75	0.75	1.5
17/01/2013	2	D3	30	-8.0	-3.0	100	112.9	0.75	0.75	1.5
Other notes: Un-uniform snow, snow was not plowed, deicing with dry road salts, sky view condition-overall sunny										

Table 4-2: Sample Processed Data from some Deicing Tests

Pavement Initial Condition	Test Date	Thickness before Plow (cm)	Snow Thickness after Plow (cm)	Snowfall (cm) during Test	Total Snow (cm) in Test Sections	Snow Weight (Kg) from a 1mx1m area	Density (Kg/m3)	Average Pave Temp (°C)	Average Air Temperature	Sunny Hours	Test Section ID	Rate	BPRT
Left over Snow after Plow	2012-12-27	8.5	0.2	1.0	1.2	11.04	129.88	-2.90	-4.43	4	D5	25	3
		8.5	0.2	1.0	1.2	11.04	129.88	-2.90	-4.43	4	D4	20	3
		8.5	0.2	1.0	1.2	11.04	129.88	-2.90	-4.43	4	D3	15	6
		8.5	0.2	1.0	1.2	11.04	129.88	-2.90	-4.43	4	D2	10	4
		8.5	0.2	1.0	1.2	11.04	129.88	-2.90	-4.43	4	D1	5	8
	2012-12-28	0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D8	35	3
		0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D7	30	5
		0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D6	25	5
		0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D5	20	6
		0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D4	15	6
		0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D3	10	7
		0.5	0.2	0.2	0.4	0.26	134.00	-7.20	-5.40	0	D2	5	7
	2012-12-30	3.5	0.2	4.0	4.2	4.21	120.29	-3.60	-4.60	3	D5	25	7.5
		3.5	0.2	4.0	4.2	4.21	120.29	-3.60	-4.60	3	Z4	20	6
		3.5	0.2	4.0	4.2	4.21	120.29	-3.60	-4.60	3	D3	15	8.5
		3.5	0.2	4.0	4.2	4.21	120.29	-3.60	-4.60	3	D2	10	9
		3.5	0.2	4.0	4.2	4.21	120.29	-3.60	-4.60	3	D1	5	9.5

4.2. Data Visualization and Exploratory Data Analysis on Snow Melting Performance

An exploratory data analysis was performed to identify the key factors influencing the snow melting performance of salt such as, application rate, temperature, and snow amount. This section discusses the effects of different factors on the snow and ice melting effectiveness of different application rates. The performance of a salting rate is measured by the fraction of bare pavement over the fraction of pavement covered by snow. Two measures of effectiveness are used: Change in snow cover over time (% of bare area of a test section) and bare pavement regain time (BPRT). As discussed previously, a large number of factors affect the snow melting performance of salt (Figure 4-3). The following section focuses on the effects of some of the main factors. It should be noted that, due to the uncontrolled nature of the testing environment, it was not possible to evaluate the effects of a given factor while controlling the levels of other factors. Instead, a statistical analysis of the observations was employed to determine the joint effect of multiple factors.

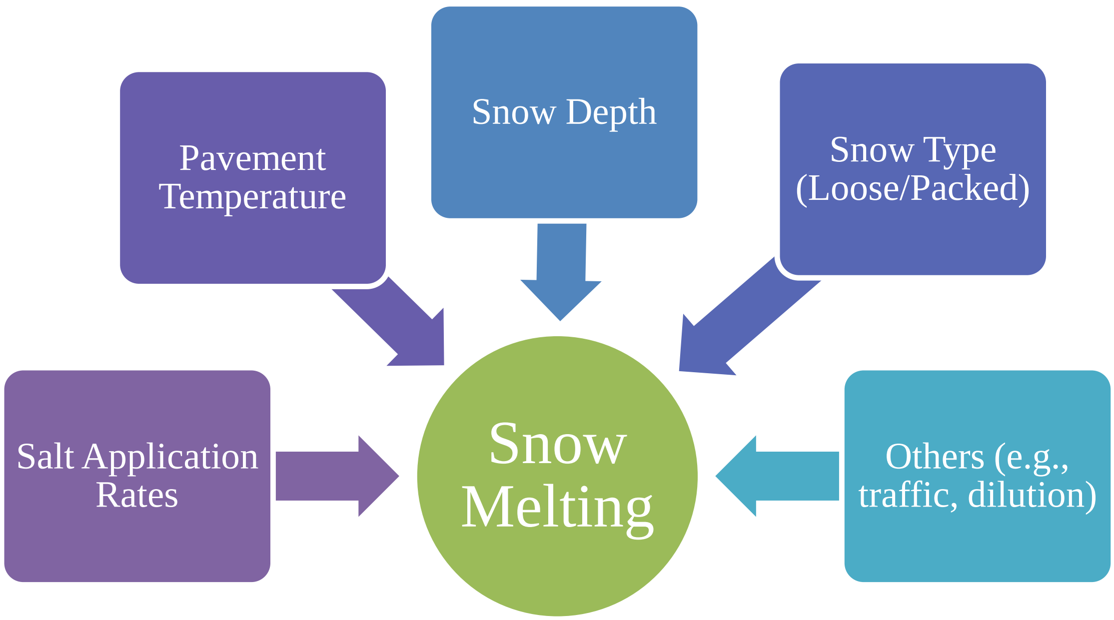
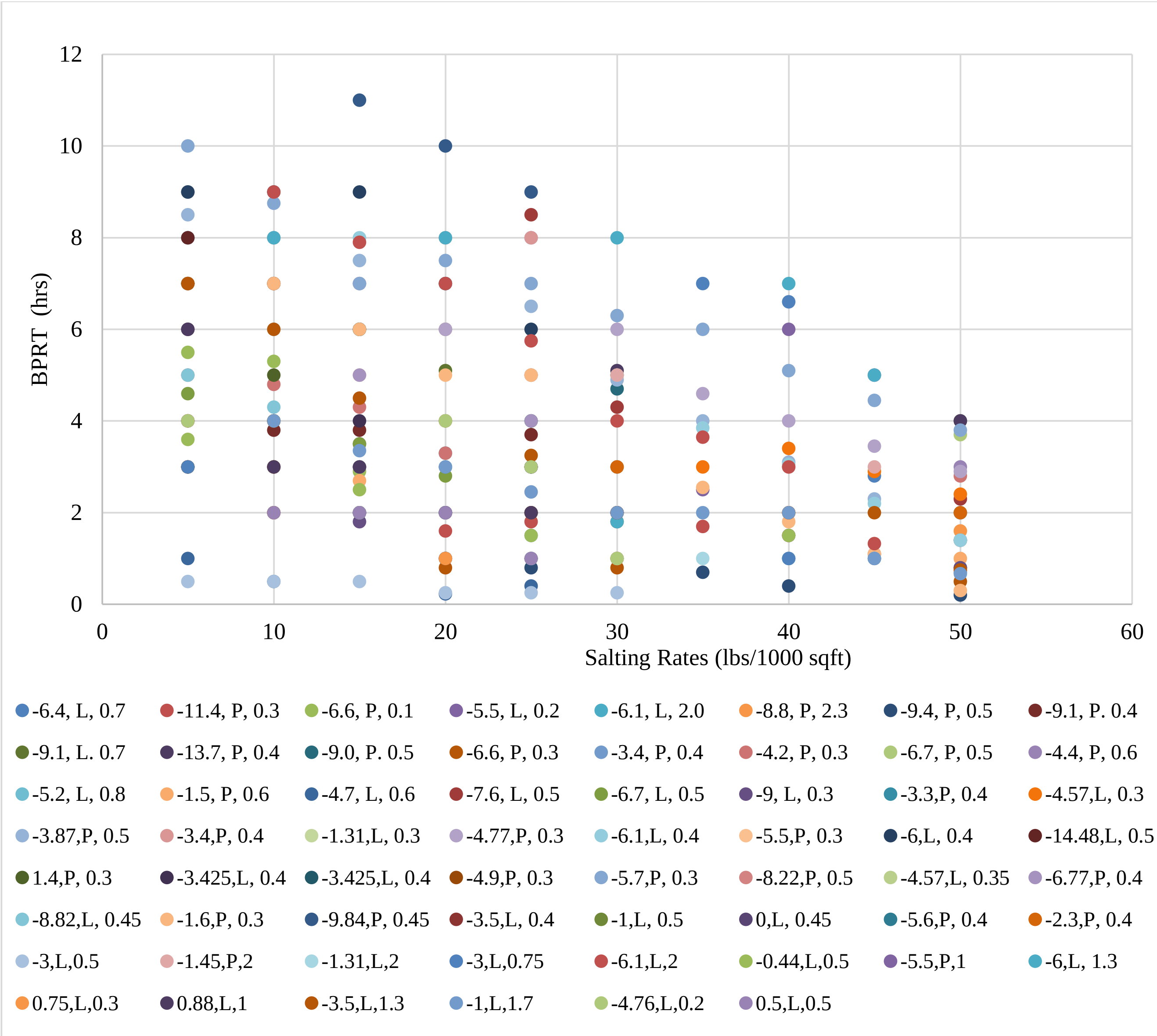


Figure 4-3: Factors Affecting Snow Melting Performance

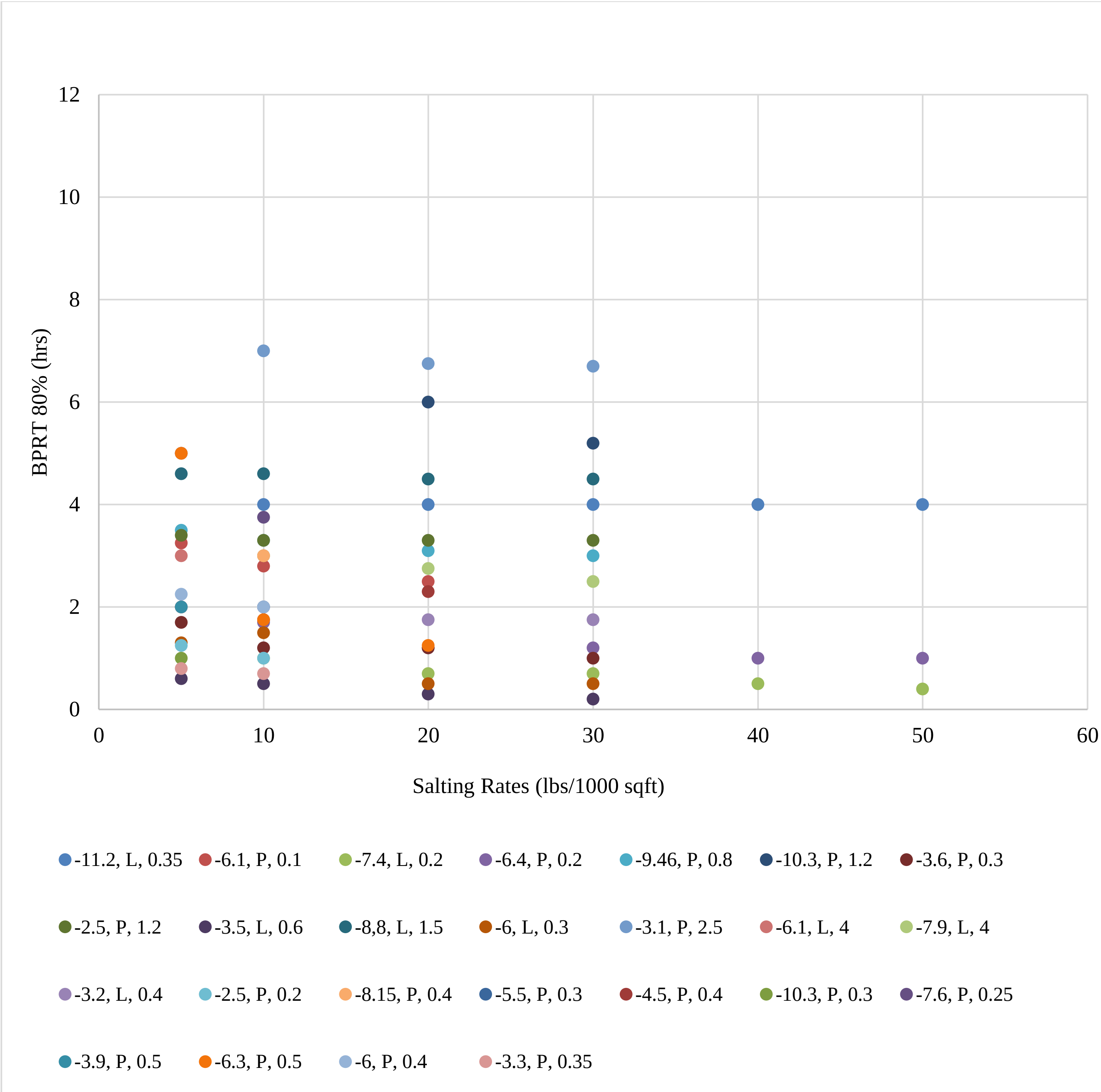
4.2.1. Effect of Salt Application Rate

Figure 4-4 shows BPRT as a function of application rates obtained over the snow events in the test sections in the stall areas and driveways, respectively. Several interesting findings can be noticed from this figure. For instance, it can first be observed that, regardless of other variables, there is a clear dependency between snow melting performance and application rates in both stall areas and driveways. However, it can be noticed this relationship is generally more clear in stall areas is higher than in the driveways. Second, the snow melting time (BPRT) in driveway sections is relatively shorter than in stall areas where all the events are considered; indeed, very few events took longer than five hours to reach the bare pavement in driveways while on number of test days it took as long as 10 hours to reach bare pavement in stall areas. Although differences in snow melting time between tests groups and events were sometimes observed, these may be due to other uncontrollable weather and external factors. Intuitively, it is expected that snow depth plays a significant role in the BPRT, but other factors such as temperature, snow type, and traffic conditions are likely to contribute as well. Note however that due to limited resources and other constraints the number of tests in driveways was less than stall areas; no tests were conducted on driveways on days with minimal traffic (e.g., weekends, heavy storm days) as the effects of traffic and other distinguishing factors that these tests measure would be obfuscated.

As indicated previously, in addition to the field tests conducted in driveways and stall areas, tests were also conducted over a total of three days to investigate the effects of parking frequency in the stalls on the performance of salt. The BPRT data were collected for the different test sections where the cars were parked for different time periods: 15 minutes, 30 minutes, and 2 hours. These tests were conducted in test sections where snow had been plowed before the application of salt. The BPRT observed in the test sections were compared. The results showed that there was a slight difference in BPRT between the days tests were conducted on; these differences a probably caused by variations in other uncontrolled factors for the test days (e.g., pavement temperature, sky view conditions). Slight differences in the BPRTs of test sections on a single day were noticed when the effects of parking frequency were considered; this difference can be attributed to the tire action and exhaust heat from the vehicles that help the snow melting process in sections where cars were more frequently moved in and out of the testing zone. Additionally, when a car is parked for a longer period of time it blocks sunlight which could otherwise accelerate snow melting by providing heat energy from the snow beneath it. However, since the overall difference in BPRT was slight, the data from stall areas with cars and without cars were merged to develop a snow melting model for stall areas. It is important to note, however, that the frequency of parking is an uncertain variable in the real world, though there may be a pattern in parking frequency between different types of establishments.



a) Stall Areas (with and without traffic): BPRT vs Rates



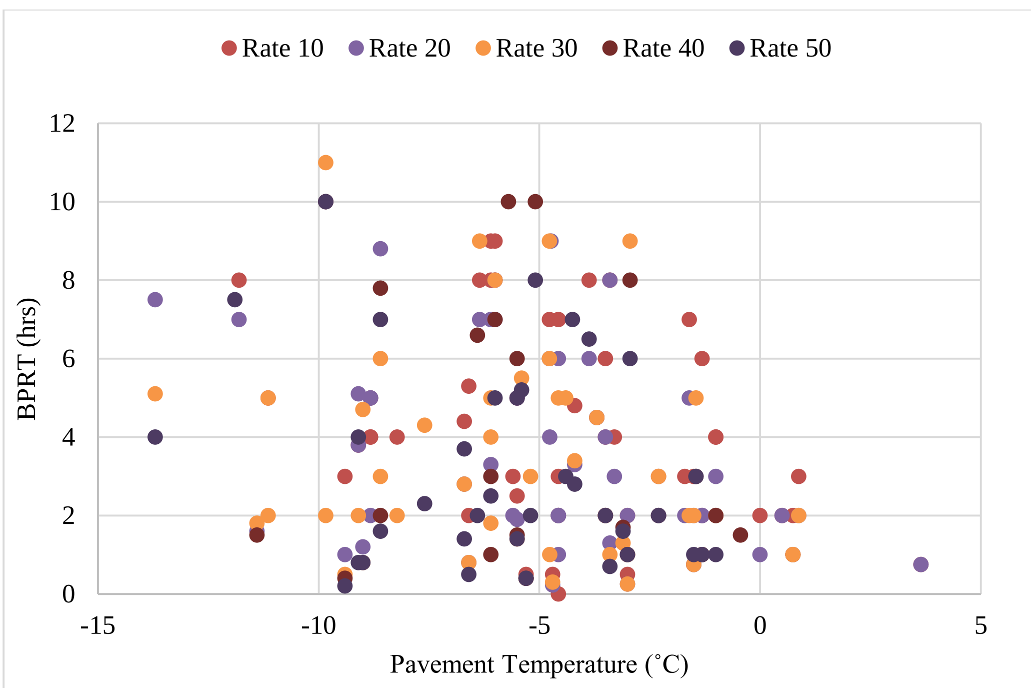
b) Driveways: BPRT vs Rates

Figure 4-4: Bare Pavement Regain Time vs. Salting Rates

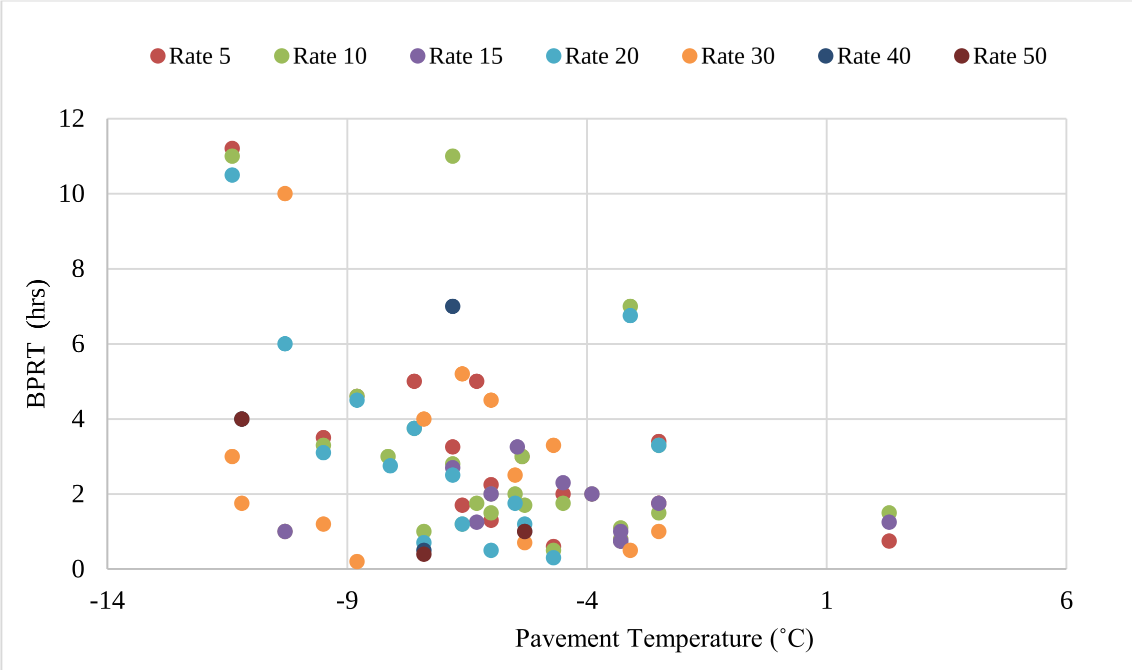
(Notes: Legend shows avg. pavement temperature, snow type and snow thickness on the testing day, P=packed snow, L=loose snow)

4.2.2. Pavement Temperature

Another well-known factor that affects the snow melting performance of salt is the pavement surface temperature. In the tests conducted, a wide spectrum of pavement surface temperature variations were observed, ranging from about -15°C to ~4°C. This large variation provided a good opportunity to observe the effect of pavement surface temperature on the snow melting rate. Figure 4-5 (a) and (b) shows the relationship between BPRT and pavement surface temperature under different application rates observed on stall areas and driveways, respectively. While there are some expected variations under any given range of application rates, a positive relationship between melting speed and pavement surface temperature can still be observed. Thus, the BPRT decreases as the pavement surface temperature increases. The variation in BPRT under a given pavement surface temperature and application rate between different days can be attributed to the effect of other factors, such as snow amount, snow type, and sky-view condition. Note that the snow depth varied from 0.5cm to 7cm for the normal events in the unplowed sections, whereas in the plowed sections snow depth varied from 0.1cm (trace amounts of snow) to 0.5cm snow, depending on the type and quality of the snow plow.



a) Stall Areas: Effect of Pavement Temperature



b) Driveways: Effect of Pavement Temperature on BPRT

Figure 4-5: Effect of Pavement Surface Temperature

4.2.3. Snow Types and Amounts

The types of snow (e.g., loose snow vs. packed snow) and amounts of snow to be melted are expected to have a significant impact on how quickly the section can reach bare pavement status. Figure 4-6 shows the effect of snow type on BPRT. It is generally understood that the pavement in test sections with packed snow (e.g., avg. density 200 kg/m^3) should take longer to become clear than those with a regular/loose snow (e.g., avg. density 100kg/m^3). This is confirmed by the test results that are summarized in Figure 4-6 and Figure 4-7. Once again, as the snow amount increases or as the type of snow is changed from loose to packed snow, the BPRT increases.

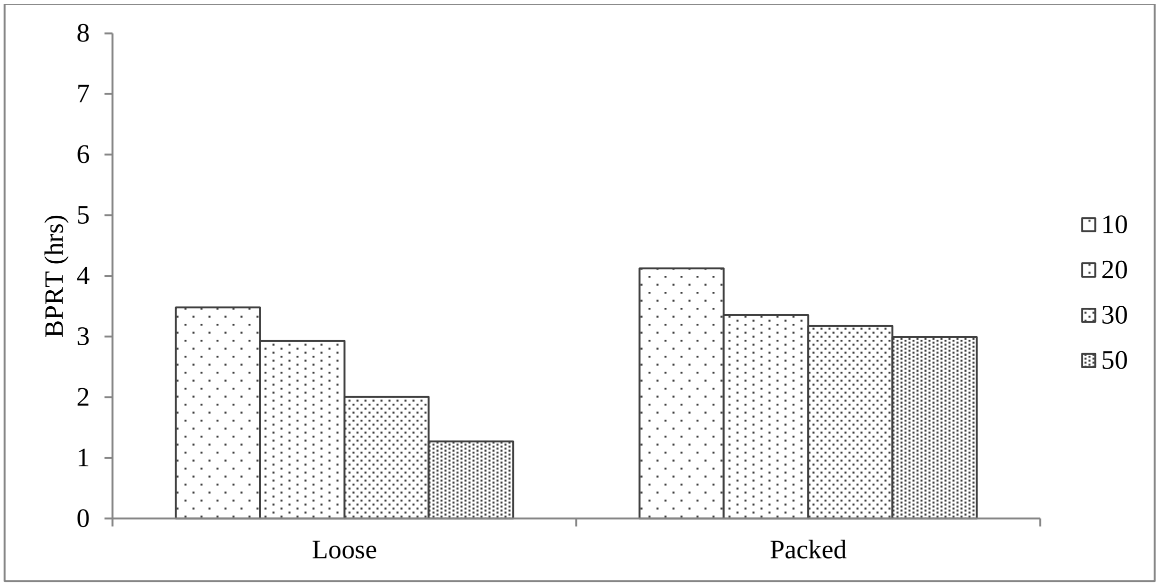


Figure 4-6: Effect of Snow Types

(10, 20, 30, 50 are the application rates in lbs/1000sqft)

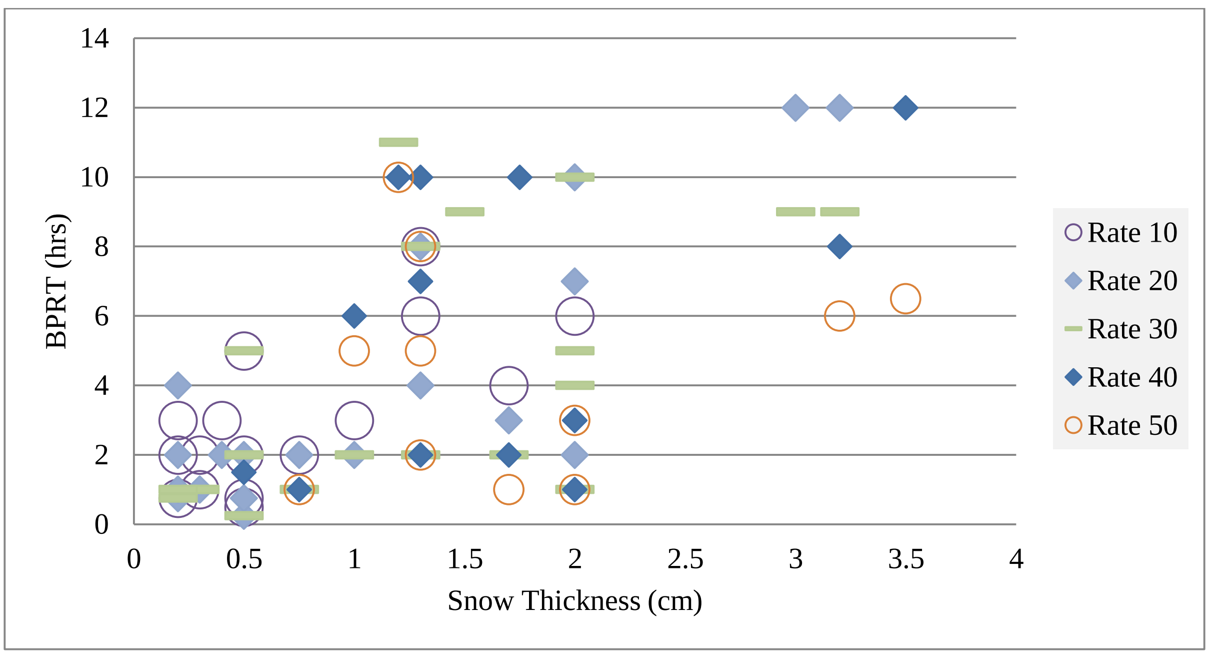


Figure 4-7: Effect of Snow Amount

(10, 20, 30, 40, 50 are the application rates in lbs/1000sqft)

4.3. Regression Analysis on Snow Melting Performance and Influencing Factors

In our exploratory data analysis, it was found that there were a number of factors affecting the snow melting performance of salt in terms of bare pavement regain time. To demonstrate the relationship between the influencing factors and the performance factors (BPRT) with statistical reliability and in a rigorous way, a multivariate linear regression analysis was performed. From this analysis, the significant factors that affect the difference in performance were determined. To do this, all the data collected from the three winter seasons were organized by stall areas and driveways. There were approximately 1000 tests for stall areas and 150 tests for driveways. Tests with incomplete data, insufficient bare pavement status, extreme conditions (e.g., 10 cm of snow), freezing rain, and do-nothing sections (control sections) were excluded from the data used for modeling. Note that the bare pavement regain time has been estimated for tests that ended with BP status of 60 to 70% through extrapolation from the last observation to an 80% BP status.

Table 4-3 gives the summary statistics of the variables which were considered in the subsequent multiple regression analysis. The total amount of snow on a section was calculated as the product of the snow density and depth of snow on the section.

Table 4-3: Descriptive Statistics of the Data

Variable	Stall Areas			Driveway		
	(Minimum, Maximum)	Mean	Std. Dev.	(Minimum, Maximum)	Mean	Std. Dev.
Salting Rates (lbs/1000sqft)	(5, 70)	25.52	14.16	(2, 40)	11.00	8.54
Pavement Surface Temperature (°C)	(-14.48, 3.65)	-5.08	3.37	(-9.5, 2.3)	-5.58	2.23
Amount of Snow in kg/m^2 (Snow Depth in cm x Density in kg/m^3)	(0.1, 7.8)	0.91	1.21	(0.1, 4)	0.56	0.84
Traffic Volume (Vehicles/hr)	(NA)	(NA)	(NA)	(20, 68)	41.49	11.40
BPRT (hrs)	(0.5, 10.0)	3.82	2.85	(0.5, 5)	2.04	1.16

4.3.1. Discussion on Regression Results

It was found that all the variables considered had significant relationship with the BPRT. The significance of each contributing variable was tested using a p-value at a level of significance of 5%. Following these steps, it was found that salting application rate, pavement surface temperature, amount of snow, and traffic count for the driveways were statistically significant. The results of the multivariate regression analysis are summarized in Table 4-4.

Table 4-4: Summary Results of Multiple Regression Analysis (Dependent Variable=BPRT)

Variables	Stall Areas			Driveways		
	Coefficient	t Stat	P-value	Coefficient	t Stat	P-value
Intercept	3.258	10.696	1E-23	2.508	4.265	0.00015
Salting Rates (lbs/1000sqft)	-0.0637	-7.07	6.4E-12	-0.040	-2.502	0.01730
Pavement Surface Temperature (°C)	-0.285	-7.45	5.5E-13	-0.270	-4.679	4.45E-5
Amount of Snow in kg/m^2 (Snow Depth in cm x Density in kg/m^3)	0.636	8.79	5.9E-17	0.327	1.776	0.08453
Traffic Volume (veh/hr)	NA	NA	NA	-0.041	-3.394	0.00017
No of Observations (n) and R^2	413, R^2=0.25			39, R^2=0.61		

4.3.2. Salt Application Rate

As anticipated, the amount of salt applied had a significant effect on BPRT. The negative model coefficient makes intuitive sense, as it suggests that a higher application rate results in a lower BPRT, thus accelerating the snow melting process. The magnitude of the coefficient (0.0637) indicates that for every 10lbs/1000sqft increase in application rate, the snow melting time is shortened by 0.637 hours for the stall areas; however, the reduction of snow melting time is 0.40 hour for the driveways (since driveway model coefficient is 0.040). This confirms the observation made in the exploratory data analysis that the BPRT in driveways in less sensitive to the application rate applied.

4.3.3. Pavement Temperature

Average pavement surface temperature was found to have a statistically significant effect on BPRT. The negative coefficient value suggests that a higher pavement temperature results in a shorter amount of time needed to reach a desired level of service. For a given snow event, this model coefficient indicates that for every 1°C increase in pavement temperature, the BPRT will be shortened by approximately 0.29 hours and

0.27 hours for stall areas and driveways respectively. This significant effect of temperature suggests the importance of having good forecasts and estimations of pavement temperature when choosing the right salt application rates.

4.3.4. Amount of Snow

As expected, the snow amount was also found to be statistically significant in the BPRT models and the association was found to be positive. This makes intuitive sense, as it suggests that either an increase in snow depth or snow density will lead to an increase in the amount of time needed to melt the snow. The coefficients are 0.636 and 0.327 for stall areas and driveways respectively, meaning the effect of amount of snow in stall areas is much higher than in driveways

4.3.5. Traffic Volume

The traffic volume in the driveways was also found to be statistically significant in the model. The negative model coefficient suggests intuitively that as traffic increases, the snow melting time will be reduced.

4.4. Modeling the Snow Melting Performance of Salt (Physical-Empirical Based)

With an understanding of the data obtained from field tests through exploratory data analysis (EDA) and regression analysis and with the knowledge of the physical behavior of snow melting discussed in the literature review (section 2.6), this section presents the snow melting model developed and how this model can be used for determining optimum salt rates for any given weather scenario. This modelling effort combines the results from the exploratory analysis in the previous section and a basic understanding of the snow melting process that occur after salt application. Recall that past studies (e.g., Zhang et al. 2009) have reported that when salt (e.g., NaCl) is dissolved in water it lowers the freezing point of the resulting solution. This concept is illustrated in Figure 4-8, and from this figure, it can be clearly seen that as the salt concentration in the solution increases the freezing point decreases. This trend continues until the mixture reaches a salt concentration of about 23%. At this point, no additional salt will dissolve in the solution as the salt concentration has reached the saturation point and, consequently, the freezing temperature of the solution will be at the lowest value possible, -21^{o}C. Intuitively, it is clear that as the pavement temperature decreases, more salt will be needed to convert the snow or ice into a liquid solution; therefore, the ideal application rate can be theoretically defined as the amount of salt required to keep the solution from re-freezing.

Using the above relationship, it can be assumed that the concentration of salt required at any temperature will follow the relationship described in Equation 4-1.

$C = \frac{c_e T}{T_e}$ (Where $T_e \leq T \leq 0$) 4-1

where:

C is the required concentration to prevent freezing

c_e is the eutectic concentration of salt solution

T is the current temperature

T_e is the eutectic temperature of salt solution

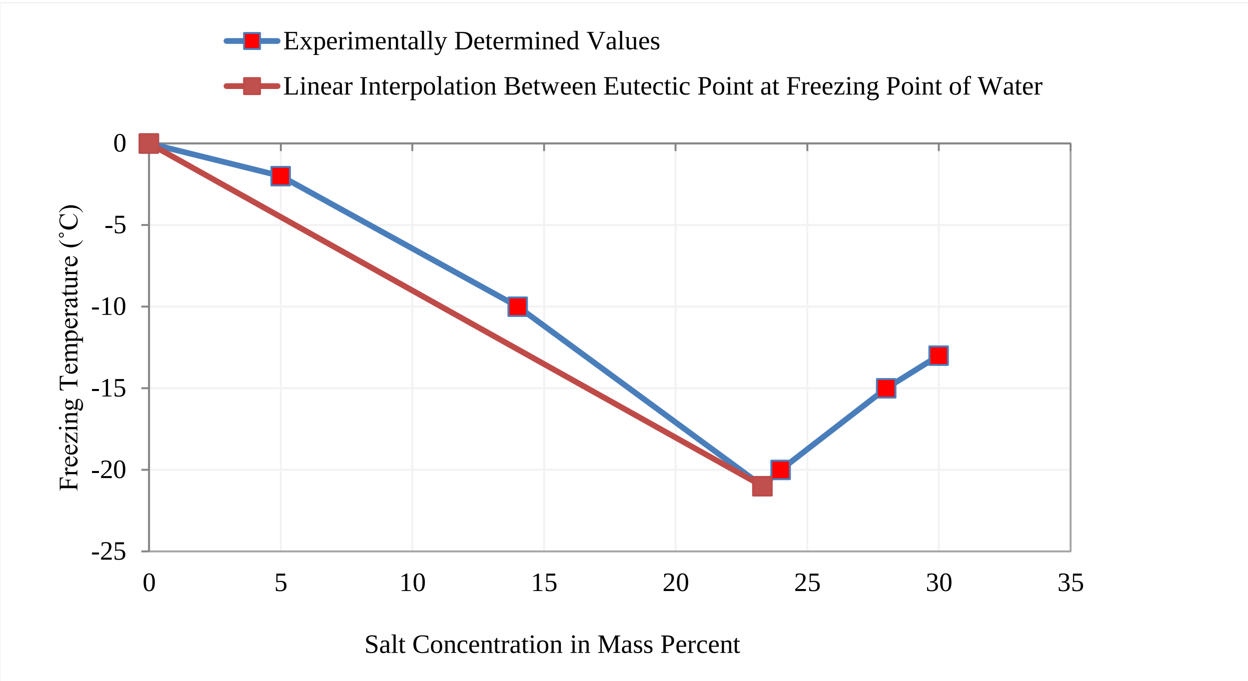


Figure 4-8: Eutectic Temperature and Concentration of Salt Solution

4.4.1. Ideal Application Rate for Prevention of Freezing

As indicated previously, the amount (i.e., concentration) of salt required to prevent the liquid from freezing can be calculated with the help of Equation 4-1. Using the results of this process, the quantity of salt needed to melt a given amount of snow/ice can be calculated. Intuitively, the amount (height) and the type (density) of snow can be used to determine the total amount of snow/ice present and thus the amount of salt that will be required to keep the concentration of the resulting solution equal to the concentration calculated in Equation 4-1. Equation 4-2 shows an expression for the ideal application rate needed to melt any quantity of snow, given its height and density.

$C = \frac{R_0}{R_0 + H_0 \rho}$ i.e.,

$$R_0 = \frac{H_0 \rho C}{1 - C} \quad 4\text{-}2$$

Where:

R_0 is the ideal application rate

H_0 is the height of snow/ice

ρ is the density of snow/ice

C is the required concentration to prevent freezing (Equation 4-1)

When Equation 4-1 is substituted into Equation 4-2, the following equation can be obtained:

$$R_0 = c_e * T * \rho * \frac{H_0}{T_e - c_e * T} \quad 4\text{-}3$$

4.4.2. Modeling Snow Melting with Respect to Time

In theory, the application rate calculated in the previous section should be sufficient to melt a given amount of snow and ice; however, the amount of time required to melt snow also depends on the application method, snow amount, pavement temperature and other factors (e.g., pavement type, sky-view etc.). It can be assumed that at any given time t, the amount of snow melted will be an exponential decay function of time (i.e., when *t* equals to 0, Q_t is 0, and when *t* tends to ∞, Q_t tends to 100%) as shown in Equation 4-4.

$$Q_t = 1 - e^{-Bt} \quad 4\text{-}4$$

Where,

Q_t is the fraction of snow that melted at given time *t*.

B is the melting speed coefficient representing the speed of melting.

It is generally understood that the melting speed (B) will depend on the actual application rate, prevailing surface temperature, eutectic temperature and concatenation of the given chemical. Intuitively, to accelerate the melting process an amount greater than the value of R_0 calculated by Equation 4-3 will have to be applied. Moreover, this relationship will also depend on the current temperature T and its difference from the eutectic temperature T_e. The impact of both these phenomena is modeled by Equation 4-5.

$$B = \frac{R}{R_0} \left(\frac{T_e - T}{T_e} \right) \beta_0 \quad 4\text{-}5$$

$$\text{i.e., } R = B * R_0 * \frac{T_e}{\beta_0 * (T_e - T)} \quad 4\text{-}6$$

Where β_0 is the constant for calibration and represents other factors that may influence the melting rate. β_0 has been calibrated and validated through the maintenance and bare pavement recovery time data collected in our field tests which is discussed in the following section.

From Equation 4-4, we know that $Q_t = 1 - e^{-Bt}$. As defined before, the bare pavement regain time (BPRT) is the amount of time (t) for at least 80% of the pavement surface to reach bare status (i.e., 80% snow is melted at a test section). We can re-write the equation as follows:

$0.8 = 1 - e^{-B*BPRT}$

$0.2 = e^{-B*BPRT}$

$$B = \frac{ln0.2}{-BPRT} \qquad 4\text{-}7$$

Finally, we substitute both Equation 4-3 and Equation 4-7 into Equation 4-6 to solve for the application rate required given the pavement temperature, snow depth, and BPRT (i.e., surrogate for level of service requirment). The eutectic temperature, eutectic concentration, and the calibration factor are the same as in the previous section and can be considered as constants. This is demonstrated below in Equation 4-8

$$R = ln0.2 * T_e * C_e * T * \rho * \frac{H_0}{(T_e - C_e * T) * (T - T_e) * BPRT * \beta_0} \qquad 4\text{-}8$$

The minimum application rate can be determined for a given weather scenario with snow type (ρ) , snow depth (H_0), pavement temperature(T), chemical type $(C_{e,}T_e)$, and bare pavement regain time. The above discussed modeling steps have been shown in Figure 4-9 through a flow chart for easy understanding.

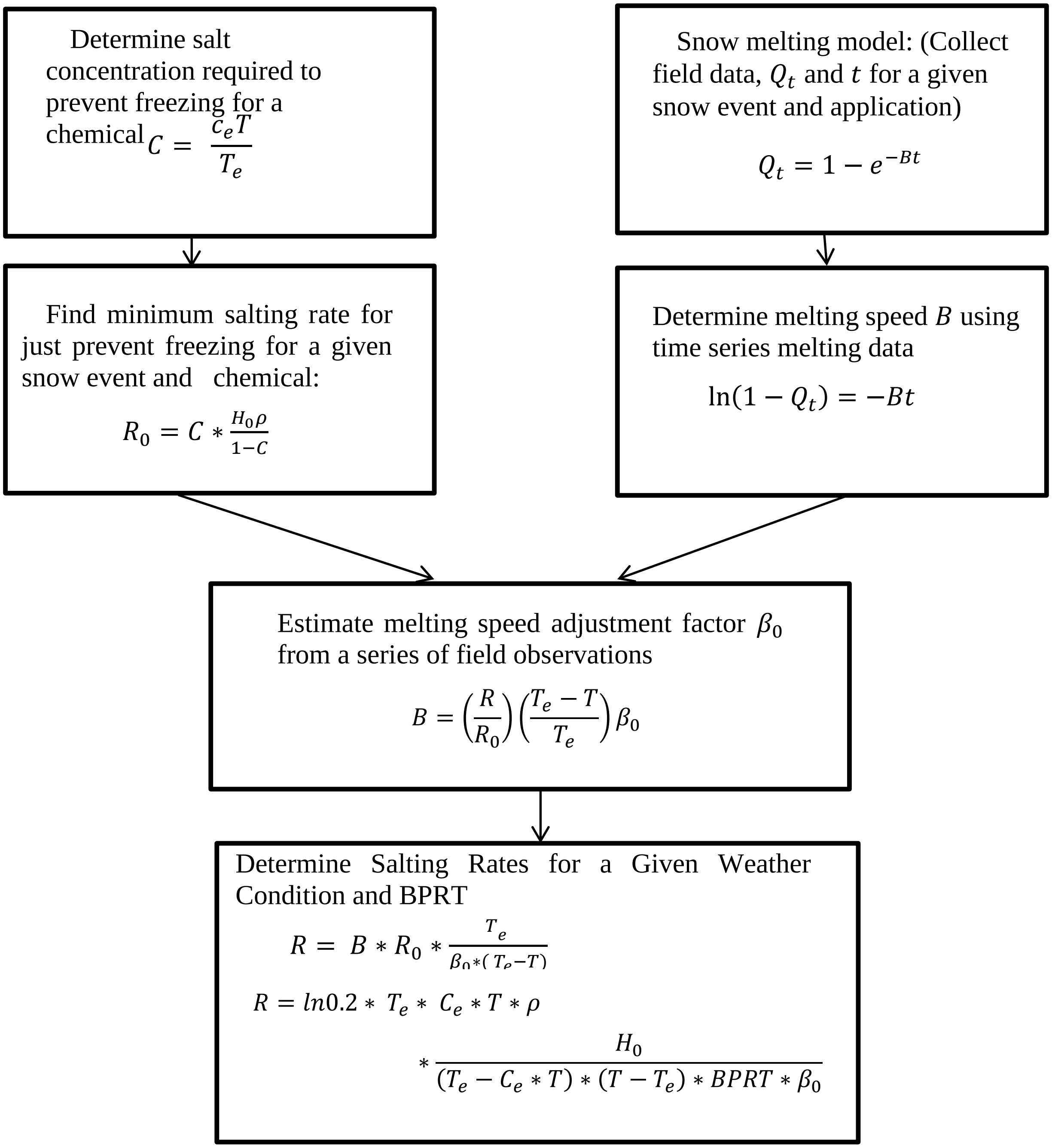


Figure 4-9: Flow Chart for Estimating Model and Salt Application Rates

4.5. Model Estimation using Field Test Data

4.5.1. Minimum (Ideal for preventing from freezing only) Application Rates, R_0

Utilizing Equations 4-1 and 4-2 from the previous section, the ideal application rate for each testing day can be obtained. From Equation 4-1, we can calculate the required salt concentration to prevent freezing, *C*, by inputting the average pavement temperature recorded on the day and by knowing from experimental data that the eutectic concentration is 23.3 mass percent and that the eutectic temperature is -21.1˚C. After obtaining the value of *C* from Equation 4-1, we can use this value in Equation 4- 2. The value of R_0 can be calculated using the density and height of snow on the test day along with the required concentration obtained previously.

Table 4-5: Sample Calculation of R_0 for Three Testing Days

Date	Avg. Pave Temp (˚C)	C (T) $[C = \frac{c_e T}{T_e}]$	Density (kg/m3)	Snow depth (cm)	R_o (Kg/m2)	R_o (lbs/1000sqft)
26/01/2013	-6.35	0.070	148	0.20	0.022	4.48
06/02/2013	-3.20	0.035	100	0.50	0.018	3.67
20/03/2013	-7.50	0.083	80	0.2	0.035	7.50

4.5.2. Melting Speed ($\boldsymbol{B}$)

The recorded field test data were used to calibrate the model. The data required for each day of testing consisted of the different application rates used on the day, % bare pavement recorded after specified time intervals for each application rate (later used for linear regression), the average pavement temperature for the day, the density and height of snow on the testing days. Recall Equation 4-3 from the previous section; with some manipulations of the equation, we can achieve Equation 4-8 as shown below:

$$Q_t = 1 - e^{-Bt}$$

$$1 - Q_t = e^{-Bt}$$

$$\ln(1 - Q_t) = -Bt \qquad 4\text{-}8$$

Using the above steps, the equation can be linearized. In this case, the natural logarithm of one minus the % of snow melted (or the % of bare pavement recovered) is the output variable and time is the independent variable; additionally, the slope is $-B$ and y-intercept is zero. On a given test day, for each distinct test section, linear regression was performed on observed % percent bare pavement and elapsed time to obtain the slope of the line by plotting $\ln(1 - Q_t)$ vs t. The B values obtained from the field tests data for stall areas of the parking lots are shown in Figure 4-10 in a scatter plot as an example.

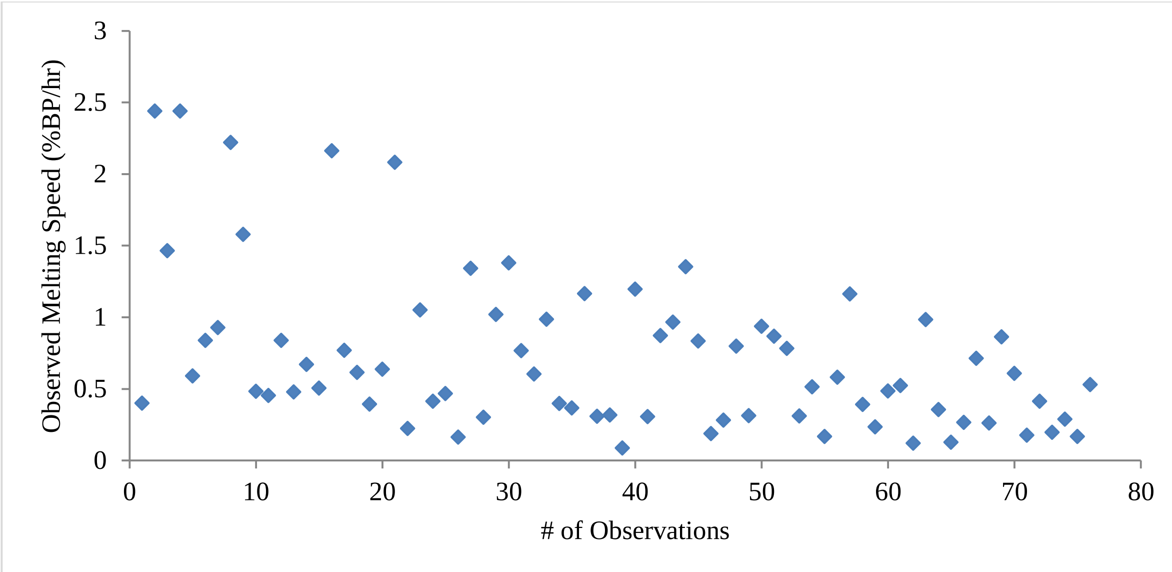


Figure 4-10: Observed Melting Speed (B) from the Field Tests Data

4.5.3. Model Calibration Factor (Melting Speed Adjustment Factor), $\boldsymbol{\beta_0}$

Once the melting speed coefficient, B, and the ideal application rate, R_0**,** were obtained for a given weather scenario, regression analysis was conducted using equation 4-5 to estimate the calibration factor, i.e., melting speed adjustment factor, β_0 as shown in Table 4-6. The regression analysis is also provided in the appendix.

Table 4-6: Calibrated Melting Speed Adjustment Factor ($\boldsymbol{\beta_0}$)

Traffic Zone	(β_0)
Stall Areas	0.49
Driveways (Low traffic,<30 veh/hr)	0.84
Driveways (Medium Traffic, 30-50 veh/hr)	1.20
Driveways (High Traffic, 50-80 veh/hr)	1.30

4.5.4. Model Validation

The quality of the calibrated model was then validated using a set of holdout data extracted from the test results in the same fashion discussed in a previous section. Figure 4-11 shows a comparison between the applied application rates during field tests and the calculated application rates from the model.

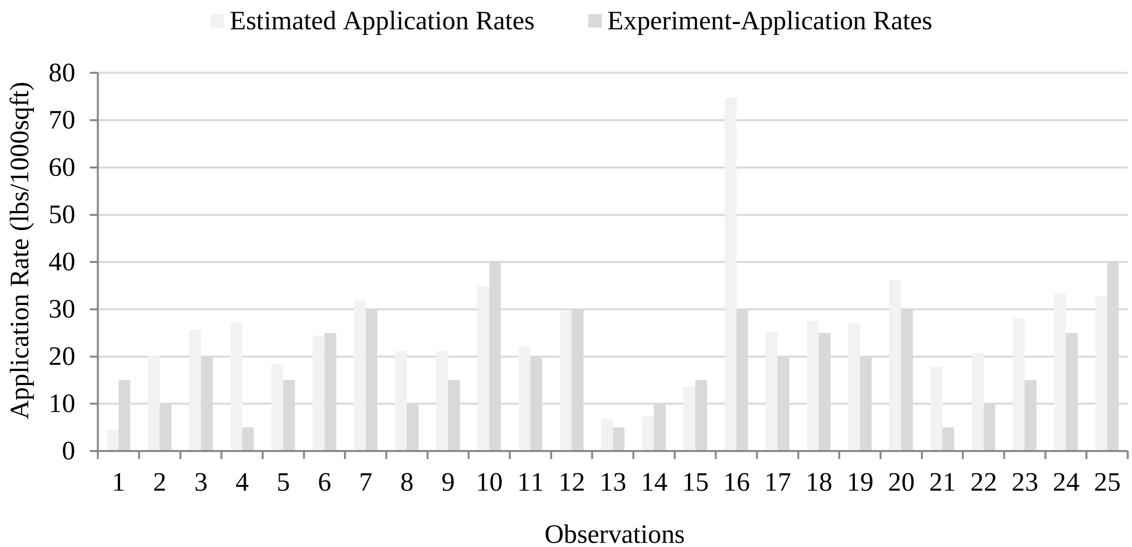


Figure 4-11: Model Validation

4.6 Development of Optimum Salts Application Rates from Snow Melting Model

The snow melting model described in the previous section can be used to determine the minimum amount of salt required to achieve a given level of service (BPRT), based on the amount of snow to be melted, the average pavement temperature over the period of interest, and the salt application rate. Table 4-7 shows salt application rates for snow amounts varying from 0.5cm to 2.5cm for regular snow type (density=100Kg/m^3) and for a given set of pavement temperature ranges. The total snow amount (depth) includes both the snow that has already existed on the pavement at the time when salt is applied and the future precipitation. As a result, the snow melting time includes both the duration of future precipitation and desired BPRT. For example, consider a particular parking lot and a particular snow event with an average pavement surface temperature of -5°C. After the snow event ends, an average of 1 cm of snow is deposited on the pavement. Suppose the parking lot needs to reach bare pavement within 3 hours (i.e., the desired BPRT = 3 hrs.), according to the Table 4-7, the minimum application rate should therefore be 19lbs/1000sqft. It should be noted again that the recommended application rates should be viewed as an upper bound as they do not account for the expected positive effects of vehicular traffic. Table 4-8 shows the application rate for aggregated conditions. Note that for practicality, three ranges were considered for both BPRT and pavement temperatures.

Table 4-7: Application Rates for Stall Areas (lbs/1000 sqft) (Base Rates)

Snow depth (cm)	(Avg Tp ˚C)	Desired LOS in BPRT (hr)					
		1	2	3	4	5	6
0.1 to 0.5	-1 to -3	6	3	2	1	1	1
0.1 to 0.5	-4 to -6	17	9	6	4	3	3
0.1 to 0.5	-7 to -9	35	18	12	9	7	6
0.5 to 1.5	-1 to -3	19	9	6	5	4	3
0.5 to 1.5	-4 to -6	58	29	19	14	12	10
0.5 to 1.5	-7 to -9	117	59	39	29	23	20
1.5 to 2.5	-1 to -3	38	19	13	9	8	6
1.5 to 2.5	-4 to -6	115	58	38	29	23	19
1.5 to 2.5	-7 to -9	235	117	78	59	47	39

Table 4-8: Aggregated Base Application Rates (lbs/1000sqft) for Stall Areas (upto 2cm snow)

Average Pavement Temperature (°C)	Bare Pavement Regain Time (1 to 2 hrs)	Bare Pavement Regain Time (3 to 4 hrs)	Bare Pavement Regain Time (5 to 6 hrs)
-1 to -3	15	6	4
-4 to -6	45	15	10
-7 to -9	85	35	20

Application Rates-Adjustment for Traffic

The snow melting model described previously can be used to derive the expected amount of salt required for meeting specific level of service (LOS) requirements under a given set of weather conditions and external conditions. With the results from this research, adjustment factors were developed to account the effect of traffic in determining the optimum application rates for parking lot driveways. While detail application rates for different weather scenarios and traffic volumes are shown in the appendix, Table 4-9 shows the adjustment factors for a set of aggregate condition. These adjustment factors were determined by calculating the application rates needed for parking lot areas with and without or little traffic effect (i.e., driveways vs. stall areas) at aggregated level. The values can be used to determine the recommended application rates from the base rate (i.e., application rates for stall areas, presented earlier) for driveway sections for a given facility with a rough estimate of the traffic volume in that facility (e.g., low traffic, less than 30 veh/hr, medium 30-50 veh/hr, high 50-80 veh/hr).

Table 4-9: Adjustment Factors for Application Rates on Driveway Areas for Different Traffic Counts

Traffic Volume	Adjustment Factor
Low Traffic (<30 veh/hr) (e.g., Staff parking lot)	0.45
Medium (30-50 veh/hr) (e.g., Restaurant)	0.35
High Traffic (50-80 veh/hr) (e.g., Shopping plaza)	0.30

Application Rates – Adjustment for Pavement Types

From the perspective of optimizing salting, applying salt to control snow and ice on pavement often raises a question: Should there be any difference in the amount of salt applied when treating different types of pavements to achieve the same level of service? It is generally understood that the performance of salt is mainly influenced by its melting properties (i.e., ice melting capacity, eutectic temperature, and dilution potential), as well as the type and amount of snow and the combined temperature of the prevailing system (i.e., pavement surface, contaminant present, snow-salt solution, and air). But, as discussed in the previous section, pavement surface temperature was found to be statically significant, indicating that it may also be affected by properties of the major surface materials. While both asphalt and Portland cement concrete pavements are often made from similar coarse aggregates (e.g., stone chips, crushed gravels, etc.) which provide the bulk of the concrete volume, the cementitious materials used to bind these coarse aggregates are different: Asphalt/bituminous materials for asphalt pavement and Portland cement for concrete pavement. If all other elements which may affect snow melting performance of salt are kept constant, the change in snow melting rate for a given salt application on these pavements can be attributed to the differential thermodynamic properties of these ingredients (Asphalt and Cement).

This section presents the results of the tests focused on investigating if that snow melting rate is varied between the pavement types, with the intent to develop an adjustment factor for pavement types that can be applied to the application rate, based on a comparative analysis of snow melting performance on different pavement types. Approximately 400 tests were conducted, covering three different pavement types. The tests were conducted in 27 snow events during the winter season of 2014. The snow melting performance of salt is compared on asphalt concrete (AC), Portland cement concrete (PCC), and interlocked concrete pavers (IC) pavements in terms of melting speed (i.e., percentage bare pavement/hour).

Asphalt Concrete vs PCC Pavements

To investigate differences in performance between two pavement surfaces, all tests where the same application rates were applied on the same day to both pavements were grouped. The results of these tests were then compared and the weather data from these dates were examined. This is followed by a statistical analysis.

Figure 4-12-a shows the melting speed observed on paired test sections. It can be seen that there are mixed results on the performances of salt on AC and PCC. However, in general, the melting speed on AC was faster than that on PCC can be seen in this figure. The opposite results were observed for quite a few cases. These variations likely occur due to other uncontrollable factors endemic to the field testing environment. Examples of such factors include but are not restricted to the non-uniformity of snow amount across the tests sections, non-uniformity in pavement surface temperatures, and the presence of trees along some test sections, blocking sunlight in some sections.

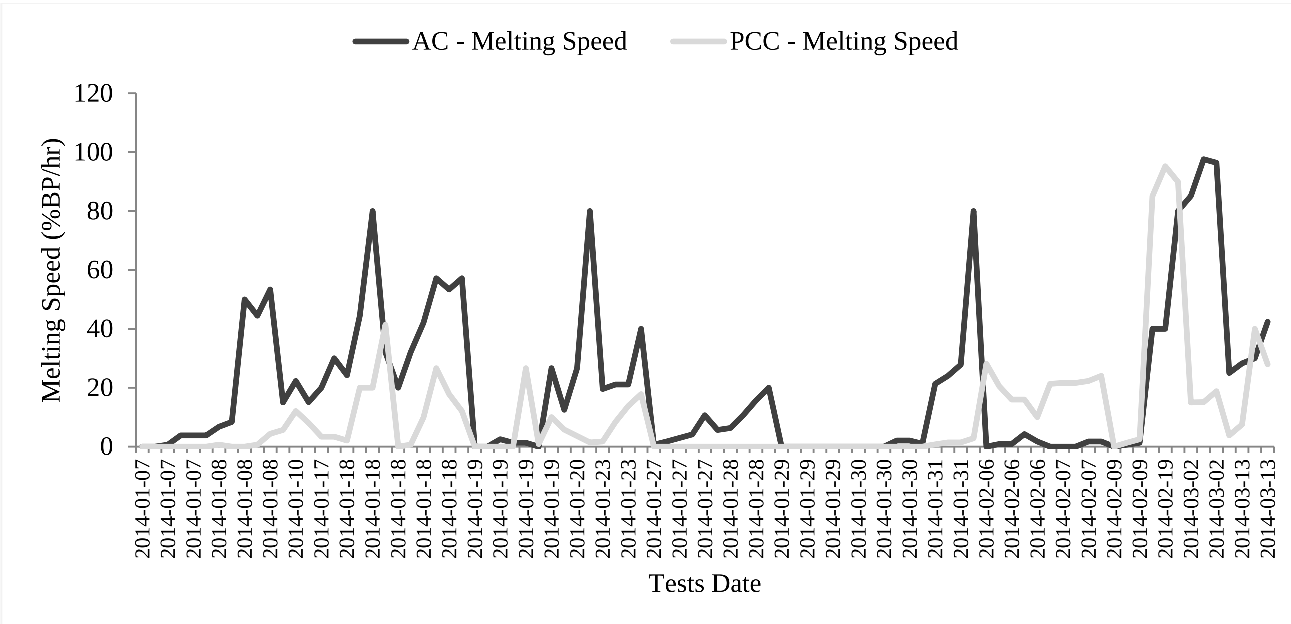
To understand the source of these variations, data were further stratified on the basis of some selected factors (e.g., snow amount, surface temperature). Figure 4-12-b shows the snow/ice amount between the two pavement types. Despite attempts being made to achieve uniformity, it was observed that there were significant differences between the total snow amounts remaining on the test sections between the pavement types. Specifically, there are a number of days in which the concrete pavement test sites had a higher total snow amount than the asphalt pavement. Recall that, regarding snow/ice data, two measurements were made: snow depth (in cm) and snow density (kg/m^3). The total snow/ice amount is estimated from these measurements. It can also be observed that there are small differences in surface temperatures between the two pavements (Figure 4-12-c).

To check whether differences in melting speed are statistically significant, and which factors contribute to this difference, two statistical analyses were performed on each pavement's dataset: t-tests for checking differences in means between the samples of two populations and a stepwise multivariate regression analysis for determining the statistically significant factors that affect the observed difference in melting speed between the pavement types.

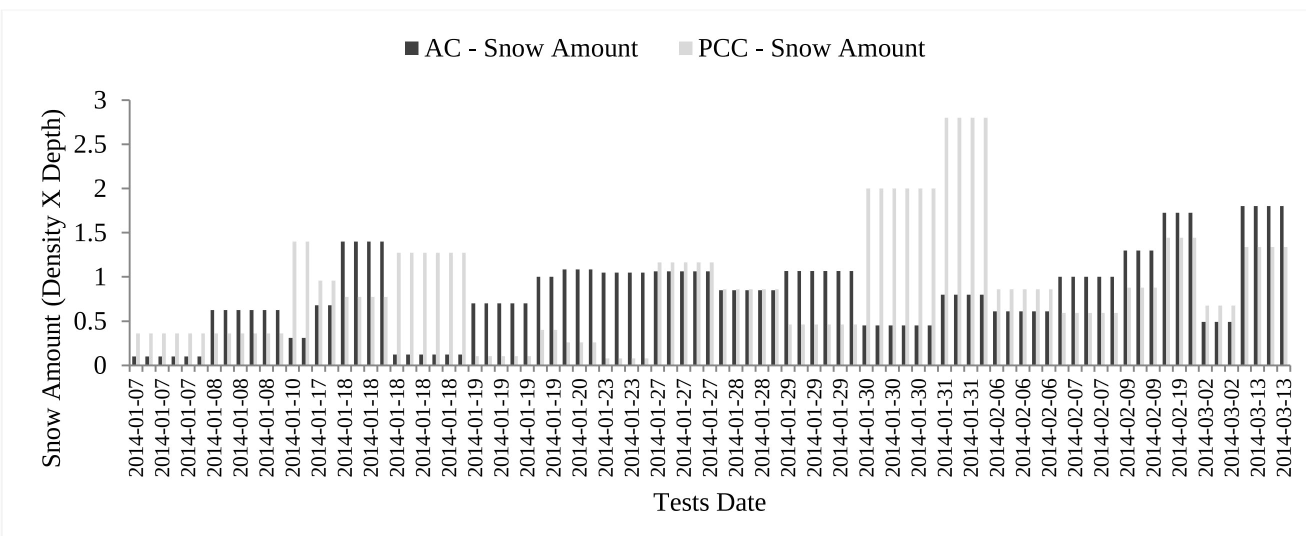
Using 178 comparable test results, it can be concluded from the t-test that the differences in average melting speed between AC and PCC are statistically significant at a 95% confidence level. On average, the snow melting rate on AC was 10% faster than PCC. If the relationship between application rate and level of service (i.e., time required to reach bare pavement) is known, the additional increase in application rate needed to achieve the same desired level of service can be found.

Next, a regression analysis between the difference in melting speed and factors suspected as being influential was performed. The summary of the results from this regression is given in Table 4-11. It can be observed that the differences in melting speed were associated with the differences in snow amount on the two types of pavement. As expected, the difference in snow amount is negatively correlated with the difference in melting speed, with a coefficient of -5.54%/hr, and this difference was found to be statistically significant. Intuitively, this means that if there is more snow on the asphalt pavement than on the concrete pavement, the comparative performance advantage of asphalt would be less. All other initially suspected factors (e.g., pavement temperature) were not found to be statistically significant in explaining the remaining difference in melting speed. This is likely due to the fact that there were little differences in these factors between the two types of pavement. Further research might be necessary to substantiate this finding, which, if done, should take into consideration details of the thermodynamic properties of surface materials or performing laboratory tests to observe the effect of surface types on snow melting.

The intercept of the regression model, which can be interpreted as the expected mean difference in melting speed between the pavement types when external factors (snow amount and temperature) are controlled, is 9.94%/hr, which is statistically significant at a 95% confidence level. This means that if the snow amount is same on AC and PCC, the difference in melting speed will be approximately equal to 10%, consistent with the t-test analysis.

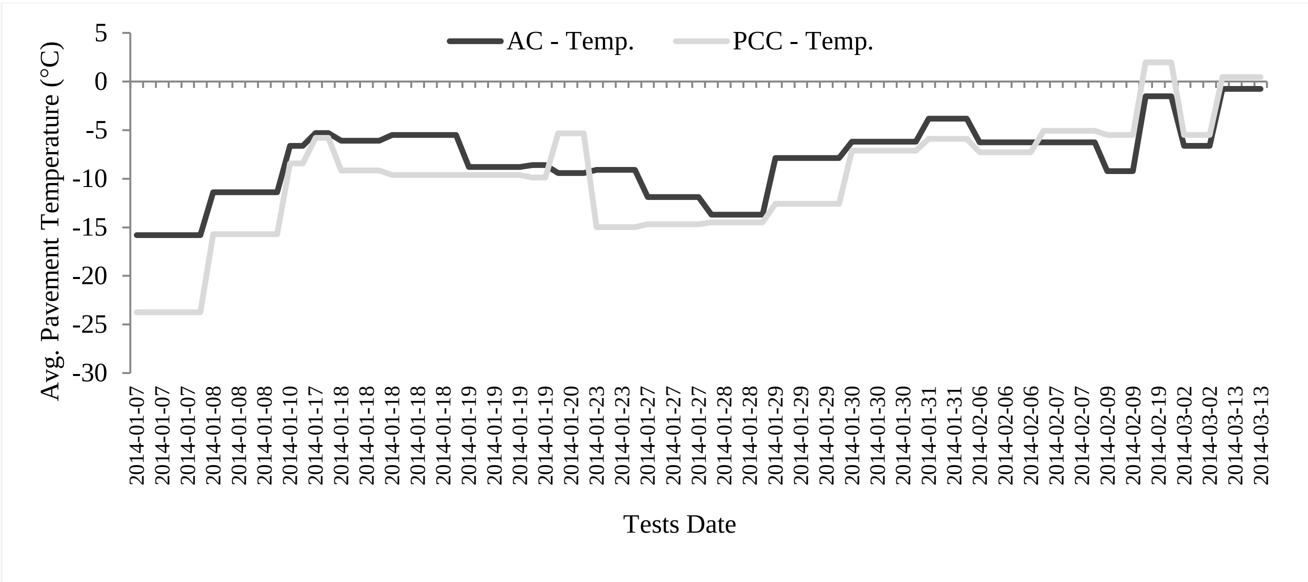


a) Melting Speed over the Test Sections



b) Snow Amount (kg/m^2)

(Note: Depth in cm and Density in Kg/m^3)



c) Surface Temperature over the Test Sections

Figure 4-12: Snow Melting Speed and Weather Features of AC and PCC Pavements

Table 4-10: t-Test Results for Checking Difference in Mean Performance between AC and PCC Pavements

Total Number of Observations on Asphalt and Concrete Pavements (AC and PCC)	178
Observed Difference in Mean Performance between AC and PCC (%BP/hr)	10.08
Standard Deviation (%BP/hr)	25.20
Standard Error (%)	2.67
Hypothesized Mean Difference (%BP/hr)	0
Significance Level	0.05
Tails	1
Degree of Freedom	88
t-calculated	3.77
p-value	0.00
t-critical	1.66
Statistical Conclusion	Reject the NULL hypothesis that "mean snow melting performances on two pavement types are the same"

Table 4-11: Summary Results of Regression Analysis for the Difference in Melting Speed between AC and PCC

Variables	Coefficient	P-value
Intercept	9.94	0.002*
Difference in Pavement Surface Temperature (°C)	0.477	0.58
Difference in Snow Amount-Density (kg/m3) X Depth (cm)	-5.54	0.02*
No of Observations (n), Significance of Model (F), and Regression Coefficient		89, F=0.04, R^2=0.06

Comparative Analysis: Portland cement concrete vs. Interlocking concrete pavers

Because tests were also conducted on pavement made of interlocking concrete pavers, a similar analysis can be used to compare the differences in melting speed between PCC and IC. In this section, data from tests where the same application rate was applied to both pavements on the same day was compared and weather data from these dates is examined.

An exploratory analysis on the melting speed was conducted on paired tests. The performances of salt on PCC and IC appeared to be very similar, apart from a few days where the melting speed of PCC was approximately double that of IC. Likewise, there are a few days where the melting speed of IC appears higher than that of PCC. Again, these variations may be a result of other uncontrollable environmental factors, such as the effectiveness of the plow trucks.

The difference in total snow amount (density multiplied by depth) between the test sections was again suspected as an influencing factor, so the snow amounts on both pavement types were analyzed, both graphically and through analytical tools. Some differences were observed, though they did not appear to correlate with days on which differences in melting speeds were observed. The average pavement temperature for the two pavements in the comparable tests was also graphed and examined, and very little difference was observed.

On average, the snow melting rate on PCC was 1.4% higher than IC. To check whether this difference in melting speed is statistically significant, t-tests for checking differences in means between the compared tests were conducted (Table 4-12). From these tests, it can be concluded that the differences in average melting speed between PCC and IC are statistically insignificant at a 95% confidence level. Intuitively, this makes sense, as the weather conditions are not only similar but the material used in the construction of the pavements is the same. The only difference is in the design of the pavement. This suggests that whatever treatment is found to be effective on PCC can also be used on IC to achieve the same level of service. In addition, it suggests that, from a winter maintenance perspective, neither of the two pavements offer an advantage over the other. However, it was found that the snow melting speed on AC was faster than on PCC/IC. This in turn suggests that an application rate that includes approximately 10% more salt is needed to achieve the same LOS for a given weather condition (Table 4-13).

Table 4-12: t-Test for Mean Performance Difference between PCC and IC

Total Number of Observations	192
Observed Difference in Mean Performance between PCC and IC (%BP/hr)	1.43
Standard Deviation (%BP/hr)	14.88
Standard Error (%)	2.67
Hypothesized Mean Difference (%BP/hr)	0
Significance Level	0.05
Tails	1
Degree of Freedom	95
t-calculated	1.33
p-value	0.09
t-critical	1.66
Statistical Conclusion	No evidence to reject that "mean snow melting performances on two pavement types are same"

Table 4-13: Adjustment Factor for Pavement Types

Pavement Type	Adjustment Factor
Asphalt Concrete	1.00
Portland Cement Concrete/Interlocking Concrete Pavers	1.10

4.6. Summary of the Chapter

This chapter presents the results of deicing tests aiming at quantifying the effect of various factors on the snow melting performance of road salt. Approximately 1200 field tests were conducted in the winter seasons of 2011-2012, 2012-2013, and 2013-2014; these tests covered approximately 100 snow events and include a variety of weather conditions. The data collected from the field tests included snow amount, snow coverage (bare pavement status), pavement and air temperature, traffic count, etc. A detailed exploratory data analysis was conducted to better understand the relationship between each factor and the snow melting performance of salt. A multiple linear regression analysis was then performed to quantify the effects of each factor. After the exploratory data analysis and regression analysis, a mechanistic-empirical model was developed for the snow melting performance of salt. The model has been calibrated and validated using the field data collected. The main findings of this research are summarized below:

- It was concluded that application rate, pavement temperature, snow amount and traffic had a statistically significant effect on the snow melting performance of salt.
- It was clearly observed that salting was more effective on the driveway test sections than the parking stall test sections. This resulted from the different traffic patterns and higher amounts of traffic in the driveway sections of the parking lot in comparison with the parking stall areas.
- The study concluded that to reduce salt usage while still achieving the desired levels of service, different application rates should be applied for stall areas and driveways.
- The research has developed salt application rate adjustment factors for a set of aggregated conditions by quantifying the effect of traffic on the snow melting performance of salt through statistical models.
- Better snow melting performance was observed on parking stalls with shorter parking durations. This is likely due to a combination the effect of sunlight, exhaust fumes and tire tractions. Parking stalls with shorter parking durations and higher turnarounds are expected to have longer exposure to sunlight, higher vehicle exhaust heat, and more tire compactions. Since the parking frequency is an uncertain variable in the real world, caution should be taken when reducing the application rate below that of the recommended amount for the stall areas without traffic.
- It is found that snow melting performance also varied depending on the surface type of the pavement. The variation between the pavements was not uniform.
- Between asphalt concrete (AC) and Portland cement concrete (PCC), it is found the snow melting speed on AC was faster than PCC. A total of 178 comparable tests were conducted on the two pavement types. From these sample tests, it was found that the mean snow melting speed on AC was 10% faster than PCC. This difference was found statistically significant at a 95% confidence level.

- A regression analysis has been conducted to understand whether the speed difference between AC and PCC can be accounted for by any influencing factors (e.g., difference in snow amount or temperature). This analysis has shown that there is a difference in melting speed between these surfaces. In addition, a difference in snow amount on the pavements was found to be statistically significant, with a coefficient of -5.54. When weather conditions were identical and when snow depth is included, the difference in melting speed predicted is approximately 10%/hr.
- The results suggest that for a given event, when the pavement temperature and snow amount are the same, the salt application rate can be reduced by approximately 10% for AC than the salt amount which is recommended for PCC and vice-versa.
- Between PCC and IC, a total of 196 comparable tests were conducted. The difference in melting speed was not found to be statistically significant. This means that if the recommended application for a given event is known for either surface type, the same application rate can be used for the other pavement type. For sidewalks, sometimes IC is constructed for aesthetic value. Maintenance operators can follow one application rate when applying salt to these pavement types.
- Since the difference in melting speed between PCC and IC was not found to be significant, and since constructing IC is expensive, from a winter maintenance perspective, making sidewalks from PCC is optimal as there is no additional advantage in snow melting speed found for IC. However, any additional advantages of friction gain or drop for choosing one material to the other should also be considered.

CHAPTER 5

DEICING WITH ALTERNATIVE SALTS AND PRE-WETTED SALTS[2]

5.1. Deicing using Alternative Salts

5.1.1. Test Overview

A series of field tests have been conducted on the comparative performance of alternative materials for deicing operations. As indicated previously selection of the alternative materials was done in consultation with the Toronto Region Conservation Authority (a regional environmental agency) and Metrolinx (a transit agency). The review process involved the creation of a short-list of materials for field testing according to a variety of criteria. The selection criteria used included the percentage of organic contents in the composition, the product's current usage, availability, price, and the performance of the product under low temperatures. The goal of these tests was to develop recommendations for selecting the right materials and application rates for any given winter weather event and site condition. Performance models were subsequently developed for estimating the relative performance ratios of different materials with respect to rock salt; adjustment factors for these materials can thus be determined from these models and applied to obtain the material's minimum application rate. A total of 21 snow events were covered in the field tests over a period of 33 days at the field test site discussed in chapter 3. In the field tests, a significant number of snow storms were experienced with snowfalls ranging from 0.2 cm to 20 cm and temperatures ranging from -14°C to 4°C. Each test usually included 10-15 test sections, giving a total of approximately 300 test sections over the life of the project. Note that, each test was unique, as inherent variations in uncontrollable factors such as precipitation type, pavement and air temperature, and sky view meant that no two test days had identical conditions. However, for simplicity variables were classified into a few simple and reasonable categories; for example, snow type was classified as packed, loose and very loose snow according to the physical composition of snow. Data has also been stratified according to the type of maintenance conducted, such as plowed tests vs. unplowed tests. This stratification can then be used to investigate the snow performance of tested chemicals according to a variety of factors, such as under a small or large amount snow. While tests conducted on plowed sections (i.e., on left over snow) were conducted after plowing snow both manually and with a plow truck (depending on snow accumulations), tests on unplowed sections were conducted without any altering of the original snow conditions.

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[2]This chapter is based on two papers; a) Field Evaluation of Deicing Performance of Alternative Solid Salts, TRB Conference, 93rd Annual General Meeting, Washington DC, 2014 (now submitted for publication in CJCE) b) To Pre-wet or Not to Pre-wet: a Field Study. TRB Conference, 94th Annual General Meeting, Washington, DC, 2015

5.1.2. Performance of Alternative Salts-An Example

This section presents the results from one of the typical tests that were conducted over the data collection period. This particular snow event started at 6:00pm and ended at 11pm on February 11, 2013. All deicing treatments were done at the end of the event (7am on February 12, 2013).The test sections were plowed before applying deicing materials, leaving about 0.2cm of snow on the pavement surface. Three materials (rock salt, Green salt, and Jet Blue) were applied at rates of 5, 10, and 20lbs/1000sqft; data collection started immediately after the application and continued every hour until 80% of the pavement's surface at all test sections was bare. The test lasted 5 hours with an average air temperature and pavement temperature of -1.6°C and -9.1°C, respectively.

Figure 5-1 shows the snow melting performance of the three materials under three rates as time progressed. It can be observed that the rock salt performed poorly when compared to the other two materials. Green and Jet Blue performed similarly in general; however, Jet Blue performed slightly better at lower rates. At the higher rates, there was practically no difference between Jet Blue and Green. The inferior performance of regular salt could be attributed to the low pavement temperatures (-9.1°C), which is close to its lowest practical effective temperature.

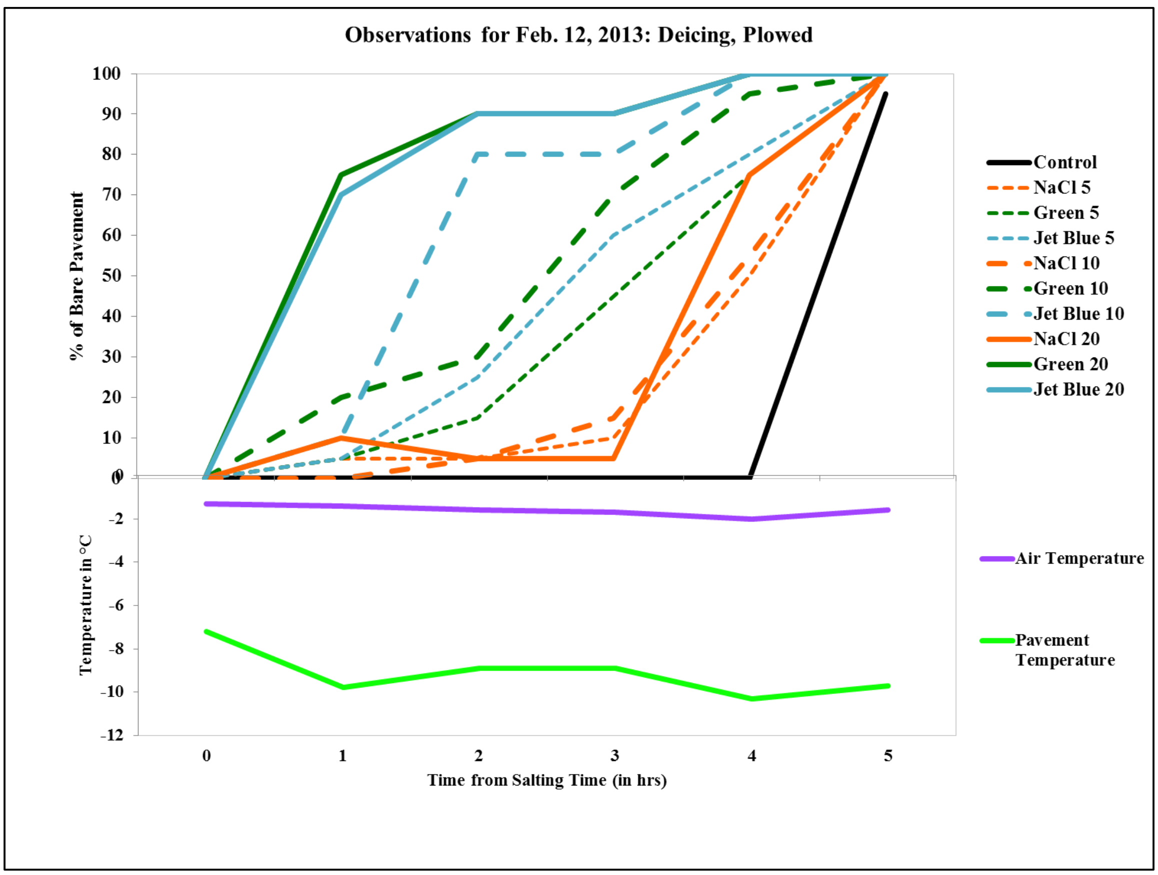


Figure 5-1: An Example Showing the Snow Melting Performance of Alternative Materials

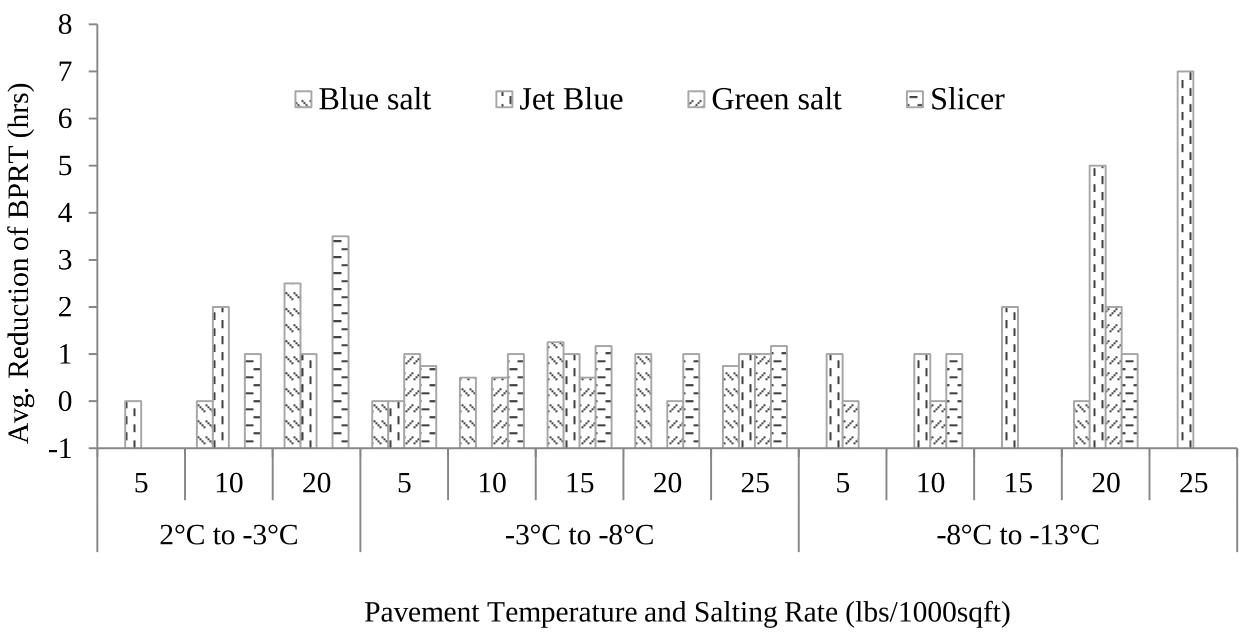
5.1.3. Comparison of Overall Performance of Alternative Salts

To evaluate the relative performance of the alternative materials compared to rock salt, the differences in bare pavement regain time (BPRT) for each alternative was considered. For a given alternative, the larger the BPRT difference with rock salt is, the better the performance of the alternative is.

Table 5-1 summarizes the average differences in BPRT for the four materials tested, stratified by whether or not snow was plowed before application. In general, all of the alternative materials performed better than regular salt.

Another interesting finding is the difference in relative performance between plowed and unplowed sections. For the plowed sections, the alternative materials had a larger difference in BPRT, that is, their performance was superior. Overall, Slicer worked best in both plowed and unplowed conditions. When considering which salt works best on only plowed snow, Jet Blue salt appears to be the best choice.

To gain insight into the effect application rate has on snow melting performance, BPRT data were subdivided into two categories: lower rates (5 to 15 lbs/1000 sqft) and higher rates (20 to 35 lbs/1000 sqft).



LOS Improvement Stratified by Temperature Rang (missing points indicate data not covered)

Figure 5-2 (a) and (b) show the improvements in level of service by using alternative salts for plowed sections and unplowed sections respectively. These concepts are explained further when the performance of each salt is discussed in the following section.

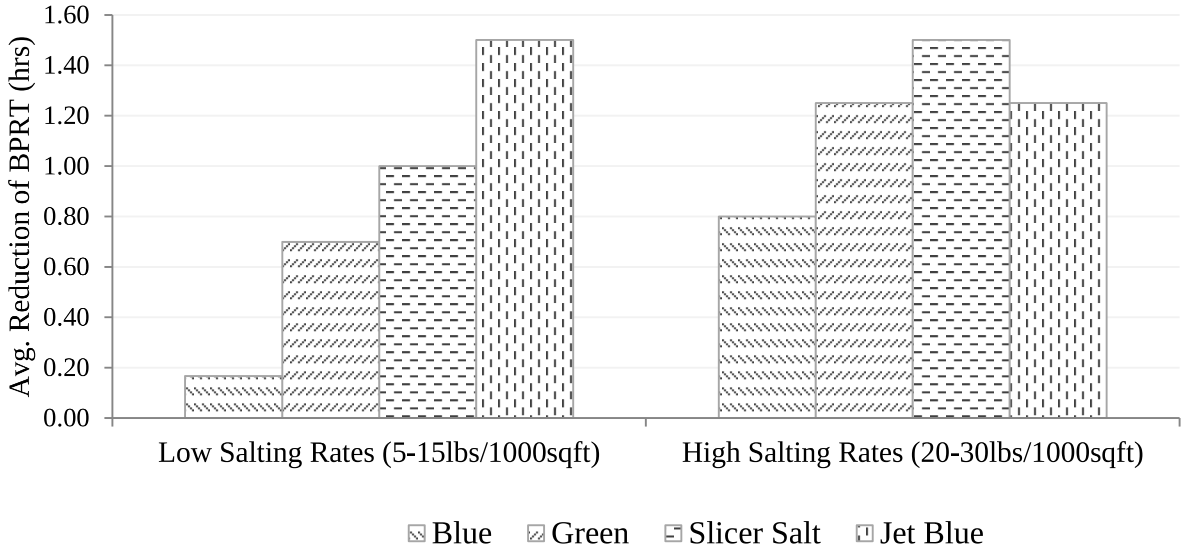
The relative performance of a deicing alternative is also expected to depend on many other factors, such as the sky-view condition and pavement temperature. Figure 5-2 (c) shows the improvement in LOS (i.e., average reduction in BPRT) when each alternative is compared to rock salt on plowed test sections under different temperature ranges. Note that not all alternatives and rates were tested with rock salt due to limitations in materials and test sections; thus, data points are missing in some tests for some of the alternative salts. In order to differentiate the missing data with data that shows no BPRT difference, the vertical axis starts at -1.

As Figure 5-2 (c) demonstrates, at the mid-range temperatures where rock salt is effective (-3°C to -8°C), alternative salts offer little improvement. That being said, there are no cases where rock salt outperformed the alternative salts. At warmer temperatures (2°C to -3°C), there is insufficient data to draw decisive conclusions, as there are no observations for the Green salt in this temperature range. However, the alternative materials tested at this high temperature range generally outperformed rock salt.

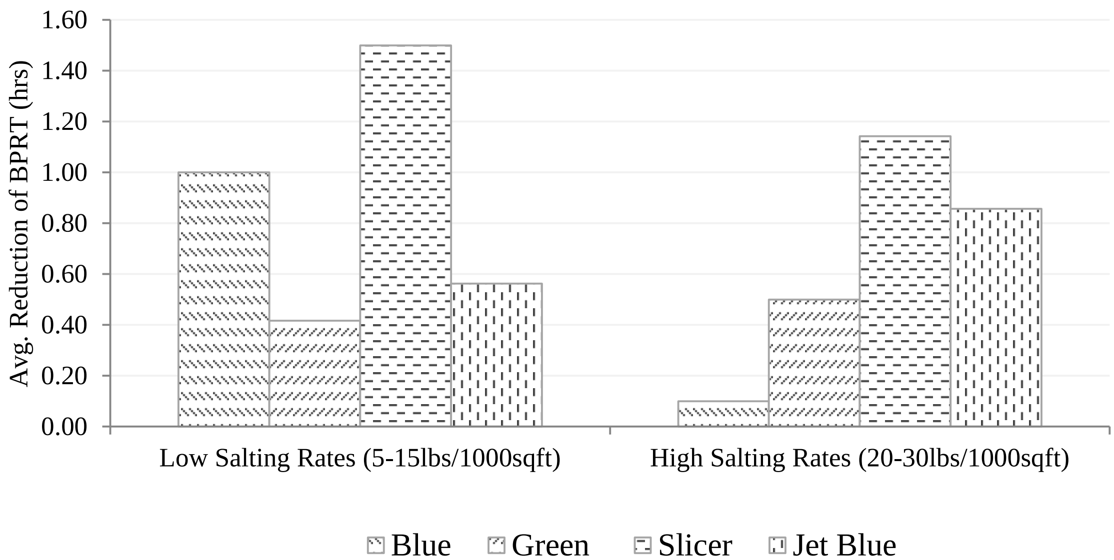
At lower temperature conditions (-8°C to -13°C), which near the end of the effective range of rock salt, there are mixed results between the different alternative salts. Based on the limited test results, Blue salt was found to be comparable to rock salt at this temperature range while Slicer performed slightly better. Green salt also offered muted performance gains until the rate reached 20lbs/1000 sqft. Jet Blue, however, greatly outperformed rock salt. At the lower rate of just 5lbs/1000 sqft, Jet Blue was 1 hour faster than rock salt and the differences in BPRT increased dramatically with the rate; at a rate of 25lbs/1000sqft, the difference in BPRT was 7 hours. It should be noted, however, that the results for Jet Blue were calculated from only a single day; therefore, these findings should be taken with caution.

Table 5-1: Average Differences in BPRT between an Alternative Material and Regular Salt for Plowed and Unplowed Cases

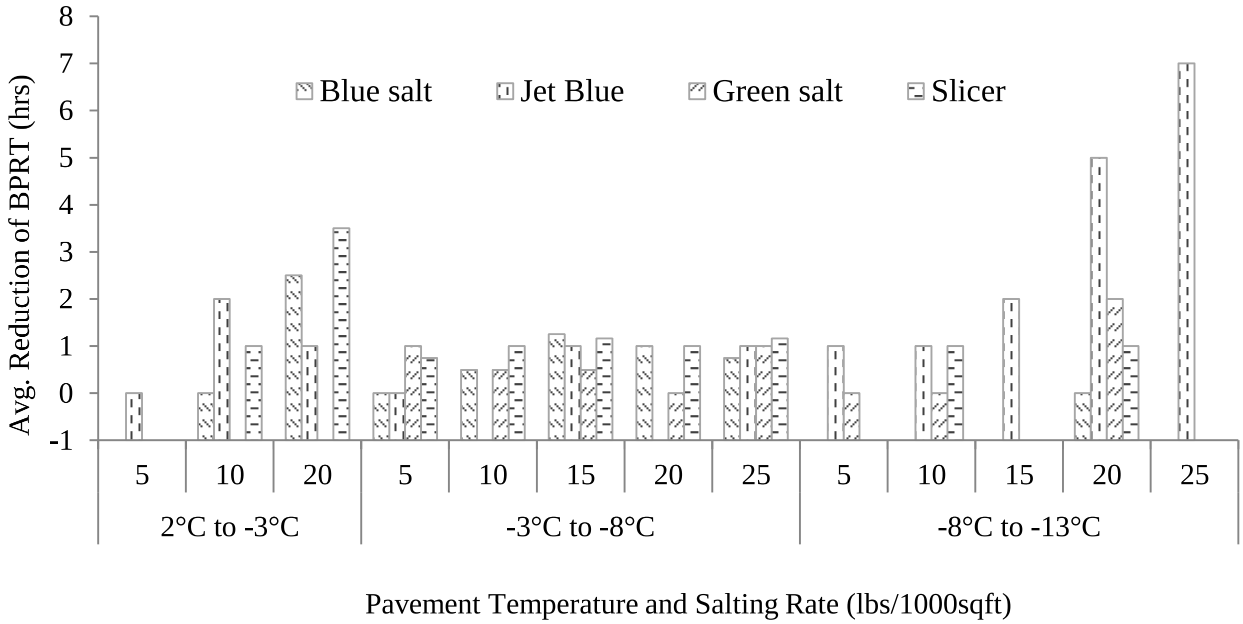
Salt Type	Plowed	Unplowed
Blue	0.5	0.3
Green	0.9	0.5
Slicer	1.2	1.3
Jet Blue	1.4	0.7



a) LOS Improvement Stratified by Application Rates-Plowed Sections



b) LOS Improvement Stratified by Unplowed Sections



c) LOS Improvement Stratified by Temperature Rang (missing points indicate data not covered)

Figure 5-2: Avg. Reduction of Bare Pavement Regain Time (i.e., Improvement of Level of Service)

5.1.4. Application Rates – Adjustment for Alternative Salts

An application rate adjustment factor for a specific alternative is defined as the ratio of the minimum application rate for a given alternative to the minimum application rate of regular salt required to achieve a given level of service (i.e., BPRT) under a given weather event, namely,

$$f_k = \frac{R_k}{R_m} \quad (5\text{-}1)$$

Where f_k = adjustment factor for alternative material k;

R_m = minimum application rate for regular salt;

R_k = minimum application rate for alternative material k.

As presented previously, the snow melting performance model has been used to determine and tabulate optimal application rates for regular salt under specific weather conditions, including the amount of snow and ice to be melted, pavement temperature, and LOS requirements. This section details the process by which an adjustment factor was calculated for each of the materials considered.

The snow melting performance data (BPRT) from the comparative tests were used to calibrate the BPRT model, which is a function of the salting rate, pavement temperature, and snow amount. The model calibration results derived from the field data collected for the comparative tests are given in Table 5-2. In general, the calibration results confirmed that the main factors were significant, including pavement temperature, precipitation, and application rate. From these models, the minimum application rate for any given type of material can be derived as a function of BPRT and the other three factors. The application rates given by the models are applied to Equation (5-1) to determine the adjustment factors. While Table 5-3 shows the adjustment factors for typical combinations of the external factors, including LOS requirement (desired BPRT), snow depth, and temperature, Table 5-4 shows the adjustment factors for some aggregated conditions for easy use. Combined with the rock salt application rates recommended in one of this project's published papers (Hossain et al. 2014), these tabulated adjustment factors can be used to determine the optimum rates for any of the given alternatives.

Table 5-2: Snow Melting Performance Model Calibrated Using Data from Comparative Tests

Material Type	Variable	Coefficients	P-value
Rock Salt	Intercept	5.163	3.11E-08
	Salting Rate	-0.081	5.72E-02
	Avg. Pavement Temp. (°C)	-0.142	7.27E-02
	Snow Amount	-0.916	1.61E-01
Slicer	Intercept	5.167	5.08E-03
	Salting Rate (lbs/1000sqft)	-0.221	5.23E-02
	Avg. Pavement Temp. (°C)	-0.130	5.34E-01
	Snow Amount	3.823	3.61E-01
Blue	Intercept	7.749	4.66E-03
	Salting Rate (lbs/1000sqft)	-0.256	6.05E-02
	Avg. Pavement Temp. (°C)	-0.254	2.36E-01
	Snow Amount	-2.689	6.44E-01
Green	Intercept	1.845	1.39E-03
	Salting Rate (lbs/1000sqft)	-0.054	1.12E-01
	Avg. Pavement Temp. (°C)	-0.191	3.09E-03
	Snow Amount	0.769	1.11E-03

Jet Blue	Intercept	3.097	1.33E-08
	Salting Rate (lbs/1000sqft)	-0.093	2.20E-05
	Avg. Pavement Temp. (°C)	-0.102	1.23E-02
	Snow Amount	0.427	4.33E-03

Note: Snow Amount= (Snow Depth in cm x Snow Density in kg/m^3)

Table 5-3: Adjustment Factors to Base Application Rates for Using Alternative Salts

Slicer							
Snow Depth	Pavement Temperature	BPRT (hrs)					
		1	2	3	4	5	6
0.1 to 0.5	-7 to -9	0.86	0.83	0.79	0.75	0.72	0.68
	-4 to -6	0.82	0.78	0.74	0.71	0.67	0.64
	-1 to -3	0.77	0.73	0.70	0.66	0.63	0.59
1.0 to 1.5	-7 to -9	0.96	0.92	0.89	0.85	0.81	0.78
	-4 to -6	0.91	0.88	0.84	0.80	0.77	0.73
	-1 to -3	0.87	0.83	0.79	0.76	0.72	0.69
1.5 to 2.5		Not covered by data					
Blue							
Snow Depth	Pavement Temperature	BPRT (hrs)					
		1	2	3	4	5	6
0.1 to 0.5	-7 to -9	Not covered by data					
0.5 to 1.5	-4 to -6	0.93	0.90	0.87	0.84	0.82	0.79
1.5 to 2.5	-1 to -3	Not covered by data					
Green							
Snow Depth	Pavement Temperature	BPRT (hrs)					
		1	2	3	4	5	6
0.1 to 0.5	-7 to -9	0.81	0.74	0.67	0.60	0.53	0.46
	-4 to -6	0.75	0.68	0.61	0.54	0.47	0.40
	-1 to -3	0.69	0.62	0.55	0.48	0.41	0.34
0.5 to 1.5	-7 to -9	0.79	0.72	0.65	0.58	0.51	0.44
	-4 to -6	0.73	0.66	0.59	0.52	0.45	0.38
	-1 to -3	0.67	0.60	0.53	0.46	0.39	0.32

1.5 to 2.5	-7 to -9	0.78	0.71	0.64	0.57	0.50	0.42
	-4 to -6	0.72	0.65	0.58	0.50	0.43	0.36
	-1 to -3	0.66	0.59	0.51	0.44	0.37	0.30
Jet Blue							
Snow Depth	Pavement Temperature	BPRT (hrs)					
		1	2	3	4	5	6
0.1 to 0.5	-7 to -9	1.00	0.89	0.64	0.38	Not covered by data	
	-4 to -6	1.00	0.83	0.58	0.32		
	-1 to -3	1.00	0.77	0.52	0.27		
0.5 to 1.5	-7 to -9	1.00	0.91	0.65	0.40		
	-4 to -6	1.00	0.85	0.59	0.34		
	-1 to -3	1.00	0.79	0.53	0.28		
1.5 to 2.5	-7 to -9	1.00	0.92	0.66	0.41		
	-4 to -6	1.00	0.86	0.60	0.35		
	-1 to -3	1.00	0.80	0.54	0.29		

Table 5-4: Aggregated Adjustment Factors to Base Application Rates for Using Alternative Salts

Average Pavement Temperature (°C)	Green	Jet Blue	Slicer	Blue
-7 to -9	0.62	0.73	0.80	N/A
-4 to -6	0.55	0.60	0.82	0.85
-1 to -3	0.48	0.60	0.85	N/A

5.2. Deicing using Pre-wetted Salt

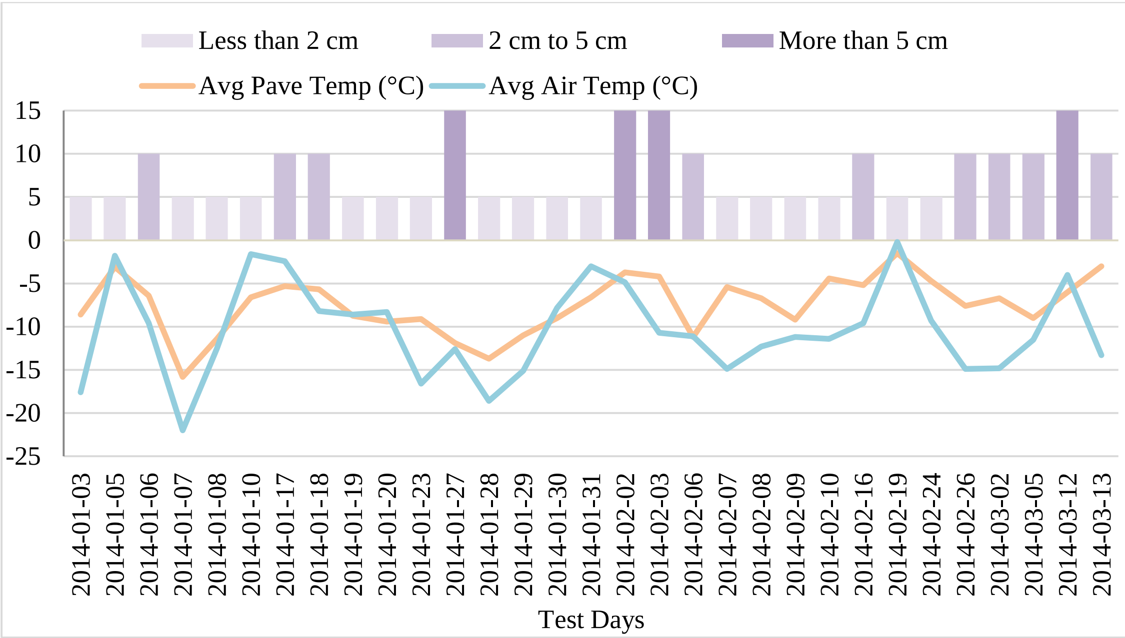
5.2.1. Overview on Tests with Pre-wetted Salt

Pre-wetting a salt refers to the process of mixing the salt with a liquid such as brine before or during application to increase the moisture content of the salt. The use of pre-wetted salts for deicing has been widely accepted due to several advantages.

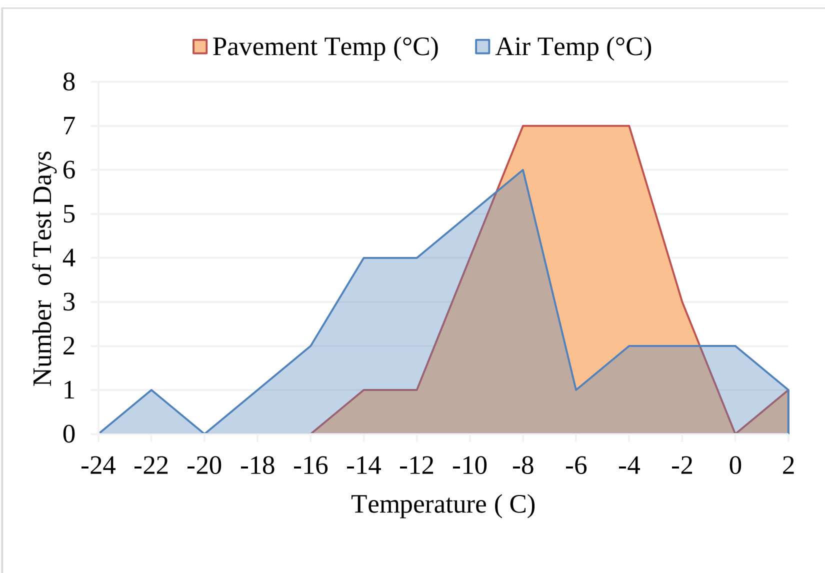
Firstly, pre-wetting is well recognized as providing a source of moisture, which is essential in accelerating the melting process. With the advantage of a faster snow melting speed, a comparatively smaller amount of salt can be used to achieve similar end results when compared to dry salt alone. Thus, pre-wetting can reduce the total amount of salt used. Secondly, pre-wetting salt is believed to reduce the amount of material wasted from salt bouncing off the targeted zone (e.g., desired road lane, sidewalks) while the salt is being spread. This bouncing effect becomes a significant concern for high-speed roadways, as traffic can easily displace salts off the road; pre-wetting salt has been extensively used to mitigate this problem, since the added moisture allows salt to adhere to the road surface and reduce dispersion by traffic. This results in further salt savings during heavy salting applications. Lastly, in cases where temperatures drop substantially below the freezing temperature (e.g., below -10°C), there is little to no moisture present in the air to help activate the salt; however, pre-wetting the salt immediately before application ensures that moisture is present to facilitate the chemical process. As a result of these benefits, pre-wetting salt has become widely used for deicing in the road sector. However, despite its popularity, there has been little research in assessing the performance of this method in a real-world setting.

To collect data on the performance of pre-wetted salt, a series of field experiments were conducted during the winter season of 2014. In the testing season, there were about 40 snow events in total with a pavement surface temperature range of approximately -20°C to 3°C and snow precipitation range of approximately 0.2 cm to 20 cm, including over 15 regular events (less than 2 cm of snow) and five heavy events (more than 5 cm of snow), as shown in Figure 5-3-a. Note that the winter season of 2014 was extreme, especially when the number of colder days are considered; over 10 events with air and pavement temperatures below -10°C were observed (Figure 5-3-b). A total of 484 side by side tests were conducted using regular dry road salt and road salt pre-wetted with brine.

In order to preserve consistency and uniformity during testing, a common test protocol was maintained. After a snow event stopped, the testing site was either plowed by University plow trucks, manually plowed, or left unplowed (when snow accumulation was minimal). Salts and pre-wetting liquids were measured and prepared. The application rates for both types of salts were 5-50lbs/1000sqft (mass) for each test event, while saturated brine (23% salt by mass) was used to pre-wet the dry salt with a ratio of 20-30% (by mass) brine to 70-80% dry rock salt (NaCl) for pre-wetted salt tests. Tests were paired based on similar surface conditions, uniformity in plowing, and the application rate used. Although the masses of the salts applied on the test sections were the same for paired test sections, due to the pre-wetting with brine, the pre-wetted salt section had a lower amount of total salt than the dry salt section. On average, the pre-wetted salt sections had approximately 20% less salt. To be specific, when compared to the dry salt sections 15.5% less salt was used when the pre-wetting ratio was 20%, and 23% less salt was used when the mixing ratio used was 30%.



a) Major Weather Data



b) Temperature Distribution in the Test Season

Figure 5-3: Summary of Events and Their Characteristics

5.2.2. Test Results- Pairwise Comparison (Dry salts vs. Pre-wetted salts)

Figure 5-4 shows an example of the comparative performance of pre-wetted salt versus dry salt for the tests that were conducted on February 3, 2014. The maintenance operation on the tests sites started at 7 am. After the plowing operation completed, previously measured amounts of salt and brine for pre-wetting were mixed and immediately applied uniformly to the test sites. The dry salt and pre-wetted salt was applied at rates of 5-50 lbs/1000 sqft in both dry salt and pre-wetted salt test sites. The total snow amount on the pavement surface was about 0.3 cm after plowing. Data collection started immediately after the salt application. The test lasted for five hours with an average air temperature and an average pavement temperature of -10°C and -4°C respectively.

It can be observed from Figure 5-4 that the melting speed (change in bare pavement percent) for both types of treatments was relatively low during initial hours. This could be attributed to lower temperatures and an absence of sunshine in the early morning hours. As expected, the melting speeds correlated significantly with application rates, with the higher changes in BP associated with higher application rates. For example, an application rate of 30 lbs/1000 sqft was able to reach over 50% bare pavement in about 3 hours, whereas less than 10% of the test section reached bare pavement in three hours when the application rate was 10 lbs/1000 sqft. More interestingly, the melting on the sections treated with dry salt was slightly faster than that with pre-wetted salt although the end result in terms of bare pavement regain time was similar. This could be attributed to the fact that the sections with pre-wetted salt had 20% less salt (NaCl), as the application rates were controlled by total weight rather than net salt amount. Similar results were observed on other test days. A more extensive analysis was performed to investigate the underlying factors that may have caused this outcome.

Figure 5-5 shows the average BPRT performance observed over 27 events for both the dry salt and pre-wetted salt sections. The average BPRT (hrs) values have been calculated from the BPRTs of all dry salt (i.e., average of all sections salted with dry salt at different rates) and pre-wetted salt sections (i.e., average of all sections salted with pre-wetted salt at different rates). From the graph, it can be seen that the performance of either treatment option was mixed; however, both treatments still performed similarly on a number of days during the study. It should also be noted that in four cases sections treated with dry salt had significantly shorter BPRT values than pre-wetted salt. The causes of these unexpected results could be due to some uncontrollable factors in the field testing environment, such as the non-uniformity of snow across the tests sections, or variation in parking frequency/vehicular traffic between the sections.

To determine whether the differences in BPRT between dry salt and pre-wetted salt sections are statistically significant, data were revisited and tests with extreme conditions, (e.g., 10 cm of snow) were removed. In addition, paired test results were also removed when the BPRT observed for either treatment option was longer than 10 hrs or where 80% bare pavement was not reached within the time allotted. Three subsequent statistical tests were performed on this dataset: t-tests for checking the differences in means, f-tests for checking variance differences, and t-tests for means assuming unequal variances after a positive result from an f-test.

It can be concluded from these three statistical tests that the differences in the average performance (BPRT) between dry salt and pre-wetted salt are statistically significant at a 95% confidence level according to the final t-test, which was conducted after concluding from f-test that the difference in performance variances by the treatments is not statistically significant. The statistical tests results are summarized are in Table 5-5.

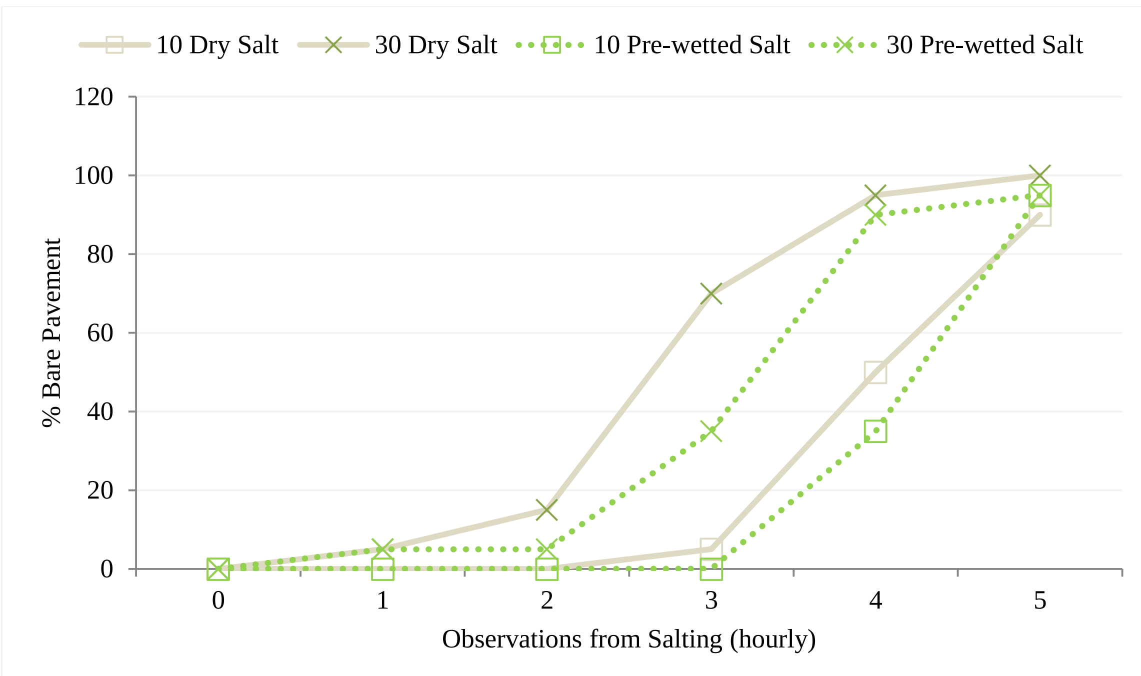


Figure 5-4: Snow Melting Performance of Dry Salt vs. Pre-wetted Salt – An Example

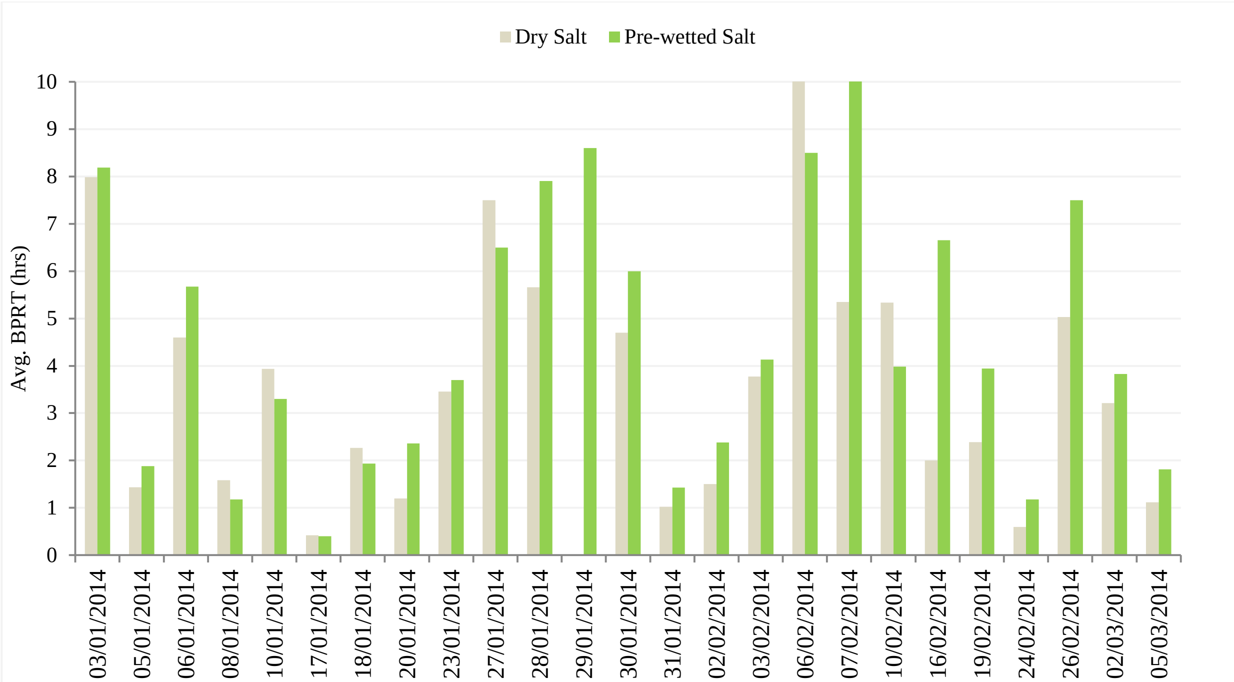


Figure 5-5: Snow Melting Performance of Dry Salt vs. Pre-wetted Salt in Terms of BPRT

(Notes: Aggregated for all application rates from each test days. For some days during the testing season, bare pavement was not reached in any of the tests sections for both types of treatments. This was due to extreme cold, large snowfalls, or other factors. These days are not included in this chart)

Table 5-5: Summary of Statistical Test Results of Paired Two Samples from Treatment Performance Data

Statistics	Dry Salt Treatment	Pre-wetted Salt Treatment
# of Observations	77	77
Avg. BPRT (hrs)	3.00	3.24
Variance	4.38	3.40
Std. Deviation (hrs)	2.09	1.84
t-test for means (5% significance level)	t-calculated=-2.21; t-critical=1.99, p=0.015 Conclusion: Since p-value obtained a little less than set value, there is moderate evidence to reject that the “mean performances of the two treatments are equal”	
F-test for variances	F-calculated=1.28; F-critical=1.46, p=0.13	

(5% significance level)	Conclusion: No evidence to reject that "variances of treatments performances are equal"
t-test assuming unequal variances (5% significance level)	t-calculated=-0.75; t- critical=1.97, p=0.23 Final Conclusion: No evidence to reject that "treatment performances are the same"

Notes: Data from a total of 77 comparable tests has been considered for the "t-test" for checking whether there is a difference in the mean BPRTs obtained from both treatments.

5.2.3. Regression Analysis on the Performance of Pre-Wetted Salt

In our exploratory data analysis, it was found that there were a number of factors affecting the performance of dry salt and pre-wetted salt in terms of BPRT. To quantify these influences in a rigorous way, the test data of both treatments used in the previous exploratory data analysis was processed by pairing tests where the application rate of dry and pre-wetted salt was the same on a given test day. Level of service (LOS) improvements for pre-wetting were calculated for each pair of tests. For example, for a given test, if, the dry salt treatment had a BPRT value of 3 hours and the pre-wetted salt treatment had a BPRT value of 2 hours, pre-wetting has a LOS improvement of 1 hour. If the LOS improvement is negative, this means that the pre-wetted salt had a higher BPRT value, and pre-wetting resulted in a drop in the LOS. This improvement or drop should be dependent on other influencing factors, such as snow type, application rate, etc.

To demonstrate the relationship between the influencing factors and the LOS with statistical reliability, a multiple linear regression analysis was performed. From this analysis, the significant factors that affect the difference in performance were determined. Table 5-6 displays the summary statistics of the variables used in the model. Dummy variables were also used to represent snow moisture content (dry snow=1, wet snow=0) and the two pre-wetting ratios tested (30%=1, 20%=0). The results of the multiple regression analysis are summarized in Table 5-7.

Table 5-6: Descriptive Statistics of the Data

Variable	Minimum	Maximum	Mean	Std. Dev.
Difference in Absolute Salt Application Rate in lbs/1000sqft (Dry salt over Pre-wetted salt)	0.75	11.50	5.45	3.03
Pavement Surface Temperature (°C)	-11.9	-1.5	-6.06	2.73
Snow Amount (Density in kg/m3 X Depth in cm)	0.12	1.75	0.62	0.52
Partial Pressure (mmHg)	0.84	4.01	2	1.04
LOS Improvement/Dropped (hours)	-2.4	2.5	-0.24	0.95
Snow Types (Moisture Content)	Dry Snow=1, Wet Snow=0			
Pre-wetting Ratio (by mass)	30%=1, 20%=0 Distribution of the total tests for mix-ratios: (50/50 approx.)			

Table 5-7: Summary Results of Regression Analysis

Variables	Coefficient	P-value
Dependent Variable	$BPRT_{dry\ salt} - BPRT_{pre\text{-}wetted\ salt}$	
Intercept	0.114	0.45
Snow Moisture Content Type (1 = Dry, 0 = Wet)	0.681	0.00[a]
Snow Amount (Density in kg/m3 X Depth in cm)	-1.034	0.00[a]
Difference in Absolute Salt Application Amount in lbs/1000 sqft (Dry salt over Pre-wetted salt)	0.184	0.07
Pavement Surface Temperature (°C)	-0.110	0.35
Partial Pressure (mmHg)	-0.098	0.34
Pre-wetting Ratio (30%=1, 20%=0)	0.183	0.11
No of Observations (n) and R^2		77, R^2=0.27

5.2.4. Discussion of Regression Results

The statistical modeling results shown in Table 5-7 provide quantitative evidence for many factors that were hypothesized to affect the performance of pre-wetted salt. The strength of the LOS improvement is indicated by the values of the model coefficients, with the sign of the coefficient indicating whether the impact is positive or negative.

5.2.5. Types of Snow (Dry Snow vs. Wet Snow)

The qualitative assessment of snow moisture content was found to be statistically significant with a p-value of 0.00, suggesting that there is an additional advantage from using pre-wetted salt over using dry salt on dry snow. The positive model coefficient suggests that if snow is dry, the performance of pre-wetted salt over dry salt will increase. This makes sense from a theoretical point of view: If salt needs moisture to activate and mix with snow, and if the advantage of pre-wetting salt comes from providing that moisture, then the observable advantage of a pre-wetted salt would be reduced when the snow is wet, since there is already a large amount of moisture available in wet snow. The model coefficient of 0.68 suggests snow with higher moisture content has an LOS improvement from pre-wetting 0.68 hours lower than snow with a lower moisture content.

5.2.6. Amount of Snow

Snow amount was found to be a statistically significant variable affecting the LOS improvement for using pre-wetted salt with a p-value of 0.00. The association is negative, suggesting that when there is a heavy accumulation of snow, treatment with dry salt becomes more effective than pre-wetted salt. This result suggests that pre-wetted salt is less advantageous than dry salt in dealing with heavy snowfalls. This also suggests that to maximize the effectiveness of pre-wetting, snow should be plowed as much as possible to reduce the amount of snow left to be melted by the pre-wetted salt.

Note that when there is a large amount of snow present, intuitively more NaCl is required to melt the snow. However, when applying pre-wetted salt, the amount of NaCl applied is comparatively less than when applying dry salt. Therefore, applying pre-wetted salt may result in the application of an amount of NaCl that is insufficient for the amount of snow present. Moreover, when there is a larger amount of snow, there is a higher potential for dilution of the pre-wetted salt, since pre-wetted salt contains additional water to expedite this dilution.

The model coefficient is 1.03, which suggests that, if a snow density of 100 kg/m^3 is assumed (which is generally the case for regular snow), for every 0.30 cm increase in depth, the LOS improvement is decreased by approximately 15 minutes.

5.2.7. Salt Application Rate

The application rate is found to be positively associated with the performance of pre-wetted salt over dry salt at a significance level of 7%. The result indicates that pre-wetted salt at larger application rates results in a larger LOS improvement than pre-wetted salt for smaller application rates. Therefore pre-wetting is particularly desirable when high application rates are needed. The application rate has a coefficient of 0.184, meaning that increasing the net application rate from 5 lbs/1000sqft to 15 lbs/1000sqft would increase the LOS improvement by approximately 0.5 hours.

5.3. Summary of the Chapter

This chapter has described the results of the analysis of the field tests data involving four alternative deicers and pre-wetted rock salt. Approximately 800 tests over 50 snow events were conducted. A wide range of application rates were tested under a variety of weather conditions and the main findings are summarized as follows:

- In general, all alternative salts tested in this field study outperformed rock salt. On average, Blue, Green, Jet blue, Slicer, had 0.4, 0.7, 1.05 and 1.25 hours shorter bare pavement regain time, respectively, than rock salt.
- It was found that the relative performance of the alternatives depended on the amount of snow to be melted (e.g., plowed vs. unplowed). For the plowed sections, the alternative salts had a larger difference in BPRT, that is, their performance was more superior. Jet Blue worked best in the plowed sections. Overall, Slicer worked best in both plowed and unplowed conditions.
- The alternatives performed significantly better than rock salt at a pavement temperature below -5°C. The BPRT reduction ranged from 1 to 5 hours depending on application rates.
- One interesting characteristic of the alternative salts is that their snow melting rate (i.e., bare pavement time reduction) differed by application rates. The bare pavement regain rate was disproportionately changing when application rates were changed from relatively low to high.
- Compared to other alternatives, Jet Blue had shown a considerable improvement in level of service by a reduction of 3.75 hours in bare pavement regain time for an event with an average pavement temperature of -8°C.
- The snow melting performance models of alternatives and rock salts from the comparative tests clearly show that the BPRT is function of application rates, pavement temperature and snow amount, and that they all were found to be statistically significant. The models were then used to derive adjustment factors for the alternative salts. These adjustment factors can be used to

determine the optimal salting rates for the alternatives under specific weather conditions and desired levels of service (BPRT).

- When comparing pre-wetted salt with dry salt, tests were conducted in side-by-side sections under a wide range of weather conditions. A multiple linear regression analysis was performed to identify the key factors affecting the comparative performance advantage of the pre-wetting strategy.
- The test results showed that the relative performance advantage of pre-wetting salt over dry salt, in terms of reduced bare pavement regain time, was affected by three main factors, including snow amount and moisture level. When these factors are accounted for, the pre-wetting strategy was shown to be more effective in deicing than the method of applying dry salt.
- It was found that the comparative advantage of pre-wetted salt over dry salt decreased as the amount of snow present on a pavement surface increased. This is likely due to the fact that in pre-wetted test sections there was less total salt (NaCl) available to melt large amounts of snow or that large amounts of melting snow reduce the effectiveness of pre-wetting by diluting the salt substantially.
- Though there was a significant relationship between the application rate of salt used and the amount of time it took to melt the snow, no statistically significant differences were observed between dry salt and pre-wetted salt for different application rates. This suggests that pre-wetting is particularly desirable for higher application rates, where the net salt (NaCl) saved is highest.

CHAPTER 6

EFFECTIVNESS OF ANTI-ICING TREATMENT[3]

6.1. Overview on Anti-icing Tests

This chapter presents the results of the field study aimed at investigating the performance of the anti-icing strategy for snow and ice control. Anti-icing treatments were performed 2 to 12 hours in advance of snow events. For each snow event, different snow control chemicals were applied to a set of test sections following test protocols; time series performance and condition data were collected as described in the previous section. Approximately 400 tests were conducted over 35 test days. The performances of the alternatives were compared using friction improvement as a measure. The objective of this component is to address several critical questions related to anti-icing operations for transportation facilities. In particular, the research aimed to answer the questions as follows: How effective is anti-icing in preventing the bonding of snow and ice to pavement? What is the relative effectiveness of anti-icing operation as compared to deicing? What is the optimal anti-icing application rate for specific weather and site conditions? What is the comparative performance of different anti-icing materials?

6.2. Effectiveness of Anti-icing in Preventing Snow and Ice Bonding

As discussed previously, anti-icing treatments are motivated by their potential in preventing the bonding of snow and ice to a pavement surface by lowering the freezing point of water through the use of salt. To evaluate the effectiveness of anti-icing operations in achieving this potential, the states of bonding and friction levels at the treated sections (i.e., anti-icing was done) are compared to those of the control sections (do-nothing sections). For both cases, the accumulated snow was first removed by the plow truck or using a shovel before observations, time stamped photos covering tests sections were then taken, and friction measurements were then taken by a friction testing device (T2-GO), while a qualitative measurement on slippery level (very slippery, slippery, no slippery) of the pavement surface were also estimated and recorded by the field observations team. A sample image covering test sections and specifications of the device used for measuring friction can be found in the Appendix.

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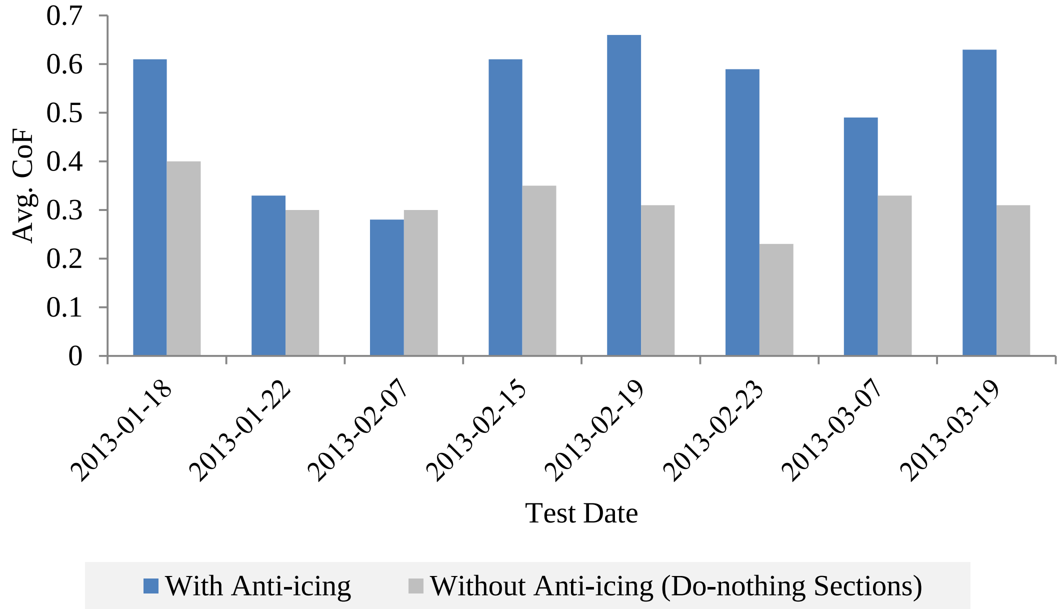
[3]This chapter is also based on two papers; a) Effectiveness of Anti-icing Operations, (2014), Canadian Journal of Civil Engineering. b) Field Evaluation of Organic Anti-icers for Winter Snow and Ice Control, (2015), Paper accepted for 94th TRB Conference, Washington DC (submitted for publication in Journal of Cold Region Science and Technology).

Figure 6-1 (a,b) shows measurements of the coefficient of friction for sections treated with regular salt as an anti-icing agent compared to those without anti-icing operations for the seasons of 2013 and 2014.

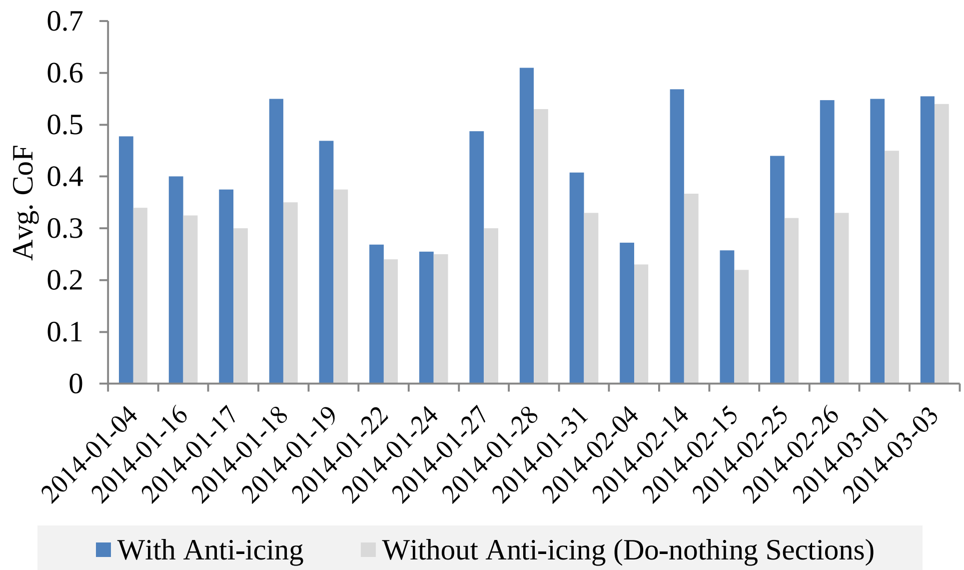
As expected, anti-icing operations were highly effective in preventing the bonding of snow and ice in general. However, there were few days when the trend of improvement was minimal in the season of 2014. This low improvement could be attributed to very cold temperatures (e.g., less than -10°C) or a higher amount of precipitation, since the winter season of 2014 was extremely cold and heavy. For example, anti-icing tests conducted for a snow event on Jan 22, 2013, were not effective; the main reasons for this were the relatively low temperatures, the high amount of precipitation of the event, and the long event duration. For this anti-icing event, the average pavement temperature was -11.5°C, which is below the effective temperature range of regular salt. However, with the exception of two cases, observed friction levels improved by over 50% when anti-icing was applied, when friction is compared between anti-icing and control sections.

Additional tests were also conducted using liquid salts (brine, Snowmelt, Fusion, Caliber) in the testing season of 2014. Figure 6-2 shows the friction of coefficients observed across the two scenarios: do-nothing and anti-icing using the liquid salts. It can be seen from the test results that anti-icing operations conducted with the liquid salts were generally found to be effective in preventing the bonding of snow and ice to the pavement, with a positive gain across almost all of the events. However, due to very cold winter season, in some cases anti-icing were not effective as liquid salts become less effective under a temperature below -7ºC (Blackburn, 1992). Figure 6-3 shows the relationship between coefficient of friction (CoF) and pavement surface temperature under an application rate of 3L/1000sqft, observed in the field tests. While there is some small variation in the CoF for different products within the temperature range, it can be seen that anti-icing was generally ineffective below -10ºC as CoF dropped significantly at this temperature.

To identify whether the friction improvements over the control sections were statistically significant, friction measurements on control sections and treated sections were paired and the differences in CoF were then computed for t-test. The mean difference of CoF was found statistically significant at a 95% confidence level for all materials. The results from the t-test analysis are summarized in Table 6-1.



a) Testing Season, 2013



b) Testing Season, 2014

Figure 6-1: Improvement of Friction by Anti-icing Using Solid Road Salt

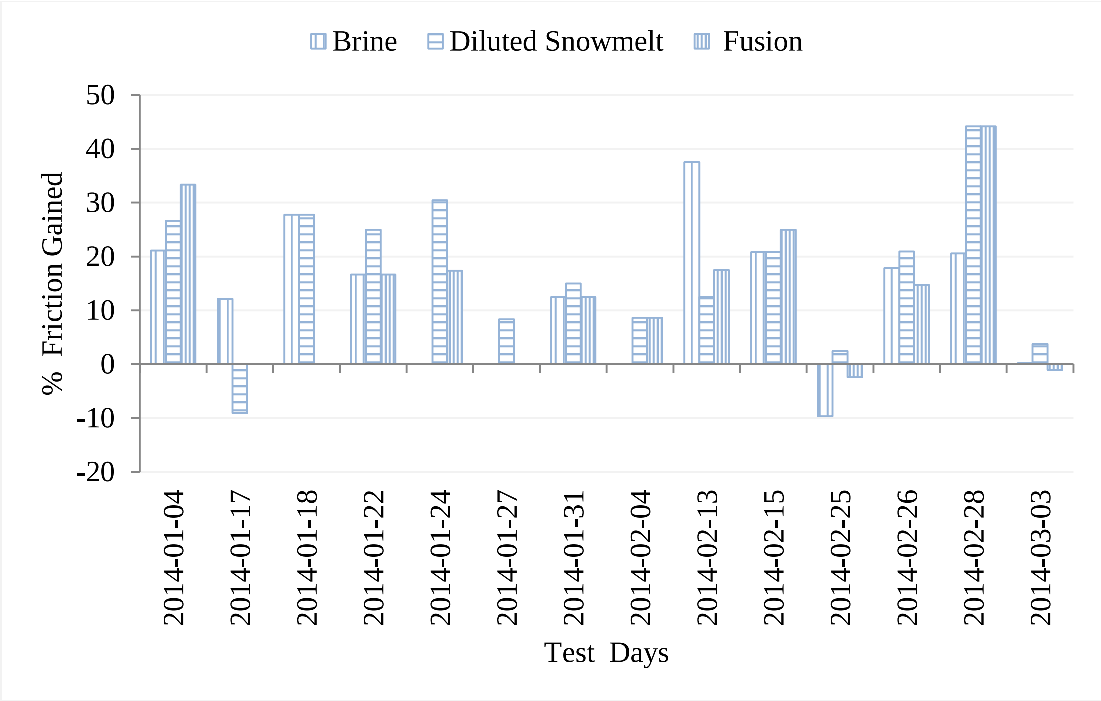


Figure 6-2: Improvement of Friction for Anti-icing by Different Liquid Salts

(Fusion was not tested on 17th and 18th. Caliber was not included in this Figure since this salt only tested 3 days)

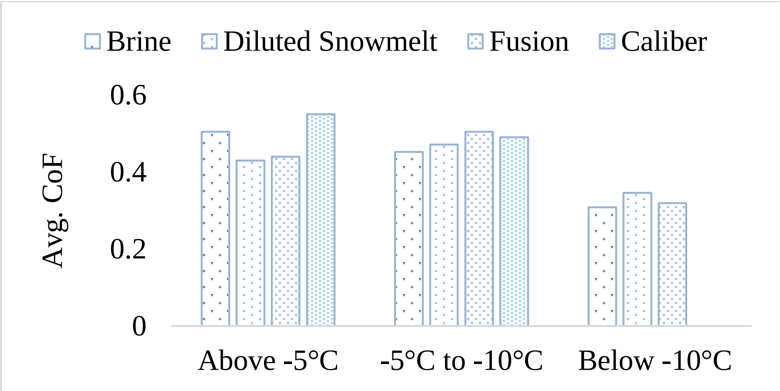


Figure 6-3: Effect of Temperatures on the CoF

(Caliber was not tested under -10 C as it was introduced towards the end of the testing season)

Table 6-1: 't-tests' Results for Improvement of Friction at Anti-icing Sections vs. Control Sections

Statistics	Dry Salt	Brine	Diluted Snowmelt	Fusion	Concentrated Snowmelt	Caliber
Observed Difference in Mean CoF (Treated site over Control Site)	0.05	0.0575	0.0615	0.0571	0.0675	0.0574
S.E	0.01	0.0124	0.0087	.0091	0.0083	0.0208
Sample Variance	0.00	0.0071	0.0033	0.0036	0.0012	0.0091
# Sample	25	44	44	38	16	21
Degrees of Freedom	24	43	43	37	15	20
Hypothesized Difference in Mean CoF (Treated site over Control Site)	0	0	0	0	0	0
t-calculated (t-critical)	5.56 (1.75)	4.63 (1.68)	7.06 (1.68)	6.27 (1.68)	8.13 (2.02)	2.78 (1.72)
P-value (at the probability of 5%)	0.00	2.49E-5	5.1E-9	5.6E-7	6.6E-7	0.0061
Statistical Conclusion	No evidence to accept the null hypothesis that the mean CoF in both treated and control sections are equal.					

6.3. Comparative Performance of Different Products

6.3.1. Regular Brine vs. Regular Dry Salt

Figure 6-4 below shows the comparative performance between regular salt (dry NaCl) and brine (23% salt brine). Regular salt applied at 5lbs/1000 sqft was compared with brine solution applied at 9L/1000 sqft. The reason for comparing the two materials at these amounts is due to the fact that the brine solution contains both regular salt and water. In the 9 L of brine, there was approximately 5 lbs of salt, which means that both application methods are utilizing the same quantity of salt. As can be seen in the graph, the brine solution performed better than regular salt in several circumstances, most notably on February 15. From this observation, it is reasonable to state that adding water to salt can improve the effectiveness of an anti-icing treatment. One of the reasons for this is the minimal loss of salt (when applied as brine) from the pavement surface due to effect of wind or traffic.

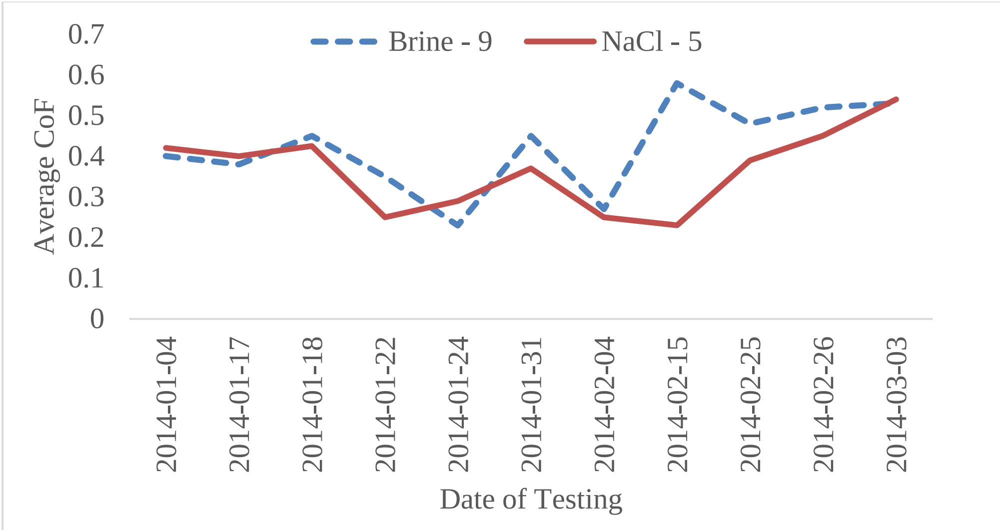


Figure 6-4: Comparing Performance of Anti-icing Between Brine and Dry NaCl (Same mass of salt)

Figure 6-5 below demonstrates the performance between regular salts and brine at minimum application rates. It can be seen from the graph that the coefficient of friction achieved at the end of a test is very similar between the two, with the exception of February 15. As stated earlier, brine solution contains salt mixed with water. This means that when 3L of brine per 1000 sqft is applied the actual amount of salt used is much less than 5lbs per 1000 sqft, which is the minimum rate applied for plain regular salts. From this observation, we can conclude that brine is indeed a more economically beneficial choice compared to regular salt for anti-icing.

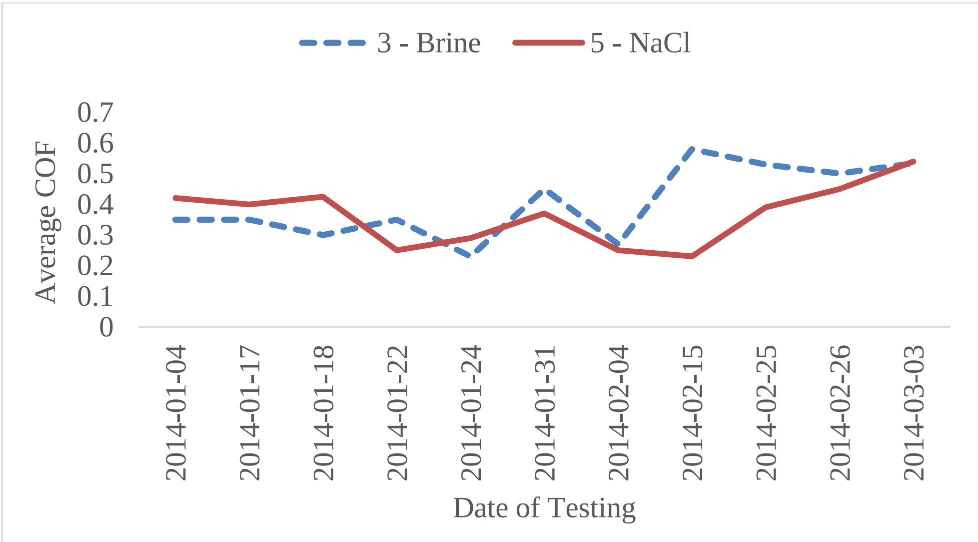


Figure 6-5: Comparing Performance of Anti-icing Between Brine and Dry NaCl (minimum rates)

6.3.2. Comparative Performance of Different Liquids

To determine whether the anti-icing performance of these alternatives had differed significantly, an ANOVA analysis is conducted on paired test results, grouped according to the testing day and the application rate used. The summary statistics of the data and ANOVA results are shown in Table 6-2 and Table 6-3. This statistical analysis concludes that the differences in performance between the alternative materials are not statistically significant. This finding suggests that the organic alternatives are at least as effective as the regular brine for anti-icing operations

Table 6-2: Summary of Treatment Performance Data for ANOVA

Statistics	Treatment by Brine: Avg. CoF	Treatment by Diluted Snowmelt: Avg. CoF	Treatment by Fusion: Avg. CoF	Treatment by Snowmelt: Avg. CoF	Treatment by Caliber M1000: Avg. CoF
Sum	18.79	18.79	16.54	6.79	10.47
Avg. CoF	0.43	0.43	0.43	0.42	0.50
Variance	0.016	0.012	0.013	0.10	0.015

Note: The total number of paired tests 162 by all products

Table 6-3: Results of ANOVA

<table>
<tr><th>Source of Variation</th><th>Sum of Squares</th><th>Degree of Freedom</th><th>Mean Squares</th><th>F-Observed (5% significant level)</th><th>F-Critical (5% significant level)</th><th>P-Value</th><th>Conclusion form ANOVA</th></tr>
<tr><td>Between Treatments (Brine, Diluted Snowmelt, Fusion, Concentrated Snowmelt and, Caliber M1000)</td><td>0.0882</td><td>4</td><td>0.0221</td><td rowspan="3">1.6236</td><td rowspan="3">2.4288</td><td rowspan="3">0.1709</td><td rowspan="3">No evidence to reject the null hypothesis that the mean performances (Avg. CoF) for all treatments are equal</td></tr>
<tr><td>Within Treatments (Brine, Diluted Snowmelt, Fusion, Concentrated Snowmelt and, Caliber M1000)</td><td>2.1471</td><td>158</td><td>0.0135</td></tr>
<tr><td>Total</td><td>2.2354</td><td>162</td><td></td></tr>
</table>

6.4. Optimal Application Rates

When anti-icing is implemented for the sole purpose of preventing the bonding of snow and ice to the pavement surface, the amount of salt being used may not need to be large. To determine the minimum application rates for achieving this anti-icing objective, a series of tests were conducted using different anti-icing application rates. As an example, Figure 7 shows the coefficient of friction of a pavement surface as a function of the anti-icing application rate for the plowed anti-icing sections. These tests were conducted on four different days. An application rate of zero means that the section was not treated with anti-icing. As it can be observed, an application rate as low as 5 lbs/1000sqft could achieve the main purpose of preventing the bonding and improving the friction level.

To confirm these results with statistical reliability, two statistical analyses were performed on the compared data: t-tests for checking the difference in means between the treated site with application rates of 5 to 20 lbs/1000 sqft and that of untreated sites and an ANOVA for checking whether there was any difference between the treated sites.

Using approximately 100 observations, it was found from t-tests conducted that the difference in mean CoF between treated and untreated sites is statistically significant at a 95% confidence level. From the ANOVA analysis, however, it can also be concluded that the difference of CoF between all the treated sites is not statistically significant. This in turn suggests that, an application rate 5lbs/1000sqft is optimal for anti-icing purpose.

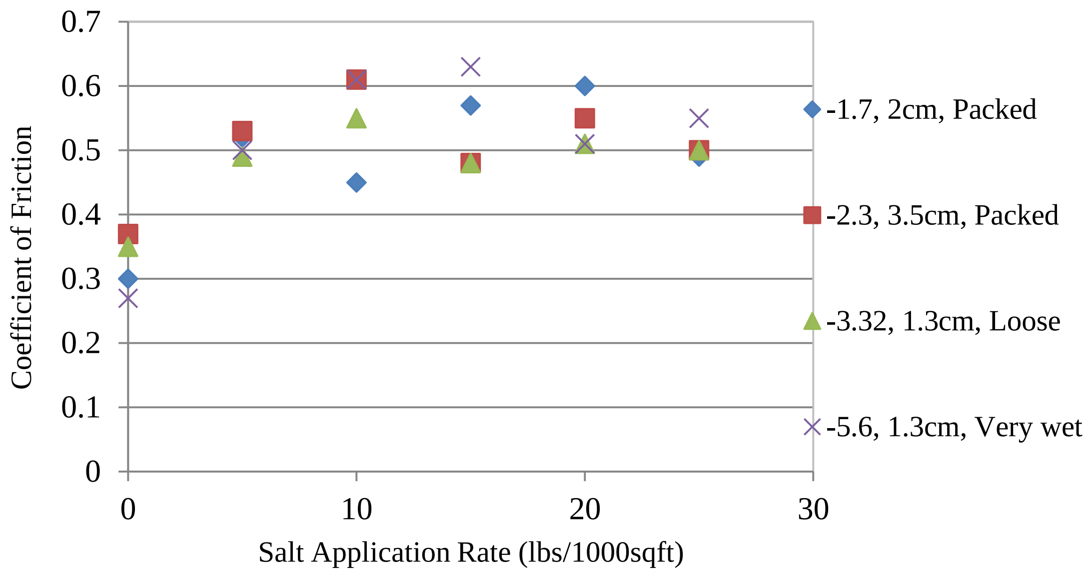


Figure 6-6: Friction Performance of Anti-icing Treatments

(Notes: Friction measurements were taken after plowing. Legend shows different test days with pavement temperature, snow amount and snow type)

Table 6-4: Descriptive Statistics of Anti-icing Data

Variable	Salting Rates (lbs/1000sqft)	Pavement Surface Temperature (°C)	Amount of Snow in kg/m^2 (Snow Depth in cm x Density in kg/m^3)	Average Coefficient of Friction
(Minimum, Maximum)	(0, 20)	(-14, -1.6)	(0.08, 9)	(0.22, 0.65)
Mean	9.56	-7.04	1.61	0.44
Std. Dev.	6.61	3.35	2.16	0.13
Variance	43.68	11.25	4.65	0.02
Kurtosis	-1.07	-0.77	5.98	-1.25
Skewness	0.16	-0.19	2.49	-0.03

Table 6-5: t-Test Results for Analyzing Difference in Snow Melting Performance between Control and Anti-icing Sections

Statistics	Rate 5	Rate 10	Rate 15	Rate 20
Observed Difference in Mean CoF (Treated over control section)	0.05	0.09	0.12	0.14
Standard Error	0.01	0.02	0.02	0.02
Sample Variance	0.00	0.01	0.01	0.01
Sample Size	17.00	17.00	17.00	17.00
Degrees of Freedom	16.00	16.00	16.00	16.00
Hypothesized Difference in Mean CoF (Treated site over Control Site)	0.00	0.00	0.00	0.00
t-calculated	5.56	4.91	6.27	5.87
(t-critical)	1.75	1.75	1.75	1.75
P-value (5% probability)	0.00	0.00	0.00	0.00
Statistical Conclusion	Improvement in snow melting performance is observed between control and anti-icing sections.			

Table 6-6: ANOVA Summary for analyzing difference in snow melting performance between different salting rates

Statistics	Rate 5	Rate 10	Rate 15	Rate 20
# of Observations	26.00	26.00	17.00	17.00
Sum	11.15	12.04	7.80	8.11
Average CoF	0.43	0.46	0.46	0.48
Variance	0.01	0.02	0.02	0.02

Table 6-7: ANOVA Results for Analyzing Difference in Snow Melting Performance between Different Salting Rates

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares	F-Observed (5% significance level)	F-Critical (5% significance level)	P-Value	Conclusion from ANOVA Results
Between Rates	0.03	3.00	0.01	0.58	2.72	0.63	No evidence to reject the null hypothesis that the mean performances (Avg. CoF) for all treatments are equal
Within Rates	1.34	82.00	0.02				
Total	1.37	85.00	N/A				

As for the liquid salt, when the application rate was increased, the coefficient of friction achieved at the end of testing also did not increase significantly. The change is most noticeable when a minimum rate of 3L/1000 sqft is applied to both control and test sections. This means that while it is necessary to apply salt for anti-icing during a snow event, only a small amount is required to achieve an optimal level of service.

6.5. Summary of the Chapter

This chapter has presented the results from a series of field tests aiming at determining the performance of anti-icing treatments. The research component was mainly concerned about the effectiveness and relative performance of anti-icing operations using different materials and application rates under different weather events. The main findings from this study include:

- Anti-icing was found highly effective in preventing the bonding of snow, improving friction levels, and improving bare pavement regain times.
- Anti-icing operations, when used as pre-application, were found to perform much better than post-application (deicing) for light snow events.
- Compared to solid salt, brine was found to be more effective under conditions where the same amount of salt (NaCl) was used.

- The two alternative liquid products were found to perform similar to regular brine for anti-icing treatments.
- The performance of anti-icing operations also depends on the nature of the snow event. For long and intense events, anti-icing operations were found to be ineffective in preventing the snow bonding with the pavement.
- It was found through an exploratory data analysis that the influential factors for anti-icing included the amount of snow, snow density, pavement surface temperature, and the snow moisture content.
- Through graphical representations, it can be observed that anti-icing using various rates improves the coefficient of friction achieved at the end of testing in comparison to controlled sites.
- It was observed that anti-icing using a brine solution results in a better performance than that of regular salt. A minimum application rate for brine used during testing, (3lbs/1000 sqft.), performs similar to that of regular salt applied at 5 lbs/1000 sqft. Brine requires a lower content of sodium chloride to manufacture, which makes it an optimal choice for an anti-icing procedure.
- Using statistical analysis, it was found that anti-icing improves the friction achieved when the results of control sections are considered. However, it was observed that only a small amount of chemical is needed to achieve results that are acceptable. No significant improvement is achieved when the application rate is increased for anti-icing.

CHAPTER 7
CONCLUSIONS

To optimize winter maintenance operations for snow and ice control of parking lots and sidewalks, the primary goal of this research is to develop a better understanding of the conditions that influence the effectiveness of commonly used treatment operations (deicing and anti-icing) for parking lots and sidewalks and to then use this understanding to develop knowledge for the optimum selection of materials, application rates and techniques. To meet this objective, the research was designed to conduct in-depth analysis of the field performance data of common winter maintenance methods and materials. One of the main problems for conducting this research was lack of data. To fill this gap, a large number of field tests were conducted during the winter seasons of 2011-12 to 2013-2014. Approximately 5000 tests were conducted covering a large number of treatment combinations in terms of snow control chemicals (e.g., regular salt, alternative salts, pre-wet salts, organic materials, etc.) and major maintenance strategies (deicing and anti-icing); the tests included 100 typical winter events. Based on the field test results and insights that have been gained in this research, this chapter presents summary of main findings, highlights important contributions, points out major limitations, and suggests future research directions.

7.1. Major Findings from Deicing Treatments

- Deicing treatments were conducted using regular rock salts, pre-wetted salts and semi to full organic salts such as, Green, Blue, Jet Blue and Slicer salts (trade names). An extensive exploratory data analysis was conducted on the performance data and influencing factors, followed by a regression analysis. From the analysis, it was found that application rates, pavement temperature, snow amount and traffic volume are statistically significant in influencing snow-melting performance (snow melting speed and BPRT) of salts.
- With a physical understanding of the snow melting behavior of salts, and after collection of empirical data from field tests, snow melting performance models were developed. These models were then used to determine minimum application rates for a given weather scenario and LOS requirement. The snow melting performance models were also used for adjusting application rates for various factors and treatment techniques (e.g., traffic, pre-wetted salts).
- From the perspective of a snow control material's performance, it was observed that when pavement surface temperatures drop below -10C, the melting speed sites treated with regular

salts substantially dropped, and it generally took significantly longer for them regain bare pavement.

- It was also observed that alternatives to regular salts outperformed regular salts in general. Among the alternatives, Green, Jet blue and Slicer generally had approximately one-hour shorter bare pavement regain time than rock salt.
- The alternatives performed significantly better than rock salt at a pavement temperature below -5°C. The BPRT reduction ranged from 1 to 5 hours depending on application rates and material types. One interesting characteristic of the alternative salts is that their snow melting rate (i.e., bare pavement time reduction) differed according to the application rate. The bare pavement regain speed was disproportionately changed when application rates were changed from relatively low to high.
- When pre-wetted salts were tested in parallel to dry rock salt, dry rock salts were first mixed with regular brine at the rate of 20 to 30% by mass of dry salts. The gross amount of materials applied in dry salts and pre-wetted sections were same, which means the pre-wetted treated sections had approximately 20% less sodium chloride. Although, there was a reduction of 20% in the amount of material applied in pre-wetted sections, similar performance was observed when the BPRT was compared between the test sections treated with pre-wetted rock salts and dry rock salts only. This indicated that if pre-wetted salts are used 20% less salt can be used to achieve similar levels of service.
- The effect of traffic was found to be significant from the data collected. It was clearly observed that salting was more effective on the driveway areas than the parking stall areas. This resulted from the different traffic patterns and the higher traffic present in the driveway sections of the parking lot when compared to the parking stall areas.
- The study concluded that to reduce salt usage while still achieving desired levels of service, different application rates should be applied for stall areas and driveways.
- It was found that snow melting performance also varied depending on the pavement's surface type. It was found the snow melting speed on AC was faster than PCC. A significant number of comparative tests were conducted on the two pavement types. From these tests, it was found that the mean snow melting speed on AC was 10% faster than PCC. This difference was found statistically significant at a 95% confidence level.
- Between Portland Cement Concrete (PCC) and Interlocking Concrete Pavers (IC), the difference in melting speed was not found to be statistically significant. This means that if the

recommended application for a given event is known for either surface type, the same application rate can be used for the other pavement type. For sidewalks, sometimes IC is constructed for aesthetic value. Maintenance operators can follow one application rate when applying salt to these pavement types.

- Since the difference in melting speed between PCC and IC was not found to be significant, and since constructing IC is expensive, from a winter maintenance perspective, making sidewalks from PCC is optimal as there was no additional advantage in snow melting speed found for IC. However, any additional advantages of friction gain or drop for choosing one material or the other should also be considered.

7.2. Major Findings from Anti-icing Treatments

- Anti-icing treatment tests were conducted using conventional chloride salts and some organic products. These include regular salt, brine, Fusion, Snowmelt and Caliber M1000 products. It was found that, all materials were effective in preventing the bonding of snow, i.e., improving friction levels. The average friction gain on the anti-icing sites over the control sites (without anti-icing treatments) varied from 10 to 70% depending on the event characteristics.
- However, the test results did not indicate statistically significant differences in performance between the organic products and chloride based salts. This finding has confirmed that the organic products are at least as effective as the regular products for anti-icing operations, though the former has the added advantage of being environmentally friendly.
- A relatively low anti-icing application rate, i.e., 5lbs/1000 sqft for solid salts and 3litres/1000sqft for regular brine, was found optimal to achieve the main purpose of anti-icing operations (i.e., preventing bonding to occur).
- Between the regular dry salt and brine, it was found that sites treated with brine outperformed those treated with regular salts when the gross amount of sodium chloride was same.
- The performance of anti-icing operations also depended on the nature of the snow event. For long and intense events, anti-icing operations were found to be ineffective in preventing the snow bonding with the pavement. Anti-icing operations, when used as pre-application, were found to perform much better than post-application (deicing) for light snow events.
- It was observed that the effectiveness of anti-icing decreased under pavement temperature below -10^{o}C. This trend was observed for all the tested anti-icers.

7.3. Major Contributions

This research has made following academic and practical contributions:

- New synthesis on the state-of-the-art knowledge: An in-depth literature review was conducted to synthesize the existing studies and knowledge about the fundamentals and performance of various deicing and anti-icing strategies, methods and materials for winter snow and ice control of transportation facilities. Two comprehensive surveys were conducted to better understand the current state of snow and ice control in snow intensive cities in the North America.
- New field experiments and performance data: This research involved a field study on a scale that has never been done before in the world. It resulted in a valuable dataset that includes detailed weather, maintenance and performance data. Note that, the main challenge of undertaking the proposed research was the limited availability of field data on the snow and ice control performance of different chemicals. Furthermore, the dataset obtained from this research could be used in other research activities, such as roadway winter maintenance, pedestrian safety and environmental effect of salts.
- New analyses and findings on the effects of various factors on the snow melting performance of different chemicals: To the best of our knowledge, this research was the first of its kind to quantify the effects of a wide range of factors that affect the snow melting performance of various chemicals in real world operations.
- A new snow melting performance model: The research has developed a completely new mechanistic snow melting model that can be used to determine the minimum salt application rate needed to meet a given LOS requirement for a given weather condition.
- New analyses on the relative performance of different treatment methods: This research has investigated the effectiveness of all major maintenance methods and chemicals by employing pair wise comparisons. This resulted in models for predicting the performance of each maintenance method and chemical. The models generated were useful in quantifying the trade-off between the methods and materials.
- New tools to support decision making in real-world scenarios: The snow melting performance model was used to determine the optimal application rates for specific weather conditions and LOS requirements. This tool was the first of its kind for the winter maintenance industry.

7.4. Limitations and Recommendations

This thesis achieves its objectives satisfactorily and is expected to contribute significantly to the research community. However, there are several limitations.

- It was really challenging to evaluate the performance of a maintenance technique or a material in a real-world setting due to the number of uncontrollable factors endemic to a field environment. The snow melting performance results obtained from the field tests can be used to compare and validate results obtained in laboratory settings, though the main goal of this research was to include factors that cannot truly be captured in a laboratory.

- In the majority of the tests, salts were applied manually. A significant amount of training was conducted to ensure uniform distribution, however, the difference in performance of two materials or methods could also be caused by unavoidable non-uniform distribution during spreading or due to wind-gusts during tests. In future research, a reliable automatic salt spreading controller can be used to address the issue and the necessary adjustment factor to the application rate can be developed.

- There was lack of data under some extreme weather conditions, such as freezing rain events and black ice conditions. Data on driveway sections was also lacking as a number of snow event occurred during weekends and holidays. On these days, although tests were conducted in stall areas, no tests were conducted on the driveways since the test sites would see very little traffic during weekend and holidays. Moreover, there were limited resources to conduct and manage so many tests combinations.
- Since the field study was conducted in one type of establishment the modeling results may not be directly applicable to other type of parking lots without careful validation, though the effect of traffic frequency in a parking stall was found to be small.
- As for tests on pre-wetting strategy, this study has several key limitations. Firstly, in this research, we were not able to conduct a sufficient number of tests on the design variable: the pre-wetting ratio that would allow us to develop a generic model relating the optimal pre-wetting ratio to specific road weather and surface conditions. Secondly, this field study did not investigate the dispersion effect of traffic under these two types of treatments, which has been considered as one of the major reasons why the pre-wetting strategy has been widely deployed, especially in the road sector. Lastly, in practice, a variety of alternative products, such as MgCl2, CaCl2 and beet juice have been used as pre-wetting agents. Their relative performance has not yet been fully investigated.

Technical Papers from this Research

Journal Articles:

1) **Hossain**, S. M. K.; Fu, L.; Lu, C., (2014), ‘’Deicing Performance of Road Salts: Modeling and Applications’’ *Transportation Research Record*, Journal of Transportation Research Board of National Academics. (In Press).

2) **Hossain**, S.M. K.; Fu, L.; Olesen J. A., (2014), “Effectiveness of Anti-icing Operations for Snow and Ice Control of Parking Lots and Sidewalks” *Canadian Journal of Civil Engineering*, 2014, 41(6): 523-530, 10.1139/cjce-2013-0587, Canadian Science Publishing (NRC Research Press).

3) **Hossain**, S.M. K.; Fu, L.; Law, B., (2014), “Winter Contaminants of Parking Lots and Sidewalks: Friction Characteristics and Slipping Risk”, Cold Region Engineering, *Journal of American Society of Civil Engineers* (In press)

4) **Hossain,** S. M. K.; Fu, L.; Lake, R., (2014), Improving Winter Road Conditions: Evaluation of Deicing Performance of Alternative Salts and Development of Adjustment Factors. *Canadian Journal of Civil Engineering*. Canadian Science Publishing (NRC Research Press). (Submitted)

Conference Papers/Proceedings:

5) **Hossain,** S. M. K.; Fu, L.; Li, S.D., (2015), “Modeling the Effect of Traffic on the Snow Melting Performance of Salts’’, Paper No: 15-3548, Paper accepted for presentation at the 94th Annual Meeting of the Transportation Research Board, Washington DC, January 2015.

6) **Hossain,** S. M. K.; Fu, L.; Li, Donnelly, T.; Lamb, Z.; (2015), “To Pre-wet, or Not to Pre-wet: a Field Investigation’’, Paper No: 15-3069, Paper accepted for presentation at the 94th Annual Meeting of the Transportation Research Board, Washington DC, January 2015.

7) **Hossain,** S. M. K.; Fu, L.; Li, Donnelly, T.; Kabir, S.; (2015), “Snow Melting Performance of Salt: Effect of Pavement Types’’, Paper No: 15-3105, Paper accepted for presentation at the 94th Annual Meeting of the Transportation Research Board, Washington DC, January 2015.

8) Hosseini, F.; **Hossain,** S. M. K.; Fu, L.; San G., P.; Seters, T. V.; (2015), “Field Evaluation of Organic Materials for Winter Snow and Ice Control’’, Paper No: 15-4555, Paper accepted for presentation at the 94th Annual Meeting of the Transportation Research Board, Washington DC, January 2015.

9) **Hossain,** S. M. K.; Fu, L.; Oleson J. A., (2014), An Experimental Study on the Effectiveness of Anti-icing Operations for Snow and Ice Control of Parking Lots and Sidewalks", Paper no-14-4398, Proceedings of the 93rd Annual General Meeting of the Transportation Research Board, Washington DC, January 2014.

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APPENDIX A: RESULTS OF THE CONTRACTOR SURVEY

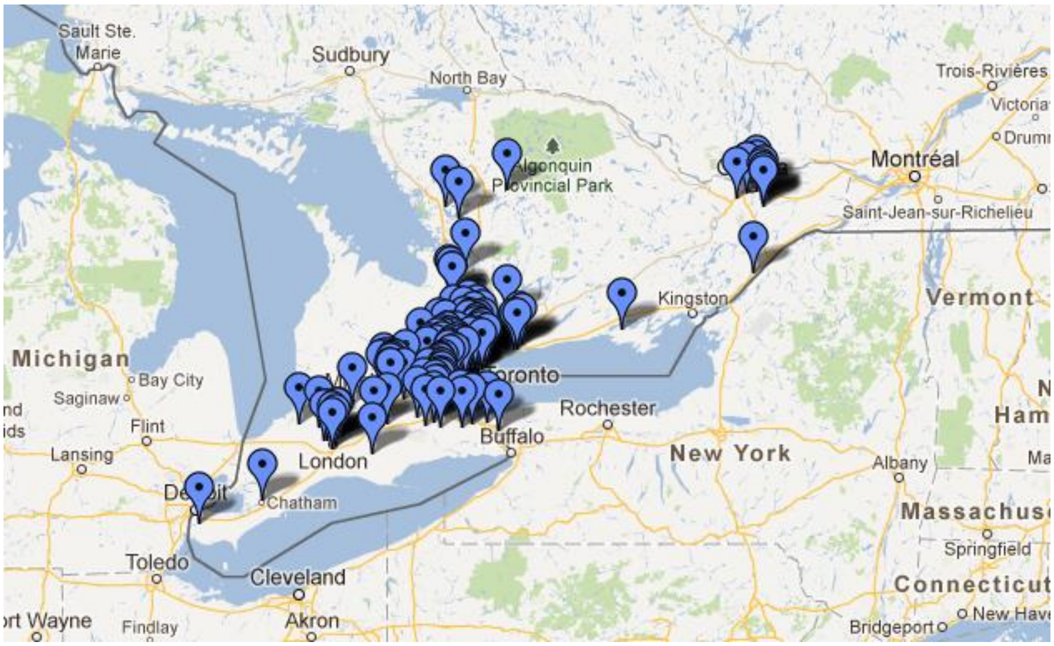

Figure A1: Geographical Location of Respondents (Contractors)

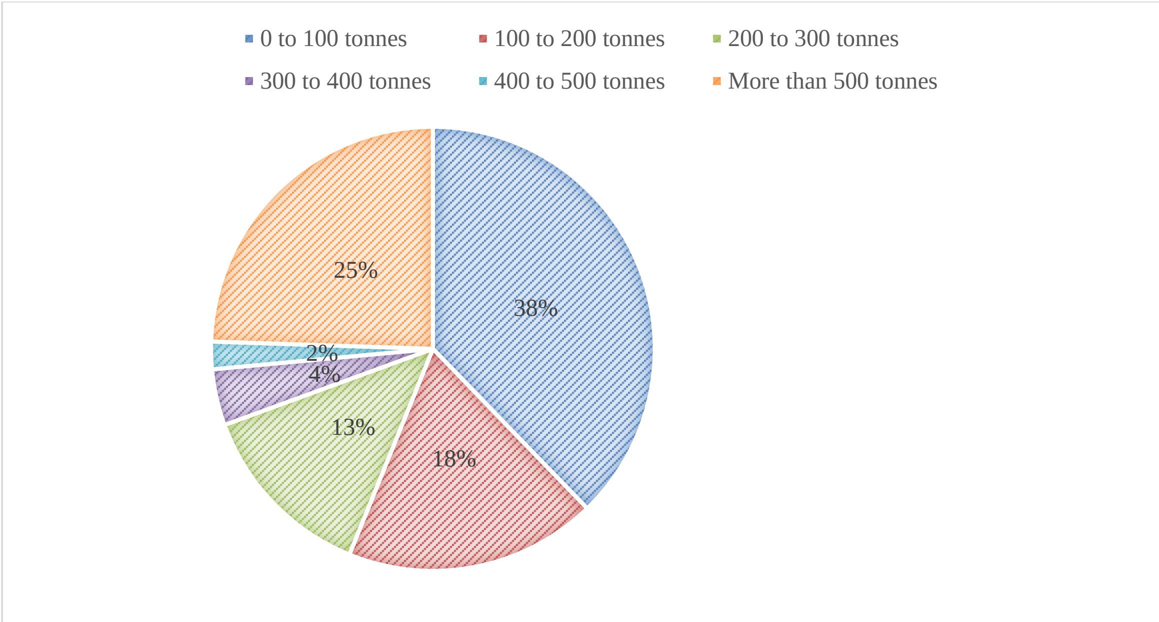

Figure A2: Distribution of Contractors by Salt Usage

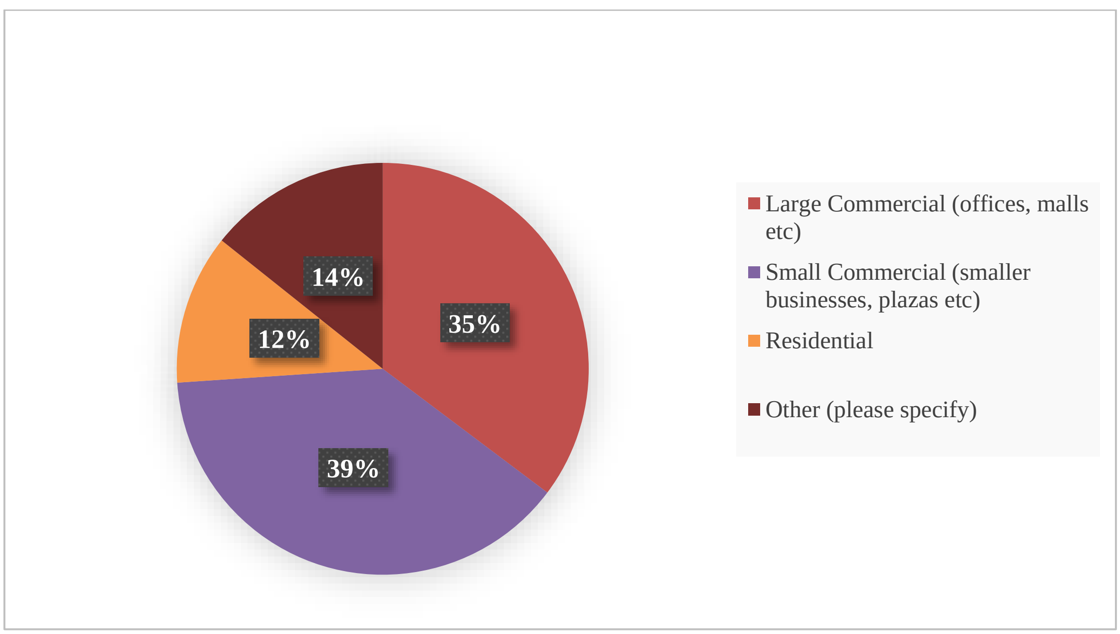

Figure A3: Distribution of Contractors by Clientele Types

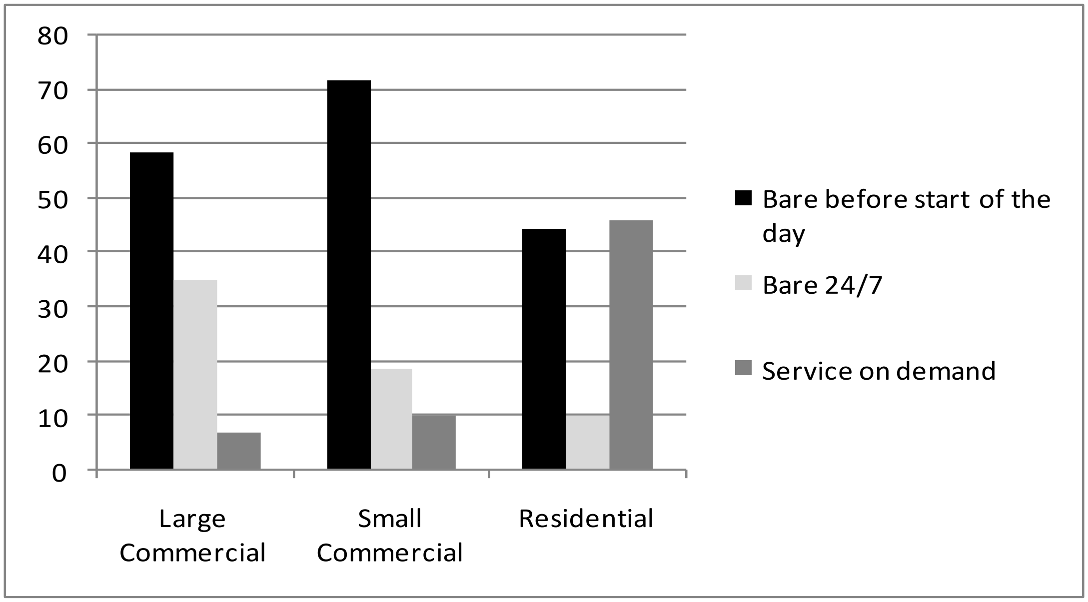

Figure A4: LOS Requirements by Types of Clients

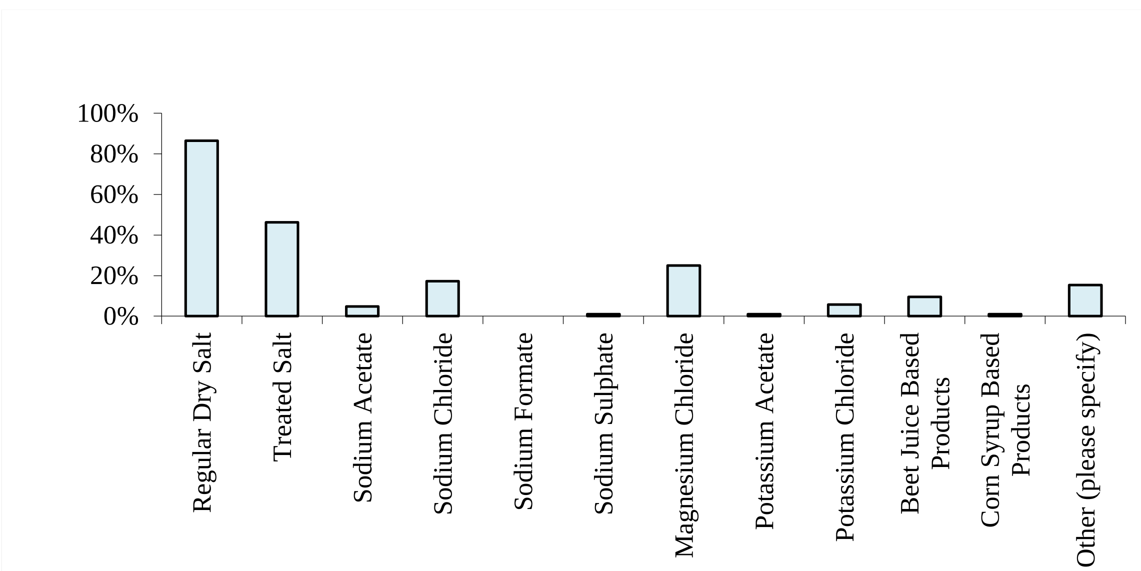

Figure A5: Use of Snow and Ice Control Materials

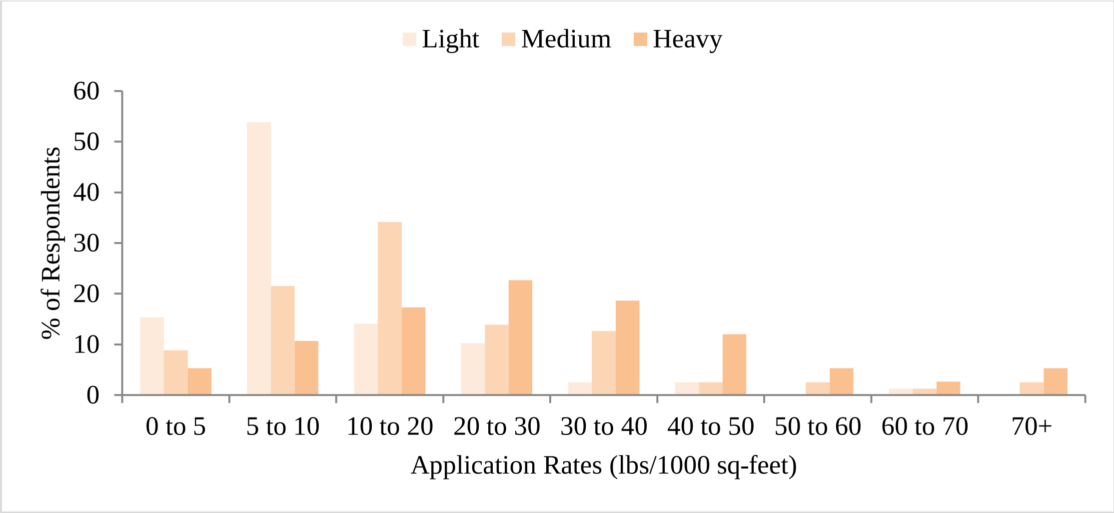

Figure A6: Distribution of Respondents by Application Rates (only 75% replied)

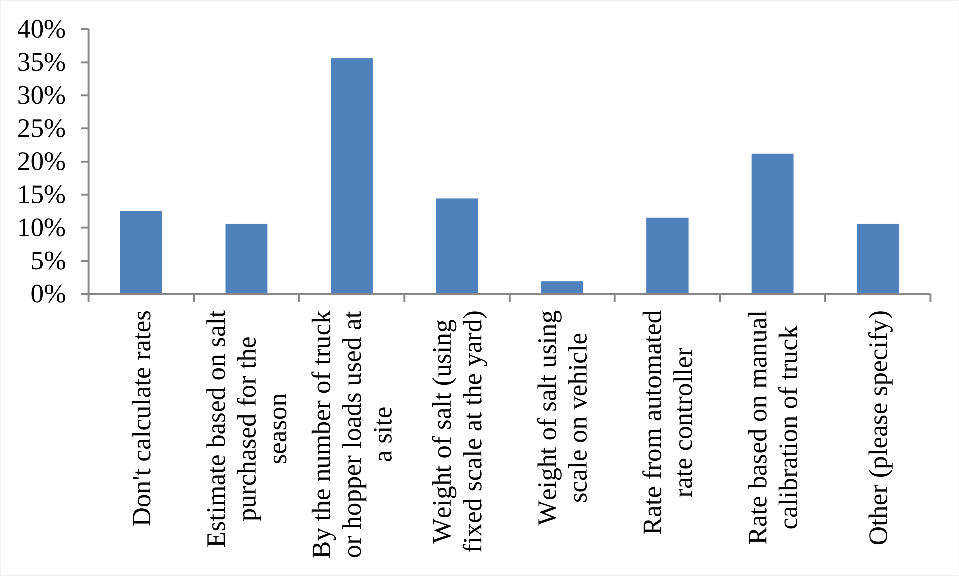

Figure A7: Distribution of Respondents by How Salt Application Rates Calculated

APPENDIX B: RESULTS OF THE MUNICIPALITY SURVEY

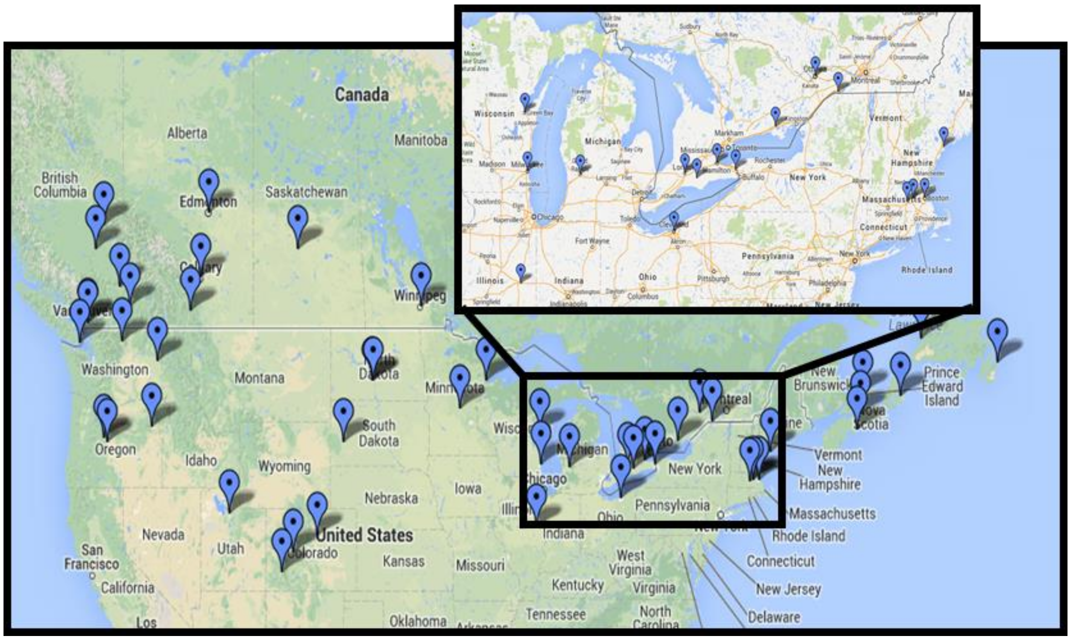

Figure B1: Locations of the Responded Municipalities

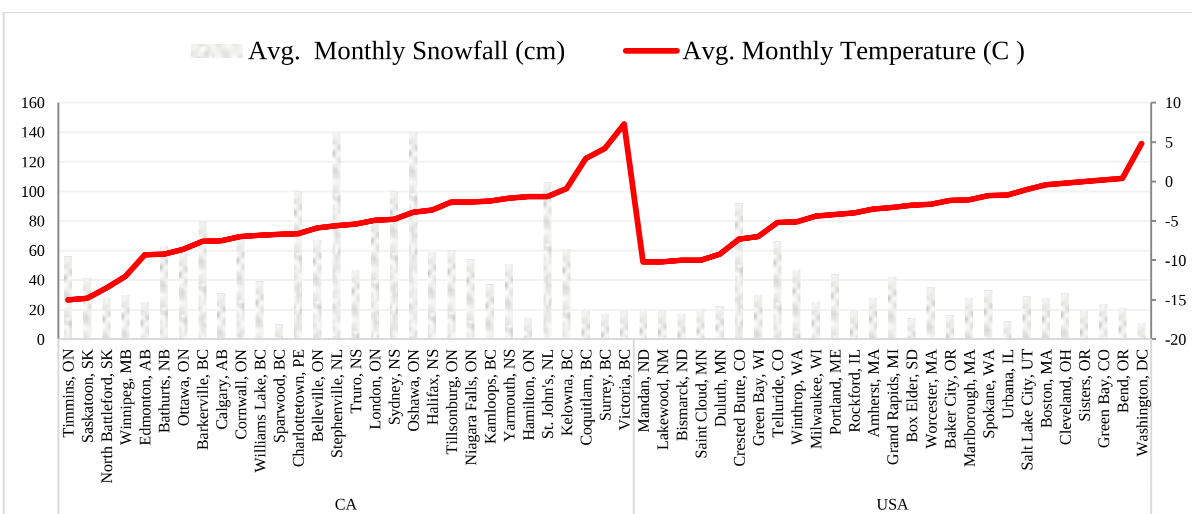

Figure B2: Average Monthly Snowfall (cm) Amount and Air Temperatures (ºC) in Respondent Cities (Dec, Jan and Feb)

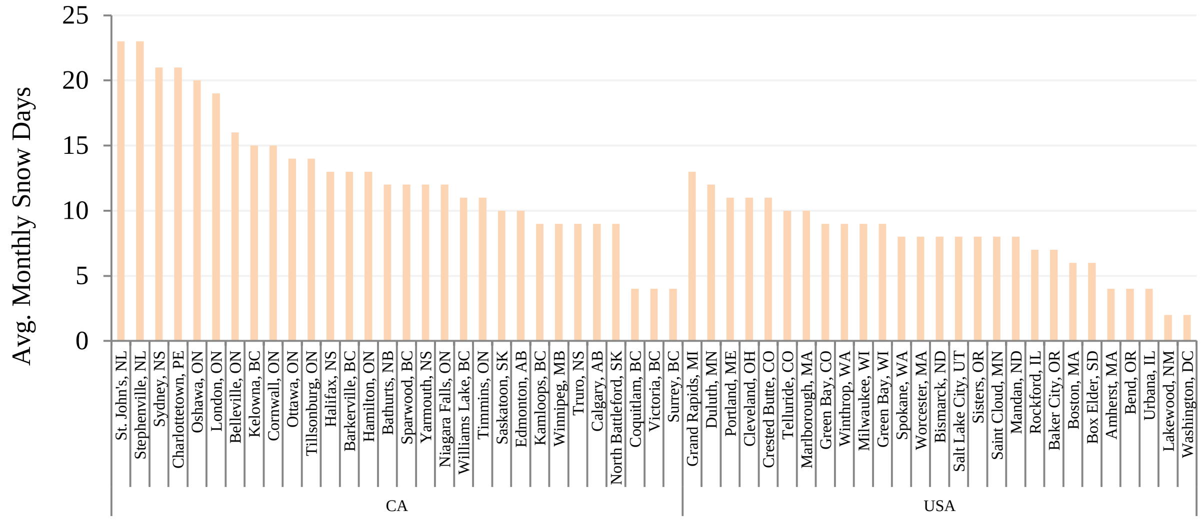

Figure B3: Average Snowfall Days per Month during Winter (Dec, Jan, Feb)

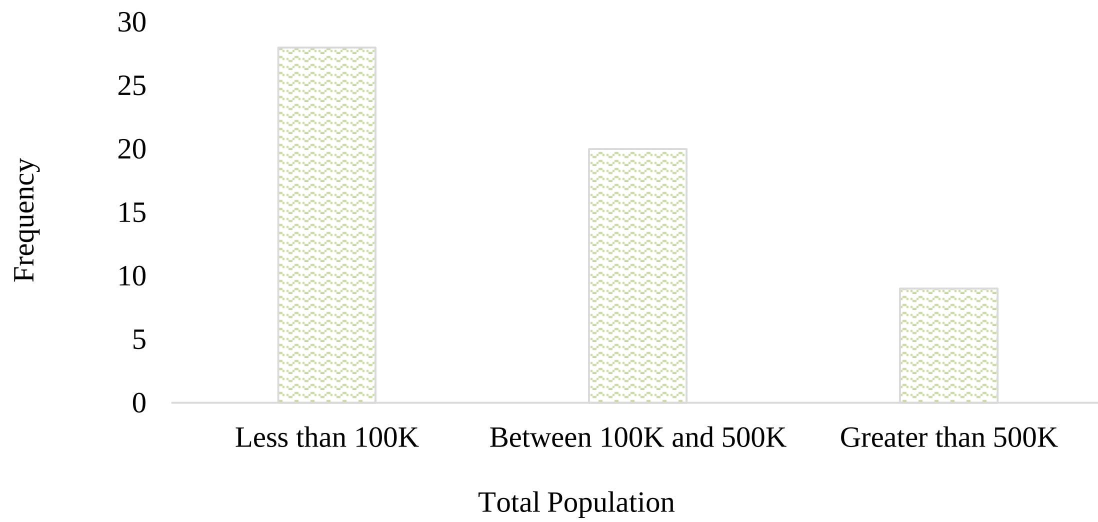

Figure B4: Population Distribution of Responded Cities

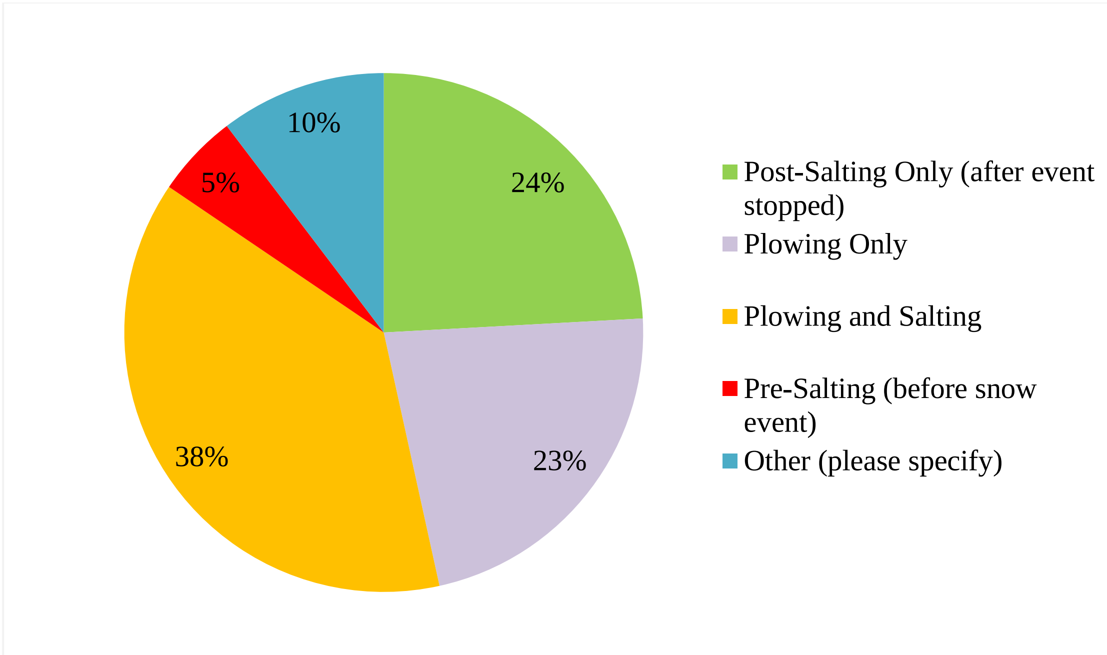

Figure B5: Distribution of Respondents by Maintenance Methods for Light to Medium Events (less than 5cm of snow)

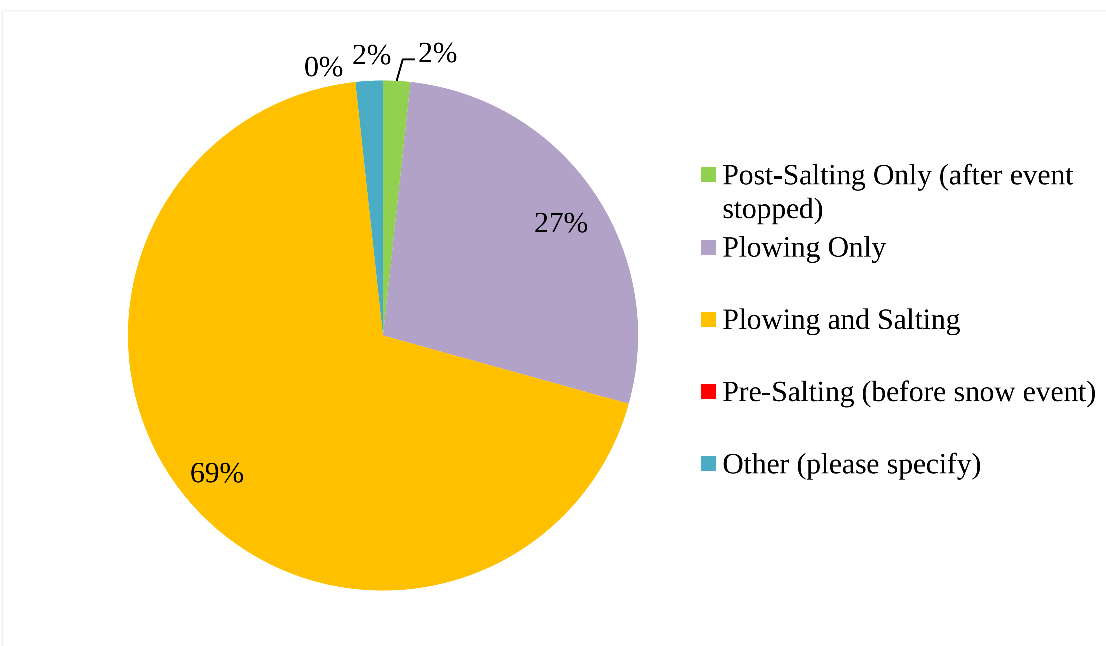

Figure B6: Distribution of Respondents by Maintenance Methods for Heavy Events (more than 5cm of snow)

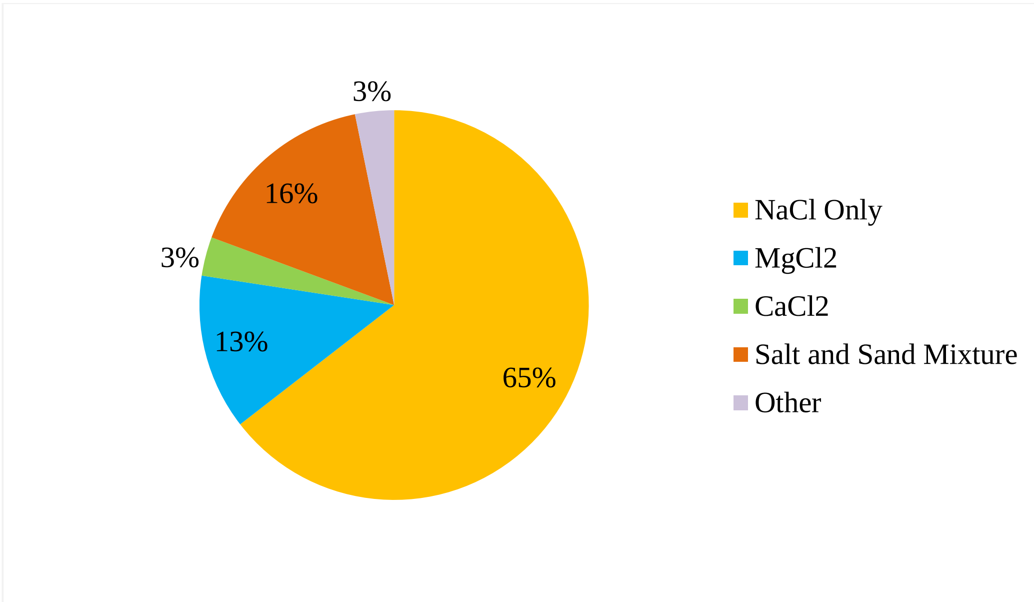

Figure B7: Distribution of Respondents by Snow Control Chemicals

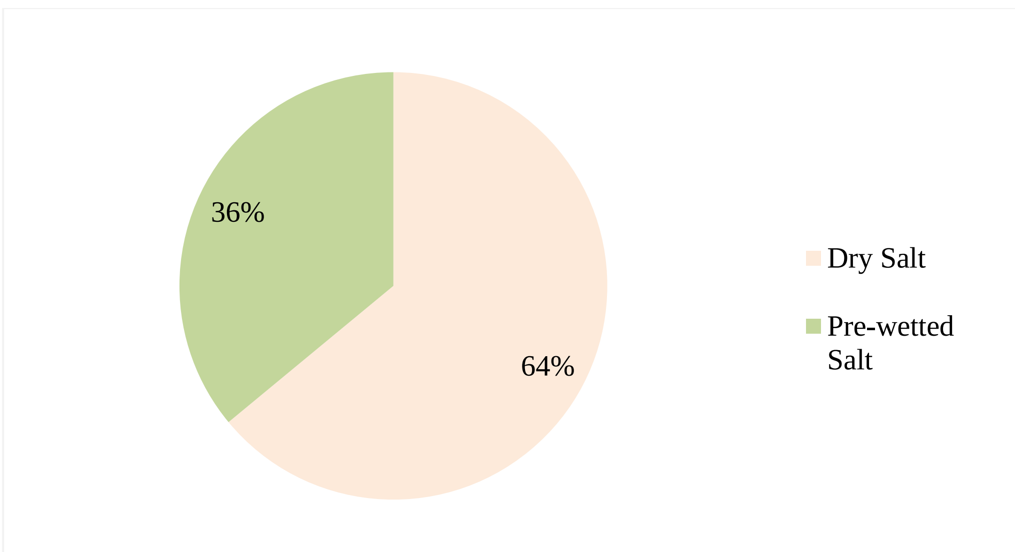

Figure B8: Pre-wetted Salts vs. Dry Salts

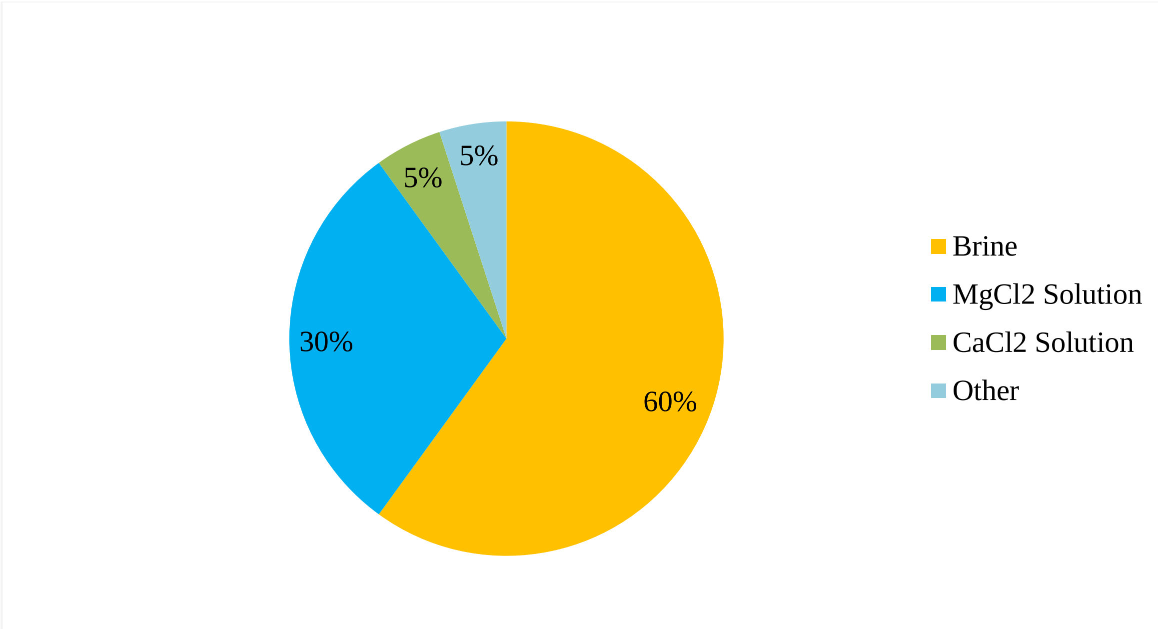

Figure B9: Pre-wetting Chemicals

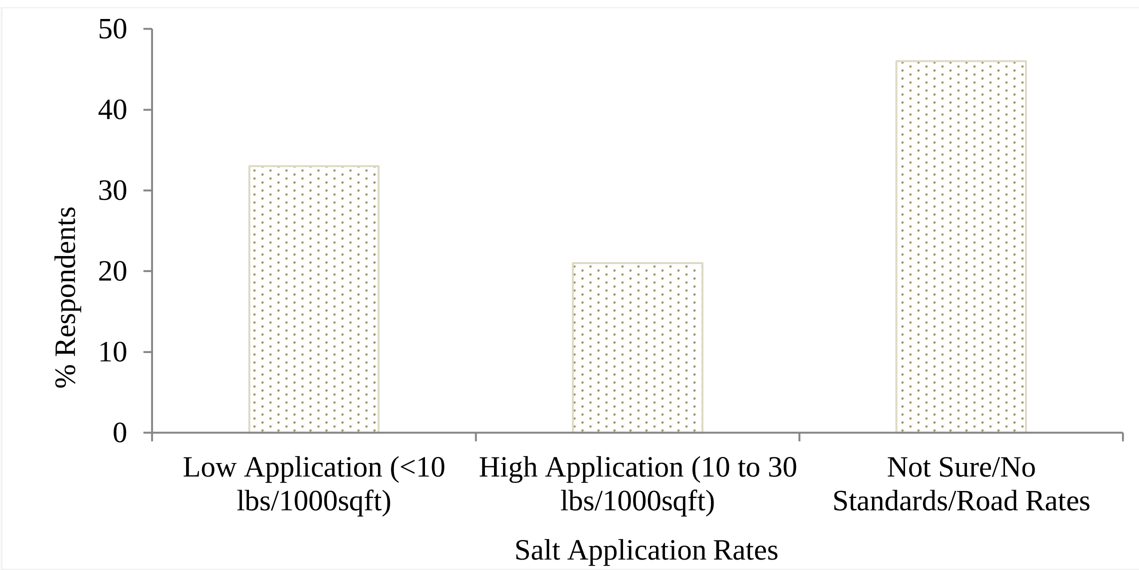

Figure B10: Application Rates for a Light Snow Event

APPENDIX C: DATA COLLECTION FORMS AND EQUIPMENT

Table C1: Data Collection Form 1-Event and Maintenance Information

Test Date:		Test Day:		Event (snow) Strat Date:		Event (snow) Sart Time:		Event complete stop		Event complete stop time:															
Total Snow depth (cm) measured (Avg of TWENTY measurements) in Parking Lot or delta site's Unaltered zone at salting time (t=0). (NB: delta site =where weight of snow, depth of	Snow depth (cm) measured in delta site's plowed zone at salting time (t=0)	If snow continues/Starts after salting, Final Snow Depth in delta site's Unaltered zone when snow completely stopped	If snow continues/Starts after salting, Final Snow Depth in delta site's plowed zone when snow completely stopped	Snow Depths in Test Sections at Salting time (t=0), in (Cm) in UD group, in (mm) in D group (2 Numbers)	If snow continues/Starts after salting, Total Snow Fall in Test Sections in D sections and UD sections {Intitial value+(Final value-Initial Value)}	Total Snow (cm) of the Day as per near by EC weather station	Total Precipitation (mm) of the day as per near by EC weather station	Weight of Snow (gm) after brushing off to bucket from 1mx1m section	Density (kg/m3) of Snow	Snow Type: Packed (1) / Loose (2) / Very loose (3) / Flurries (4) / Freeze Rain (5)/ other-specify	If plowed, Plowing Method: Manual (1), Plow Truck (2), Not Plowed (3)	Plowing Conditions: Uniform (1), Nonuniform (2), Not Plowed (3)	Avg. Pave Temp at Salting Time (t=0) at test sections	Average Pav. Temperature (without outliers) of the Day on Test Section	Min Pave Temp on the Day on a Test Section	Max Pave Temp on the Day on a Test Section	Friction Coefficient (In non-snow strip, delta zone) at Salting Time (initial value)	Qualitative Friction Level after removing some snow (Very Slippery-1, Slippery-2, Non Slippery-3) in Delta site at Salting Time (initial time)	Snow-pave bond state at delta site after removing top snow at salting time: Not-bonded-1, Bonded (ice formed)-2, Bond breaking (started mellting)-3, other	Avg Air Temp of the Day as per EC	Max Air Temp of the Day as per EC	Min Air Temp of the Day as per EC	Images Check list (Snow index-1, snow-pave bonding-2, salt weighing-3, salt spreading-4, residual salt-5, friction index-6 etc.)	Salting Time	Snow Type (in respect to moisture content): Dry snow (1) / Wet Snow (2) / oth
Maintenacne/Treatmeant at a Glance:																									
Test Section IDs																									
Test Type																									
Chemicals Name used in Test Sections																									
Salting /Application Rates (lbs/1000sft)																									
Notes																									
Test Team Members																									
Images/Video from Delta Site/Test Site		Site Activites Images, Image before plow, Image after plow, Images of Test Process will Filed as separate folders																							

Table C2: Data Collection Form 2-Periodical Observation Sheet

Obs No and Time		Air Temp (°C)			Wind Chill		Humidity		Wind Speed And		Pressure (kPa)		Visibility (km)		Dew Point		Wind Gust			Plowed Zone Snow Depth (Delta Section)		Unplowed Zone Depth (Delta Section)	
Avg. Pave Temp		Current Weather:		Weather State: Solid Snowing (1), Wet Snowing (2), Flurries (3), Freezing Rain (4), Slight Rain (5), Med Rain (6), Heavy Rain (7), Ice Pelletes (8) No Precipitation (9), Other (10)						Skyview condition: Overcast (1) , Sunny (2), Cloudy (3), Dark (4) , Clear (5), Other (6)													
Test Section IDs																							
Test Type																							
Chemicals' Name & Type used in Test Sections																							
Salting /Application Rates (lbs/1000sft)																							
Pave Temp (°C) and Snow Temp																							
% Bare Pavement																							
Friction Coefficient																							
Qualitative Friction Level: Very Slippery-1, Slippery-2, Not Slippery-3																							
Snow-pave bond state: not-bonded-1, bonded (ice formed)-2, Bond breaking (started mellting)-3, No more bonding-4, other (Specify)-5 (supported by images)																							
Contaminant type (Most or 51% case) : snow-1, icewater-2, slush-3, wetpave-4, clear pave-5, drypave-6, Other (specify)																							
Notes																							
Images/Video	Every section Images will be stored in Folder as per section ID, Time, Date																						

Figure C3: Liquid Salt Sprayer*

*The liquid sprayer used for the field experiments is the SnowEx SL-80 as shown in Figure C1. The SnowEx SL-80 is equipped with an electric powered pump and a professional duty spray wand making this walk behind sprayer ideal for small areas. The sprayer was calibrated several time during the tests season.

Capacity: 45.4 L

Spraying Width: 91.4-121.9 cm (adjustable)

Battery: 12V

Battery Life: 454.7L

Charging Time: 12hrs-16hr

Figure C4: Friction Measurement Device (T2-GO)*

*Description of T2-GO

T2-GO is a Continuous Friction Measuring Equipment (CFME) designed to measure the coefficient of friction of a confined area. Its major components include two T991 rubber wheels by Trelleborg, a belt, a load sensor, and an onboard display and computer. It measures friction in accordance with European Norm EN 1436. Regulators such as the International Civil Aviation Organization (ICAO), UK Civil Aviation Authority, and Federal Aviation Administration (FAA) utilize it in accident investigations, documentation of civil litigation and general winter maintenance. The working principles of the device are as follow:

- The two wheels are interconnected with a belt such that they rotate at a different rate. A longitudinal slip of about 20% assigned by the manufacturer.
- As it is pushed along the test section, depending on the contaminant type, the 20% slip will result in a different tension in the belt.
- The tension is measure by a load sensor that is in contact with the belt.
- After some calculation done by a onboard computer, the display will show the respective CoF value.

T2-GO had been calibrated several times during the testing seasons. However, there are some factors which can affect the reading of T2-GO.

Temperature: The operational temperature of the device is between -25ºC and +55ºC.

Length of test section: The longer the test section, the more data points can be obtained for averaging the coefficient of friction for the specific run;

Uniformity of the test section: While the test section can be set up as mainly contains only one type of contaminant, it always consists of multiple ones; the randomness of the contaminant type could result in varying coefficient of friction measured. In addition, the presence of particles (e.g. salt) and the uneven surface may cause bouncing of the device, which may affect the accuracy of the readings.

Pavement Material: When the tires can displace the contaminant (e.g. thin snow) or bare pavement is available, the micro and macro texture of the pavement will then be a contributing factor to the friction level.

Inclination of the test site: Test site with a gradient affects the weight distribution of the friction measuring device on tires, thus alters the grip of tires on pavement and also the reading on the load sensor.

APPENDIX D: SAMPLE SURFACE CONDITION IMAGES AND SUMAMRY OF DATA

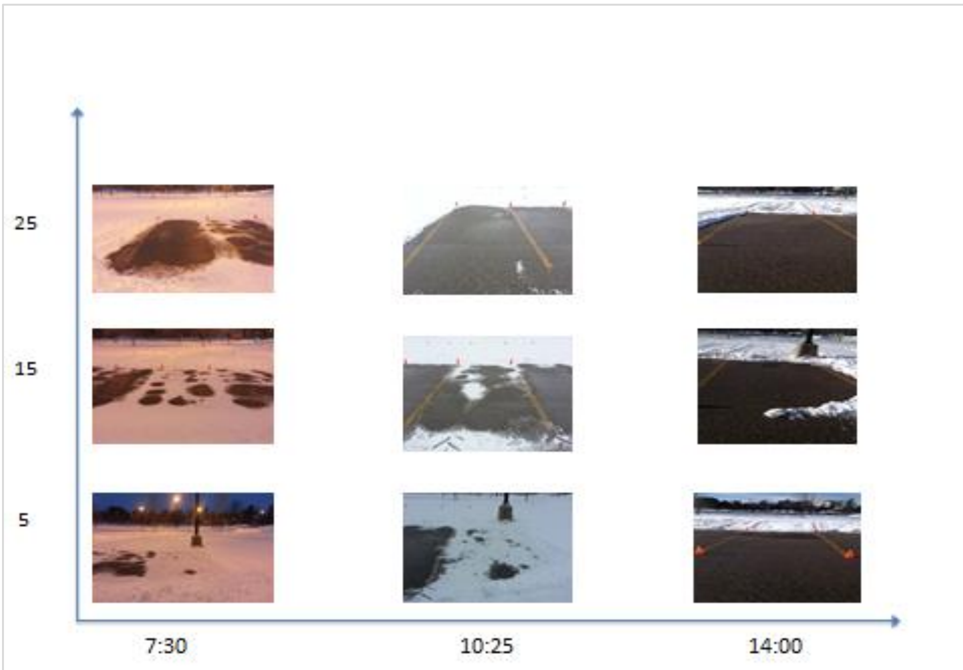

Figure D1: Sample Pavement Surface Condition Images in Deicing Sections (27 Dec 2012)

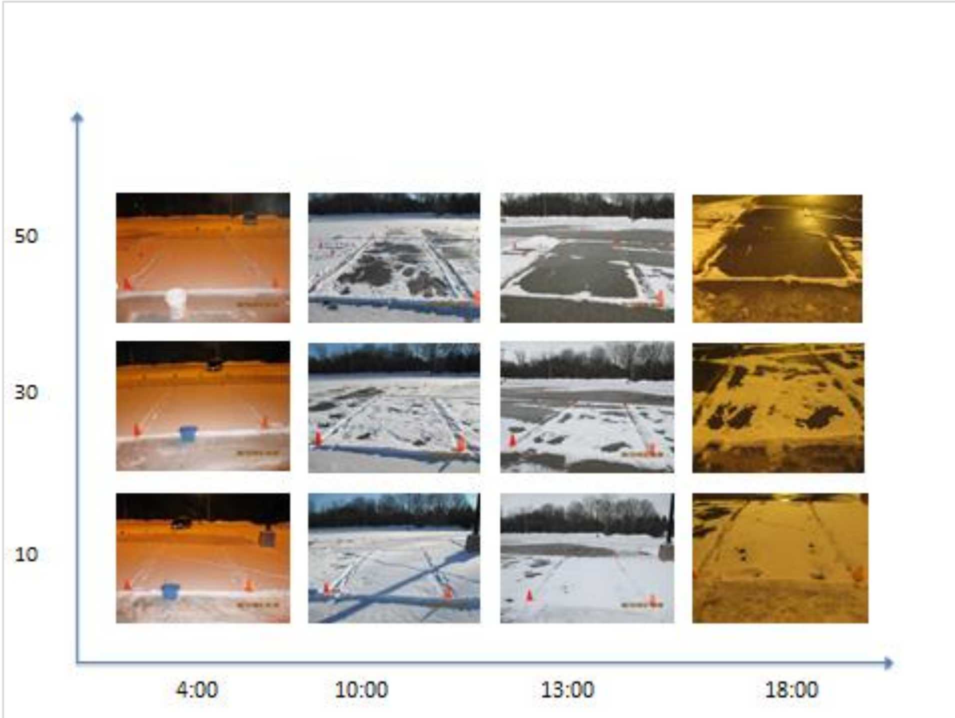

Figure D2: Sample Pavement Surface Condition Images in Deicing Sections (30 Dec 2012)

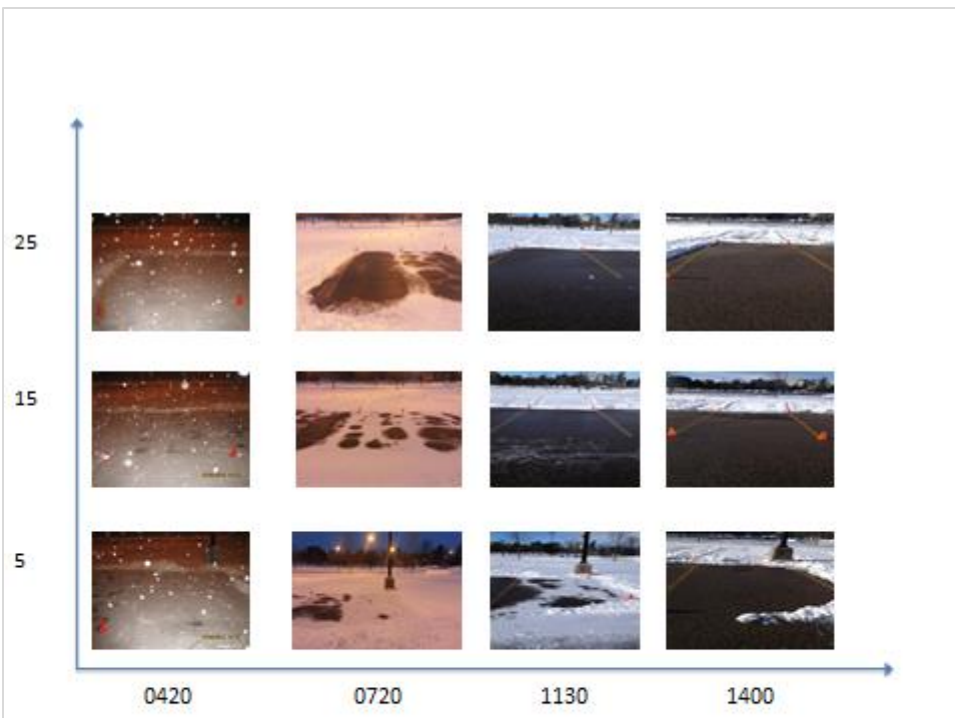

Figure D3: Sample Pavement Surface Condition Images in Deicing Sections (3 Jan, 2013)

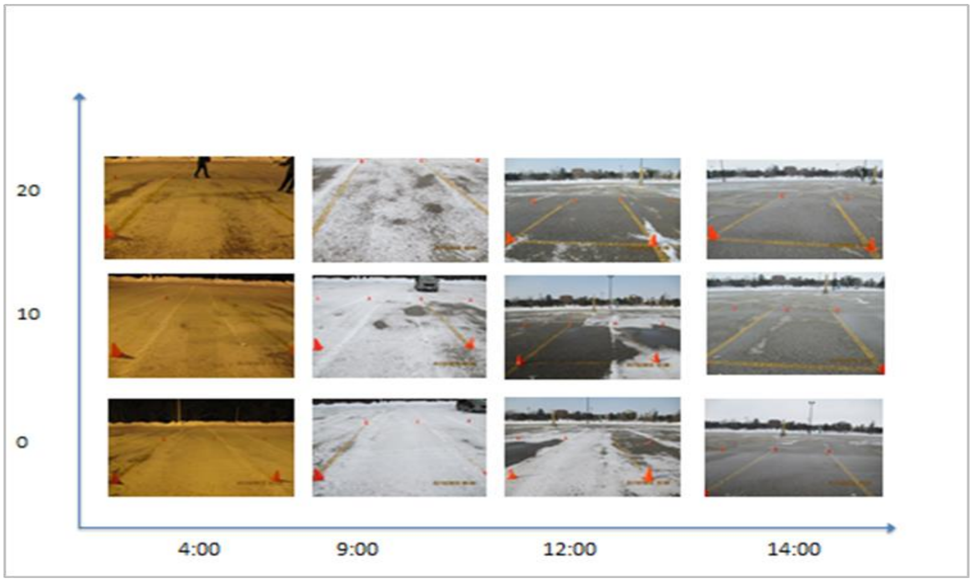

Figure D4: Sample Pavement Surface Condition Images in Deicing Sections (23 Dec 2013)

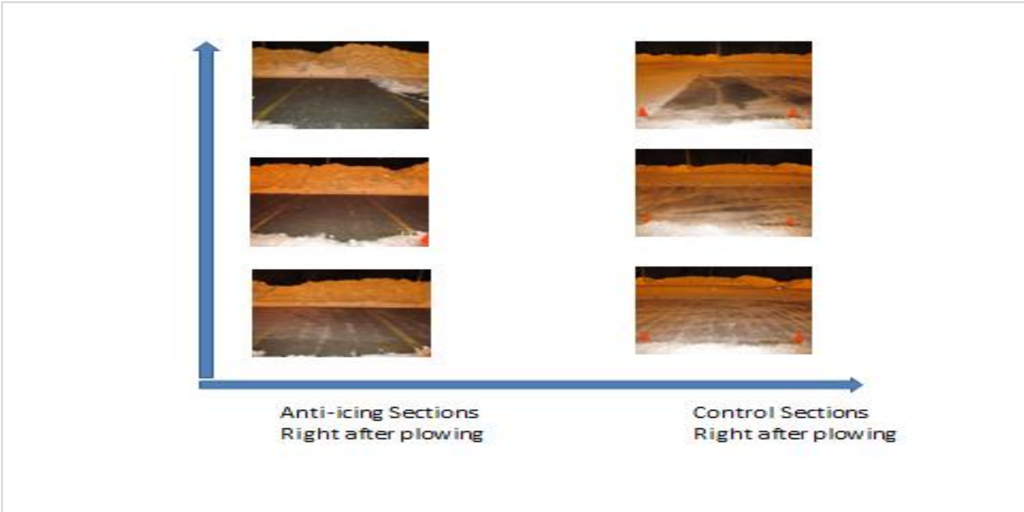

Figure D5: Sample Pavement Surface Condition Image in Anti-icing and Control Sections (15 Feb 2013)

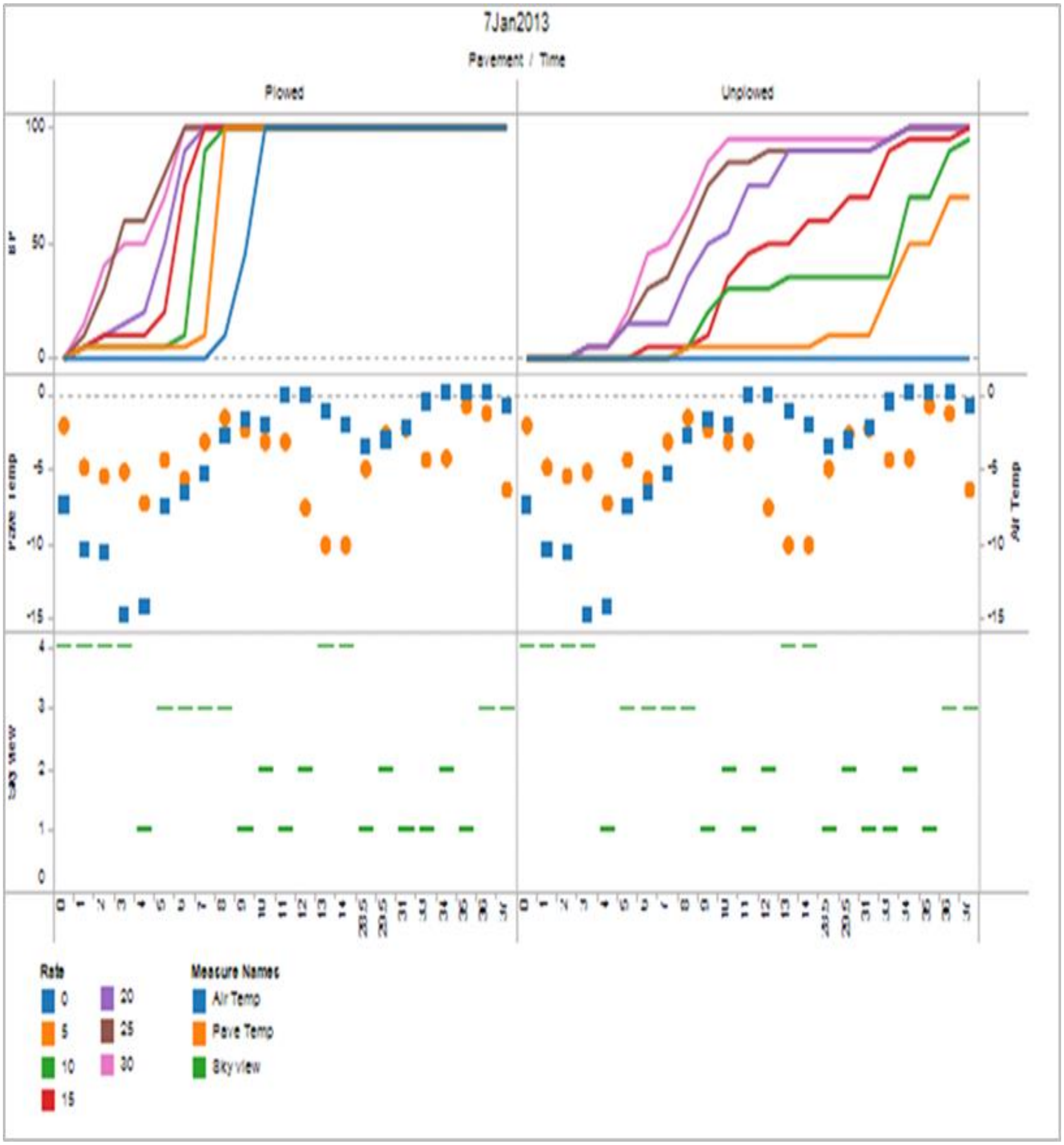

Figure D6: Sample-Pavement and Weather Condition Changes over Time (7 Jan, 2013)

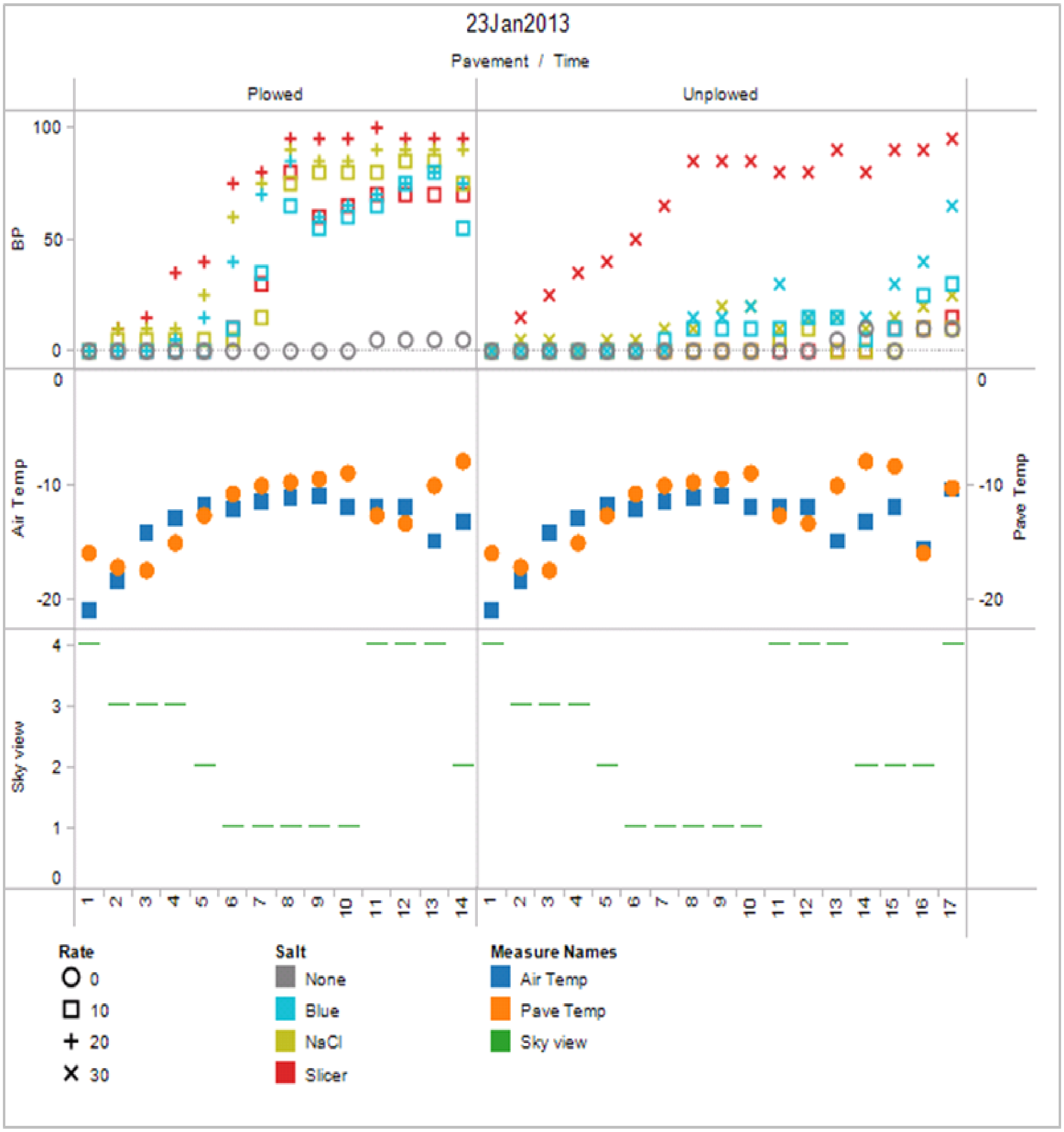

Figure D7: Sample-Pavement and Weather Condition Changes over Time (23 Jan, 2013)

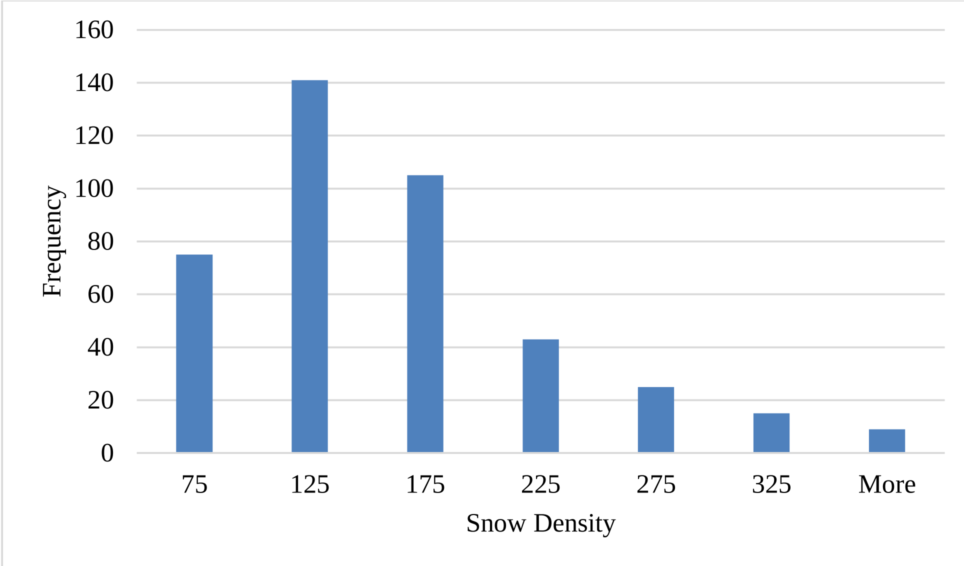

Figure D8: Snow Density (kg/m3) Distribution in Parking Lot Test Site

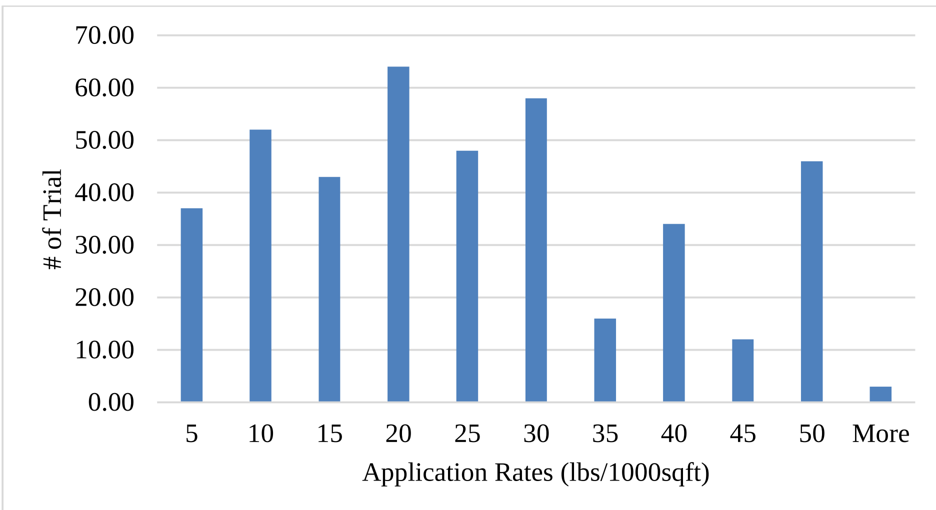

Figure D9: Salt Application Rates for Stall Areas in Parking Lot Site

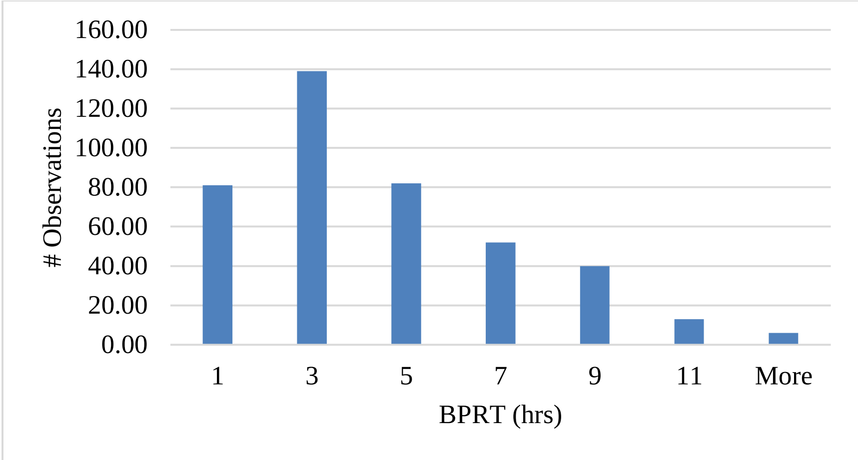

Figure D10: BPRTs in Stall Areas (BPRT not reached ~500 tests)

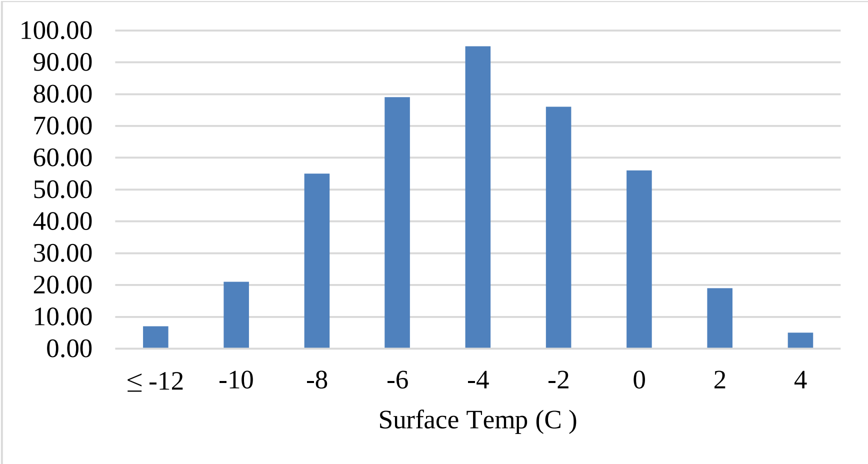

Figure D11: Surface Temperatures in Stall Areas of Parking Lot Test Site

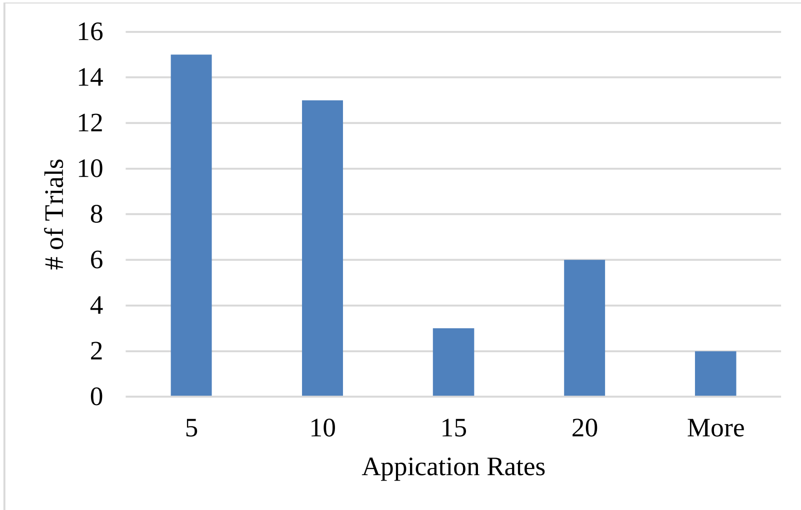

Figure D12: Salt Application Rates (lbs/1000sqft) in Driveway Test Site

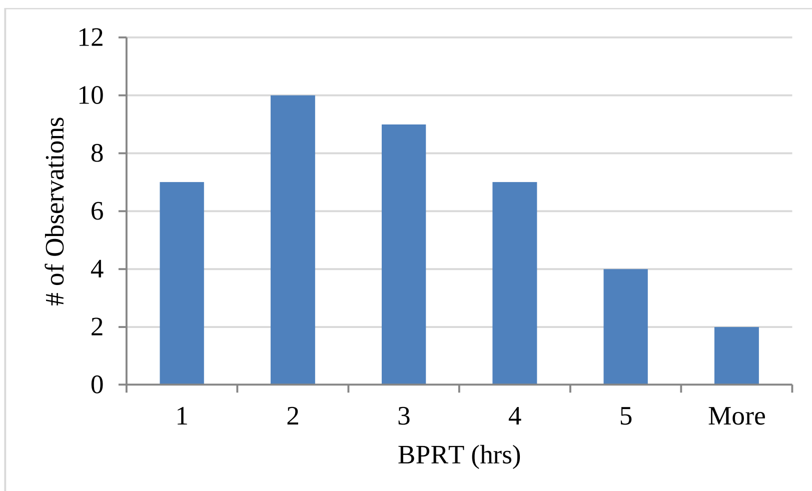

Figure D13: Observed BPRT in Driveways (BPR not reached ~100tests)

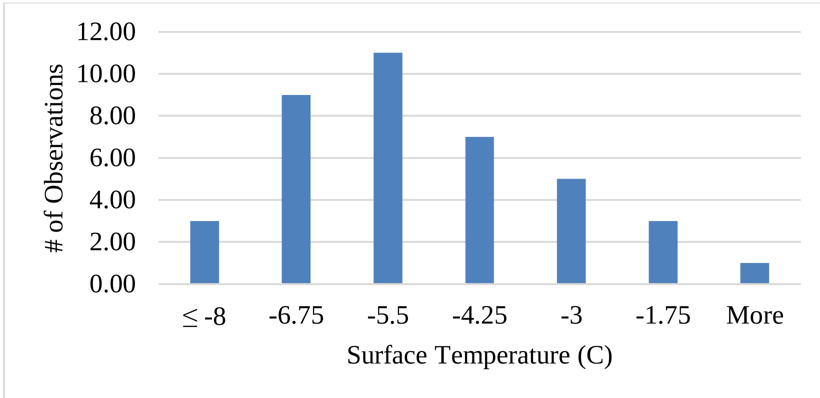

Figure D14: Pavement Surface Temp in Driveway Test Sections

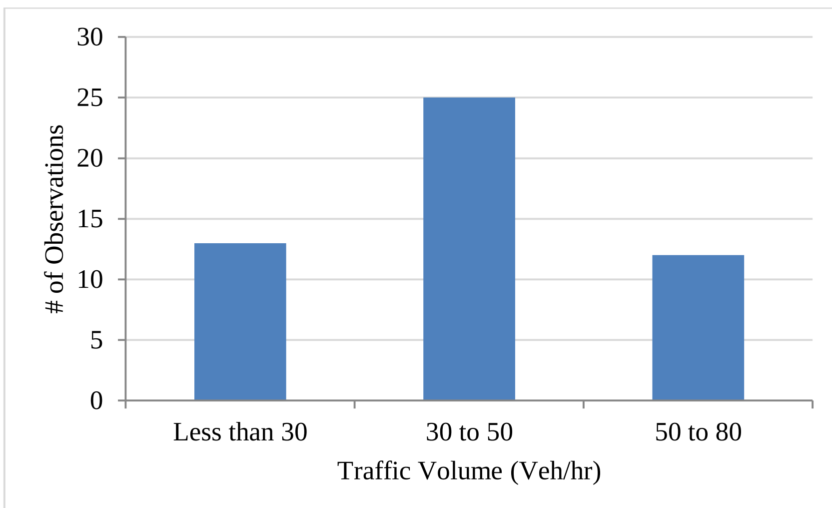

Figure D15: Traffic Volume (veh/hr) in Driveways

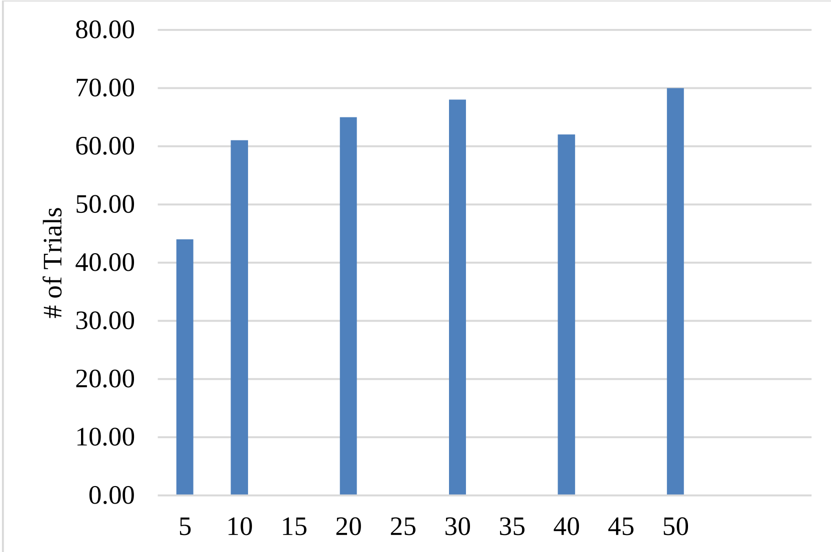

Figure D16: Application Rates Tried in Types of Sidewalks

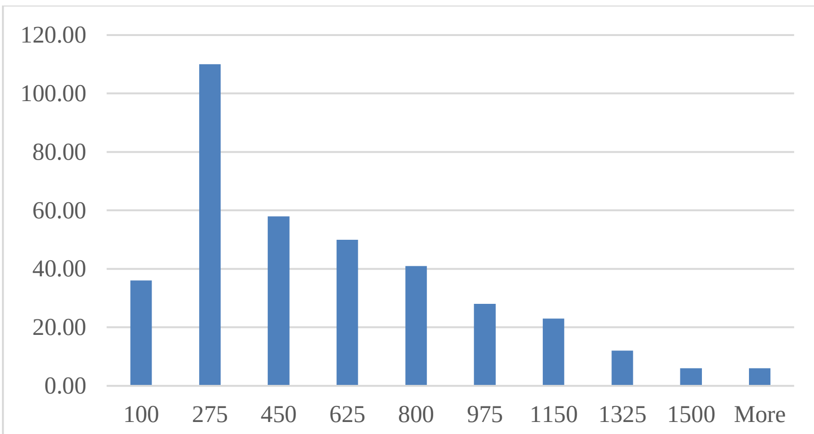

Figure D17: Snow Density (kg/m3) Observed in Sidewalk Sections

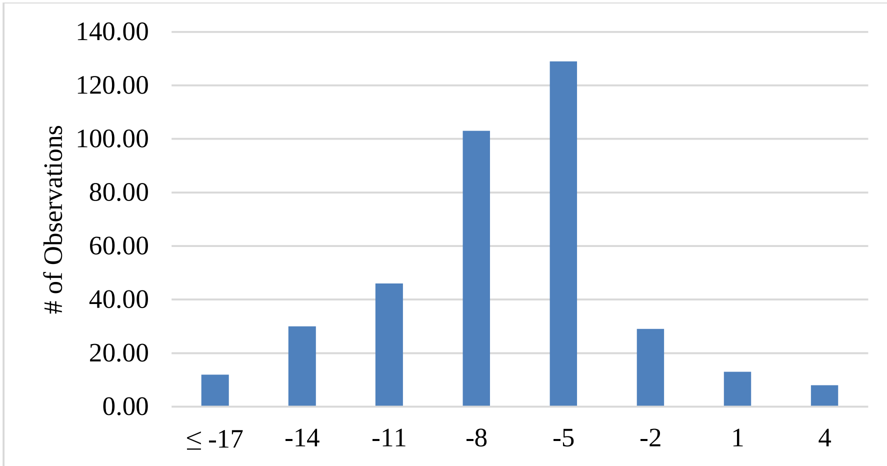

Figure D18: Avg. Surface Temp (C) in Sidewalks Sections

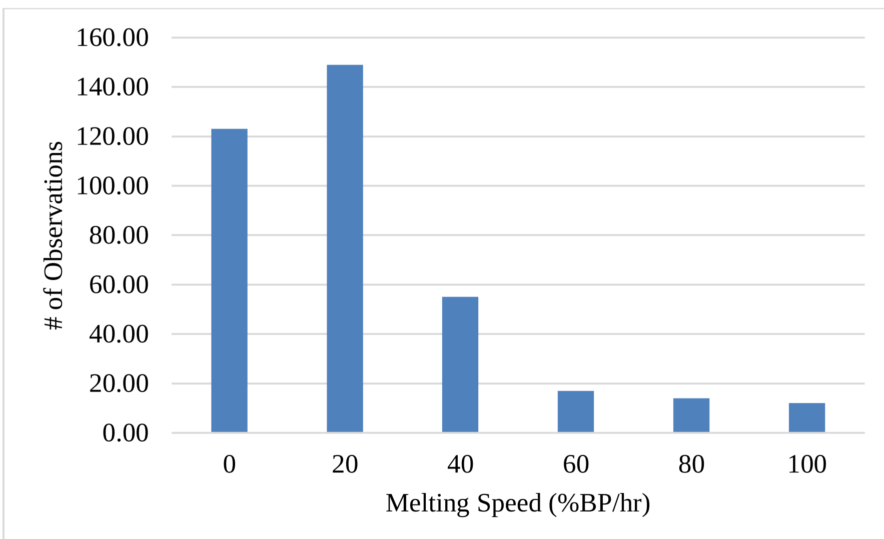

Figure D19: Melting Speed (%BP/hr) Observed in Sidewalks

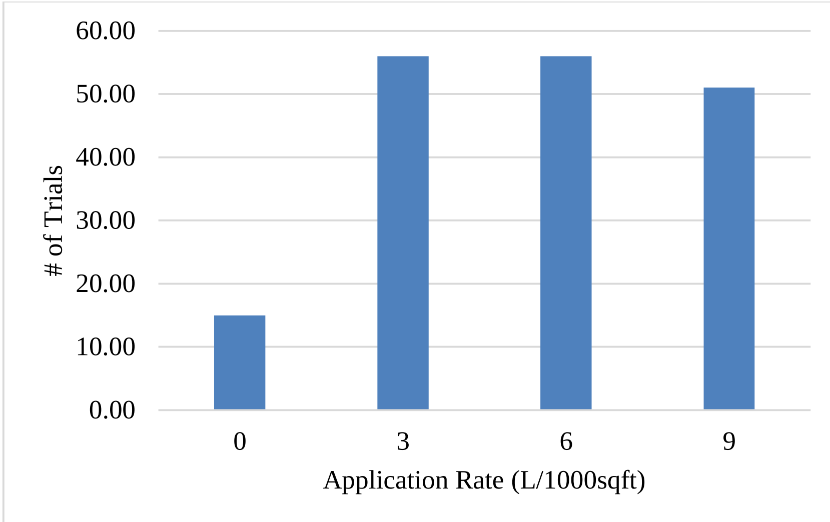

Figure D20: Liquid Salt Application Rates

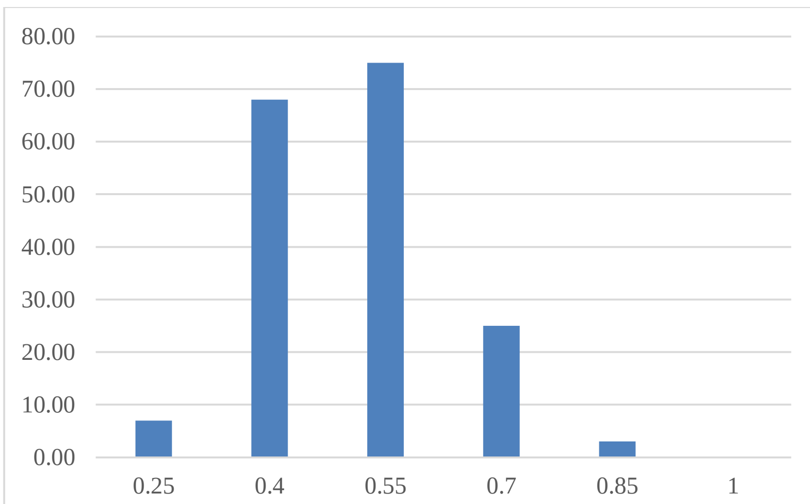

Figure D21: Avg. CoF on Test Days on Liquid Salt Sections

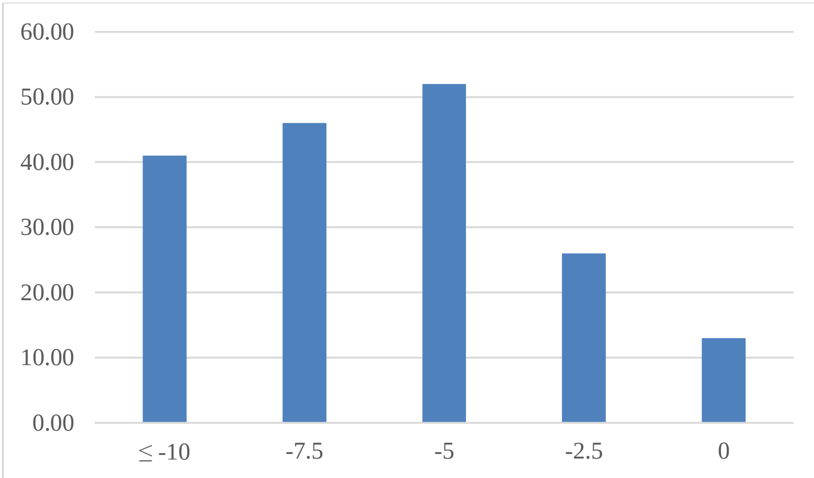

Figure D22: Avg. Surface Temp on Liquid Salt Testing Days

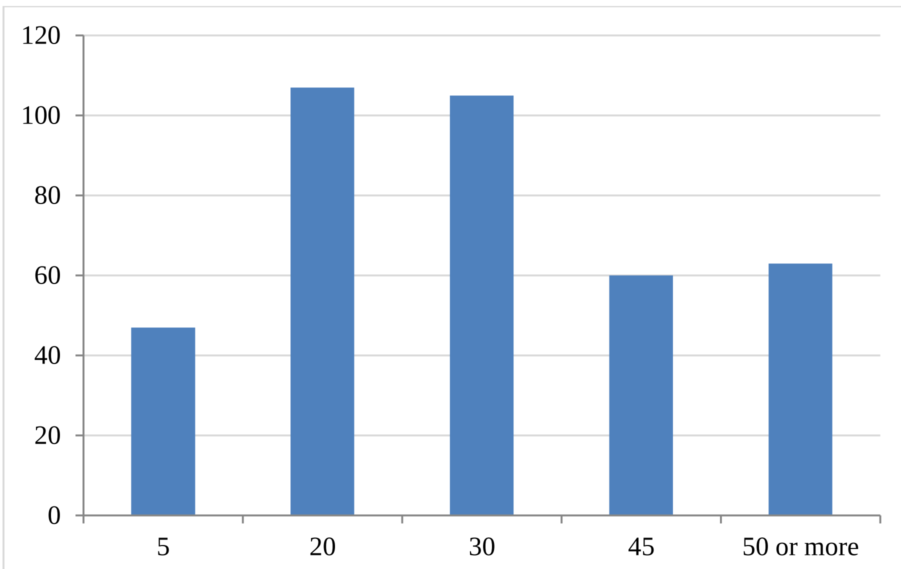

Figure D23: Pre-wet Salt Application Rates

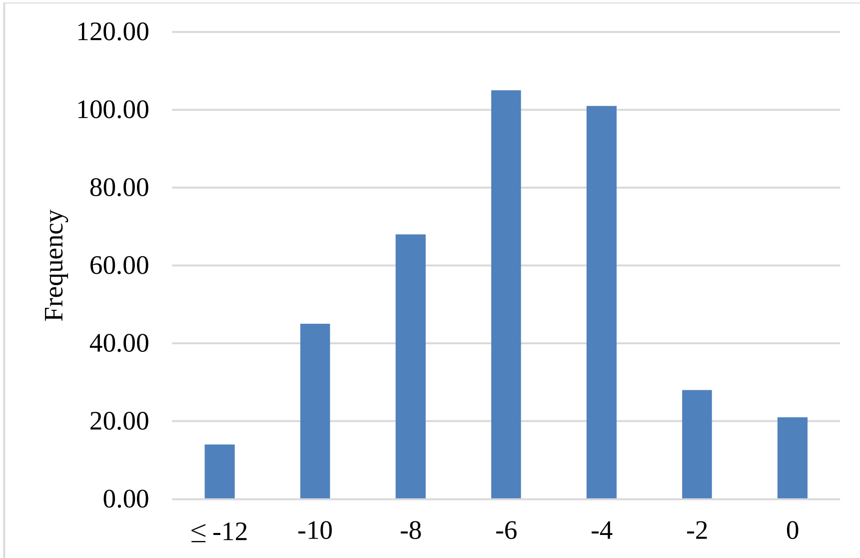

Figure D24: Surface Temperature Observed on Pre-wetting Testing Days

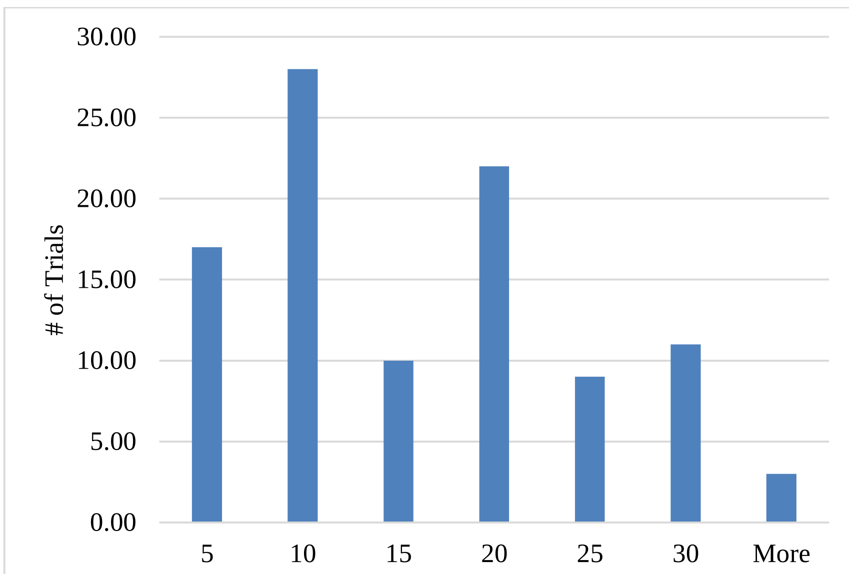

Figure D25: Alternative Solid Salt Application Rates

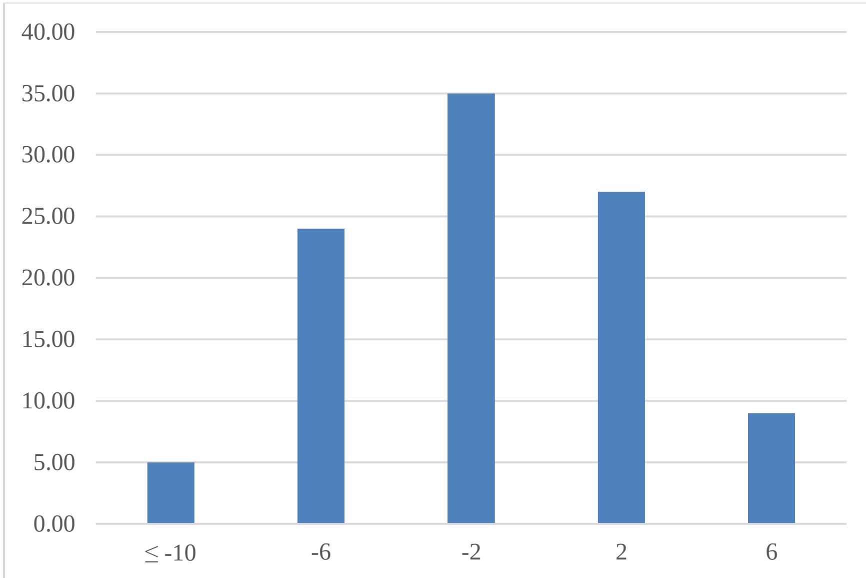

Figure D26: Surface Temperature Observed during Alternative Salt Tests

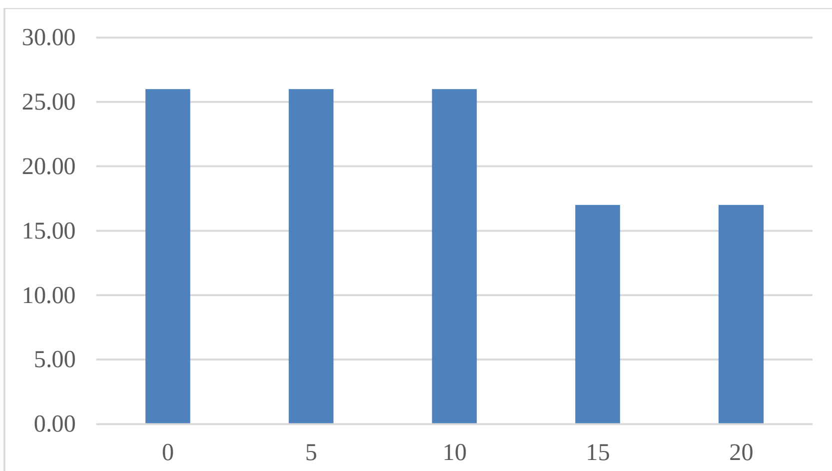

Figure D27: Rock Salt Application Rate Tested for Anti-icing

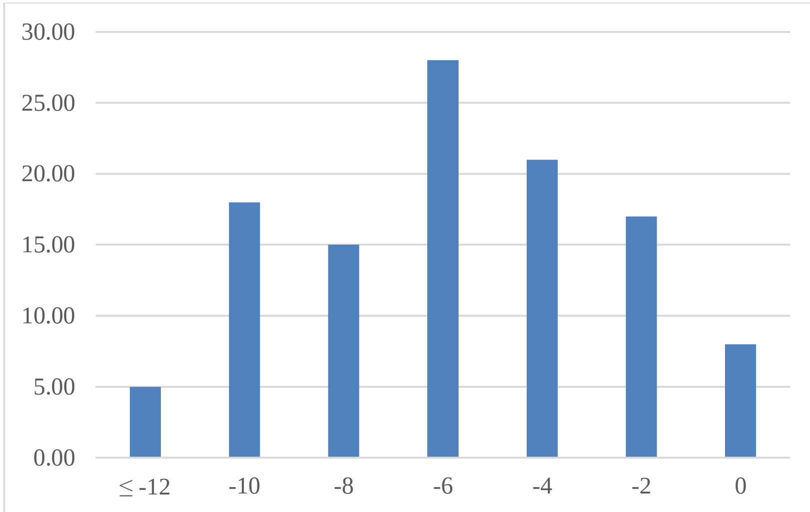

Figure D28: Avg. Surface Temp on Anti-icing Days with Regular Salts

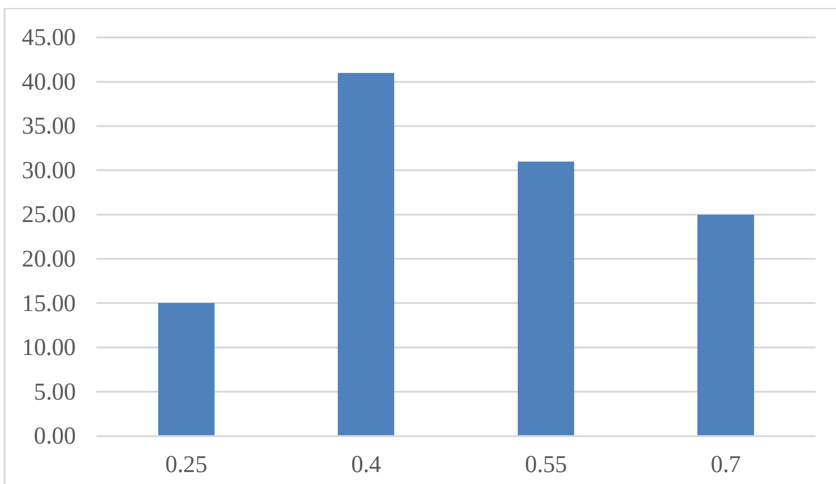

Figure D29: Observed CoF on Anti-icing by Regular Salt

Table D30: Summary Statistics of Data from Stall Area Test Sections using Regular Salt

Variable	BPRT	Rate	Avg Pave Temp (°C)	Total Snow Amount in Kg (density in kg/m3 x total depth in cm/100)	Density (kg/m3)
(Minimum, Maximum)	(0.2, 13.5)	(5, 70)	(14.48, 3.65)	(0.035, 15.231)	(35, 461.54)
Mean	3.818	25.521	-5.081	1.186	135.949
Std. Dev.	2.854	14.160	3.367	1.777	73.408
Variance	8.146	200.517	11.336	3.158	5388.676
Kurtosis	0.100	-0.462	0.036	28.402	2.699
Skewness	0.906	0.494	-0.144	4.593	1.447

Table D31: Summary Statistics of Data from Driveway Test Sections using Regular Salts

Variable	BPRT (80%)	Salting Rate (lbs/1000 sq ft)	Avg Tp	Total Snow Amount in Kg (Density in Kg/m3 X Depth in cm/100)	Density (kg/m^3)	Traffic (Veh/hr)
(Minimum, Maximum)	(0.5, 5)	(2, 40)	(-9.5, 2.3)	(0.07, 3.45)	(35, 338)	(20, 88)
Mean	2.044	11.000	-5.577	0.632	140.654	41.487
Std. Dev.	1.162	8.541	2.226	0.705	92.111	11.404
Variance	1.349	72.947	4.956	0.497	8484.502	130.046
Kurtosis	0.252	5.288	2.854	7.095	0.228	1.012
Skewness	0.799	2.164	1.104	2.641	1.224	1.187

Table D32: Summary Statistics of Data from Anti-icing Tests using Liquid Salts

Products Name	Variable	Salting Rates (lbs/1000sqft)	Pavement Surface Temperature (°C)	Amount of Snow in kg/m^2 (Snow Depth in cm x Density in kg/m^3)	% Improved in CoF
Brine	(Minimum, Maximum)	(3, 9)	(-14.8, -1.7)	(0.08, 4.74)	(-12.73, 87.5)
	Mean	5.930	-8.320	1.120	15.790
	Std. Dev.	2.460	3.970	1.300	21.690
	Variance	6.070	15.740	1.700	470.460
	Kurtosis	-1.510	-0.840	2.140	3.850
	Skewness	0.040	-0.430	1.710	1.750
Diluted Snowmelt	(Minimum, Maximum)	(3, 9)	(-14.8, -1.7)	(0.08, 4.74)	(-9.09, 50)
	Mean	5.930	-8.320	1.120	17.700
	Std. Dev.	2.460	3.970	1.300	17.160
	Variance	6.070	15.740	1.700	294.610
	Kurtosis	-1.510	-0.840	2.140	-0.640
	Skewness	0.040	-0.430	1.710	0.460
Fusion	(Minimum, Maximum)	(3, 9)	(-14.8, -1.7)	(0.08, 4.74)	(-12.73, 53.33)
	Mean	5.930	-8.520	1.150	16.040
	Std. Dev.	2.460	4.230	1.400	16.110
	Variance	6.070	17.900	1.960	259.680
	Kurtosis	-1.520	-1.150	1.410	0.070
	Skewness	0.050	-0.270	1.560	0.700
Snowmelt	(Minimum, Maximum)	(3, 9)	(-14.8, -1.7)	(0.2, 4.74)	(3.7, 50)
	Mean	5.630	-7.040	2.160	19.840
	Std. Dev.	2.420	4.740	1.660	11.630
	Variance	5.850	22.450	2.750	135.310
	Kurtosis	-1.370	-0.780	-1.190	1.700
	Skewness	0.250	-0.790	0.340	1.150

	(Minimum, Maximum)	(3, 9)	(-9, -4.4)	(0.08, 2.51)	(-16.67, 87.5)
Caliber	Mean	6.000	-6.660	0.600	13.050
	Std. Dev.	2.510	1.860	0.820	23.980
	Variance	6.300	3.440	0.670	574.900
	Kurtosis	-1.580	-1.840	2.480	3.490
	Skewness	0.000	-0.120	1.960	1.380

Table D33: Summary of Regression Analysis for Melting Speed Calibration Factors

Variables	Coefficient	R-Squared (P-value)
Dependent Variable	Observed Melting Speed (B)	
Independent Variable	$\left(\frac{R}{R_0}\right)\left(\frac{T_e - T}{T_e}\right)$	
Intercept	0	
Calibration Factor for Stall Areas (β_0)	0.49	0.65 (0.00)
Calibration Factor for Driveways Low Traffic (less than 30veh/hr) (β_0)	0.84	0.41 (0.02)
Calibration Factor for Driveways Medium Traffic (30-50 veh/hr) (β_0)	1.20	0.37 (0.00)
Calibration Factor for Driveways High Traffic (50-80 veh/hr) (β_0)	1.30	0.26 (0.19)
# of Samples	121	

APPENDIX E: UNAGGREGATED APPLICATION RATES FROM THE SNOW MELTING MODEL

Table E1: Application Rate for Driveways (Low Traffic-Parking Lot) for Regular Snow

Snow depth (cm)	(Avg Tp ˚C)	Desired LOS in BPRT (hr)					
		1	2	3	4	5	6
0.1 to 0.5	-1 to -3	3	1	1	1	1	0
0.1 to 0.5	-4 to -6	8	4	3	2	2	1
0.1 to 0.5	-7 to -9	16	8	5	4	3	3
0.5 to 1.5	-1 to -3	8	4	3	2	2	1
0.5 to 1.5	-4 to -6	26	13	9	6	5	4
0.5 to 1.5	-7 to -9	52	26	17	13	10	9
1.5 to 2.5	-1 to -3	17	8	6	4	3	3
1.5 to 2.5	-4 to -6	51	26	17	13	10	9
1.5 to 2.5	-7 to -9	104	52	35	26	21	17

Table E2: Application Rate for Driveways (Medium Traffic-Parking Lot) for Regular Snow

Snow depth (cm)	(Avg Tp ˚C)	Desired LOS in BPRT (hr)					
		1	2	3	4	5	6
0.1 to 0.5	-1 to -3	2	1	1	1	0	0
0.1 to 0.5	-4 to -6	7	3	2	2	1	1
0.1 to 0.5	-7 to -9	13	7	4	3	3	2
0.5 to 1.5	-1 to -3	7	4	2	2	1	1
0.5 to 1.5	-4 to -6	22	11	7	5	4	4
0.5 to 1.5	-7 to -9	45	22	15	11	9	7
1.5 to 2.5	-1 to -3	14	7	5	4	3	2
1.5 to 2.5	-4 to -6	44	22	15	11	9	7
1.5 to 2.5	-7 to -9	89	45	30	22	18	15

Table E3: Application Rate for Driveways (High Traffic-Parking Lot) for Regular Snow

Snow depth (cm)	(Avg Tp ˚C)	Desired LOS in BPRT (hr)					
		1	2	3	4	5	6
0.1 to 0.5	-1 to -3	2	1	1	0	0	0
0.1 to 0.5	-4 to -6	6	3	2	1	1	1
0.1 to 0.5	-7 to -9	12	6	4	3	2	2
0.5 to 1.5	-1 to -3	6	3	2	2	1	1
0.5 to 1.5	-4 to -6	19	10	6	5	4	3
0.5 to 1.5	-7 to -9	39	19	13	10	8	6
1.5 to 2.5	-1 to -3	12	6	4	3	2	2
1.5 to 2.5	-4 to -6	38	19	13	10	8	6
1.5 to 2.5	-7 to -9	78	39	26	19	16	13