Evaluation of the Effects of Deicers on Concrete Durability

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16. Abstract
The objectives of this study were to identify the use of different deicing and anti-icing materials in Wisconsin, and to investigate whether and how the currently used snow and ice control materials adversely affect concrete durability. Tasks completed in this project were a literature review, survey, existing data assembly and analyses, and field visit. Both the survey and WisDOT data analysis revealed that salt and salt brine are the primary materials used in Wisconsin. Other materials are $CaCl_2$, Freeze Guard, Beet55, and GMLT. The application rate was reported as 200 to 400 lb/lane-mile for deicing and 20 to 50 gal/lane-mile for anti-icing for each winter event. In terms of impact to concrete, accelerated deterioration near joints and bridge decks were pointed out by survey respondents based on anecdotal impression. Statistical analyses of existing data at WisDOT did not provide significant evidence to show the different impact from salt and brine or different application rate. This complexity was attributed to the challenge of confounding factors that were not available in this study. Field visit revealed a faster rate of joint deterioration in counties with a higher amount of NaCl, $CaCl_2$, $MgCl_2$ application. Based on results from this study, it was recommended for WisDOT to continue using prewetting and anti-icing for its effectiveness, and rock salt and salt brine for their cost benefit, while striving for less salt application through equipment update, training, and optimization. Blended products of rock salt and other products should also be pursued. The automatic vehicle location system should be expanded to cover all highway network in Wisconsin. In terms of concrete technology, it is recommended to continue the practice of using supplementary cementitious materials in concrete. The application of topical treatments such as penetrating sealers to protect concrete is also worthy of investigation.

17. Key Words
Deicers, Anti-icing, Winter maintenance, Snow and ice control, Concrete pavements, Joint spalling, Concrete durability, Automatic vehicle location

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Executive Summary

Wisconsin has seen continuing increase of new deicing/anti-icing chemicals other than rock salt for winter maintenance. Laboratory studies indicated that these new chemicals especially calcium chloride and magnesium chloride could cause more damage to concrete than rock salt does. In addition, anti-icing raises a concern of its possible damage to concrete because it is applied on dry concrete before a winter event.

The overall objectives of this study were to identify the use of different deicing and anti-icing materials in Wisconsin, and to investigate whether and how the currently used snow and ice control materials adversely affect concrete durability. To achieve these objectives, the following four tasks were performed:

i. Literature review: A literature review of deicing/anti-icing material types and application rate in Wisconsin and neighboring states was conducted. Past studies on the impact of deicing/anti-icing materials on concrete were also synthesized.

ii. Survey: A survey was performed to collect the experience and knowledge from winter operation managers in counties and major cities in Wisconsin.

iii. Analysis of winter maintenance and pavement performance data: Existing data available at Wisconsin Department of Transportation (WisDOT) about deicing/anti-icing materials and pavement performance were assembled and analyzed.

iv. Field study: Seven sites were visited for visual inspection to identify the relationship between various deicers and concrete durability.

A summary of key findings is as follows:

1. Deicing/anti-icing material types: Both the survey and WisDOT data analysis revealed that salt and salt brine are the primary material used in Wisconsin. Other materials are $CaCl_2$, Freeze Guard, Beet55, and GMLT.

2. Deicing/anti-icing material application rate: Survey respondents reported 200 to 400 lb/lane-mile for deicing and 20 to 50 gal/lane-mile for anti-icing for each winter event, which agreed with the WisDOT *Winter Maintenance Guidelines*. Cumulatively, each lane mile of roadway in each winter received an average of 13.78 ton NaCl, 0.31 ton $CaCl_2$, 0.16 ton $MgCl_2$ according to the Storm Report; 9.9 tons salt and 39.3 gallons salt brine according to Automatic Vehicle Location (AVL) database.

3. Impact of deicing/anti-icing material on concrete durability: Accelerated deterioration near joints and bridge decks were pointed out by the survey, but no specific roadways were identified in follow-up interviews. Statistical analyses of existing data at WisDOT did not provide significant evidence to show different impact of salt and brine or application rate on concrete pavement durability. This complexity was attributed to the challenge of confounding factors that were not available in this study. Field visit revealed a faster rate

of deterioration in counties with a higher amount of NaCl, $CaCl_2$, $MgCl_2$ application. Performance at adjoining counties in three of seven sites were statistically different at the 90% confidence level.

Recommendations

The following recommendations are provided on the basis of the analysis of this study:

1. Deicing/anti-icing material types: Rock salt and salt brine will still be the number one material of choice for its cost benefit. Blended products can combine benefits of various chemicals, such as the low cost of rock salt with the low freezing point of calcium chloride. The Department can also conduct pilot trials of new materials that are environmental friendly and cause less damage to infrastructure.

2. Deicing/anti-icing material application rate: The current guideline (2008 and 2012) could be revisited to reflect current technological trends. Prewetting and anti-icing have been proved to increase the effectiveness and reduce the amount of salt application by many state highway agencies. Therefore, it is recommended for WisDOT to continue pursuing equipment update, training, and optimization of prewetting and anti-icing.

3. Concrete technology: Several laboratory studies have demonstrated the benefit of using supplementary cementitious materials to reduce the impact from deicing/anti-icing chemicals. Fly ash reacts with available lime and alkali in concrete, producing additional cementitious compounds (C-S-H), and hence reduces the pore interconnectivity of concrete The addition of supplementary cementitious materials also reduces the amount of $Ca(CO)_2$, therefore decreasing the available amounts for the formation of calcium oxychloride. SCM is commonly used by contractors in Wisconsin and allowed in WisDOT Specification. This practice should be continued.

4. Another method to protect concrete from deicing/anti-icing chemicals is the application of topical treatments such as penetrating sealers. Penetrating sealers can seal the concrete, hence reduce the ingress of water and chemicals. Field trials in Indiana in 2011 showed success in protecting concrete joints and the ongoing fieldwork at MnROAD has shown promising results.

5. Automatic Vehicle Location (AVL) system: Currently the AVL system operations only covers 55% of Wisconsin's highway network. It is recommended to expand the system to cover the whole network. More options should be given in the AVL system so that different deicing/anti-icing materials could be recorded. In addition, the AVL database should be made compatible with the other databases in WisDOT to facilitate data management for future data analysis and decision making.

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Chapter 1 - Introduction

1.1 Background

Traditionally, rock salt (i.e., sodium chloride) in solid form has been the primary deicing chemical used for winter maintenance on Wisconsin's highway system. In recent years, two changes have been made regarding the use of deicers for highway maintenance in Wisconsin. The first change involves the frequent use of a variety of newer deicing chemicals for highway maintenance, including calcium chloride, magnesium chloride, and some agricultural byproducts such as beet juice. These aggressive chemicals are known to cause rapid and severe distress to concrete such as significant reduction in the compressive strength, tensile strength and micro-hardness occasionally without any sign of surface distress. Various studies indicate that concrete exposed to calcium chloride and magnesium chloride experience significant deterioration, including scaling, cracking, mass loss and compressive strength loss compared to one exposed to sodium chloride. The second change is that many transportation agencies have introduced "anti-icing" practices of applying high-concentration liquid solutions of deicers to dry the pavement prior to the beginning of a snow event. This practice causes much more rapid ingress of the deicing chemicals because the dry concrete surface absorbs the anti-icing solution very readily, whereas the old scheme of applying rock salt to a wet, saturated concrete surface allowed for much less penetration of the deicing chemicals.

Although these adverse impacts of various chemicals in deicer to concrete are commonly recognized in laboratory studies, there is limited information on the usage of deicers in Wisconsin. For example, what kinds of chemicals are used for deicing and anti-icing in counties across the state? How does the use of different deicing and anti-icing materials impact pavement condition in Wisconsin? How long have various department and local governments been applying certain deicers? How old is the concrete that the deicer has been applied to, etc.

1.2 Objectives

The objectives of this project were to:

1) identify the use of different deicing and anti-icing materials in Wisconsin, and
2) investigate whether and how the currently used snow and ice control materials adversely affect concrete pavement durability.

1.3 Methodology

This study started with a literature review of deicing/anti-icing application practices in Wisconsin and nearby states. The current knowledge of deicing chemical's impact on concrete was gathered. A survey to counties and major cities in Wisconsin was then performed to seek maintenance engineers' opinion of what deicing/anti-icing were used in Wisconsin and whether any particular damages were noticed due to deicing chemicals. For quantitative analysis, various data sources were accessed at WisDOT, including winter maintenance data, historical pavement performance data, roadway inventory, and traffic counts. Each individual database was first evaluated and then integrated into one GIS database, on which statistical analyses were conducted to (1) show the geographic distribution of deicing/anti-icing application (type and rate), (2) evaluate whether salt and brine led to different concrete performance, and (3) investigate whether salt application rate had impact on concrete performance. Finally, field studies were conducted for seven sites that extend through adjoining counties. The field visit was carried out to verify the pavement performance, identify any abnormality that were not present in the database, and visually check whether deicing/anti-icing had caused concrete durability issues.

1.4 Organization of Report

The report is written in six chapters following the same sequence as the flowchart shown in Figure 1.1, Chapter 1 is this introduction. Chapter 2 contains reviews of literature from national studies, with special emphasis on Wisconsin and neighboring states. Chapter 3 explains the process and results obtained from the survey. Chapter 4 describes each data source and the creation of an integrated GIS database. Analyses of the database are also included in the chapter. Chapter 5 describes the field visit process. Three sites are discussed in detail followed by a summary of the seven sites. Finally, Chapter 6 summarizes the project and provides recommendations for Wisconsin DOT and Industry.

Chapter 2 – Literature Review

2.1 Practice of deicing and anti-icing applications at the national level

Roadway snow and ice control strategies used in winter maintenance operations can be classified into four general categories: anti-icing, deicing, mechanical removal of snow and ice together with friction enhancement, and mechanical removal alone *[1]*.

- Anti-icing is a snow and ice control strategy of preventing the formation or development of bonded snow and ice to a pavement surface by timely applications of a chemical freezing-point depressant. Anti-icing can be initiated before a winter weather event or very early in the event.
- Deicing is a snow and ice control strategy of removing compacted snow or ice already bonded to the pavement surface by chemical or mechanical means or a combination of the two.
- Mechanical removal of snow and ice together with friction enhancement is a strategy in which abrasives or a mixture of abrasives and a chemical are applied to the plowed or scraped roadway surface that may have a layer of compacted snow or ice already bonded to the pavement surface. Abrasives, by themselves, are not ice-control chemicals and will not support the fundamental objective of either anti-icing or deicing. Its only real applications are in very low pavement temperature situations (about 12°F) where chemical treatments are not likely to be effective.
- Mechanical removal alone is a strategy that involves the physical process of attempting to remove an accumulation of snow or ice by means such as plowing, brooming, or blowing without the use of snow and ice control chemicals. Warm pavement temperatures above 32°F will usually not allow light to moderate rates of precipitation to bond. Very cold pavement temperatures, lower than about 12°F, together with dry or powder snow will usually not produce a bond between ice and pavement. In either case, mechanical removal alone may be all that is necessary.

Materials used in snow and ice control can be classified as four types: abrasives, solid ice control materials, pre-wet solid ice control chemicals, and liquid ice control chemicals *[1]*.

- Solid chemicals, particularly those with a "coarser" gradation or particle size distribution, are well suited to deicing operations. The larger particles can "melt" through snow/ice on the surface and continue to cause melting at the ice/pavement interface until the ice/pavement bond is broken and the snow/ice can be removed mechanically. The use of fine-graded salt during anti-icing operations generally is not cost effective compared to the use of coarse-graded salt. Fine-graded salt applications are not well suited for deicing operations because of the high dilution potential. Solid ice control chemicals are often mixed in small quantity (less than 10 percent) with abrasives to prevent "chunking" and freezing in stockpiles.

- Pre-wet solid ice control chemicals are used in the same way as solid chemicals except that they are generally not mixed with abrasives. They consist of solid ice control chemicals that have been "coated" with liquid ice control chemicals by a variety of mechanisms. The water in the liquid ice control chemical starts the process of allowing the solid chemical to generate "brine" more quickly than "uncoated" solid chemical. The coating also allows the solid chemical to better "stick" to the surface. This reduces bounce and scatter and accelerates deicing.

- Liquid ice control chemicals are generally a solution of solid ice control chemicals with water being the predominant component. Liquid chemicals are particularly well suited for anti-icing to pretreat roadways prior to a general snow or ice event. Since liquid ice control chemicals are mostly water, they are already fairly well diluted. They are not well suited to deicing operations as they have little ability to penetrate thick snow ice. However, they may be used in limited situations for deicing if the treatment is immediately followed by an application of solid chemicals or the process is reversed, a variation of pre-wetting.

NCHRP Report 577 *[2]* further analyzed these materials. Table 2.1 shows the commonly used materials for snow and ice control.

Table 2.1 Snow and ice control materials *[2]*

Material Type	Snow and Ice Control Material	Primary Components
Chloride Salts	Sodium Chloride (NaCl)	Na, Cl
	Calcium Chloride ($CaCl_2$)	Ca, Cl
	Magnesium Chloride ($MgCl_2$)	Mg, Cl
Organic Products	Calcium Magnesium Acetate (CMA)	Ca, Mg, $C_2H_3O_2$
	Potassium Acetate (KA)	K, $C_2H_3O_2$
	Agricultural By-Products	Complex sugars; cheese brine
	Manufactured Organic Materials	Varies with product (i.e. glycol, methanol)
	Beet Juice	Beet juice mixed with salt brine
Nitrogen Products	Urea	Urea, Ammonia
Abrasives	Abrasives	Varies with the source of the material

Road salt or sodium chloride (NaCl) is the most commonly used snow and ice control chemical. Most of the road salt used in the United States and Canada comes from underground mining, solution mines, and solarization. Calcium chloride ($CaCl_2$) is primarily produced from natural well brines and as a by-product of the Solvay process. Magnesium chloride ($MgCl_2$) is most commonly obtained through solarizing natural salt brines. Organic snow and ice control products are, for the most part, manufactured products. Calcium Magnesium Acetate (CMA) was the result of an FHWA effort to find a low corrosion biodegradable substitute for road salt. Although CMA meets the project objectives, it is relatively costly to produce. Potassium acetate (KA) is a non-chloride, high-performance product originally designed for use as a runway deicer. Agricultural additives for snow and ice control are refined from various agricultural feedstock, including corn, wheat, and rice. Beet juice mixed with salt brine is effective at melting ice during extreme temperature lows below 20ºF, and has been used by the departments of transportation in New Jersey, Pennsylvania, Indiana and Missouri.

In terms of the application of these materials by state highway agencies, the survey conducted in NCHRP Project 6-16 *[2]* found that solid NaCl (a total of 4.7 million tons annually) was the most commonly used snow and ice control chemical and was considered a first preference for 57% of the respondents. NaCl brine, in most cases produced on site by the agency, was a first or second choice for 43% of the respondents. Several respondents had both salt and salt brine as their first preference. Magnesium chloride ($MgCl_2$), used as a liquid, was the next preferred chemical with 29% of the respondents rating it as their third preference. Calcium chloride ($CaCl_2$), primarily used as a liquid, was the next most popular, with 18% of the respondents rating it as the third preference.

2.2 Practice of deicing and anti-icing applications in Wisconsin

On average, Wisconsin's annual snowfall ranges from 15 inches in the south to as much as 132 inches along the shores of Lake Superior. About 13 to 55 winter weather events occur in Wisconsin each winter *[3]*. To provide a safe winter travel for the public, the Wisconsin DOT contracts with all 72 county highway departments in the state to maintain a total of 34,620 lane miles roadways. In line with other states, road salt is the primary material for winter road maintenance. During 2016~2017 winter, WisDOT used 526,199 tons of salt, 2,783,720 gallons salt brine for pre-wetting, 1,865,565 gallons salt brine for anti-icing.

A variety of newer deicing chemicals have also been frequently used in recent years, including calcium chloride, magnesium chloride, and some agricultural byproducts such as beet juice and cheese brine *[4]*. These materials are applied in new techniques such as anti-icing and pre-wetting beside the traditional methods – snow plowing and deicing. Deicing uses chemical or mechanical means to break the bond that has formed between ice and the pavement. Pre-wetting is the addition of calcium chloride, magnesium chloride, salt brine or other liquid agents to salt and sand. This helps the mixture stick to the road instead of blowing off to the shoulder, which reduces the amount of material needed. It also helps the salt start working more quickly. Several studies have shown that with pre-wetting, up to 30% more salt stays on the roadway. Anti-icing applies liquid chemicals before or early in a snow storm to prevent the formation of frost and the bonding of snow and ice to the pavement, hence save time and money by reducing the effort and materials needed to remove snow and ice. For the winter of 2016-17, salt use was 32% higher than the previous year and sand use was 38% decrease from the average of the five previous winters. Meanwhile, use of anti-icing materials was up 0.5% over last year. 66 of 72 counties in Wisconsin are equipped to perform anti-icing operations *[3]*.

2.3 Practice and past/on-going studies on deicing and anti-icing in neighbor states

2.3.1 Minnesota

During the 2016~17 winter season, Minnesota DOT (MnDOT) used 46,000 tons of sand, 197,417 tons of salt, and 3.0 million gallon of salt brine to maintain its 30,517 lane miles of roads. The average cost of salt was $73.99 per ton *[5]*. MnDOT has two documents pertinent to winter maintenance. One is the Winter Chemical Catalog which provides information of vendor's name and contact information, as well as the product information (active ingredient and suggested use rate) *[6]*. The other is a Field Handbook for Snowplow Operators *[7]*, which provides detailed instructions before the winter, before the storm, during the storm, and after the storm, as well as the application rate of different ice-control materials.

In terms of deicer materials, Minnesota DOT funded a review project searching for "chloride free snow and ice control material" due to the concern of high chloride levels in Minnesota's waterbodies *[8]*. The review identified several types of non-chloride deicers, including acetates, formates, urea, glycerol/glycol, succinate, organic additives, and abrasives (sand). The concerns were mainly corrosion of steel and impact on aquatic system. An early study focused on roadside vegetation also suggested using products that are not harmful to the soil or vegetation, such as calcium chloride, magnesium chloride, and CMA *[9]*.

For existing materials, Minnesota DOT provides a detailed procedure to evaluate and compare the performance of different deicing chemicals *[10]*. Three tests were described: simple garage test, single roadway test, and side-by-side test. However, the focus is to see which product functions better to keep the road free from ice/snow; the impact on concrete was not considered.

To implement anti-icing, the proactive snow and ice control strategy, MnDOT funded a review project *[11]* that summarizes the state of practice of anti-icing in winter maintenance operations in other states.

Recently Minnesota DOT supported a study *[12]* which evaluated the ice melt capacity and field performance factors of deicers and deicer blends in both solid (for deicing) and liquid (for anti-icing) forms. A total of 24 products with main component of NaCl, $MgCl_2$, $CaCl_2$, potassium acetates, sodium acetate, sugar beet, and corn salt were studied. Since the objective of the study was to help snowplow operators apply deicers and anti-icers in "the right amount at the right time in the right way" so as to reduce the cost of winter maintenance materials, the impact of deicers on infrastructure (e.g. concrete) was not considered in the study. The phase II of this project expands the study to field experiments at two proximal facilities across six and three parallel treatment lanes of 1,000 feet length.

2.3.2 Michigan

The practice of pre-wetting solid deicers with a liquid can increase the melting ability and prevent bouncing of deicer crystals. Michigan DOT supported a project *[13]* to study the pre-wetting characteristics of serval liquid deicing chemicals using a standard laboratory melting test. Application rates of 6, 8 and 10 gallons/ton were compared at temperatures of 15°F, 20°F and 25°F.

A study *[14]* aimed to understand the premature (within 8 years) joint deterioration concluded that the deterioration developed within the Portland cement binder, originating in a narrow mortar zone around the coarse aggregate. Surface scaling occurred earlier in the deicer salt solution than it was in water. Inadequate air-void system was a major reason for the joint deterioration. The research recommended that fresh air content slightly over 7% is sufficient for field resistance to deicer salt and freeze-thaw. Adequate drainage can also reduce the likelihood of premature deicer-related freeze-thaw deterioration. In addition, concrete with slag cement (328 lbs Type I, and 162 lbs slag cement) has improved deicer scaling resistance. The improvement was attributed to a better quality paste-coarse aggregate interface (i.e. without air-void clustering) and air-void system (smaller sized bubbles), and lower paste permeability (i.e. lower water uptake rate).

2.3.4 Iowa

A pooled fund study (TPF-5(042)) led by South Dakota DOT and participated by Iowa, Colorado, Montana, Illinois, Wyoming, Texas, and California was completed to investigate the short and long-term effects of high concentrations of salts (including magnesium, sodium, and calcium chloride as well as CMA or other alternative liquid deicers) on Portland cement concrete *[15]*. This comprehensive six-year project (2002~2008) conducted a series of laboratory tests and found that magnesium chloride and calcium chloride chemically interact with hardened Portland cement paste in concrete resulting in expansive cracking, increased permeability, and a significant loss in compressive strength. The chemical attack of the hardened cement paste is significantly reduced if supplementary cementitious materials are included in the concrete mixture. Both coal fly ash and ground granulated blast furnace slag were found to be effective at mitigating the chemical attack caused by the deicers tested. Additionally, siloxane and silane sealants were effective at slowing the ingress of deicing chemicals into the concrete and thereby reducing the observed distress.

Another project *[16]* evaluated four tests (specific gravity, viscosity, ice melting capacity, and freeze point determination) to ensure deicer composition and performance. These simple tests can be performed on every load of product delivered so that an agency can have a high degree of confidence in the performance of the ice-control products in three areas: temperature related performance, product consistency, and negative side effects (such as corrosion of vehicles and damage to concrete).

Lead by Iowa DOT, a pool fund study *[17]* was conducted to evaluate deicer scaling resistance of concrete pavements, bridge decks and other structures containing slag cement. The study showed that construction-related issues played a bigger role in the observed scaling performance than did the amount of slag in the concrete mixture.

Recently lab tests of a new deicing product, named Ossian Season One, was evaluated in terms of damage to concrete, effect on skid resistance, and sealing effect *[18]*. It was found that Ossian Season One caused less damage to concrete than salt solutions. The mass loss, strength loss, and visual rating under freezing thawing from the new product were better than from salt solutions (sodium chloride and calcium chloride).

2.3.5 Illinois

The rise in cost of traditional deicing/anti-icing chemicals because of supply shortages leads to greater competition from other products on the market such as those documented by Illinois DOT Bureau of Materials and Physical Research *[19]*.

Bridge deck concrete is often flawed by cracks. These cracks provide ingress for chloride ions to the reinforcement of the deck and structure. To prevent the further ingress of chloride ions, sealers and laminates are often considered practical methods of protection. Illinois DOT supported a research project *[20]* to evaluate concrete sealer and laminate effectiveness in protecting bridge deck concrete from chloride ion ingress. This research showed that the use of protective coat, penetrating sealers and laminates deters the ingress of chloride ions into Portland cement concrete. Hard deck overlay provided the best overall performance because the overlay did not allow ingress of chloride to the original concrete surface. Solvent-based sealers did perform better overall than the water-based counterparts. The study recommended IDOT to develop Special Provisions for the use of protective coat and penetrating sealers on bridge decks.

2.3.6 Indiana

A study *[21]* recently completed by Purdue University and Indiana DOT investigated how mixtures of deicers can damage the joints in concrete pavement. The investigation was completed by using low temperature differential scanning calorimetry (LTDSC) to detect a reaction between the deicer and the cement matrix and investigated the potentially sources of calcium oxychloride from the blended salt deicers. The results from this study showed deterioration at the joints from increased saturation from deicers and a chemical reaction between deicing salt and the cement matrix. Also, there was a direct relationship between the increase of calcium hydroxide in the paste and increase of calcium oxychloride formation.

Purdue University completed a study *[22]* with Indiana DOT to understand the premature deterioration of concrete pavement. This study looked at core samples from 11 pavement sections with different material, ages, deicer exposure, and construction to identify durability of concrete. Findings from this study concluded that the prolong use of deicers and the rate with the duration of a freeze thaw cycle would influence the durability of pavement joints in concrete.

Indiana DOT supported a research project *[23]* partnered with Purdue University to investigate the interaction between concrete and deicers. The chemical material from deicers that were evaluated in this study were sodium chloride, calcium chloride, magnesium chloride, and Ice Ban. Results from the study that sodium chloride had the least impact on concrete comparing to other deicer chemicals. Fly ash modified concrete performed better than plain concrete when exposed to deicing chemicals.

2.3.7 Ontario

Ontario Ministry of Transportation (MTO) winter maintenance plan includes anti-icing and deicing with salt and sand. Before a storm event anti-icing liquid can be sprayed on a highway, especially at locations prone to icing. When a winter storm begins, salting will occur within 30 minutes. Deicers are dependent on the temperature until temperatures of -12˚C, while sand use is recommended for temperatures below -18˚C *[24]*.

Different from Wisconsin, Ontario MTO has outsourced winter maintenance to the private sector since 1996. In 2009, the ministry began the shift to a performance-based contract model where the contractor decides how best to achieve the results the ministry requires. According to the Winter Highway Maintenance Action Plan *[25]*, Ontario sought out to improve facilities for storage, increase winter equipment, accuracy of reporting roadways, and improve reporting weather and road conditions. Actions related to winter materials were

- Increasing the use of anti-icing liquids before winter storms.
- Appropriate use of road salt.
- Opportunities for pre-treated and pre-wet salt.

2.4 Effects of deicing and anti-icing materials on concrete

Concrete is a composite material consisting of stone and sand held together in a matrix of hydrated cement paste. The two major components of the hydrated cement paste are calcium-silicate-hydrate (C-S-H) and calcium hydroxide [$Ca(OH)_2$]. The C-S-H phase provides the bond strength of concrete. The $Ca(OH)_2$ does not contribute significantly to the strength, but increases the pH of the pore solution to about 12.5.

Snow and ice control chemicals are known to affect concrete structures—either through deterioration of the concrete paste or corrosion of the reinforcing steel. Corrosion of reinforcing steel has typically been the primary deterioration mechanism and has been linked to use of chloride based snow and ice control chemicals such as NaCl, $CaCl_2$, and $MgCl_2$. NaCl has been used for more than 50 years and associated long-term effects to reinforced concrete are fairly well understood. Although there has been extensive research into the use of alternative materials (e.g., $MgCl_2$, $CaCl_2$, and CMA), there is limited data about their long-term effects.

Winter conditions (i.e., freezing and thawing cycles and application of chloride-based snow and ice control chemicals) can affect the durability of reinforced concrete in several ways *[2]*:

- Physical deterioration of the concrete surface through scaling,
- Chemical reactions between the salt and the cement paste or aggregates causing degradation of the cement paste, and
- Diffusion of chloride ions resulting in corrosion of the reinforcing steel.

Without salt application, scaling of concrete can occur because of the expansive forces of freezing pore water near the concrete surface. As the number of freeze-thaw cycles increases, so does the potential for scaling. When salts are applied to the concrete surface, they increase the frequency of freezing and thawing cycles over what would be experienced under ambient conditions. This effect occurs when the applied salt reduces the freezing point at the concrete surface, then the salt is diluted because of precipitation or meltwater, after which the surface water is allowed to re-freeze because of its lower salt content.

Research *[26]* has shown that different chloride-based snow and ice control chemicals (i.e., NaCl, $MgCl_2$, and $CaCl_2$) can cause varying degrees of damage to concrete. This is mainly a result of specific chemical reactions between the associated cations (i.e., Mg^{2+}, Na^{+}, Ca^{2+}) with various phases of the cement paste. Several researchers agree that $MgCl_2$ causes more severe deterioration to concrete than do NaCl or $CaCl_2$, because of the reaction of Mg^{2+} with components of the cement paste. Detrimental effects on concrete structures as a result of $CaCl_2$ use do not appear to be more significant than those of NaCl, although laboratory studies *[27]* suggest that the extent of deterioration caused by $CaCl_2$ falls between the levels produced by NaCl and $MgCl_2$. Concrete samples exposed to $CaCl_2$ deteriorated in similar ways to samples exposed to $MgCl_2$, although the deterioration was slower and less severe for $CaCl_2$. Calcium chloride primarily affected concretes containing reactive dolomite aggregates because $CaCl_2$ enhanced the dedolomitization reactions, releasing magnesium to form $Mg(OH)_2$ and M-S-H.

The detrimental effect of calcium oxychloride was explained by *[28]*. Calcium oxychloride is an expansive product formed from the reaction between the chlorides in the deicing salt with the calcium hydroxide ($Ca(OH)_2$) in the cementitious matrix. The chemical equation is

$$CaCl_2 + 3Ca(OH)_2 + 12H_2O \rightarrow 3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O \quad (1)$$

While it is possible that this reaction can occur with sodium chloride (NaCl), little damage can be attributed to the formation of an expansive phase in mortars saturated by NaCl solutions. However, when other deicing salts, such as calcium chloride ($CaCl_2$) or magnesium chloride ($MgCl_2$) are used, the potential for calcium oxychloride formation increases dramatically. Furthermore, acoustic emission tests of mortars showed that samples saturated with solutions stronger than approximately 15% (by mass) of $MgCl_2$ or $CaCl_2$ cracked and were damaged at room temperature without freezing and thawing *[29]*. The study recommended three approaches that could minimize the damage:

- using SCMs to reduce $Ca(OH)_2$ content through dilution and pozzolanic reaction,
- using carbonation to reduce the availability of $Ca(OH)_2$, and
- using topical treatments to provide a physical separation between applied deicing salts and $Ca(OH)_2$ in the matrix.

2.5 Summary

The 2004 national survey revealed that the top four deicing and anti-icing materials were, in the order of preference, solid NaCl, NaCl brine, magnesium chloride, and calcium chloride. In line with other states, road salt is Wisconsin’s primary material for winter road maintenance.

Due to the concern of high chloride levels in Minnesota’s waterbodies, Minnesota DOT has funded several projects searching for “chloride free snow and ice control material”. However, salt is still the first choice of winter maintenance because it is more affordable than other non-chloride based chemicals. For example, it was estimated that the cost of sodium chloride is about $7 per lane-mile, calcium chloride $42 per lane-mile, magnesium chloride $36 per lane-mile, while potassium acetate costs about $135 per lane-mile *[30]*.

Inadequate air-void system was found as the major reason for the premature (within 8 years) joint deterioration in Michigan. The study also found that concrete with slag cement has improved deicer scaling resistance.

The impact on concrete from chloride-based snow and ice control chemicals may lead to three types of distresses: surface scaling, degradation of the cement paste, and corrosion of the reinforcing steel. Several lab studies have shown that $CaCl_2$, and $MgCl_2$ cause more damage to concrete than NaCl. The chlorides in the deicing salt could react with the calcium hydroxide $Ca(OH)_2$ in the cementitious matrix to form calcium oxychloride, is very expansive product that breaks concrete. Even worse, if the content of $MgCl_2$ or $CaCl_2$ is higher than 15% (by mass), concrete was damaged at room temperature without freezing and thawing.

Detrimental impact from deicing/anti-icing materials can be minimized by using SCMs to reduce $Ca(OH)_2$ content through dilution and pozzolanic reaction, and using topical treatments (e.g., penetrating sealer) to provide a physical separation between applied deicing salts and $Ca(OH)_2$ in the matrix.

Chapter 3 – Survey

3.1 Introduction

A survey was developed and deployed to winter maintenance managers in counties and major cities in Wisconsin. The survey sought information about (1) the types of commonly used deicing and anti-icing materials, (2) application rates, (3) factors considered when choosing different materials, and (4) type of distresses attributed to the use of deicers and/or anti-icing materials.

3.2 Survey Process

The survey was conducted through *SelectSurvey*^{TM}, an online survey tool available to the Wisconsin Department of Transportation. The survey consisted of 12 questions and was first sent to 72 counties on February 23, 2017. The survey questionnaire is included in Appendix A. The survey was later sent to major cities in Wisconsin on April 18, 2017. To encourage more survey responses, several follow-up emails and phone calls were made until the survey was closed on May 31, 2017. In total, the survey received responses from 44 out of the 72 counties (response rate 61%) and 9 out of the 13 cities (response rate 69%).

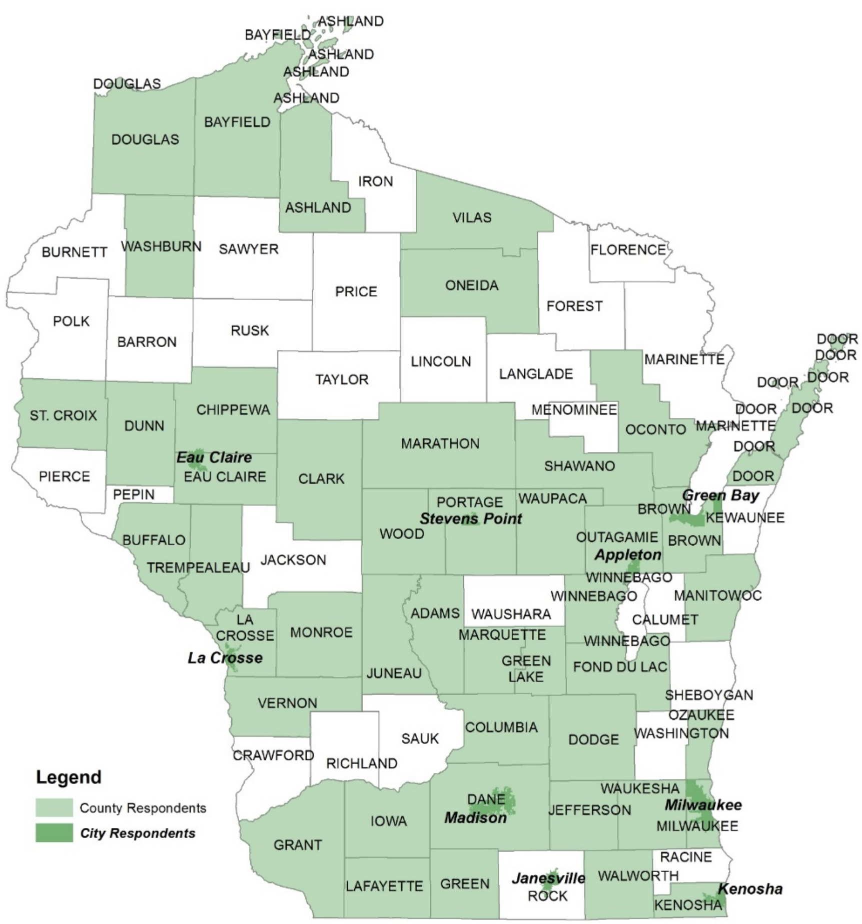


Figure 3.1 Survey respondents from 44 counties and 9 cities

3.3 Results Analysis

3.3.1 Types of Deicing/Anti-icing Materials

As shown in Figure 3.2, the survey revealed that Sodium Chloride (rock salt and salt brine) is the main material for both deicing and anti-icing. The second most used materials are Calcium Chloride, Beet55, Magnesium Chloride, and GeoMelt. Other materials mentioned in the survey include AMP, beet juice, and SuperBlend. It should also be pointed out that many materials listed in the Storm Report such as ClearLane, IceBan M50, Dow Armor, Caliber M1000, M2000, IceStop, ArticClear, BioMelt, and IceBite55 were not used any more based on the survey. Details of the survey results are listed in Appendix B and C.

The survey included a question asking whether anti-icing materials are used in the respondent's jurisdiction. All answered "yes" meaning that anti-icing material use is a common practice during winter maintenance in Wisconsin. Follow-up interviews also reveal that agencies use similar materials for deicing and anti-icing due to the convenience of material storage and handling.

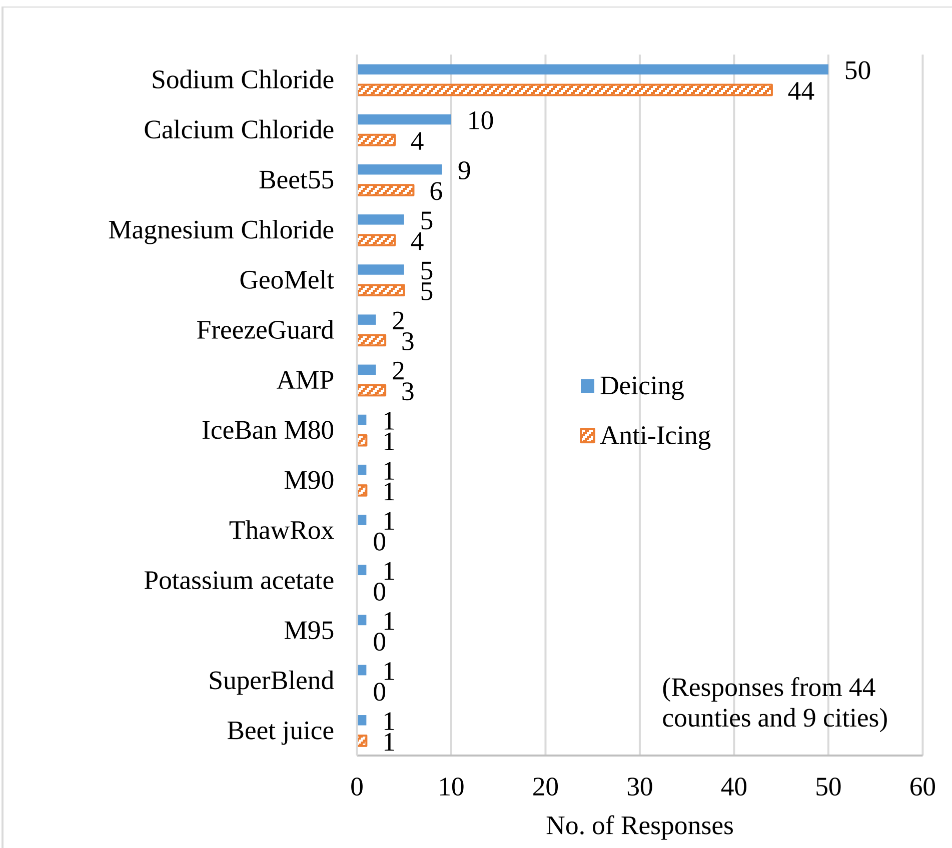


Figure 3.2 Types of deicing/anti-icing materials used in Wisconsin

3.3.2 Application Rate of Deicing/Anti-icing Materials

The application rate is shown in Figure 3.3. Approximately 200 to 400 lb per lane-mile (lb/lane-mile) is the normal rate for deicing, with a range from 50 to 600 lb/lane-mile depending on specific conditions such as temperature and the amount of snow fall. These application rates agree well with the WisDOT Winter Maintenance Guidelines section 06-20-20 of the Highway Maintenance Manual (Appendix E). Other deicing materials are mostly in liquid form and being added to rock salt. For example, magnesium chloride was applied at 5 to 10 gal per ton of salt.

For anti-icing, the survey showed that 40 gal per lane-mile (gplm) was the average with a range between 20 and 50 gplm. This agrees well with the WisDOT Winter Maintenance Guidelines section 06-20-25 (Appendix E) where 20 to 50 gplm is recommended for anti-icing. It is worth comparing the chemical content (sodium chloride NaCl) of deicing and anti-icing at the average application rate. Considering the average of 300 lb/lane-mile for deicing salt and 40 gplm for anti-icing brine at a concentration level of 24%, the amount of sodium chloride NaCl applied on roadway from anti-icing is only about 1/4 of it from deicing. This is one of the reasons why anti-icing is recommended and Wisconsin has seen a consistent increase of anti-icing application in the past years.

Other materials are blended with salt brine at certain proportions for anti-icing. For instance, Ashland County blends salt brine, Beet55 and FreezeGuard at 70/15/15 ratio; Dunn County blends 10 to 15% of GeoMelt with salt brine; 15 to 20% of Beet55 is usually blended with salt brine; and AMP is mixed with salt brine at 10/90 ratio.

Additionally, the chemical components of each deicing and anti-icing material were collected based on manufacturers' safety data sheet. The main components are NaCl, $CaCl_2$, and $MgCl_2$. Details as listed in Appendix C were used in further data analysis of this project.

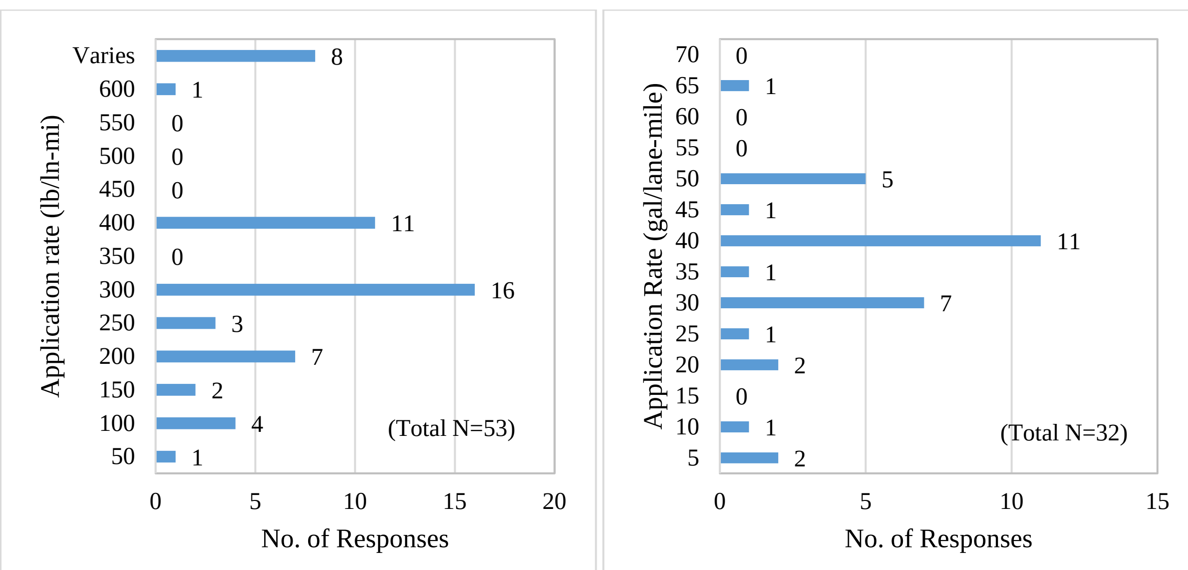


Figure 3.3 Application rate of deicing/anti-icing materials in Wisconsin

3.3.3 Factors in Selecting Deicing/Anti-icing Materials

The survey included a question asking respondents to rank the main factors that dictate the choice of deicing and/or anti-icing materials for concrete roadways. Factors included effectiveness, precipitation, temperature, and wind from weather forecast, cost, availability, environmental concerns, and others. Respondents ranked each factor from "most important" to "least important" in five levels. A total of 41 responses from counties and 9 from cities were received.

Figure 3.4(a) shows the number of responses that ranked a factor the "most important". It indicates that effectiveness is the primary factor for both counties and cities, followed by temperature and precipitation from weather forecast. Cost is also a factor for counties but not for cities. Wind speed and availability received 13 responses (32% of the 41 total county responses). Very few respondents ranked environmental concern as "most important". Wind was not a concern for cities.

Since there were five rank levels, another method to look at the data is to calculate a weighted importance score by

$$Weighted\ Importance\ Score = \frac{\sum_{i=1}^{5}(N_i \times W_i)}{N_{Total}} \quad (1)$$

where, N_i is the number of response who selected the i^{th} importance, i =1 to 5.

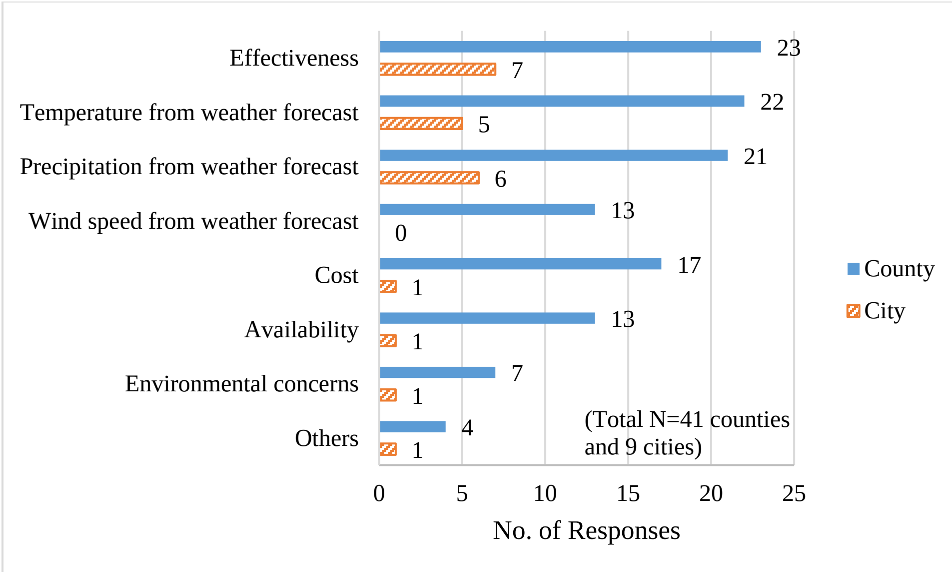
W_i is the weight for the i^{th} importance, W_1=5 for i=1 "most important", W_5=1 for i=5 "least important", etc.

N_{Total} is the total number of responses, N_{Total} =41 for counties, and N_{Total} =9 for cities.

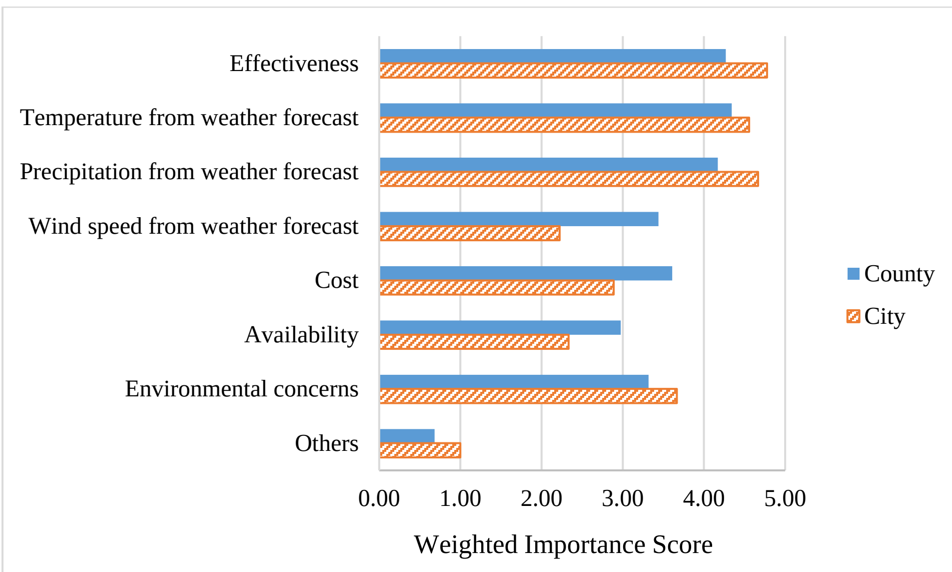
For example, the weighted importance score for the factor "effectiveness" by counties can be calculated by

$$\frac{(23*5 + 15*4 + 0*3 + 0*2 + 0*1)}{41} = 4.27 \quad (2)$$

Results are shown in Figure 3.4(b). For counties, top factors are temperature, effectiveness, and precipitation, followed by cost, wind speed, and environmental concern. For cities, top factors are effectiveness, precipitation, and temperature, followed by environmental concern and cost.



(a) Most important factor



(b) Weighted importance score

Figure 3.4 Factors in selecting deicing/anti-icing materials

3.3.4 Noticeable Impacts Deicing and Anti-icing Materials on Infrastructure

One of the question of the survey asked

> Are there specific distresses associated with your roads that are attributed to the application of deicing and/or anti-icing materials that you use?

Only 11 responses were received concerning two problems: joints and bridge decks. Details are listed in Table 3.1.

Table 3.1 Comparison of Two Deicer Database

Noticeable Distresses	**County/City**
Accelerated deterioration at joints and cracks	
1. Joint problems related to salt penetration open joints.	Juneau County
2. Unsure, but suspect accelerated concrete deterioration especially at joints.	Green County
3. I would assume that the deterioration of joints is caused by deicing materials.	Iowa County
4. In general spalling has been attributed to the application of roadway deicers.	City of Appleton
5. We see premature degradation of gutter lines, storm inlets and conveyance piping, and joint failures in the concrete roads.	City of Eau Claire
6. Stress cracks deteriorating fastest than norm.	Oneida County
7. Premature deterioration of the concrete.	City of La Crosse
Bridge decks	
1. Bridge deck drip edges.	Outagamie County
2. Bridge deck deficiencies.	Manitowoc County
3. Bridge decks.	Ozaukee County
4. Bridges.	St. Croix County

Follow-up interviews via telephone and email were conducted to help identify specific roadway locations that had the noticeable impacts. Most respondents pointed to bridges, city streets, and roundabouts. Others replied that the impact was a general observation with no specific location.

3.4 Summary

An online survey was conducted from February 23, 2017 to May 31, 2017 to examine the use of deicing and anti-icing materials in counties and major cities of Wisconsin. A total of 45 counties and 9 cities completed the survey. An analysis of the survey results reveals the following:

1) Rock salt and salt brine are the main materials for winter maintenance, with an application rate of 200 to 400 lb/lane-mile for deicing and 20 to 50 gal/lane-mile for anti-icing. Other materials used in order of prevalence include Magnesium Chloride, Calcium Chloride, GeoMelt, and Beet55.

2) The main factors in choosing deicing and anti-icing materials are the effectiveness of materials, temperature and precipitation from weather forecast, followed by cost and availability.

3) 11 out of the 54 responses pointed out two problems with deicing and anti-icing materials: accelerated deterioration near joints and bridge decks.

Chapter 4 – Analysis of Winter Maintenance and Pavement Performance Data

4.1 Introduction

The objective of this chapter was to investigate (1) the types and application rate of deicing/anti-icing materials, and (2) whether a relationship exists between deicers (type and amount) and concrete performance. This chapter first briefly describes each database and then explains how winter maintenance and pavement performance data were integrated. Then, the created database is analyzed to specifically address the project objectives.

4.2 Winter Maintenance Data

There are two winter maintenance databases that contain information about deicing/anti-icing materials: Storm Report and Automatic Vehicle Location (AVL). Table 4.1 shows a side-by-side comparison of the two databases.

Table 4.1 Comparison of Two Deicer Database

	Storm Report	**AVL**
Data source	Manually reported by county engineer	Automatic data from AVL/GPS sensor
Year of Coverage	1998~2017	2010~2017
Area of Coverage	All counties of Wisconsin	Only segments patrolled by trucks with AVL/GPS sensors (about 55% of the roadway system)
Total number of records	89,050	6,239
Data included	Snow depth, total amount of deicers used in a county, time of storm and crew operation	Amount of deicers used in a winter operation segment
Deicer types	Salt, salt brine, CaCl2, MgCl2, sand, preweting, anti-icing, etc. (all commercial products used in Wisconsin)	Liquid CaCl2, salt, brine, sand, unspecified, unrecognized

4.2.1 Storm Report

The Storm Report contains a total of 89,050 records, covering the date from 11/6/1998 to 5/18/2017. As its name implies, each record in this Storm Report was reported by individual county engineers after one winter maintenance event and includes data for the start and end time, temperature, event type (snow, freezing rain, sleet, etc.), type and amount of deicers used, as well as hours of crew work. This database provides a reliable source to analyze the total amount of deicers used for each county and the states as a whole. However, a shortcoming of this database for analysis purposes is the records in Storm Report not indicating which roadway or section the deicers were applied.

Figure 4.1 shows the total salt (solid form) used in Wisconsin from 1998 to 2017 according to the Storm Report records. The statewide average snow depth is also presented.

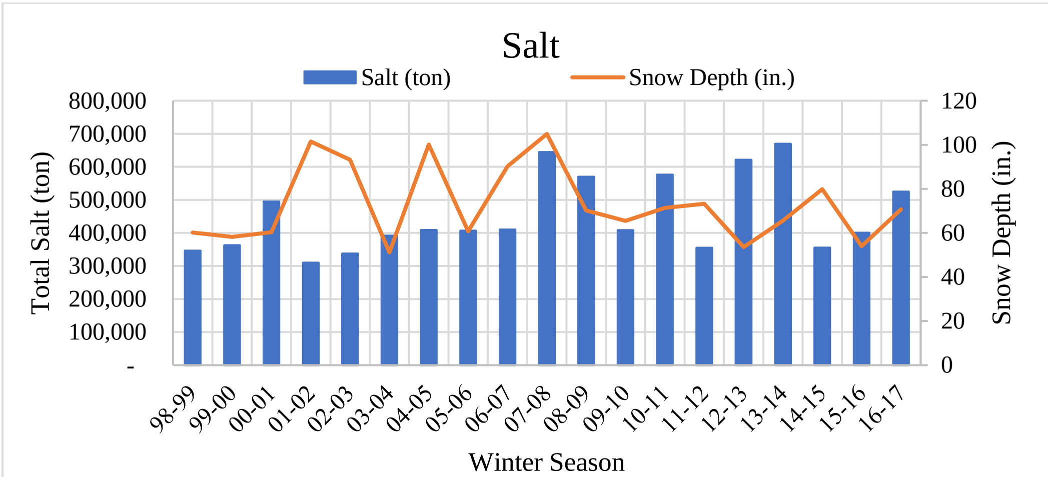


Figure 4.1 Total salt application and snow depth for Wisconsin according to Storm Report

Similarly, Figure 4.2 shows the total sand application in Wisconsin for the same period. Again, there is scatter with little relationship between snow depth and sand application. Wisconsin applied about 20,000 CY of sand for the past 19 winter seasons except for five winters.

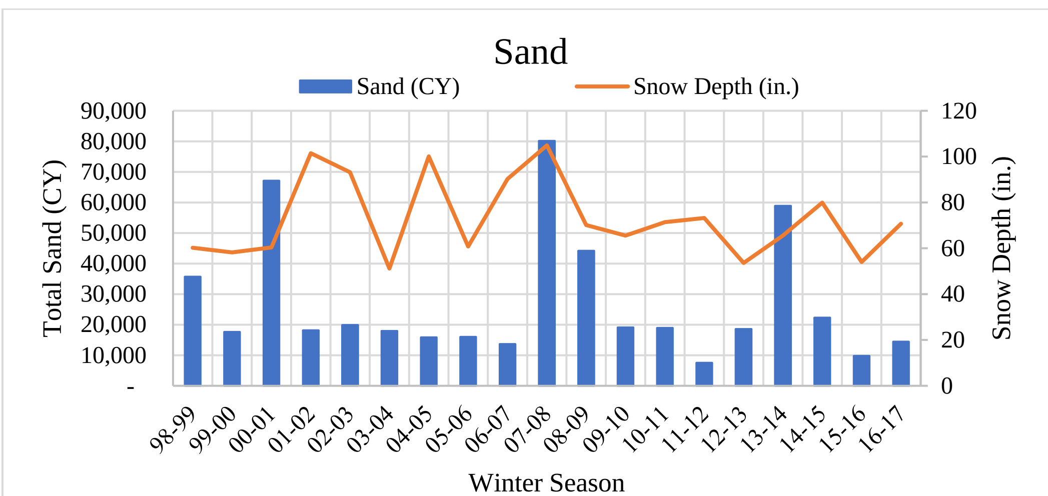


Figure 4.2 Total sand application and snow depth for Wisconsin according to Storm Report

4.2.2 Automatic Vehicle Location (AVL)

The other deicer database is the Automatic Vehicle Location (AVL). AVL database contains a total of 6,239 records for seven winter seasons from 2010 to 2016. Each record shows the total amount of deicer materials used on a winter maintenance segment in one winter season. For the convenience of winter maintenance operation, AVL database indicates that Wisconsin roadway system is divided into 1,172 segments with average length of 9.94 miles. In terms of deicer materials, AVL database only contains six fields:

- liquid $CaCl_2$
- prewet salt
- prewet sand
- salt
- salt brine, and
- sand.

Two more fields named “unrecognized” and “unspecified” stores all materials that do not belong to the six types.

4.2.3 Comparison of the Two Database

Since AVL data are generated from sensors and not all snow plow trucks were equipped with this sensor, an accuracy check was conducted by comparing AVL data with its counterpart in the Storm Report. Table 4.2 lists the total deicer materials used in the past 7 winter seasons according to AVL data. Figure 4.3 shows the comparison of statewide total salt and total brine from the two databases. It is found that AVL is consistently lower than Storm Report. A closer look found out that the total lane-miles of coverage in AVL is about half of it in Storm Report, as shown in Figure 4.4. In fact, the average salt application (ton per lane-mile) is comparable for the two databases, except the 2016 winter season. This agrees with the 2010 implementation process of AVL in Wisconsin (Figure 4.5). In the first year, trucks were installed with AVL/GPS sensor to cover 28% of the state highway system. After the second year, the coverage was doubled to about 55% (Figure 4.4). No significant improvement was observed since then. For this project, however, it was concluded that the AVL data *does provide* useful information in terms of salt application.

Table 4.2 Summary of AVL data from Winter 2010 to 2016

Year	LIQUID_CACL2	PREWET_SALT	PREWET_SAND	SALT	SALT_BRINE	SAND	unrecognized	unspecified	Segment Length	Avg Salt
	gallon	ton	ton	ton	gal	CY	ton	ton	lane-mile	ton/lm
2010	-	40,145	59	150,051	-	11,003	17,690	-	9,584	15.7
2011	-	87,497	3,779	168,420	-	7,631	29,371	147,629	18,450	9.1
2012	3,248	8,755	462	348,428	712,259	15,492	8,071	6,750	18,843	18.5
2013	10,282	4,653	4,412	339,765	2,421,793	27,942	1,546,055	374,695	19,168	17.7
2014	3,090	96	4,805	215,206	1,741,653	14,054	12,947	209	18,955	11.4
2015	3,660	134	2,946	183,825	1,504,648	5,963	1,649,975	502	18,806	9.8
2016	659	115	1,216	126,468	816,615	4,481	2,004	444	18,866	6.7

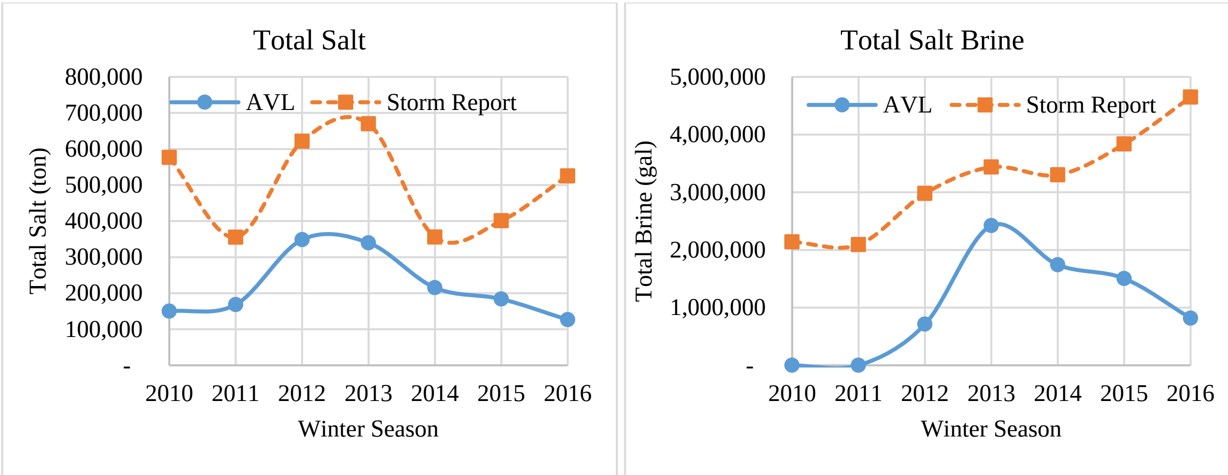


Figure 4.3 Total salt and brine applications in Wisconsin from 2010 to 2016

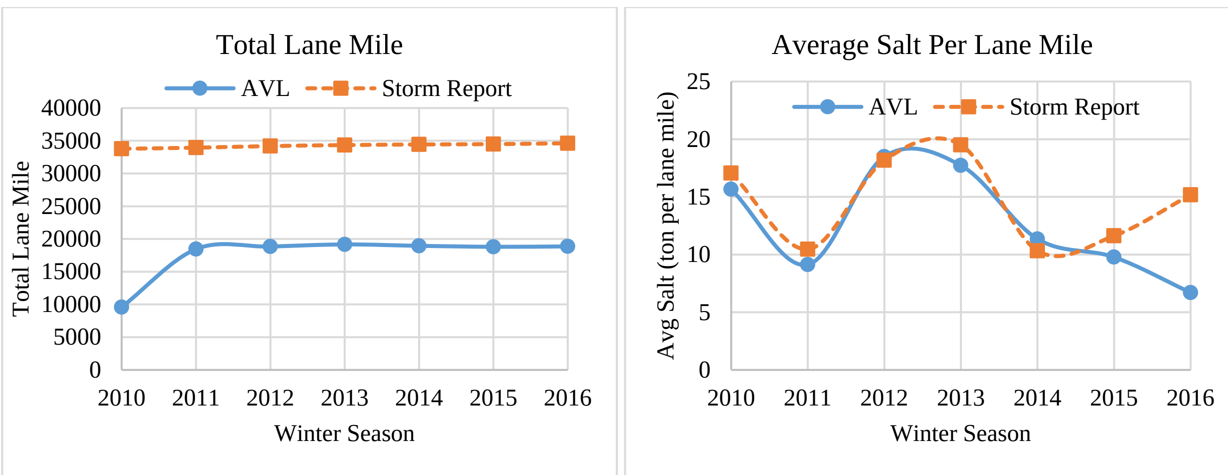
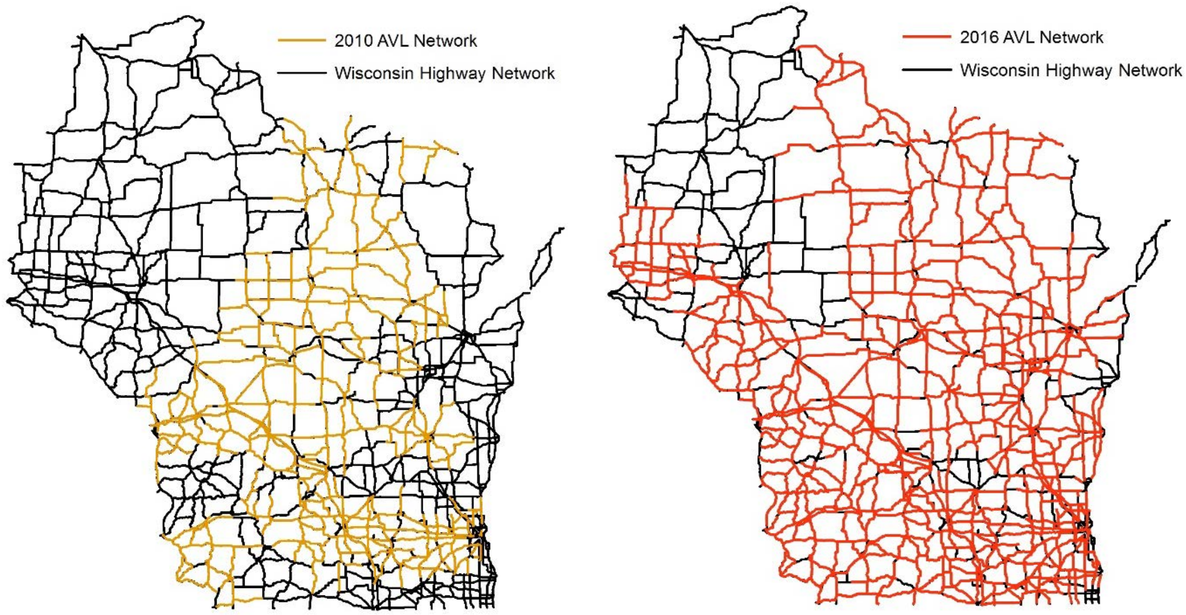


Figure 4.4 Total lane mile and average salt application in Wisconsin from 2010 to 2016



(a) 2010 (b) 2016

Figure 4.5 Maps of Roadway Segments with AVL Data

4.3 Pavement Performance Data

The available pavement performance data contains a total of 52,640 data records (Sequence Numbers), in which 10,002 records are for Type 8 (JPCP) pavements. These data were collected from 8/18/2008 to 12/31/2015. Each section contains a maximum of four performance records, corresponding to the four data collection cycles, 2008~09, 2010~11, 2012~13, and 2014~15. These data were for 2,631 individual sections (counted by Sequence Number), with a total length of 2,858 miles and average section length of 1.1 mile. In terms of pavement age, these sections were constructed between 1986 and 2015, with the majority between 1995 and 2005, as shown in Figure 4.6.

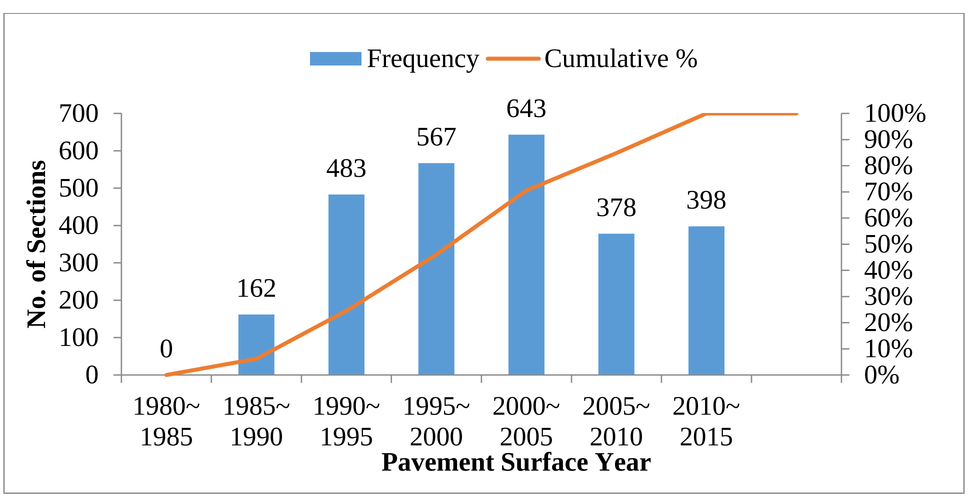


Figure 4.6 Histogram of Surface Year for Type 8 JPCP Pavements

Among the 10,002 records, there are 1,069 records corresponding to reconstructed sections (performance data were collected earlier than the pavement surface age). Among the remaining 8,933 records, there are 2,015 records, or 23%, with joint faulting data. The relationship between joint spalling and pavement surface age is shown in Figure 4.7. A preliminary increasing trend is fairly clear, indicating the older the pavement, the more distress. The data points of low joint spalling for older pavement surface age are mostly likely due to maintenance which changes joint spalling to patching. In terms of the scale of joint spalling, the maximum 1,600 ft indicates that 41% of transverse joints had full length (12 ft) of spalling (using 1.1 mile average section length and the median joint spacing 18 ft as the reference).

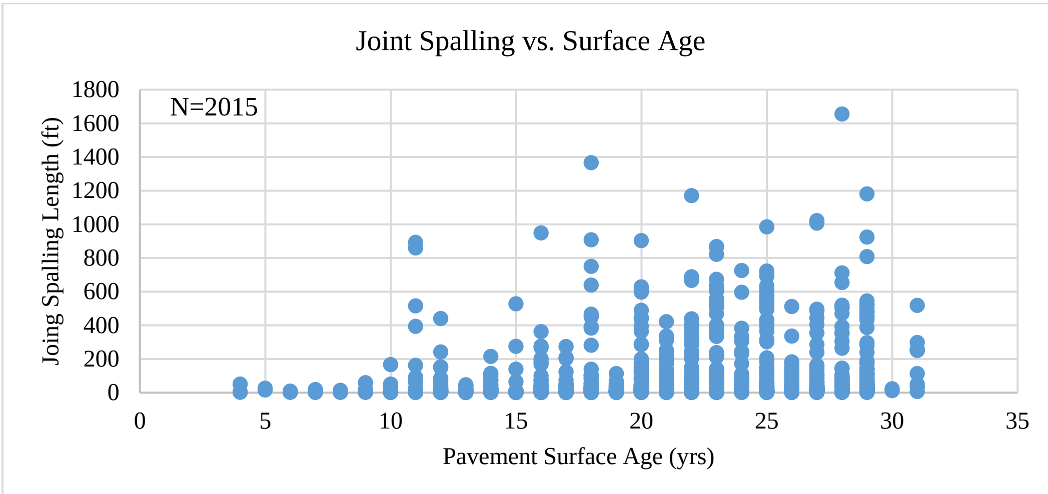


Figure 4.7 Joint Spalling vs. Pavement Surface Age as of 2017

Similar analyses were conducted on scaling, durability "D" cracking, patching, and corner spalling. In summary, based on the available data from the pavement performance database, the distresses related to deicer impact include joint spalling, corner spalling, and patching. These data were further merged with deicer data to analyze the relationship between deicer application and concrete durability.

Table 4.3 Summary of Available Data Records in the PMS Database

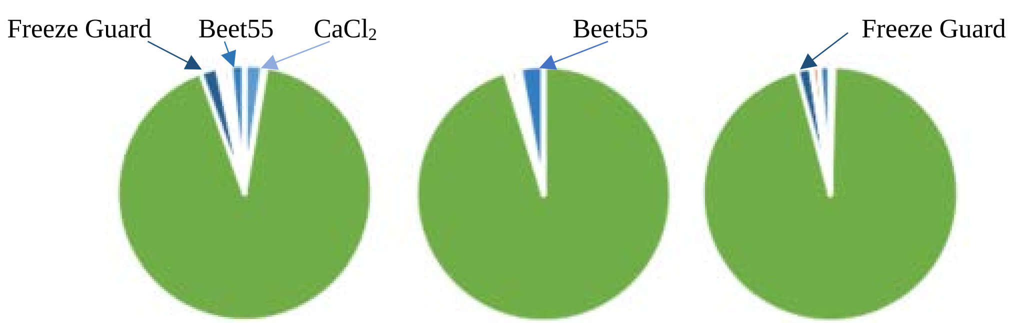
Database Attribute	Total # of Records
Total records of the PMS database	52,640
Total records of Type 8 JPCP pavement	10,002
After excluding reconstructed sections	10,002 – 1,069 =8,933
• No. of records with Joint spalling (length)	2,015
• No. of records with Corner spalling (area)	1,126
• No. of records with Patching (area)	1,788
• No. of records with Scaling (area)	134
• No. of records with D-Cracking (area)	52
• No. of records with Popout (count)	44

4.4 Data Integration in GIS

The AVL route network distinguishes between segments using identification codes not linked with the standard sequence numbers used by the WisDOT Pavement Management Unit (PMU) for pavement performance monitoring. Hence, to align the AVL data with pavement performance data, maps from the PMU and AVL networks were both imported into GIS software environment and manipulated using spatial join overlay techniques. Through this process, AVL segments with their identification codes were matched with corresponding PMU established segment sequence numbers; this resulted in 1,348 records with complete performance and AVL data. This data set was further linked with traffic and pavement structural information based on sequence numbers. The dataset reduced to 1,073 records that had data values for all variables excluding sections reconstructed after the latest performance survey. The 1,073 records were then subjected to further analysis as presented in the next section.

4.5 Types of Deicing/Anti-icing Materials

In terms of types of deicers applied, Figure 4.8 shows a pie chart of 21 deicers being used for prewetting salt, prewetting sand, and anti-icing. The green color piece represents salt brine which is the primary material for the three applications. The top four materials are further listed in Table 4.4.



(a) for prewetting salt (b) for prewetting sand (c) for anti-icing

Figure 4.8 Types of deicers used in 2015-2016 winter

Table 4.4 Top Four Deicer Materials used for Prewetting and Anti-Icing in 2015-2016 Winter

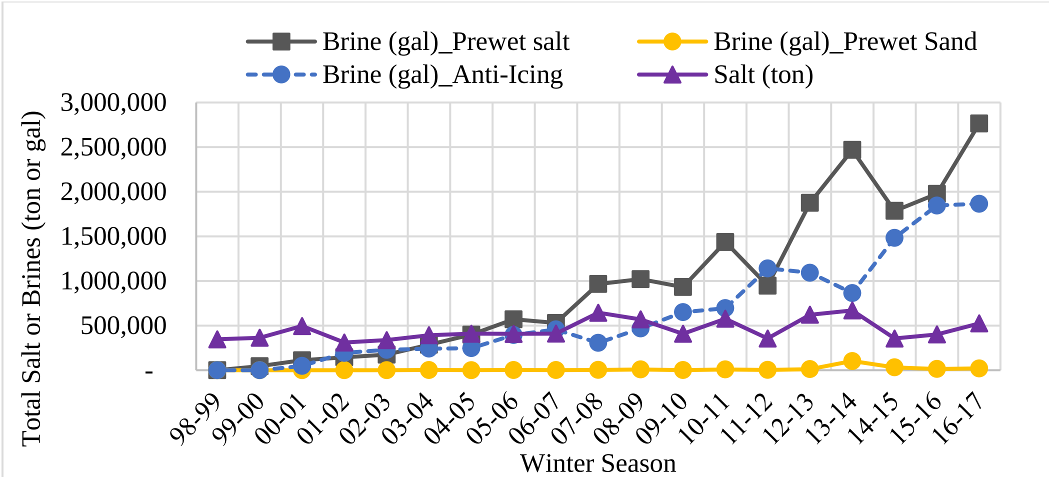
Application	1st	2nd	3rd	4th	Total
For prewetting salt	Salt brine	$CaCl_2$	Freeze Guard	Beet55	
• Amount (gal)	1,976,508	50,111	47,007	38,310	2,157,135
• Percentage	91.6%	2.3%	2.2%	1.8%	100%
For prewetting sand	Salt brine	Beet55	MC95	GMLT	
• Amount (gal)	14,066	435	107	82	14,782
• Percentage	95.2%	2.9%	0.7%	0.6%	100%
For anti-icing	Salt brine	Freeze Guard	Beet55	GMLT	
• Amount (gal)	1,845,559	33,927	26,202	17,528	1,935,609
• Percentage	95.3%	1.8%	1.4%	0.9%	100%

Figure 4.9 shows the total amount of salt and brine, the primary deicer materials used in Wisconsin, in the past 19 winter seasons. Although the chemical component is the same, NaCl, salt can be applied in solid format (rock salt) and liquid format (brine). Brine can be used in three ways, prewetting the solid format salt, prewetting sand, and directly for anti-icing. Figure 4.9(a) shows the trend that the amount of brine for prewetting salt and anti-icing has continuously increased in the past 10 years. Solid format salt has kept at about 500,000 ton level, fluctuating most likely depending on the amount of snow in a winter season. Brine for prewetting sand is negligible comparing to prewetting salt and anti-icing.

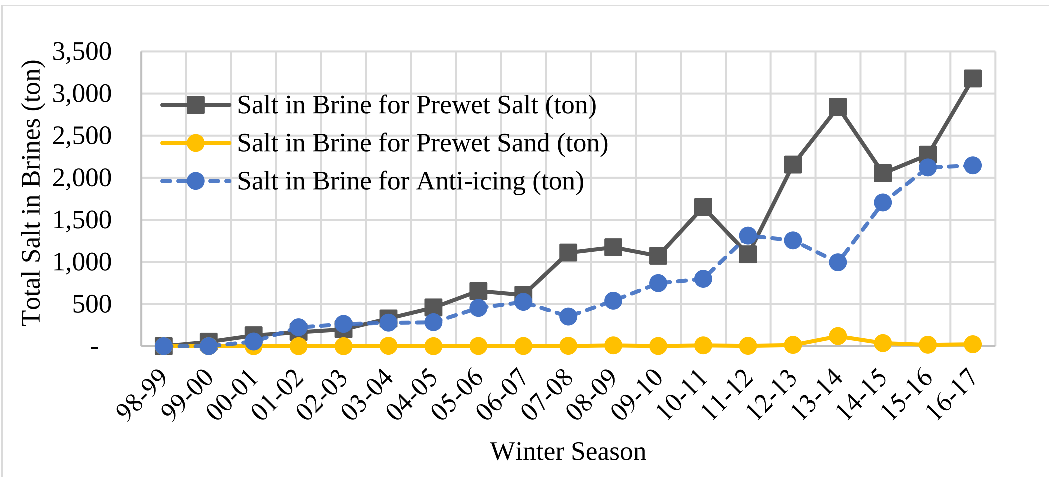
It should be pointed out that the unit in Figure 4.9(a) is tons and gallons for salt and brine, respectively. Since one gallon of brine only contains about 2.3 lb of salt, the net amount of salt in brines was calculated and presented in Figure 4.9(b) for quantitative analysis. Again, the increasing trend of brines is obvious in Figure 4.9(b). However, the amount of salt (NaCl) when converted to tons has a magnitude difference from the amount of salt in solid format (Figure 4.9(c)). Taking 16-17 winter season as an example, the NaCl in preweting salt and anti-icing was 3179 tons and 2145 tons, respectively. The solid form salt applied was 525,276 tons. In other words, salt used in brines only accounted 1.0% of the total NaCl applied on Wisconsin roadways. Therefore, considering the effectiveness of prewetting and anti-icing, more application of brine will theoretically reduce the total amount of solid format salt while still maintain the level of service for winter operation.

4.6 Application Rate of Deicing/Anti-icing Materials

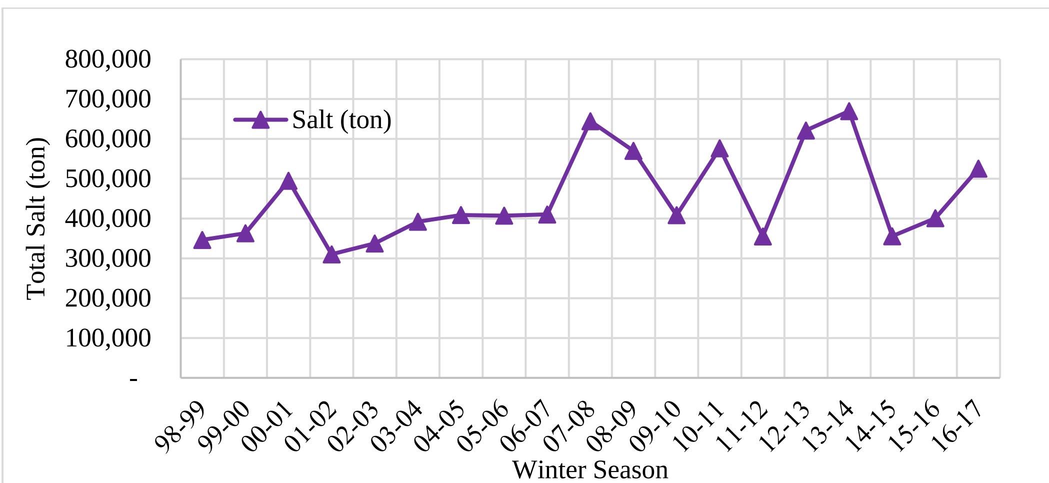
The created Storm Report database was utilized to compare the different products used in each county containing one of the four main chemicals in deicers. The main chemical compositions for deicers are sodium chloride, calcium chloride, magnesium chloride, and sugar beet molasses. Once the 26 products from Storm Report were compiled for each county, units were converted from gallons to tons for liquid products. This unit conversion was done by using the unit weight from Material Safety Data Sheet (MSDS), product information sheets provided by manufactures, or response from county engineers in the survey. To have an estimate of the deicer amount, the average application rate in the unit of ton/lane-mile per year was calculated by dividing the final summation by the total lane-mile of each county and the numbers of years, in this case 7 years from 2010 to 2016. Results are presented in Figures 4.10 through 4.13 using color graduation, from lighter to darker colors. Darker colors represent the highest amount of ton per lane mile for that specific chemical. The top five counties using NaCl-based products are Dane, Columbia, Dodge, Ozaukee, and Vilas. The top five counties using $CaCl_2$-based products are St Croix, Ozaukee, Milwaukee, Waukesha, and Forest. The top five counties using $MgCl_2$-based products are Jackson, Trempealeau, Pepin, Burnett, and Marquette. The top five counties using sugar beet-based products are Waukesha, La Crosse, Juneau, Ashland, and Manitowoc. Table 4.5 lists the descriptive statistics of the data shown in Figures 4.10 through 4.13. On average, each lane-mile roadway received 13.78 ton NaCl, 0.31 ton $CaCl_2$, 0.16 ton $MgCl_2$, and negligible sugar beet.



(a) Total salt (tons) and brine (gals) in one figure



(b) Total salt applied in liquid format (tons)



(c) Total salt applied in solid format (tons)

Figure 4.9 Total salt and brine applications in Wisconsin from 1998 to 2017

Table 4.5 Descriptive statistics of average application rate (unit: ton/lane-mile)

Statistics	Storm Report database				AVL database	
	NaCl	**$CaCl_2$**	**$MgCl_2$**	**Sugar beet**	**Salt**	**Salt brine**
Maximum	23.45	4.67	1.39	0.08	122.88	2.53
Mean	13.78	0.31	0.16	0.01	9.64	0.05
Standard deviation	3.90	0.91	0.30	0.02	12.42	0.11
Median	13.66	0.00	0.02	0.00	6.31	0.01
Minimum	5.95	0.00	0.00	0.00	0.00	0.00

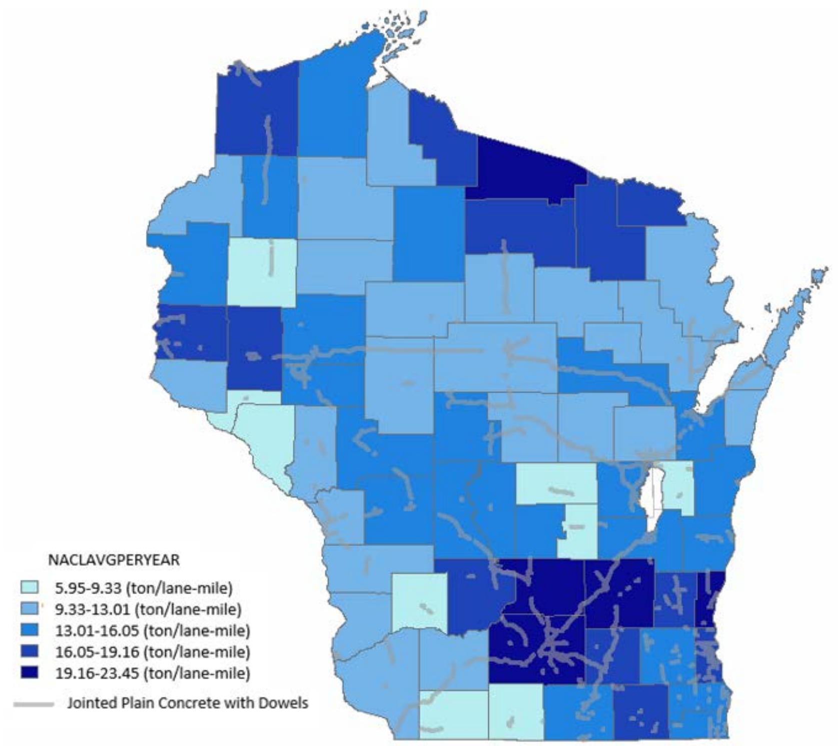


Figure 4.10 Sodium Chloride NaCl products used from 2010 to 2016

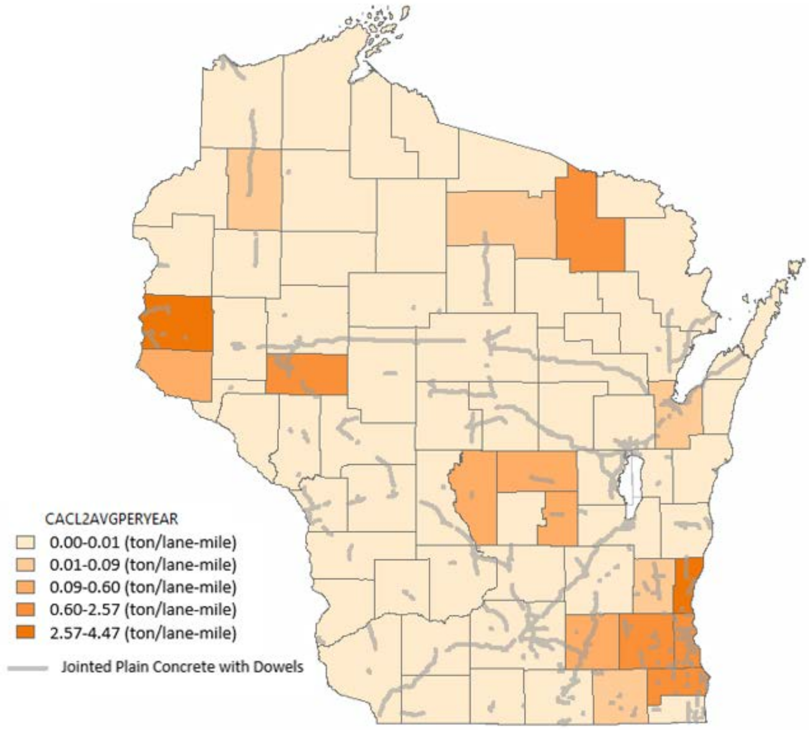


Figure 4.11 Calcium Chloride $CaCl_2$ products used from 2010 to 2016

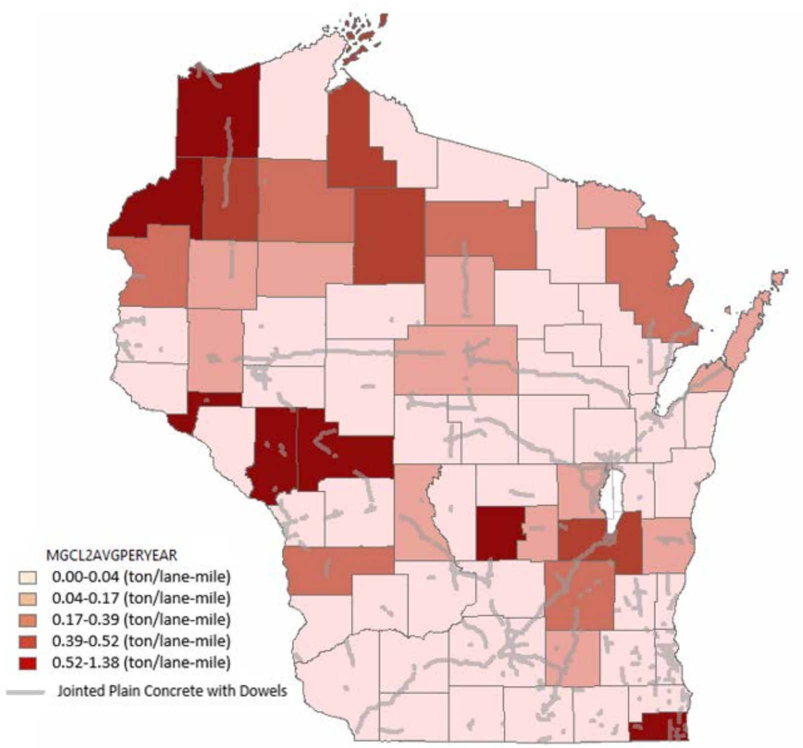


Figure 4.12 Magnesium Chloride $MgCl_2$ products used from 2010 to 2016

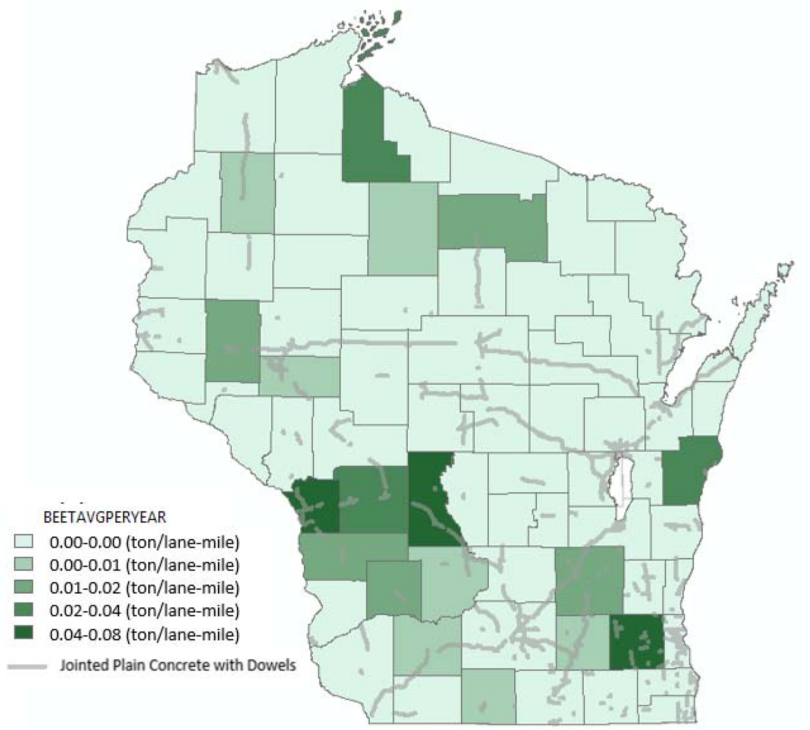


Figure 4.13 Sugar Beet products used from 2010 to 2016

AVL provides deicer details to roadway segments. The average salt concentration (ton per lane-mile) based on AVL data is shown in Figure 4.14. The statewide average is 9.64 ton/lane-mile, slightly lower than the Storm Report summary (3). There are a few segments (5%) with extremely high concentration level over 50 ton/lane-mile; most of them are close to urban areas. Descriptive statistics are listed in Table 4.5.

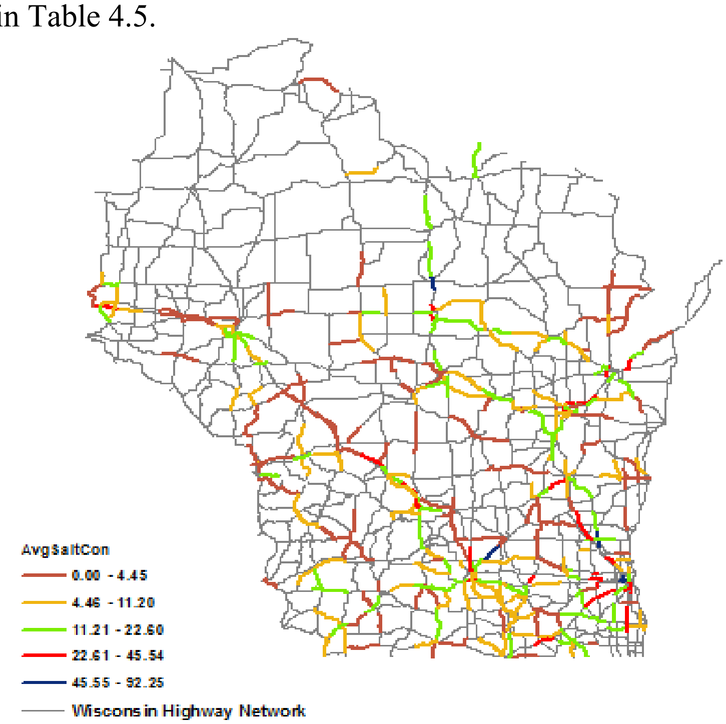


Figure 4.14 Average salt application in Wisconsin from 2010 to 2016 based AVL data

4.7 Impact of Deicing/Anti-icing Materials on Concrete Performance

The hypothesis was that the more deicing/anti-icing materials applied on a road, the worse the concrete would perform. To test this hypothesis, the dataset prepared in section 4.2.3 was used. The dataset contains 1,073 records of deicer, pavement performance, traffic, and roadway inventory data. Records of zero values in pavement performance (642 records), deicer application rate (36 records), and traffic (46 records) were excluded. Outliers were excluded based on quantile range (values one time the interquantile range past the lower and upper quantiles, 33 records). Figure 4.15 shows the data before and after excluding zero values and outliers. All statistical analyses were conducted using the statistical software JMP version 13.2.1 developed by SAS Institute Inc.

4.7.1 Salt vs. Salt Brine

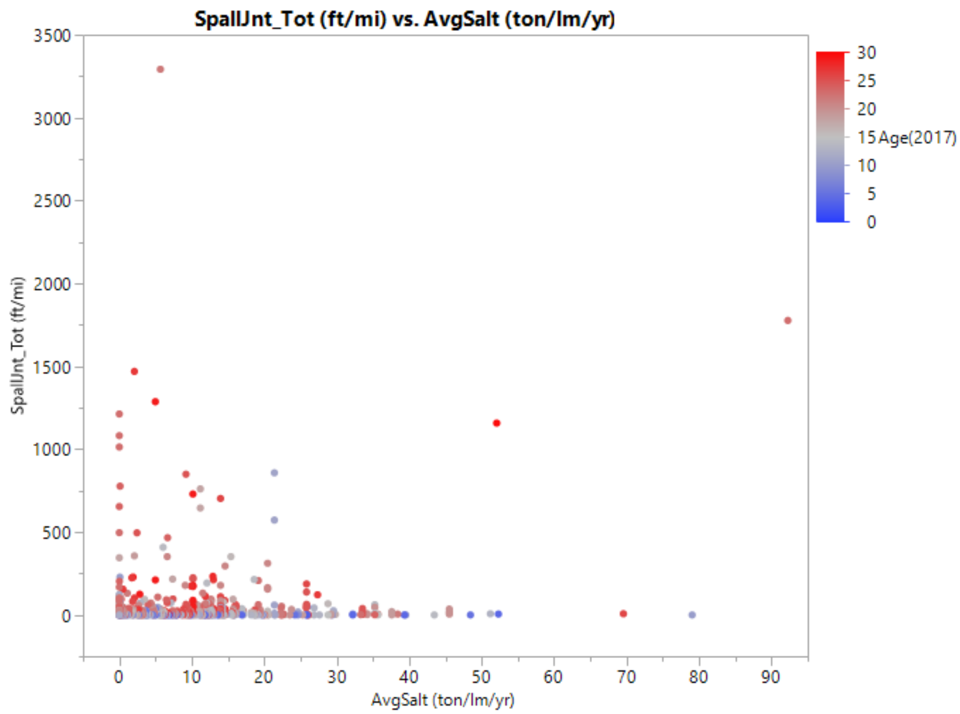
The AVL database contains salt and salt brine data. As shown in Figure 4.9, the amount of brine for prewetting salt and anti-icing has continuously increased in the past 10 years in Wisconsin. A concern of using liquid format of salt brine (in anti-icing) rather solid format salt is that the dry concrete surface absorbs the anti-icing solution very readily, whereas the old scheme of applying rock salt to a wet, saturated concrete surface allowed for much less penetration of the deicing chemicals. A simple hypothesis was formulated to test whether average joint spalling is the same or different among three salt application levels, as follows:

Hypothesis #1

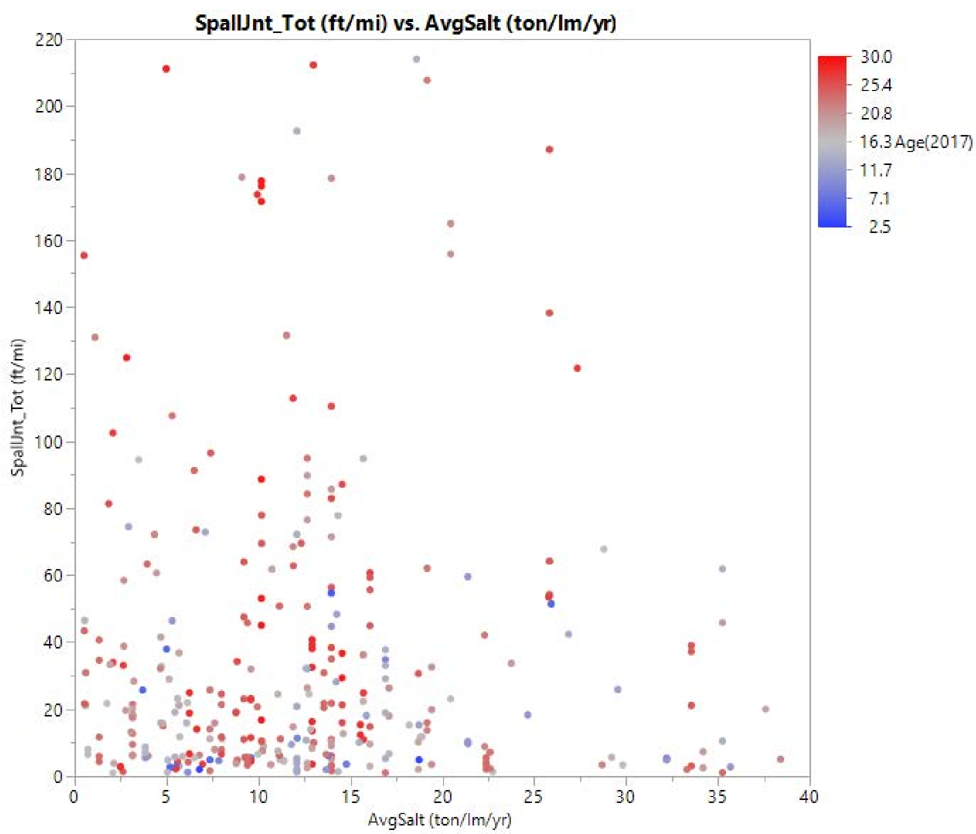
H_O: Mean joint spalling is equal among three salt levels ($\mu_{,\text{Solid \& Liquid}} = \mu_{,\text{More Liquid}} = \mu_{,\text{More Solid}}$).

H_A: Mean joint spalling is not equal among three salt levels ($\mu_{,\text{Solid \& Liquid}} \neq \mu_{,\text{More Liquid}} \neq \mu_{,\text{More Solid}}$).

To test this hypothesis, the average application rate in the unit of ton/lane-mile and gal/lane-mile from 2010 and 2016 were calculated for salt and salt brine, respectively. Then, salt and salt brine were plotted in one graph along with the total joint spalling, as shown in Figure 4.16. In general, most data line in the middle of the two axes, meaning that both solid and liquid format salt were applied on the pavement section. There are some roadways received more solid salt and very few liquid brine, and vice versa.



(a)



(b)

Figure 4.15 Scatterplot showing (a) before and (b) after excluding zero values and outliers

Considering joint spalling as the dependent variable and salt type as the only factor, one-way Analysis of variance (ANOVA) was conducted. Figure 4.17(a) shows the result. *No significant difference* was observed for the mean joint spalling between the three levels. More solid salt led to a mean of 40.08 ft/mi joint spalling while more liquid salt brine led to a mean of 32.91 ft/mi. However, the variation (standard error) was large enough to offset differences in any mean. The analysis of variance reported a *p*-value of 0.2394, well exceeding the 0.05 cutoff level. Hence, the hypothesis cannot be rejected. In other words, the available data did not provide statistical evidence that liquid salt brine might cause more concrete distress.

Since Figure 4.16 contains all pavements with construction year from 1988 to 2014, and the statewide application of salt brine did not surpass salt until 2005 (Figure 4.9), another analysis was conducted looking at pavements after 2005. As shown in Figure 4.17(b), the joint spalling is less for newer pavements (maximum value of 60 vs. 220 for y-axis). The average value is slightly different but when variation is considered, there is no significant difference between solid salt and liquid salt brine (*p*-value=0.5507).

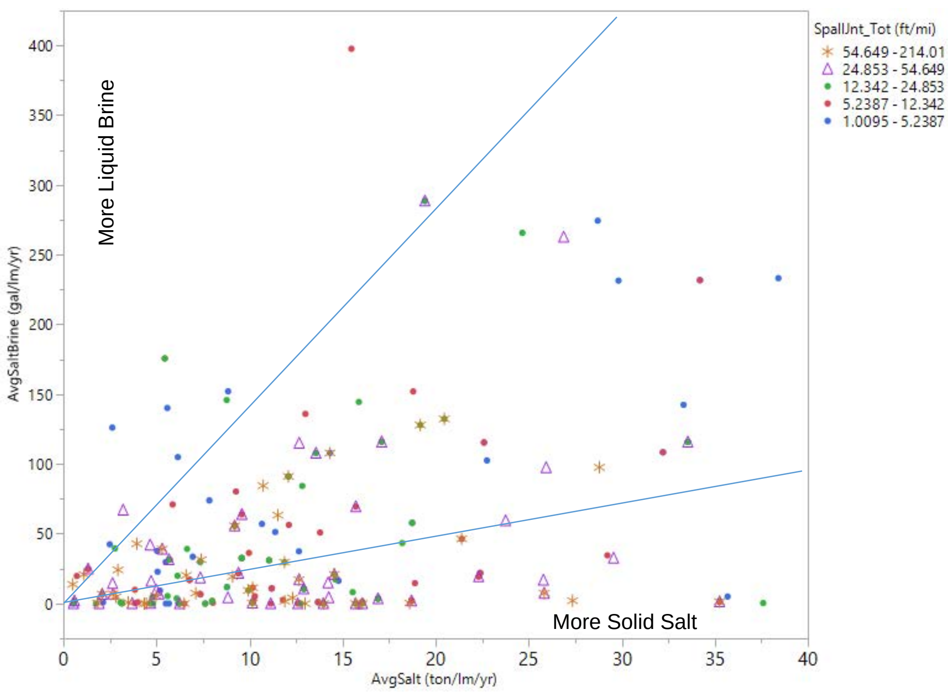
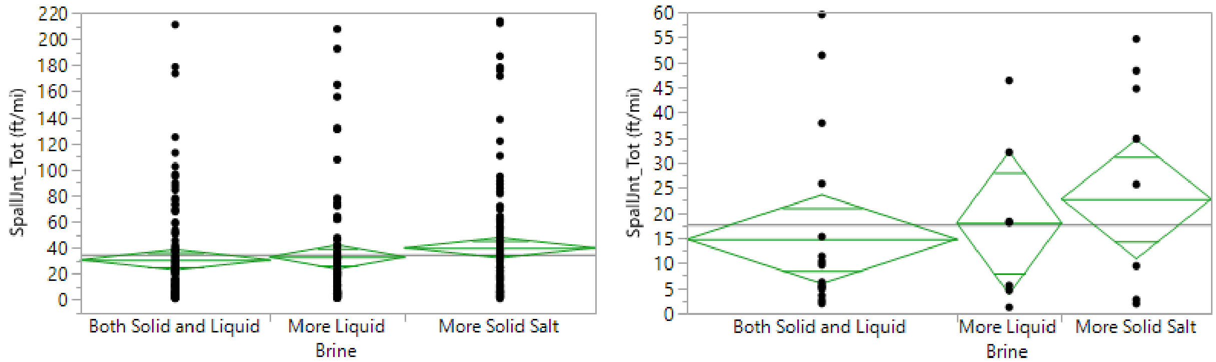


Figure 4.16 Scatterplot of salt, brine, and joint spalling



	(a) All Pavements			(b) Pavements After 2005		
Mean	30.76	32.91	40.08	14.77	18.03	22.78
Std. Error	4.04	4.78	4.03	4.35	6.97	5.83
p-Value	0.2394			0.5507		

Figure 4.17 One-way ANOVA of solid vs. liquid salt

4.7.2 Salt Application Rate

Three analyses were completed to evaluate the impact of salt application rate on concrete performance including scatter plots, correlations, and model fitting.

Scatter Plots

The first analysis conducted was scatterplot and fit for the two variables:

- dependent variable *y*: pavement performance (joint spalling)
- independent variable *x*: deicing/anti-icing type (or concentration)

No distinctive relationship was observed between any of the *x* and *y* variables. For example, Figure 4.18 shows the scatterplot between joint spalling and average salt application rate, which does not show a clear trend. Based on the histogram showing by the side of the figure, the majority of joint spalling was lower than 100 ft/mi (the median value is 18.9 ft/mi). In other words, most of these records had very low joint spalling. Furthermore, field performance is a combined result of all factors such as pavement structure, joint spacing, concrete thickness, concrete material strength, traffic volume, truck load, pavement age, and impact from deicing/anti-icing materials. Therefore, more specific analysis than the one-to-one relationship is needed to isolate the effect from other variables.

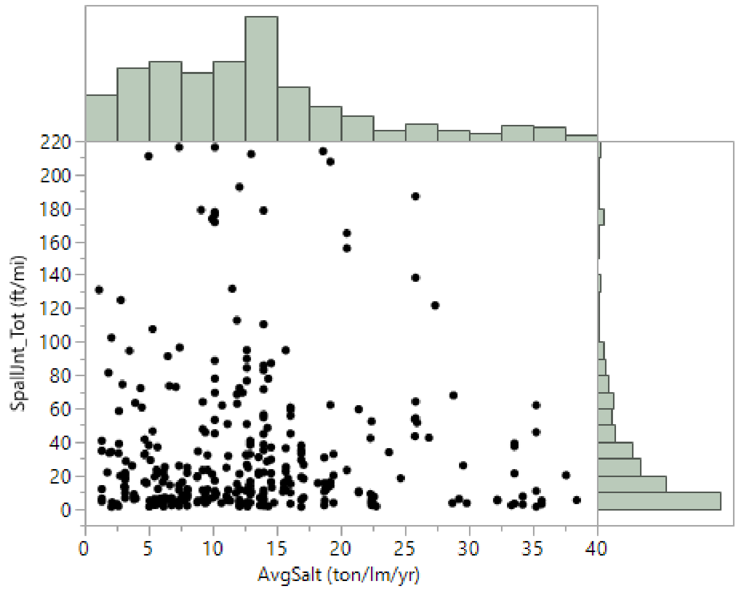


Figure 4.18 Scatterplot of pavement performance (joint spalling) and average salt concentration

Correlations

The second analysis conducted was correlations to help understand the relationship between each pair of variables. Table 4.6 shows the Pearson correlation coefficients and Table 4.7 shows the corresponding *p*-value. According Table 4.6, only layer thickness and AADTT has a fairly strong relationship (correlation coefficient =0.74). Apparently, this should be true because a roadway with higher volume of truck traffic should be designed with thicker pavements. In terms of joint spalling, it has a statistically significant correlation with age, as well as layer thickness and AADTT. The correlation between joint spalling and average salt concentration is not significant. As discussed before, the challenge of field performance is that it is an accumulated result of several factors, many of which are not considered during this analysis such as aggregate types, construction variation, and maintenance history.

Figure 4.19 visually depicts these relationships. Again, the two distinctive trends are:

- Joint spalling and age: older sections showed more spalling.
- AADTT and layer thickness: larger AADTT correlates to thicker pavement.

Table 4.6 Pearson correlation coefficients between multiple variables

	SpallJnt_Tot (ft/mi)	**Age (2017)**	**Layer Thickness (in)**	**AADTT (2015)**	**JNT_SPCG (ft)**	**AvgSalt (ton/lm/yr)**	**AvgSaltBrine (gal/lm/yr)**
SpallJnt_Tot (ft/mi)	1.0000	**0.2382**	**0.1104**	**0.1393**	-0.0063	-0.0149	**-0.1164**
Age(2017)	0.2382	1.0000	0.1996	0.2894	0.3087	-0.1107	-0.1525
Layer Thickness (in)	0.1104	0.1996	1.0000	0.7404	0.3086	0.1766	0.0187
AADTT(2015)	0.1393	0.2894	0.7404	1.0000	0.2329	0.1674	-0.0844
JNT_SPCG (ft)	-0.0063	0.3087	0.3086	0.2329	1.0000	-0.0832	0.0239
AvgSalt (ton/lm/yr)	-0.0149	-0.1107	0.1766	0.1674	-0.0832	1.0000	0.3743
AvgSaltBrine (gal/lm/yr)	-0.1164	-0.1525	0.0187	-0.0844	0.0239	0.3743	1.0000

Note: A number close to 1 or -1 means a strong correlation.

Table 4.7 *p*-value for the correlation coefficients in Table 4.5

	SpallJnt_Tot (ft/mi)	**Age(2017)**	**Layer Thickness (in)**	**AADTT (2015)**	**JNT_SPCG (ft)**	**AvgSalt (ton/lm/yr)**	**AvgSaltBrine (gal/lm/yr)**
SpallJnt_Tot (ft/mi)	<.0001	**<.0001**	**0.0499**	**0.0132**	0.9111	0.7918	**0.0387**
Age(2017)	<.0001	<.0001	0.0004	<.0001	<.0001	0.0492	0.0066
Layer Thickness (in)	0.0499	0.0004	<.0001	<.0001	<.0001	0.0016	0.7411
AADTT(2015)	0.0132	<.0001	<.0001	<.0001	<.0001	0.0028	0.1344
JNT_SPCG (ft)	0.9111	<.0001	<.0001	<.0001	<.0001	0.1398	0.6726
AvgSalt (ton/lm/yr)	0.7918	0.0492	0.0016	0.0028	0.1398	<.0001	<.0001
AvgSaltBrine (gal/lm/yr)	0.0387	0.0066	0.7411	0.1344	0.6726	<.0001	<.0001

Note: A numbers less than 0.05 means the correlation is statistically significant.

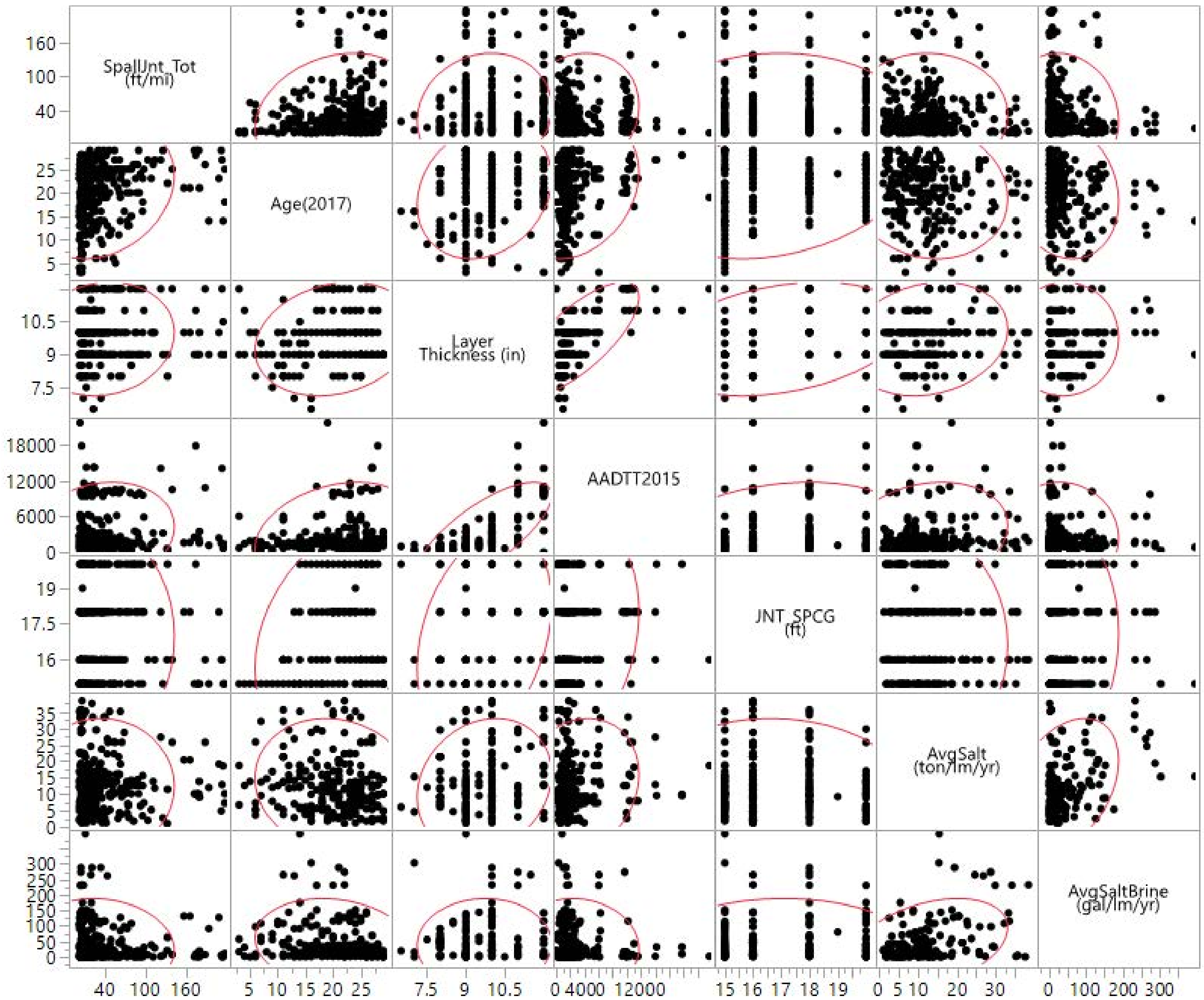


Figure 4.19 Scatterplot matrix for the multiple variables

Model Fitting

The third analysis conducted was model fitting. The purpose was to isolate the effects of other variables by giving them the right consideration in a model to reveal any potential impact of the variable of interest (deicing material). A series of models were tried such as linear, second degree polynomial, full factorial, and response surface. In all these trials, the following variables were kept the same:

- dependent variable y: pavement performance (total joint spalling)
- independent variable x_i: salt concentration, age, joint spacing, layer thickness, and AADTT

Table 4.8 lists the statistics of each model such as R-squared and the statistically significant variables. It shows that the full factorial model has the highest R-squared of 0.29. Age and layer thickness appear to be the main factors. Salt concentration only appears as a partial contribution in the full factorial model and response surface model. Like the correlation analysis, overall data do not show any significant relationship between salt application rate and concrete performance.

Table 4.8 Statistics of Different Model Fitting

Model Type	R-squared	Statistically significant variables	*p*-Value
Linear	0.08	AGE	0.00011
Second degree polynomial	0.11	AGE	0.00000
		JNT_SPCG	0.03047
		LayerThickness	0.04069
Full factorial	0.29	LayerThickness*AADTT	0.00403
		AvgSalt* LayerThickness*AADTT	0.01027
		LayerThickness	0.04587
Response surface	0.18	AGE	0.00039
		LayerThickness*AADTT	0.02111
		AvgSalt*Age	0.02468
		JNT_SPCG	0.03529
		LayerThickness	0.03543

Note: *p*-value less than 0.05 defines the statistically significant variable.

4.8 Summary

This chapter utilized the available data from WisDOT to investigate: (1) the types and application rate of deicing/anti-icing materials, and (2) whether a relationship exists between deicers (type and amount) and concrete performance.

Storm Report provides accurate summary of deicer usage in the county level. The Automated Vehicle Locator (AVL) database provides GIS-based deicer usage in the roadway level. However, AVL data only covers 55% of the state highway network. In addition, Storm Report has detailed types of deicers approved by WisDOT, but AVL database has very limited input options of deicer type.

According to the pavement performance management database, the main distresses observed for Type 8 JPCP pavements are joint spalling, corner spalling, and patching.

In terms of deicing/anti-icing materials, salt and salt brine are the preferred (number 1) choice, followed by $CaCl_2$, Freeze Guard, Beet55, and GMLT. The amount of brine for prewetting salt and anti-icing has continuously increased in the past 10 years, while the amount of salt application kept at about 500,000 ton since 1998.

Based on the Material Safety Data Sheet (MSDS) of deicing/anti-icing materials, all materials were broken down to four basic chemical compounds: NaCl, $CaCl_2$, $MgCl_2$, and sugar beet molasses. Application rate was obtained to county level based on the Storm Report.

Regarding the impact of deicing/anti-icing materials on concrete performance, the available AVL data did not provide statistical evidence that liquid salt brine caused more concrete distress than solid format salt does. Because pavement performance is a combined result of all factors such as pavement structure, traffic load, pavement age, and deicing/anti-icing materials, the one-to-one relationship between joint spalling and salt concentration was not a simple linear curve. Further statistical analyses only indicate that (1) concrete performance is certainly positively related to age; and (2) layer thickness is positively related to AADTT. No significant trend between deicer application rate and concrete performance was identified using the AVL dataset.

Chapter 5 – Field Study

5.1 Introduction

This chapter describes the field study of seven sites intentionally selected to (1) validate the quality of data collected in Chapter 4, (2) visually inspect the pavement condition, and (3) identify the relationship between various deicers (type and application rate) and concrete durability on adjoining projects.

Based on deicing material type and application rate as shown in Figures 4.10 through 4.13, candidate sites were selected to include (1) the border of two counties where different winter maintenance was conducted, (2) on the same travel direction of the same roadway to remove the effects from traffic level and pavement structure, and (3) pavement has performed differently. Figure 5.1 shows the location of the 10 candidate sites. Details of the seven visited sites are listed in Table 5.1. Site 4 was recently overlaid; Site 5 and 7 were not visited due to storm on the field study day.

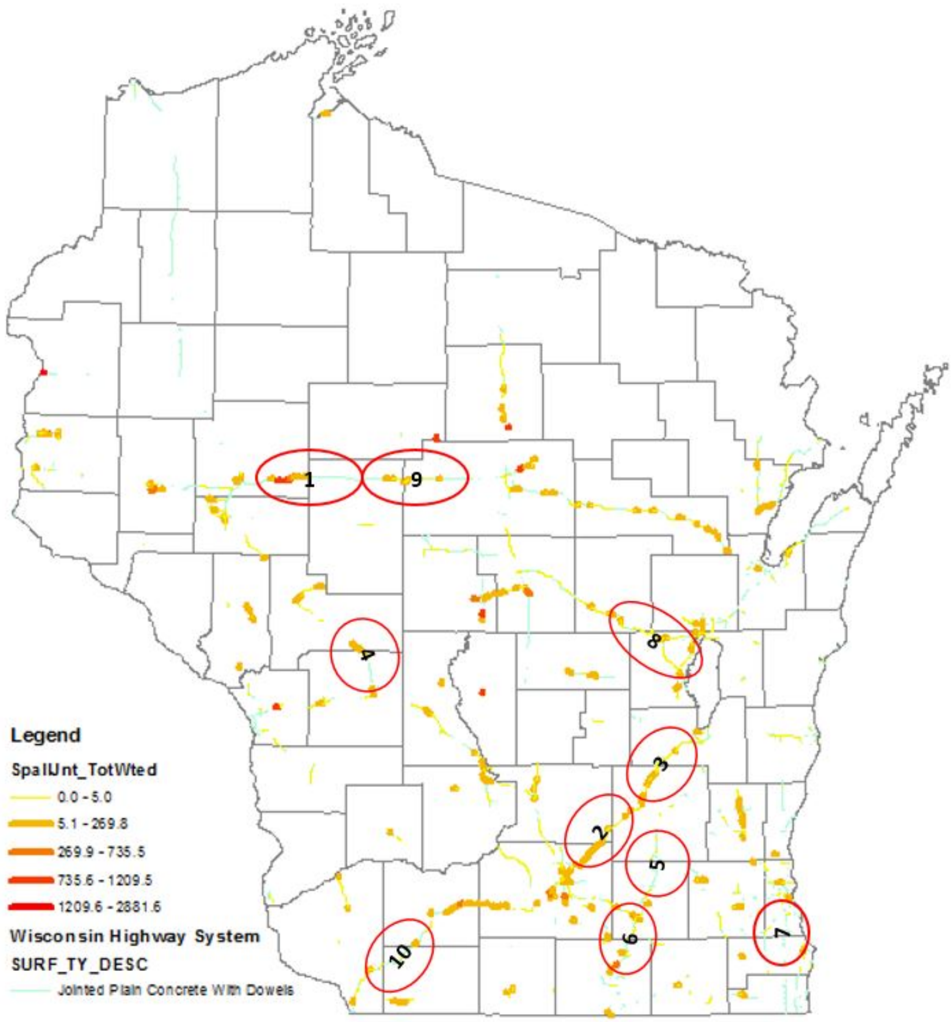


Figure 5.1 Location of the Field Study Sites

Table 5.1 Location and Pavement Structure of the Field Study Sites

Site No	County	Hwy	Dir	From	To	Year	PCC	Base
1	Chippewa	29	E	CTH G	CTH NN	1994	11	9"PCC+6"CABC+ 9"Granular
1	Clark	29	E	CTH NN	KOSER AVE	1994	11	9"PCC+6"CABC+ 9"Granular
2	Dane	151	N	CTH VV STR	CTH V (OH)	1991	10	4" OG1 + 6" CABC
2	Columbia	151	N	MAPLE AVE STR	OLD 73 OH(COLU/DODG)	1991	10	4" OG1 + 4" CABC
2	Dodge	151	N	OLD 73 OH(COLU/DODG)	MAIER RD	1993	10	4" OG1 + 6" CABC
2	Dane	151	S	STH 73 STR	CTH V (OH)	1991	10	4" OG1 + 6" CABC + 9"PCC +6"CABC +9"Granular
3	Dodge	151	N	STH 26 STR	STH 49 STR (DOD/FON)	1997	10	4" OG1 +6"CABC +12"Breaker Run
3	Fond Du Lac	151	N	STH 49 STR (DOD/FON)	STH 26N (GORE)	2004	10	4" OG2 + 8" CABC
6	Jefferson	26	N	STH 106 STR	USH 12 STR	1995	9	4" OG1 + 6" CABC
6	Rock	26	N	WRIGHT RD OH	TOWN LINE RD OH	1999	10	4" OG1 + 6" CABC
8	Waupaca	10	E	STH 96 STR	MARTEN RD STR	2003	10	4" OG2 + 6" CABC
8	Winnebago	10	E	MARSH RD STR	TOWNLINE RD STR	2003	10	4" OG2 + 6" CABC
9	Clark	29	E	DIVISION DR	HI LINE RD (OH)	1997	11	9" PCC+6"CABC+ 9"Granular
9	Marathon	29	E	MAPLE RD (OH)	CTH F	2000	10	4" OG1 + 6" CABC
10	Iowa	151	N	S OAK PARK RD	CTH O (OH)	2002	9.5	10" OG2
10	Lafayette	151	N	BURR OAK RD	LAFA/IOWA CO LN	2003	9.5	6" OG2

*PCC = Portland cement concrete, CABC = Crushed aggregate base course, OG = Open-graded

5.2 Procedure of Site Visit

The research team visited these sites from November 17 through 19, 2017. Keeping safety first, the following procedure was followed during site visit.

1. Review the historical pavement performance from the PMS database before field visit.
2. Drive through the site at highway speed and visually verify the pavement performance.
3. Identify a safe section (straight, no on a curve, good visibility) to park on the shoulder.
4. Rebound hammer test (ASTM C805), surface resistivity test (AASHTO TP95), and air temperature were performed during a safe gap between traffic. At least five repetitions were collected for rebound number and surface resistivity to account for variation. One measurement of joint spacing was also conducted.

5.3 Analysis of Field data

First, historical performance of the visited section and nearby sections (about 3 miles or until the pavement structure, construction year changes, whichever is shorter) were retrieved from the pavement management system and compared with the field visit records. The location of site visit was pinpointed by comparing Google Maps, Street view, and the pictures taken during the field visit. Like Chapter 4, joint spalling, corner spalling, and patch area were combined together as one distress (total joint spalling in the unit of ft/mi) to facilitate the performance comparison. Plots of distress versus time were used to compare the pavement performance of nearby sections. Both the amount of distress in the latest survey and the deterioration rate were evaluated.

The average and standard deviation of rebound numbers were calculated. The average number was used to correlate to compressive strength based on the manufacture's correlation curve. Results of surface resistivity test were first adjusted to the typical temperature of 68°F based on the manufacture's recommendation: a one degree increase in temperature can reduce the resistivity by 3% for saturated concrete and 5% for dry concrete. Then the average and standard deviation were calculated. To understand the resistivity value, both the recommendation from the manufacture and AASHTO TP95 were referred.

A fundamental objective of this study was to evaluate and confirm the effect(s) of deicing and anti-icing materials on concrete durability. A comparison of adjoining counties using different deicing practices and materials offered an opportunity to assess the effect on joint spalling, D-cracking, and scaling. Adjoining counties in rural sections have nearly identical structural design (pavement thickness, K value, etc.), traffic levels, and age. After the site locations were determined, the project ID was identified in the Layer & Base database which records the pavement structure of all projects in Wisconsin. The pavement structure is listed in Table 5.1. Furthermore, the concrete mixture design and properties such as aggregate source, aggregate gradation, air content, and concrete cylinder strength was obtained from WisDOT's Highway Quality Management System. The remaining difference between counties is their maintenance practices that including deicing materials and the county's overall maintenance program. A simple hypothesis was formulated to test whether average joint spalling is the same or different between counties for deicing materials and concentration level, as follows:

Hypothesis #2
H_O: Mean joint spalling is equal among county deicing materials ($\mu_{,County\ A} = \mu_{,County\ B}$).
H_A: Mean joint spalling is not equal among county deicing materials ($\mu_{,County\ A} \neq \mu_{,County\ B}$).

If the hypothesis was rejected, an additional investigation assessed the effect of both deicing materials (NaCl, $CaCl_2$, $MgCl_2$) and the associated concentration level (ton/lm/yr).

5.3.1 Sodium Chloride NaCl

Site #1 is on US 29 near the border of Chippewa and Clark Counties. The eastbound was visited on Nov. 19, 2017 as shown in Figure 5.3. According to the inventory data, both sections were reconstructed in 1994, with 11 in. concrete surface over the old concrete pavement. Joints were skewed at a spacing of 18 ft. Other features include widened slab (14 ft), transverse tining and unsealed narrow joints.

According to the Storm Report, Chippewa County applied more NaCl (15.3 ton/lm/year) than Clark County did (11.7 ton/lm/year).

(a) Chippewa County, logmile 100~101 (b) Clark County, logmile 104

Figure 5.3 Field study of Site #1, US 29, Eastbound

Distresses observed during the field visit were primarily half-slab or full slab replacement and transverse crack. Figure 5.4 shows the performance records retrieved from the pavement management system. Clearly joint spalling is accelerating at both sections (3 miles on both sides of the county line) for this 23-years-old pavement. In addition, Chippewa County does seem to experience a higher speed of deterioration. A t-Test was also performed to test whether the performance in the latest PMS survey was statistically different. The *p*-value was reported as 0.068. This means that the performance is indeed different at the 90% confidence level. Since the two sections have the same pavement structure, traffic, and climate condition, this acceleration of performance could be attributed to the different practice of winter maintenance between Chippewa and Clark Counties.

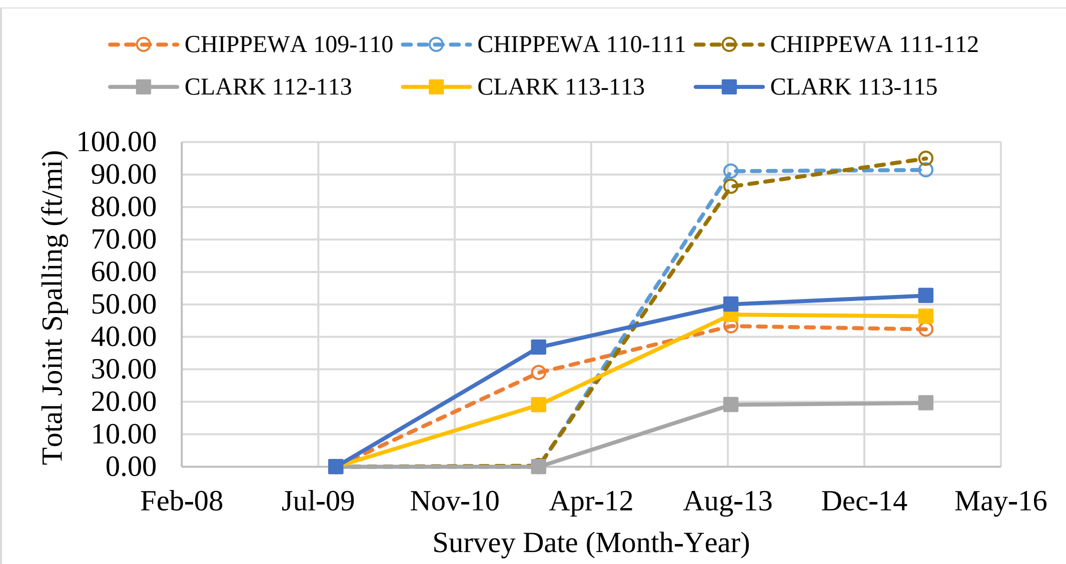


Figure 5.4 Pavement Performance of Site #1, US 29, Eastbound

The results of rebound hammer test and surface resistivity test conducted during field visit are listed in Table 5.2. Compared to the section in Chippewa County, the concrete in Clark County appears to have a slightly higher compressive strength, but the resistivity is very low, meaning that the concrete is prone to chloride ion penetration.

Table 5.2 Results of Field Study Site #1

Deicers and NDT Results	Chippewa County	Clark County
Project ID	1052-07-88	1052-07-85
Pavement Age	23 years	23 years
Avg. Joint Spalling (ft/mi)	76.2	39.6
AVL Salt (ton/lm/yr)	0.00007	N/A
NaCl (ton/lm/yr)	15.33	11.71
$CaCl_2$ (ton/lm/yr)	0.027	0.025
$MgCl_2$ (ton/lm/yr)	0	0.023
Rebound number (Avg.)	33.3	37.7
fc' (psi)	4100	5000
Rebound number (Std. dev.)	2.4	4.7
Resistivity (Avg.) (kΩ·cm)	36.1	7.3
Resistivity (Std. dev.)	13.9	0.9
Joint spacing (ft)	18	18

5.3.2 Calcium Chloride $CaCl_2$

Site #6 is US 26 on the boarder of Rock and Jefferson County. The northbound was visited on Nov. 17, 2017 as shown in Figure 5.5. According to the inventory data, the section in Rock County between John Paul Rd and Town Hall Rd was built in 1999, with 10'' concrete over 4'' open graded base course and 6 in. crushed aggregate base. The section in Jefferson County between Whitetail Lane and USH 12 interchange was constructed in 1995, with 9'' concrete over 4 in. open graded base course and 6 in. crushed aggregate base. Joint spacing for both sections is 20 ft. According to Storm Report, Jefferson County applied more $CaCl_2$ (0.26 ton/lm/year) than Rock County did (0.00057 ton/lm/year).

(b) Rock County, logmile 6~7 (b) Jefferson County, logmile 21~22

Figure 5.5 Field study of Site #6, US 26, Northbound

During field evaluation, windshield survey revealed that pavement in Jefferson County performed worse (mainly corner break and patching at joints) than it in Rock County. Figure 5.6 shows the PMS performance records of 3 miles on each side of the county line. Log mile 9 to 24 were reconstructed in 2014 so they were not compared. In addition, log mile 6 to 7 in Rock County is urban area in Janesville, WI. Jefferson County 25-26 had more joint spalling than Rock County 7-8 in the 2015 survey.

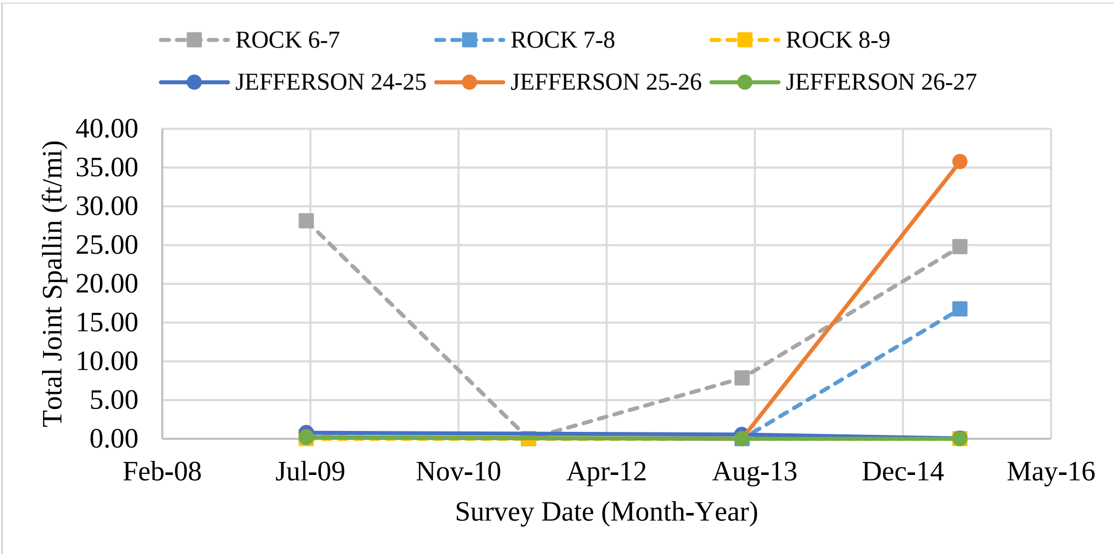


Figure 5.6 Pavement Performance of Site #6, US 26, Northbound

Table 5.3 lists the result of rebound hammer and resistivity test. In terms of concrete strength, the two sections had no difference, both at 4500 psi. However, the resistivity is quite different. According to AASHTO TP95, a higher resistivity number is correlated to a low permeability of chloride ion. Hence, the Jefferson County section is more prone for salt related distresses. It is very likely that the level of salt application combined with the concrete permeability have contributed to the distress observed in the field.

Table 5.3 Results of Field Study Site #6

Deicers and NDT Results	Rock County	Jefferson County
Project ID	1390-03-72	1393-02-73
Pavement Age	18 years	22 years
Avg. Joint Spalling (ft/mi)	8.4	17.9
AVL Salt (ton/lm/yr)	13.33	4.66
NaCl (ton/lm/yr)	13.5	17.0
$CaCl_2$ (ton/lm/yr)	0.0006	0.2604
$MgCl_2$ (ton/lm/yr)	0.0052	0.0887
Rebound number (Avg.)	35.4	35.4
fc’ (psi)	4500	4500
Rebound number (Std. dev.)	4.2	2.7
Resistivity (Avg.) (kΩ·cm)	183.4	61.2
Resistivity (Std. dev.)	24.3	17.6
Joint spacing (ft)	18	18

5.3.3 Magnesium Chloride $MgCl_2$

Site #8 was on eastbound of US 10 near the border of Waupaca County and Winnebago County, Figure 5.7. Inventory data shows that both sections were constructed in 2003 with a structure of 10 in. concrete + 4 in. open graded base + 6 in. crushed aggregate base. Other features include transverse tining, narrow saw cut joints unsealed, perpendicular joints at spacing of 20 ft, and widened slab to 14 ft. Rumble strips are on the asphalt shoulder. Storm Report indicates that Winnebago County used more NaCl and more $MgCl_2$ than Waupaca County did (Table 5.4).

(a) Waupaca County, logmile 268~269 (b) Winnebago County, logmile 271

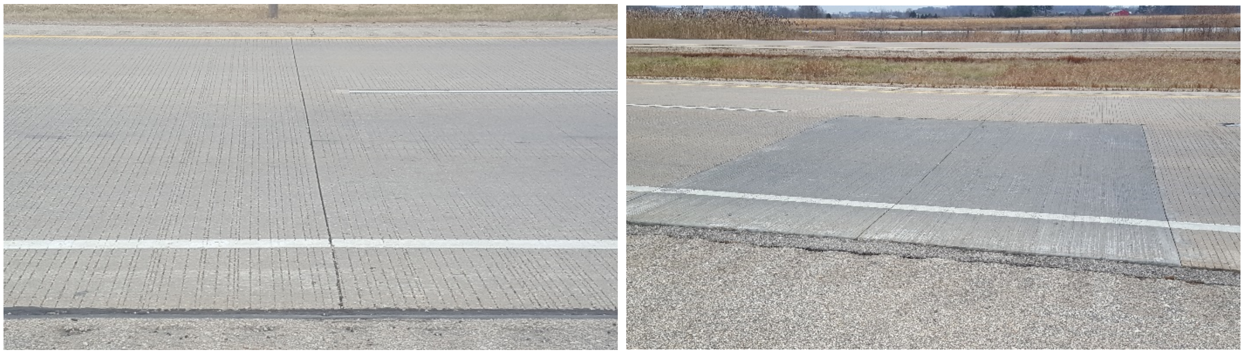
Figure 5.7 Field study of Site #8, US 10, Eastbound

Table 5.4 Results of Field Study Site #8

Deicers and NDT Results	Waupaca County	Winnebago County
Project ID	1517-04-82	1517-04-82
Pavement Age	14 years	14 years
Avg. Joint Spalling (ft/mi)	0	0
AVL Salt (ton/lm/yr)	5.45	5.45
NaCl (ton/lm/yr)	12.53	14.95
$CaCl_2$ (ton/lm/yr)	0	0.00014
$MgCl_2$ (ton/lm/yr)	0.016	0.062
Rebound number (Avg.)	37.0	38.4
fc' (psi)	4900	5100
Rebound number (Std. dev.)	5.0	2.3
Resistivity (Avg.) (kΩ·cm)	91.0	72.5
Resistivity (Std. dev.)	20.9	10.0
Joint spacing (ft)	18	18

The road was very smooth during the field visit. No major distress was observed. This verifies the pavement management data, which shows no joint spalling in both sections. However, field evaluation found three patches (half-slab replacement) in the Winnebago County section (Figure 5.8). PMS data did not show this distress. Visually these patches are new; most likely being completed after the last PMS distress survey (7/1/2014). The point of interest is that no patch nor severe distress was found in the Waupaca County section. In other words, the Winnebago County section starts to deteriorate faster than the Waupaca County one.

According to Table 5.4, Winnebago County used more deicing materials. Rebound hammer test and surface resistivity test indicate that the concrete in both sections have very similar property (strength and permeability). It is very likely that the additional deicing materials on the Winnebago County section are causing the concrete to deteriorate faster than the nearby section.



(a) Waupaca County, logmile 268~269 (b) Winnebago County, logmile 271

Figure 5.8 Different performance was observed at Site #8, US 10, Eastbound

5.4 Summary

A total of seven sites were visited to verify the database used in Chapter 4 as well as to evaluate the impact of deicing/anti-icing materials to concrete durability. One unique feature of these sites is that they are at the border of two counties who used different deicing/anti-icing materials (type and application rate).

Field visit included windshield survey at highway speed, observation on the shoulder without traffic control, and limited non-destructive test (rebound hammer and surface resistivity).

Through comparing sections with the same pavement structure, construction history, traffic, and climate condition, it was observed that counties with a higher amount of NaCl, $CaCl_2$, $MgCl_2$ application tended to experience a higher speed of concrete deterioration. The distress started as joint spalling and led to partial or full slab replacement. As shown in the summary Table 5.5, pavement performance in three of the seven sites were statistically different at the 90% confidence level.

Table 5.5 Results of pavement performance t-Test for the field study sites

Site No	HWY	Direction	Counties	*p*-Value
1	29	East	Chippewa and Clark	**0.069**
2	151	North	Dane and Columbia	**0.081**
2	151	North	Columbia and Dodge	0.479
3	151	North	Dodge and Fond du Lac	0.106
6	26	North	Rock and Jefferson	0.339
8	10	East	Waupaca and Winnebago	N/A*
9	29	East	Clark and Marathon	**0.004**
10	151	North	Lafayette and Iowa	0.148

Note: * t-Test was not applicable to Site #8 because PMS data show zero distress for both counties.

Chapter 6 – Conclusions and Recommendations

6.1 Conclusions

The objectives of this project were twofold: (1) to synthesize the type and application rate of deicing/anti-icing materials in Wisconsin, (2) to investigate, using field performance data, whether deicing/anti-icing materials have led to severe damage on concrete pavements as demonstrated in past laboratory studies.

Findings from the literature review are:

1. The effectiveness of prewetting and anti-icing has driven the increasing usage of salt brine in the past decade. The increasing demand for safety on roads during winter is the driving force for the application of chemicals other than salt (e.g. $CaCl_2$, $MgCl_2$). At the same time, environmental concerns on water quality, vegetation, and aquatic animals have promoted the development and adoption of non-chloride chemicals (e.g. acetates, formates, glycols, and succinates) and environmental-friendly products (e.g. beet juice). However, due to the large amount of deicing/anti-icing materials needed each winter season, as well as the cost advantage, salt and salt brine are still the primary choice for state highway agencies.

2. Regarding infrastructure, the literature suggests that deicing/anti-icing materials damage concrete and concrete structures. The foremost concern is the corrosion of reinforcing steel. This is the main reason why airports cannot use salt but must use other more-expensive products such as potassium acetate and glycols. The impact on concrete was confined to a few laboratory projects. No field study was found in the literature addressing this specific topic. The long-term effects on concrete is mainly anecdotal impression based on engineers' experience.

3. The pooled fund study TPF-5(042) conducted a series of laboratory tests and found that magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$) chemically interact with hardened Portland cement paste in concrete resulting in expansive cracking, increased permeability, and a significant loss in compressive strength. This difference has been proved by a few other laboratory studies. The detrimental effect of calcium oxychloride on concrete was discovered recently. Calcium oxychloride is an expansive product formed from the reaction between the chlorides in the deicing salt with the calcium hydroxide ($Ca(OH)_2$) in the cementitious matrix. Furthermore, tests showed that samples saturated with solutions stronger than approximately 15% (by mass) of $MgCl_2$ or $CaCl_2$ cracked and were damaged at room temperature without freezing and thawing.

The opinion and experience of maintenance engineers from counties and major cities in Wisconsin were collected through an online survey. The survey revealed that

4. Rock salt and salt brine are the main materials for winter maintenance, with an application rate of 200 to 400 lb/lane-mile for deicing and 20 to 50 gal/lane-mile for anti-icing. Other

materials used in order of prevalence include Magnesium Chloride, Calcium Chloride, GeoMelt, and Beet55.

5. Respondents pointed out the two problems with deicing and anti-icing materials were accelerated deterioration near joints and bridge deck damage. However, most of these were based on anecdotal overall impression without specific project.

Quantitative analysis of this study mainly relied on the existing data gathered from different divisions at WisDOT. Findings and challenges encountered from data analysis are

6. There are two sources that contain information about deicing/anti-icing applications in Wisconsin: Storm Report and AVL. Storm Report provides accurate summary of deicer usage at the county level. The Automated Vehicle Locator (AVL) database provides GIS-based deicer usage in the roadway level. However, AVL data only covers 55% of the state highway network. In addition, Storm Report has detailed types of deicers approved by WisDOT, but AVL database has very limited input options of deicer type.
7. Like the survey results, data showed that salt and salt brine are the main choice, followed by $CaCl_2$, Freeze Guard, Beet55, and GMLT. The amount of brine for prewetting salt and anti-icing has continuously increased in the past 10 years, while the amount of salt application kept at about 500,000 ton since 1998.
8. Several methods were tried to evaluate the impact of deicing/anti-icing materials on concrete performance. The available AVL data did not provide statistical evidence that liquid salt brine caused more concrete distress than solid format salt did. Nor was a significant trend between deicer application rate and concrete performance identified using the AVL data. It should be pointed out that pavement performance is a combined result of several factors such as pavement structure, traffic load, pavement age, maintenance history, and deicing/anti-icing materials, many factors were not available in this study. In addition, the variation of pavement distress survey has long been recognized as a challenge for field studies.

Seven sites near county borderlines were visited. The intention was to isolate the factor of deicing/anti-icing materials from other factors because adjoining counties in rural sections most likely have similar pavement structure, traffic levels, construction year, and weather condition. The site visit was primarily visual inspection supplemented by limited nondestructive testing. It was found that

9. Counties with a higher amount of NaCl, $CaCl_2$, $MgCl_2$ application seemed to experience a faster speed of concrete deterioration. The distress started as joint spalling and led to partial or full slab replacement. Statistically, three of the seven sites between adjoining counties exhibited different performance at 90% confidence level.

6.2 Recommendations

1. In terms of deicing/anti-icing materials, rock salt and salt brine will still be the number one material of choice for its affordable cost benefit. Blended products can combine benefits of various chemicals, such as the low cost of rock salt with the low freezing point of calcium chloride. The Department can also conduct pilot trials of new materials that are environmental friendly and cause less damage to infrastructure.

2. In terms of application rate, the current guideline (2008 and 2012) could be revisited to reflect current technological trends. Prewetting and anti-icing have been proven to increase the effectiveness and reduce the amount of salt application by many state highway agencies. Therefore, it is recommended for WisDOT to continue pursuing equipment update, training, and optimization of prewetting and anti-icing.

3. Regarding concrete, several laboratory studies have demonstrated the benefit of using supplementary cementitious materials to reduce the impact from deicing/anti-icing chemicals *[28]*. Fly ash reacts with available lime and alkali in concrete, producing additional cementitious compounds (C-S-H), and hence reduces the pore interconnectivity of concrete *[31]*. The addition of SCM also reduces the amount of $Ca(OH)_2$, therefore decreasing the available amounts for the formation of calcium oxychloride. SCM is commonly used by contractors in Wisconsin and allowed in WisDOT Specifications. This practice should be continued.

4. Another method to protect concrete from deicing/anti-icing chemicals is the application of topical treatments such as penetrating sealers *[15, 32]*. Penetrating sealers can seal the concrete, hence reduce the ingress of water and chemicals. Field trials in Indiana in 2011 showed success in protecting concrete joints *[33]* and the ongoing fieldwork at MnROAD has shown promising results *[34]*.

5. In addition, the AVL system can determine the amount of materials used and its location rather than the operator manually filling out a worksheet. Currently the AVL system only covers 55% of Wisconsin's highway network. It is recommended that AVL system operations be expanded to cover the whole network. More options should be given in the AVL system so that different deicing/anti-icing materials could be recorded. It was also found that AVL defines sections by Segment Number unlike other databases such as PMS and Meta Manager which define sections using Sequence Number. It is recommended that the AVL database be made compatible with the other databases in WisDOT to facilitate data management for future data analysis and decision making.

6. The available data in this study did not provide a statistically significant evidence of deicing/anti-icing materials' impact on concrete. However, the complexity of other factors could have shadowed the factor of interest. Future research should set up "controlled" field sections in which the type and amount of deicing/anti-icing materials are accurately recorded, and the project-level pavement performance data is collected. Additionally, samples from the "controlled" field sections should be collected to examine the chemical penetration in concrete, followed by laboratory test on the field sample to evaluate the

durability. Nearby water sample and soil sample could also be collected to investigate the environmental impact of deicing/anti-icing materials.

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Appendix A. Survey Questionnaire

WISCONSIN DEPARTMENT OF TRANSPORTATION

Deicing and Anti-icing Applications in Wisconsin

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Objectives and Instructions

Wisconsin DOT is in partnership with County Highway Departments and the University of Wisconsin-Platteville to investigate the impact of deicing and anti-icing materials on concrete pavement durability. Phase 1 of the investigation is a survey to understand current practices. Phase 2 is a field study to collect additional data for analysis and to develop recommendations.

Your survey input is critical in:
1. Understanding the different types of deicing and anti-icing materials used by your department, and
2. Identifying best practices to address the impact of deicing and anti-icing materials on the performance of concrete pavements.

This survey will take about 10 minutes to complete. Survey responses will be confidential and be solely used for this research project. Your name and affiliation will not be released to anyone other than the research team. Please also note that deicing and anti-icing materials are considered separately in this survey. Thank you!

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WISCONSIN DEPARTMENT OF TRANSPORTATION

Deicing and Anti-icing Applications in Wisconsin

Contact Information

1. Please provide your name and contact information.

Name:

County:

Organization:

Phone number:

Email:

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WISCONSIN DEPARTMENT OF TRANSPORTATION

Deicing and Anti-icing Applications in Wisconsin

Deicing Applications in Wisconsin

Deicing is removing compacted snow or ice already bonded to the pavement surface by chemical and/or mechanical means.
Pre-wetting is injecting or spraying a liquid chemical on solid chemicals or abrasives to enhance their effectiveness and reduce material loss and other forms of waste.

2. What **deicing** materials (including prewetting) do you use on **concrete roadways** under your jurisdiction? ***Mark all that apply***.
What are the top three (3) most used **deicing** materials (including prewetting) and their *application rates*?

	Used in my jurisdiction	Rank the top 3 most used materials (1, 2, 3)	Application rate (lb/lane-mi)
Sodium chloride (rock salt and salt brine)	No		
ThawRox	No		
ClearLane	No		
Magnesium chloride	No		
Potassium acetate	No		
IceBan M50	No		
IceBan M80	No		
FreezeGuard	No		
Dow Armor	No		
M95	No		
M90	No		
Caliber M1000	No		
Caliber M2000	No		
GeoMelt	No		
IceStop	No		
ArticClear	No		
BioMelt	No		
IceBite55	No		
Beet55	No		

3.

Did you use other **deicing** materials (including prewetting) that are not listed above? Please provide the name and application rate.

	Name	Application rate (lb/lane-mi)
Other 1		
Other 2		
Other 3		
Other 4		

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Deicing and Anti-icing Applications in Wisconsin

Anti-icing Applications in Wisconsin

Anti-icing is a snow and ice control strategy of preventing the formation or development of bonded snow and ice to a pavement surface by timely applications of a chemical freezing-point depressant. Anti-icing can be initiated before a winter weather event or very early in the event.

4. Is anti-icing used in your jurisdiction?*

Yes

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Deicing and Anti-icing Applications in Wisconsin

Anti-icing Applications in Wisconsin

Anti-icing is a snow and ice control strategy of preventing the formation or development of bonded snow and ice to a pavement surface by timely applications of a chemical freezing-point depressant. Anti-icing can be initiated before a winter weather event or very early in the event.

5. What **anti-icing** materials do you use on **concrete roadways** under your jurisdiction? ***Mark all that apply***. What are the top three (3) most used **anti-icing** materials and their *application rates*?

	Used in my jurisdiction	Rank the top 3 most used materials (1, 2, 3)	Concentration (lbs/gal or other rate)	Application rate (gal/lane-mi or lb/lane-mi)
Sodium chloride (rock salt and salt brine)	No			
ThawRox	No			
ClearLane	No			
Magnesium chloride	No			
Potassium acetate	No			
IceBan M50	No			
IceBan M80	No			
FreezeGuard	No			
Dow Armor	No			
M95	No			
M90	No			
Caliber M1000	No			
Caliber M2000	No			
GeoMelt	No			
IceStop	No			
ArticClear	No			
BioMelt	No			
IceBite55	No			
Beet55	No			

6. Did you use other **anti-icing** materials that are not listed above? Please provide the name, concentration and application rate.

	Name	Concentration (lbs/gal or other rate)	Application rate (gal/lane-mi or lb/lane-mi)
Other 1			
Other 2			
Other 3			
Other 4			

7. When do you normally apply the **anti-icing** agent? ***Mark all that apply***.

☐ Prior to frost or black ice
☐ Prior to sleet
☐ Prior to freezing rain
☐ Prior to light snow (<1/2'' in./hr.)
☐ Prior to moderate or heavy snow (>=1/2'' in./hr.)
☐ Others, please specify

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Deicing and Anti-icing Applications in Wisconsin

Impact on Concrete Pavement Performance

8. The main factors that dictate the choice of **deicing and/or anti-icing materials** for concrete roadways under your jurisdiction are
[using a scale of 1(most important) to 5 (least important)]

	1 (most important)	2	3	4	5 (least important)
Cost	○	○	○	○	○
Availability	○	○	○	○	○
Effectiveness of deicing material	○	○	○	○	○
Environmental concerns	○	○	○	○	○
Temperature from weather forecast	○	○	○	○	○
Precipitation from weather forecast	○	○	○	○	○
Wind speed from weather forecast	○	○	○	○	○
Other (please specify in the following question)	○	○	○	○	○

10. Do you have records of **deicing and/or anti-icing materials** applications on concrete roadways in your jurisdiction?

○ No record
○ Yes, I have _____ years of records.

11. Are there specific distresses associated with your roads that are attributed to the application of **deicing and/or anti-icing materials** that you use?

○ No
○ Yes, please specify distress types

12. Do you have any roadway sections that you believe need field investigation because of deterioration from the application of **deicing and/or anti-icing** materials?

○ No

○ Yes, they are located at

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Deicing and Anti-icing Applications in Wisconsin

Thank You!

Thank you again for completing this survey! Your response is very important to us. If you have any questions or comments, please feel free to contact:

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B. Deicing Materials Used in Wisconsin Counties and Cities

Materials	County/City	Rank	Application rate
Sodium chloride (rock salt and salt brine)	Adams	1	varies
	Ashland	1	200~600 salt and 20~30 gal. of liquid per ton of salt
	Brown	1	400
	Buffalo	1	400
	Chippewa	1	300
	Clark	N/A	300
	Columbia	1	Varies
	Dane	1	N/A
	Dodge	N/A	200~400
	Door	1	N/A
	Douglas	1	300 lb and 10 gal. average
	Dunn	1	N/A
	Eau Claire	1	300
	Fond du Lac	1	150
	Grant	1	400
	Green	1	300
	Green Lake	1	200
	Iowa	1	various
	Jefferson	1	N/A
	Juneau	1	100~400
	Kenosha	1	300
	La Crosse	N/A	300
	Lafayette	1	200~300
	Manitowoc	N/A	400
	Marathon	1	10 gal. per ton
	Marquette	1	300
	Milwaukee	1	100
	Monroe	1	varies
	Oconto	1	150~400
	Oneida	1	N/A
	Outagamie	1	50~600 rock salt, 8~15 gal. per ton for prewet
	Ozaukee	1	300
	Portage	N/A	varies
	Shawano	1	400
	Trempealeau	1	65 gplm
	Vernon	1	300
	Walworth	1	250
	Washburn	1	400
	Waukesha	1	400
	Waupaca	1	varies
	Winnebago	1	300
	Wood	1	Depends on situations
	City of Appleton	1	100~300
	City of Eau Claire	N/A	200
	City of Green Bay	1	varies on weather
	City of Kenosha	1	200
	City of La Crosse	1	100
	City of Madison	1	300/two lane mile
	City of Milwaukee	1	300
	City of Stevens Point	1	200
Magnesium chloride	Chippewa	2	5 gal/ton
	Fond du Lac	2	Liquid applied on top of salt 150
	Kenosha	2	10 gal/ton
	Marathon	2	10 gal/ton
	Winnebago	2	N/A
GeoMelt	Dunn	2	N/A

Materials	County/City	Rank	Application rate
	Monroe	2	varies
	Waukesha	3	N/A
	City of Kenosha	2	4 gal/mile
	City of Stevens Point	2	N/A
Beet55	Ashland	2	N/A
	Buffalo	2	N/A
	Green	2	100 lb/lane-mi
	Jefferson	2	N/A
	Juneau	1	3-12 gal
	St. Croix	3	mixed
	Vernon	2	5-10 gplm
	Washburn	2	
	Winnebago	3	N/A
Calcium Chloride	Eau Claire	N/A	3~4
	Kenosha	N/A	10
	Milwaukee	N/A	N/A
	Ozaukee	N/A	N/A
	St. Croix	N/A	prewet
	Waukesha	2	N/A
	City of Appleton	N/A	5~15
	City of Kenosha	N/A	8 gal/ton of salt
	City of Green Bay	N/A	varies on weather
	City of Milwaukee	N/A	N/A
AMP	Dodge	N/A	N/A
	Iowa	N/A	7 gal/ton
SuperBlend	Chippewa	3	25 gplm
Pre-wet brining Liquid chloride Brine	City of Madison	N/A	40 gal/one mile
	City of Eau Claire	N/A	12 gal/mile
	City of La Crosse	N/A	N/A
Salt/Sand	City of La Crosse	N/A	100 lb/lane-mi
Beet juice	La Crosse	N/A	N/A
IceBan M80	Trempealeau	2	65 gplm
FreezeGuard	Douglas	2	N/A
	Ashland	3	N/A
M95	Marquette	3	6 gal/ton
M90	Oneida	2	N/A
ThawRox	Jefferson	3	N/A
Potassium acetate	Fond du Lac	3	minimally potassium pellets
ClearLane			
Dow Armor			
IceBan M50			
Caliber M1000			
Caliber M2000			
IceStop			
ArticClear			
BioMelt			
IceBite55			

*Note: gplm = gal per lane-mile

C. Anti-icing Materials Used in Wisconsin Counties and Cities

Materials	County/City	Rank	Concentration	Application rate (gplm)
Sodium chloride (salt brine)	Adams	1	N/A	varies
	Ashland	1	70%	N/A
	Brown	1	N/A	40
	Buffalo	1	2.25	5
	Chippewa	3	100 lb/lane-mi	N/A
	Columbia	1	23% solution	30
	Dane	1	N/A	N/A
	Dodge	1	N/A	40
	Door	1	23%	N/A
	Douglas	1	27% brine	10
	Dunn	1	23% in salt brine	30
	Eau Claire	1	N/A	30
	Fond du Lac	1	23%	35
	Grant	1	23	50
	Green	1	80	20
	Green Lake	1	N/A	40
	Iowa	1	23.30%	40
	Juneau	1	N/A	47
	Kenosha	1	100	300
	La Crosse	N/A	300	50
	Manitowoc	N/A	N/A	5
	Marathon	1		10 gal. per ton
	Marquette	1	23.60%	50
	Milwaukee	1	N/A	40
	Monroe	1	N/A	N/A
	Oneida	2	24%	40
	Outagamie	1	23.30%	20~40
	Ozaukee	1	N/A	N/A
	Shawano	1	N/A	30
	Trempealeau	1	N/A	65
	Vernon	1	2000/10	1.5
	Walworth	1	N/A	25
	Waukesha	1	N/A	40
	Waupaca	1	Not sure	Not sure
	Winnebago	1	N/A	30~50
	Wood	1	23%	30
	City of Appleton	1	Brine in solution	50
	City of Eau Claire	N/A	N/A	40
	City of Green Bay	1	N/A	30
	City of Kenosha	1	90% of blend	40
	City of La Crosse	1	100	200
	City of Madison	N/A	300 lb/two lane mile	40
	City of Milwaukee	N/A	23.30%	8 gal
	City of Stevens Point	1	23.30%	N/A
Magnesium chloride	Chippewa	1		25
	Douglas	2	100%	10
	Kenosha	2	20	1.06?
	Marathon	2		10 gal/ton
GeoMelt	Dunn	2	10~15% w salt brine	
	Monroe	2		
	Waukesha	2		
	City of Kenosha	2	10% of blend	40
	City of Stevens Point	2		
Beet55	Ashland	2	15%	
	Chippewa	2		25
	Green	2	20%,	20

Materials	County/City	Rank	Concentration	Application rate (gplm)
	Juneau	2	3	
	Vernon	2	20/80 mix w brine	
	Washburn	2		
Calcium Chloride	Kenosha		32%	1.06?
	Ozaukee			
	Waukesha	3		
	City of Green Bay		90/10 ratio with salt brine	
AMP	Dodge		90/10% mix	
	Grant		10%	50
	Iowa		10%	
IceBan M80	Trempealeau	2		65
FreezeGuard	Ashland	3	15% (70/15/15 salt/Beet55/FreezeGuard)	
	Douglas	3	100%	10
	Oneida	1	80/15/5	40
Beet juice	La Crosse			
M95				
M90				
ThawRox				
Potassium acetate				
ClearLane				
Dow Armor				
IceBan M50				
Caliber M1000				
Caliber M2000				
IceStop				
ArticClear				
BioMelt				
IceBite55				

*Note: gplm = gal per lane-mile

D. Chemical Components of Deicing and Anti-icing Materials

The following table was assembled based on materials safety data sheets (SDS) from winter maintenance materials manufactures.

Major Chemical	Materials	Chemical Components	Concentration (%)	Notes
NaCl	Sodium chloride (rock salt and salt brine)	Solid rock salt: NaCl	100%	
		Salt brine: NaCl	24%	
	ClearLane	NaCl	91~96%	
		MgCl2	1~1.3%	
	SuperBlend	NaCl	90~98%	
		MgCl2	0.06~0.2%	
		KCl	0.2~0.4%	
		CaCl2	0.3~1.4%	
CaCl2	Dow Armor	CaCl2	29~31%	
		KCl	1~3%	
		NaCl	1~4%	
	IceBite55	NaCl	7~11%	
		CaCl2	8~10%	
		MgCl2	2~2.5%	
		KCl	0.5~1.5%	
MgCl2	ThawRox	MgCl2	N/A	a combination of rock salt and high performance liquid additive
	Magnesium chloride	MgCl2	100%	
	IceBan M50	MgCl2	50%	IceBan derived from corn byproducts and serves as a corrosion inhibitor.
	IceBan M80	MgCl2	80%	
	FreezeGuard	MgCl2	15~40%	
	AMP	CaCl2	6~10%	
		MgCl2	12~15%	
	M95	MgCl2·6H2O	51%	
	Caliber M1000	MgCl2	26~29%	
	Caliber M2000	MgCl2	22~25%	
Sugar beet	GeoMelt	desugared sugar beet molasses	25~99%	
	BioMelt	sugar beet molasses		no chloride concentration
	Beet55	Sugar beet molasses	55%	
	Potassium acetate			
	M90			
	IceStop			
	ArticClear			

E. WisDOT Recommended Deicing and Anti-icing Application Rates

The following tables are copied from WisDOT Highway Maintenance Manual, available at http://wisconsindot.gov/Documents/doing-bus/local-gov/hwy-mnt/mntc-manual/chapter06/06-20-25.pdf

and

http://wisconsindot.gov/Documents/doing-bus/local-gov/hwy-mnt/mntc-manual/chapter06/06-20-20.pdf

DE-ICING APPLICATION RATES FOR PRE-WETTED SALT – (4-LANES AND GREATER)

This guide is not meant to be a substitute for the use of judgment and the observation of the result of treatments on existing conditions. It is meant to show variables that usually occur together and the treatment that has proven to be the most successful. This guide should then be used to assist in deciding on the best course of action depending on existing conditions. This table assumes the salt is pre-wetted. (Allow de-icing agents time to begin working before making additional plowing passes.)

4-lane Highways Application Guidelines #/LM **Pre-wetted** Salt	Pave. Temp. 28° to 32° F		Pave. Temp. 23° to 28° F		Pave. Temp. 15° to 23° F		Pave. Temp. Less than 15° F	
	Initial	Subsequent	Initial	Subsequent	Initial	Subsequent	Initial	Subsequent
Frost	100	50-100	100-150	50-150	100-200[2]	100-150[1]	100-300[1,2]	100-200[1,2]
Black Ice	200	100-200	100-300	100-200	100-400[2]	100-300[1]	200-400[1,2]	100-300[1,2]
Sleet/Freezing Drizzle	200	100-200	100-300	100-200	200-400[2]	100-300[1]	200-300[1,2]	100-300[1,2]
Freezing Rain	100-300	100-200	200-400	100-200	200-400[2]	200-300[1]	300-400[1,2]	200-300[1,2]
Dry Snow	100-200	100-200	100-300	100-200	Plow Only[1]	Plow Only[1]	Plow Only[1]	Plow Only[1]
Wet Snow	200	100-200	100-300	100-200	200-400[2]	100-300[1]	200-400[1,2]	200-400[1,2]

- Mechanical means of snow removal is the preferred method. Before applying any de-icing agents, the surface should be cleared of as much snow and ice as possible by mechanical means.
- Application rates are "MAXIMUM RECOMMENDED RATES". **Only apply the amount of pre-wetted salt necessary to accomplish the desired level of service.** Rates may vary with regard to pavement temperature, type of roadway surface, and weather conditions.
- Abrasives should not be used on roadways where speeds in the sanded areas exceed 45 mph.
- When wind speed is over 15 mph, use caution when salting and applying moisture drawing de-icing agents.
- [1] Intersections and **low** speed hazardous areas may be treated with pre-wetted abrasives when warranted.
- [2] If necessary, use alternate de-icing agents like calcium chloride and magnesium chloride in combination with a **lower application rate** of salt.

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DE-ICING APPLICATION RATES FOR PRE-WETTED SALT – (2-LANES)

This guide is not meant to be a substitute for the use of judgment and the observation of the result of treatments on existing conditions. It is meant to show variables that usually occur together and the treatment that has proven to be the most successful. This guide should then be used to assist in deciding on the best course of action depending on existing conditions. This table assumes the salt is pre-wetted. (Allow de-icing agents time to begin working before making additional plowing passes.)

2-lane Highways Application Guidelines #/LM **Pre-wetted** Salt	Pave. Temp. 28° to 32° F		Pave. Temp. 23° to 28° F		Pave. Temp. 15° to 23° F		Pave. Temp. Less than 15° F	
	Initial	Subsequent	Initial	Subsequent	Initial	Subsequent	Initial	Subsequent
Frost	100	50-100	100-150	50-150	100-200[2]	100-150[1]	100-300[1,2]	100-200[1,2]
Black Ice	200	100-200	100-300	100-200	100-300[2]	100-300[1]	100-300[1,2]	100-300[1,2]
Sleet/Freezing Drizzle	200	100-200	100-300	100-200	100-300[2]	100-200[1]	100-300[1,2]	100-300[1,2]
Freezing Rain	100-300	100-200	100-300	100-200	100-300[2]	100-300[1]	200-300[1,2]	100-300[1,2]
Dry Snow	100-200	100-200	100-300	100-200	Plow Only[1]	Plow Only[1]	Plow Only[1]	Plow Only[1]
Wet Snow	200	100-200	100-300	100-200	100-300[2]	100-200[1]	100-300[1,2]	100-300[1,2]

- Mechanical means of snow removal is the preferred method. Before applying any de-icing agents, the surface should be cleared of as much snow and ice as possible by mechanical means.
- Application rates are "MAXIMUM RECOMMENDED RATES". **Only apply the amount of pre-wetted salt necessary to accomplish the desired level of service.** Rates may vary with regard to pavement temperature, type of roadway surface, and weather conditions.
- Abrasives should not be used on roadways where speeds in the sanded areas exceed 45 mph.
- When wind speed is over 15 mph, use caution when salting and applying moisture drawing de-icing agents.
- [1] Intersections and **low** speed hazardous areas may be treated with pre-wetted abrasives when warranted.
- [2] If necessary, use alternate de-icing agents like calcium chloride and magnesium chloride in combination with a **lower application rate** of salt.

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Guidelines

Anti-Icing

PREDICTED PRECIPITATION EVENT	Recommended Locations	Rate: *Application* Liquid (gal/lane-mi.)	Rate: Pre-wetted Salt (lb/lane-mi)	*COMMENTS*
Frost or Black Ice	Bridge Decks and Trouble Spots	20-30 (frost) 30-40 (Black Ice)	50-150	1) Consider treating approaches as well as bridge decks. 2) Treat ice patches, if needed, with pre-wetted salt at 100 lb/lane-mi.
Sleet	Bridge Decks and Trouble Spots and Intersections	20 Recommended 30 Maximum	200-400(1) 100-300(2)	1) Consider treating approaches as well as bridge decks.2) Treat ice patches, if needed, with pre-wetted salt at 100 lb/lane-mi.
Freezing Rain	Any area of concern	Not Recommended	200-400(1) 100-300(2)	It is not recommended to apply liquid de-icing agents in an anti-icing mode prior to freezing rain events.
Light Snow (< 1/2" in./hr.)	Trouble Spots and Intersections	30 Recommended 40 Maximum	100-200	If anti-icing is performed prior to a snow event, re-application may be necessary to prevent re-freeze. It also may be necessary to switch to a de-icing mode.
Moderate or Heavy Snow ($\geq$ 1/2 in./hr)	Trouble Spots and Intersections	40 Recommended 50 Maximum	100-300	1) Do not apply liquid anti-icing agents onto heavy snow accumulation or packed snow. 2) Applications will need to be more frequent at lower temperatures and higher snowfall rates. 3) If anti-icing is performed prior to a snow event, re-application may be necessary to prevent re-freeze. It also may be necessary to switch to a de-icing mode.

Notes:

- Anti-icing operations typically should be conducted during normal, non-overtime working hours and low traffic volume periods.
- It is not recommended to apply de-icing agents in an anti-icing mode when the pavement temperature is below 15ºF or drifting is a problem.
- Time initial anti-icing agent applications and subsequent de-icing agent applications to prevent deteriorating conditions or development of packed and bonded snow.

(1) 4-Lanes and Greater
(2) 2 Lanes