FIELD INVESTIGATION OF ANTI-ICING / PRETREATMENT

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by

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To my parents; Sevil & Shafi NOORANI.

For their great love and support all throughout my life…
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Chapter 1 Introduction

Winter highway maintenance is a very important issue for the safety of people in urban areas of the 21st century. The good highways are the ones that are safe. That is why it is very essential to keep the roads cleared from ice and frost either before or after the snow events. Nowadays, de-icing and anti-icing technologies are generally accepted as part of the winter maintenance activities. These technologies provide safety and essential mobility for motorists, commercial vehicles, police, fire and other emergency vehicles. Actually, if responsible agencies fail to keep the roadways cleared from ice and snow, they can be sued. Therefore, currently state agencies strive arduously to assure they have done enough anti-icing applications in order to meet their winter maintenance needs (SI-1 Online, April 2003).

1.1 What is anti-icing and de-icing?

According to the definition given by Alaska Street Maintenance Municipality (ASMM Online, April 2003), “anti-icing” is the ice and snow control application of preventing the formation and/or development of strongly bonded ice and snow by timely practices of freeze-point depressant chemicals. Andrew Mergenmeier defines anti-icing as a revolutionary new technology which takes preventive ice control actions rather than reactive (Spring 1995). It is a early storm treatment technology that has developed after observing the disadvantages of reactive storm event treatment practices (SI-1 Online,
April 2003). Anti-icing strategies provide the user with two major capabilities. Firstly, they provide the capability of maintaining roadways in the best condition possible during a snow event, and secondly they provide the capability to do the maintenance in the most efficient way. As a consequence, anti-icing applications have the capacity to obtain the benefit of increased traffic safety with the lowest cost. However, in order to achieve this important benefit, the agencies must adopt a systematic approach to ice and snow control and must make sure that the performance of the applications is consistent with the objective of preventing the formation and development of bonded snow and ice (ASMM Online, April 2003).

Different from anti-icing operations, traditional snow and ice control application is to wait until an inch or more of snow accumulates on the pavement before beginning to plow the roads and clean the highway with chemicals or abrasives. This strategy is called “deicing”. It is a bond breaking operation. De-icing is commonly started after 25 mm (1 inch) or more of snow has accumulated and bonded to the road (U.S. Federal Highway Administration (FHWA), June 1996). De-icing is also defined by Alaska Street Maintenance Municipality as an operation where a certain amount of a deicer such as sodium chloride (NaCl) or magnesium chloride (MgCl) is applied to the top of an accumulated snow, ice, or frost, which has already developed and bonded to the surface of the pavement (ASMM Online, April 2003).

Although a de-icing procedure is straightforward, it mostly leads to a compacted snow layer (pack), which is strongly bonded to the surface of the pavement. The de-icing of the pavement is essential, usually requiring large amounts of chemicals to work their way through the pack in order to reach the snow/pavement interface and destroy or
weaken the bond between the snow and the pavement. This operation requires less judgment than anti-icing because it is reactionary. Deicing generally provides less safety at a higher cost than anti-icing because of its inherent delay. However, the de-icing technique will remain and be applied by the users because it does not require high priority service levels for snow and ice control (ASMM Online, April 2003).

The difference between anti-icing and de-icing has not always been very clear. This is because anti-icing is a relatively new term compared to de-icing. Some state agencies that have instinctively adopted anti-icing operations to the roadways over the years have used the term de-icing to describe their operations, even when they were intended to prevent the forming of a strong ice-pavement bond (U.S. FHWA, June 1996).

Overall, anti-icing and de-icing are two different snow and ice control strategies that make use of chemical freezing-point depressants. They differ from each other mainly in their fundamental objective. To summarize, anti-icing operations are conducted to prevent the formation or development of bonded snow and ice for easy removal, while deicing operations are performed to break the bond of already-bonded snow and ice. Deicing is more common to the state agencies because it has been the most widely used strategy of snow and ice control in the past years (U.S. FHWA, June 1996).

This thesis study has focused on data collection for anti-icing strategies, and it does not cover de-icing applications. However, in order to clarify the difference between anti-icing and de-icing, basic definitions of them were presented in this section.

1.2 History of applications of anti-icing technologies on highways

"Not all new innovations are as new as people think they are" says Bob Hogan in his article entitled “Anti-icing Dates from the 30’s” published in Better Roads Magazine
in January 2001. “It is quite amusing that the preventive treatment process for snow and ice, called as anti-icing, is being portrayed as a new innovation. Actually a lot of highway organizations have been using this prescribed method for more than half a century” (Hogan, January 2001).

The use of snow and ice control strategies started in the late 1930s. In 1938, the application of straight granular sodium chloride was first used by the New Hampshire State Highway Department in a laboratory based setting. Between the years of 1933 to 1961 New Hampshire’s Maintenance Engineer LeRoy F. Johnson conducted the direct windrow-application method by using granular sodium chloride. This method became the standard operating practice on the state highway system of New Hampshire during the winter of 1940-1941. The historic documentation of snow-and-ice prevention technologies revealed this method is used at the early stages of a snowfall event (Hogan, January 2001).

In November 1948, the Highway Research Board (currently the Transportation Research Board) published a second revision to the original Wartime Road Problems Bulletin No. 9 in its Current Road Problems series named “Recommended Practice for Snow Removal and Treatment of Icy Pavements”. This title was placed under the subtitle as “Application of Chloride without Abrasives”. Then, the method of ice prevention began to be implemented in some states. It consisted of the application of dry sodium chloride directly to the surface of the road. During the application, the salt was spread for approximately two feet wide area along the center line and it formed a solution that prevented the formation of ice (Hogan, January 2001).

The third revision (No. 9-3R) was published in January 1954 and stated that,
"A method of prevention now being used in many states is the application of sodium chloride or calcium chloride, or a mixture of these chlorides, directly to the pavement surface, highways or streets carrying large volumes of traffic should be treated as soon as possible, if it appears that snow will compact and adhere to the pavement. The use of sodium chloride of the coarse commercial size at the beginning of a storm prevents the snow from compacting and adhering to the pavement.” (Hogan, January 2001).

The fourth revision of (No 9-4R) was published in August 1962, and in part under subtitle of “Bare Pavement Maintenance” stated,

"An established winter maintenance goal on most primary routes and an increasing number of secondary and local roads is often referred to as bare pavement maintenance. The usual procedure is to apply chemicals as soon as there is a definite indication of snow sticking to the pavement or of the formation of ice. In some cases it is practical to make this application slightly ahead of the actual storm to prevent the development of a slippery condition.” (Hogan, January 2001).

In 1970, Foster Smiley an Iowa Maintenance Engineer, brought a new concept of prewetting the granular sodium chloride with liquid calcium chloride (Hogan, January 2001).

The demanding requirements of higher service levels were the real causes of the many maintenance forces in the United States in implementing the anti-icing strategies. Sufficient evidence had accumulated from two years of Strategic Highway Research Program (SHRP) and two years of FHWA anti-icing testing to demonstrate the effectiveness of anti-icing practices in the United States (U.S. FHWA, June 1996).

In 1987, the total of $150 million by SHRP, was started and involved many state transportation agencies. One of the focuses for the SHRP program was Highway Operations, and it included research into snow and ice preventative operations as well as other maintenance activities. Anti-icing strategies were concluded to be one of the future needs when the SHRP Program ended in the early 1990s. The initial anti-icing strategies
were carried out in nine states in a two year time period. The operation involved the application of the anti-icing chemical to the roadways ½ to 2 hours before the occurrence of the precipitation. The results showed how effective and time-saving the anti-icing operations are. Towards the middle of 1990’s, six more states were added (which started to implement anti-icing techniques) by the help of the Test and Evaluation Project 28 initiated by FHWA. These states started using the same anti-icing strategies as the other states, and they conducted experiments under various weather conditions at different sites. The Test and Evaluation Project 28 resulted in the formation and implementation of the Manual of Practice for an Effective Anti-Icing Program (Chollar, 1996; Boselly, March 2001). Ohio was one of the states, which was involved in the project. However, the research approach and data collection techniques were not defined well and the results were not documented clearly.

As a result of field-tests conducted in 15 states during the winters of the years 1993-1994 and 1994-1995, the anti-icing practices have become a viable strategy in the United States. These tests were sponsored by the FHWA as a continuation of the SHRP project. The FHWA/SHRP program advanced the anti-icing practice by using a variety of equipment and materials, especially liquid anti-icers (Sunley, November 1996).

L. David Minsk states in his 1998 publication entitled Snow and Ice Control of Transportation Facilities, "In truth, it [anti-icing] is not a new technique. It has been practiced to some extent for many years by forward-thinking maintenance managers." (Hogan, January 2001).
1.3 Justification for current research

State highway agencies of the United States spend approximately $1.5 billion every year for plowing, salting, and sanding of roads during winter storms in order to provide safe road conditions for drivers (Mergenmeier, Spring 1995). Traditional winter road maintenance applications have focused on reactive strategies in order to clear snow and ice from the roads. However, current emphasis has shifted toward preventive actions like anti-icing practices. In light of this there is a need to perform preventive anti-icing treatment applications and identify the controlling parameters that are effecting the salt dissipation.

The review of anti-icing, best application practices, types and properties of widely used liquid anti-icing chemicals, and lab and field study of anti-icing applications on highways of Ohio were performed in this research study.

1.4 Objectives of study

The objectives of this thesis study are presented below:

- Provide background information about the need for anti-icing applications, the history of anti-icing strategies, best management practices, and most recently used anti-icing chemicals with their properties.
- Conduct laboratory tests on asphalt and concrete pavement samples and plastic material in order to determine the controlling parameters and interrelationships of these parameters and to develop a protocol for field testing.
- Analyze the rate of decrease in the concentration of salt brine residue for both asphalt and concrete pavements under field conditions.
• Correlate data and information with controlling parameters and recommend decay equations of salt dissipation versus time, traffic, pavement temperature and humidity.

1.5 Overview of methodology

This project includes background information on the definition and comparison of anti-icing and de-icing, which are two different snow and ice treatment strategies. It provides the need for anti-icing practices with the history of applications of anti-icing chemicals on roads. In addition, this study summarizes the benefits of using anti-icing chemicals on highways.

During the laboratory testing for this thesis project, tests were conducted to develop and refine brine residual measurement techniques, in order to develop a protocol for field testing. Specimens from rigid Portland cement concrete (PCC) pavement and asphalt concrete (AC) pavement were obtained from sources and locations identified by the Ohio Department of Transportation (ODOT) with sizes of 1 foot x 1 foot squares and cylinders of 4 inch diameter. Different brine concentrations were applied to these specimens while temperature and humidity were changed periodically.

From the help of the literature review study, comparisons of the available salt residual measuring equipments were made. For this thesis study, the salt quantity meter SOBO 20 which is manufactured by Boschung Mecatronic AG (Switzerland) was used (BC Online, March 2003). SOBO 20 provided a digital readout of salt concentration in mass per area (kg/m²). Concentration of brine solution in the laboratory and in the application truck at the time of field study were determined by using a salimeter.
(hydrometer), atomic absorption spectroscopy (for Na\(^+\) determination) and ion chromatographer (for Cl\(^-\) determination) devices.

The field tests for this thesis project were conducted on the following five sites.

- ATH-50 (PCC),
- ATH-50 (AC),
- DEL-23 (PCC),
- DEL-23 (AC),
- ATH-33 (AC).

These five sites have different pavement types and traffic conditions. The ATH-50 PCC and DEL-23 sites contain weather stations that can measure solar radiation, air temperature, wind speed, wind direction, relative humidity, and rainfall. ATH-33 AC has a weather station located 18 miles away, while ATH-50 AC has a weather station, which is located 16 miles away.

The test results obtained from the laboratory and field studies were integrated in this thesis project. Appropriate charts and tables were then developed that could be used to ascertain appropriate application rates of brine for anti-icing.

1.6 Outline of thesis

Chapter 1 gives the definition and differences of anti-icing and de-icing which are two different snow and ice control strategies. It contains a brief description on the history of the anti-icing strategies. It also discusses the objectives of this study and the methodology used. Chapter 2 concentrates on the types, best application practices, properties and benefits of anti-icing chemicals. It also discusses the salt residual measurement techniques for the field and the lab study of this thesis project. Chapter 2
also talks about the formation of black ice, how it adversely affects the conditions of the roads and the salt brine residue levels required to preclude the formation of black ice.

A brief description of the methodology followed during the field and lab study of this thesis project is presented in Chapter 3. The sites chosen for the study are described and compared with each other in this chapter. The calibration procedure of the salt residual measuring equipment (SOBO 20) on concrete pavement of the parking area of Stocker Engineering Building is provided in detail in this section. In addition, the calibration and testing procedure of the same device (SOBO 20) that was conducted in the laboratory study is explained for asphalt, concrete and plastic specimens.

Chapter 4 discusses the results obtained at the end of the field and laboratory testings of this research study. It presents the effectiveness of the salt residual measuring equipment (SOBO 20) by showing the results of the calibration tests conducted in the laboratory study using different specimens. In addition, Chapter 4 also presents the decline of applied brine concentrations versus time, traffic and weather conditions for nozzle and profile tests that are performed in the field study.

Finally, Chapter 5 provides conclusions for this research project by commenting on the performance of all the tests conducted and gives recommendations regarding future study on anti-icing treatment technologies.
Chapter 2 Literature Review

2.1 Introduction

Anti-icing, by applications of chemical freezing-point depressants at certain times, is a snow and ice control technology, which requires the state highway agencies to take preventive actions rather than reactive actions in order to obtain clean road conditions for 24 hours (U.S. FHWA, June 1996). The application of preventative anti-icing methodology rather than the conventional, reactive measures offers better solutions (Chollar, 1996).

There are three operations for spreading anti-icing chemicals: using liquid chemicals, using prewetted solid chemicals, and using solids. The liquid anti-icing application is the most preferrable because it is cleaner, the agents do not cake in the truck (as they do in prewetting), the chemicals do not corrode the truck as much and, in addition, there is no need for abrasive usage (it is needed during solid chemical application) (Chollar, 1996).

Overall, anti-icing keeps the roads in the best possible condition during a winter storm and permits the maintenance manager to do it in the most efficient manner. As a consequence, anti-icing results in increased traffic safety at the lowest cost when applied systematically and in an efficient manner (U.S. FHWA, June 1996).
2.2 Anti-icing applications on roadways

Applications of anti-icers on roads at the exact time, concentration and temperature are really important due to the different properties of anti-icers.

In order to achieve the advantages of anti-icing technologies, the maintenance manager must adopt a systematic approach to snow and ice control and must ensure that the performance of the operations is consistent with the objective of preventing the formation or development of bonded snow and ice. An approach like this requires use of considerable judgment in making decisions, available information sources must be utilized methodically, and requires that the preventive operations must be implemented just in time (U.S. FHWA, June 1996).

The following headings discuss the need and goals of anti-icing practices with the benefits, properties, best application measures, protocols and residual determination techniques in order to achieve the best results and cleanest roads.

2.2.1 The need for application of anti-icing chemicals on roads

Cold weather conditions have a great impact on the operation of the roads, from rural routes to the Interstate system. As an example, in a major metropolitan area, a one-day shutdown of the roads due to heavy snowfall can cost tens of millions of dollars. Snow and ice on pavements and bridges can create treacherous driving conditions and approximately 6,600 people in United States (US) lose their lives while 470,000 people have injuries because of adverse weather each year (RWM Online, March 2003).

In order to prevent adverse effects of cold weather conditions and accidents and injuries from happening, anti-icing practices are being applied to the roads. The goal of anti-icing applications is to facilitate deployment of integrated road weather systems, to
support applications, tools and practices of preventive anti-icing actions (rather than reactive actions), which will meet the needs of all transportation system users, in response to adverse weather (RWM Online, March 2003).

**2.2.2 Benefits of using anti-icing strategies on highways**

The following are the overall benefits of the anti-icing applications given by the state agencies that are implementing anti-icing strategies.

- Better pavement condition and improved friction is achieved
- Ice formation can be prevented
- Less chemical usage compared to de-icing (WSDOT Online, October, 2003)
- “Decrease in accident rates can be observed
- Decrease in sand usage can be obtained
- Less time spent on equipment compared to deicing
- Positive feedback from public
- Contingency shifting yields more productive maintenance over the season of winter
- Satisfied and happier environmentalists
- Overtime went to regular employees, not temps
- Better personnel management with regional effort and initial training
- Increase in the number of the people involved
- Increase in the amount and the quality of interaction
- Greater acceptance by public” (Boselly, March 2001).

Some benefits are shown in more detail below and are individually stated and grouped.
2.2.2.1 Benefits achieved on level of service

- It offers new ways to decrease weather related road hazards (VDOT Online, October 2003)
- “Improved driver information for drivers
- Reduced insurance claims
- Reduced accident rates
- Reduced snow and ice bondings on the pavement
- Reduced number of road closures and time savings” (Boselly, March 2001)
- Safer driving conditions are obtained (FHWA Online, October 2003).

2.2.2.2 Benefits achieved on cost savings

- Decrease in the maintenance costs
- “Reduced costs because of using rock salt which is relatively less expensive than other anti-icers
- Reduced chemical usage
- Reduced abrasives usage
- Reduced overtime
- Decrease in the time spent while clearing roads
- Decrease in the number of cleanup, both for drains and for sweeping” (Boselly, March 2001 & FHWA Online, October 2003).

2.2.2.3 Benefits achieved on maintenance response to information

- Managers can plan their snow and ice control operations better (VDOT Online, October 2003)
• “More efficient plowing can be obtained

• More efficient use of materials can be obtained while doing anti-icing instead of de-icing

• Buys time for response compared to de-icing” (Boselly, March 2001).

2.2.2.4 Benefits achieved on environmental quality

When the usage of chemicals and abrasives decreases through anti-icing, environmental quality increases. The abrasive usage can damage the aquatic floor life, fill in habitats and cloud the streams. The abrasives can erode the stream banks and other landscapes since it is carried to the surface waters by storm water runoff. (UOM Online, October 2003).

The abrasives have an impact in streams where some species of fish have been identified as endangered under the Endangered Species Act. Less usage of abrasives will result in the fish ecosystem not getting disturbed in streams. The reduced amount of abrasive usage results in improved air quality in places where abrasives have been identified as contributors to air pollution (Boselly, March 2001).

In addition, the abrasive chemicals can damage the pavement surfaces and cause them to deteriorate faster. Corrosion of the structures on the vehicles is found to be the largest in chloride containing chemicals. Soil and vegetation can be damaged even if they are 60 feet away from the road. De-icing chemicals are highly soluble and therefore they have the ability to follow any water flow (Better Roads, April 2001).

2.2.2.5 Indirect or other benefits of anti-icing

• Clear roads means safer driving conditions
• Fewer chemical applications results in less damage to cars, pavements, and roadside landscaping (FHWA Online, October 2003).

2.2.2.6 Negative benefits of anti-icing

Disadvantages have also been part of the anti-icing applications, however; these occur on a case-by-case basis and in most situations can be prevented with the proper use of the information obtained from RWIS. The following bulleted items show some of the negative benefits of the anti-icing strategies (Boselly, March 2001).

• When the liquid chemicals are used under high wind conditions, the snow adheres to the roadway and if the pavement is left dry, snow will blow over the road.

• Anti-icing roadways with liquid chemicals can cause freezing surfaces when the pavement temperatures drop below certain thresholds.

• Level of service problems can come into consideration at garage, area, district, agency, or state boundaries. When one unit applies anti-icing strategies and an adjacent unit does not, drivers will have to travel from bare or wet pavement to icy or snow-covered roadways when they cross a boundary.

• The research of anti icing applications in British Columbia has showed that although the number of accidents is reduced through anti-icing, the severity of the accidents has increased. This may be caused by the vehicles traveling at higher speeds on bare/wet pavements.

• The usage of brine solutions can deteriorate paved surfaces, buildings, infrastructures, vehicles and the environment

• The brine solution gradually starts to lose its effectiveness and dissipates after becoming embedded in snow and ice (UOM Online, October 2003).
2.2.3 Application protocols of anti-icing practices

Various tactics, which can be employed while performing anti-icing, are presented below (Boselly, March 2001):

- Performing pretreatment with liquid chemicals before a winter snow event.
- Performing pretreatment with liquid chemicals every week to bridge decks or other potential frost areas, in order to prevent frost formation.
- Performing pretreatment with pre-wetted solid anti-icing chemicals. These chemicals should be used when pavement temperatures are very cold or expected to be very cold for the spreading of liquid chemicals.
- Performing pretreatment with the help of solid chemicals. This tactic is usually used in circumstances where precipitation has just started, and the wet pavement surface will help to the retention of the solid chemicals on the pavement.

- Application of pre-wetted solid chemicals and/or solid chemicals at the beginning of a storm (preventive treatment action).
- Application of pre-wetted solid chemicals and/or solid chemicals at the presence of the winter storm (reactive treatment action).

The application of anti-icing chemicals must be timed in order to prevent the formation of bonded snow or ice no matter if dry solid chemicals, liquid chemicals, or pre-wetted solid chemicals are being used as an initial anti-icing treatment (TS Online, April 2003). Whichever is used, the timing of the application should be consistent with the objective of preventing the formation and/or development of bonded snow or ice. In order to obtain anti-icing success early applications should be made when the pavement condition is no worse than wet, slushy, or lightly snow covered. If this is not always
possible, due to a limited fleet or heavy traffic, pretreating the highway before a snow event can be the only solution to make sure that all roads are treated before conditions get worse. In the Manual of Practice for Effective Anti-icing Program (U.S. FHWA, June 1996), guidance for initial liquid treatments is given for four major snow events. These events are light snowstorm, light snowstorm with period of moderate or heavy snow; moderate or heavy snowstorm; and frost or black ice. Application of liquid anti-icing treatment is not recommended during freezing rain or sleet storms because large quantities are needed to sustain effective concentrations and anti-icing applications are not effective at pavement temperatures below -5°C (23°F) (U.S. FHWA, June 1996).

During the snowstorm weather conditions, initial liquid applications are advised as a pretreatment or early-storm treatment. A pretreatment can be applied before the storm if the storm does not begin above freezing temperatures and rain, because then the storm can wash the chemical away. While applying early-storm treatment, the application should be made onto dry, wet, light slush, or lightly snow covered pavement. The applications onto pavements with more than a light covering of slush or snow can result in excessive dilution of the chemical, and can end up in a failure. These operations must always be applied together with plowing (TS Online, April 2003).

In order to prevent frost or black ice, the anti-icing chemical solution must be applied before the ice forms so that the water component of the brine solution can evaporate or can be washed away by the help of traffic action. In this way, only the chemical will be left on the road surface, and therefore this will result in the largest concentration when frost or black ice conditions occur.
In order to prevent icing (frosting) conditions, a state agency has found that a solution of 27 percent magnesium chloride (MgCl₂) can be applied to bridge decks near valley areas. The chemical solution is applied at the rate of 100 L (25 gallons) per lane-mile and at the speeds up to 50 km/h (30 mph). Depending on the traffic and weather conditions, the residual chemicals were reported to prevent frosting conditions for approximately one week on roads with low volumes and 3 to 4 days on freeways with higher volumes (TS Online, April 2003).

A Survey on Anti-Icing Technology and Usage was conducted in the 1999-2000 by SHRP. A total of 517 surveys were mailed to American Association of State Highway and Transportation Officials (AASHTO) member states, customers of the anti-icing/Road Weather Information Systems (RWIS) marketing materials, 99 counties in Iowa, and all cities in Iowa with a population of 5,000 or greater. The survey was also distributed to all Canadian provinces. Survey results showed that from 1997 to 1999 (Blackburn et al., 1994).

- The use of anti-icing technologies increased from 79% to 90%
- The proportion of states with application guidelines increased from 43% to 60%
- The states which have doubled their anti-icing treatment training programs have increased from 27% to 57%
- The 86% (majority) of the survey respondents are planning to start or expand their anti-icing efforts
- Majority of the respondents chose sodium chloride and magnesium chloride for their choice of anti-icing chemicals
- Application with using electric pumps is preferred to hydraulic pumps
• The primary method of storing anti-icing chemicals is made by the use of bulk tanks.

• The ratio of vehicles that have anti-icing application equipment increased from 1/10 to 1/5.

• The lane miles that have been treated by anti-icing have shown an increase of 50%.

• In the year 1999, about 25% of all the treated lane miles were cleared with anti-icing strategies (Blackburn et al, 1994).

2.2.4 Application equipment of anti-icing chemical solutions

Application of anti-icing chemical solutions to roadways are made by two major types of liquid appliers. One of the types of application equipment contains spinners with multiple rotating disks or a single disk, as can be seen from Figure 2.2.4.1. The other type of the application equipment contains nozzles that are attached to a distributor bar, as can be seen from the Figure 2.2.4.2 (U.S FHWA, June 1996). Both of the types of the liquid application equipment can be chassis-mounted which means that they can be fixed on the frame as can be seen from Figure 2.2.4.3. They both can have a "slip-in" unit, which can be placed temporarily in the bed of a dump truck or on the frame, and removed after the season passes. The “slip-in” unit can be seen from Figure 2.2.4.4. This unit can be a trailer or "tow-behind" unit as shown in Figure 2.2.4.5 (U.S FHWA, June 1996).
Figure 2.2.4.1 Single disk liquid spreader (U.S. FHWA, June 1996)

Figure 2.2.4.2 Liquid spreader using a distributor bar with nozzles (RS Online, October 2003)
Figure 2.2.4.3 Chassis-mounted liquid spreader (U.S. FHWA, June 1996)

Figure 2.2.4.4 Slip-in liquid spreader (RS Online, October 2003)
Until the last few years, most of the liquid applicators were made in Europe and Scandinavia. However, currently United States firms also provide highway spreader equipment and spreader components for the application of liquid chemicals and prewetted solids (U.S. FHWA, June 1996).

Below, detailed descriptions and the capabilities of both of the liquid anti-icer application equipments (nozzle-type and spinner-type spreader) are presented.

2.2.4.1 Nozzle-type spreader

This liquid application equipment, which is shown in Figure 2.2.4.2, sprays the liquid chemical from nozzles at a low height above the roadway in order to reduce the influence of air turbulence behind the truck that can result in the dispersion of liquid chemical before it hits the pavement. A vehicle containing a liquid tank tows the nozzle spreader. The spreader’s ground speed can be controlled and the spreader is powered by its traction-driven wheel (U.S. FHWA, June 1996).
In nozzle type spreaders, the liquid chemical flows by gravity from a clear 75 mm (3 in) plastic hose that is in between the tank and the spreader. There are two liquid pumps, which provide an adequate supply of liquid chemical to an array of nozzles. A common inlet filter is shared between these two diaphragm pumps. The length of the spraying bar is 2.3 m (89 in) and it generally has six nozzles; three of them being large and three of them being small. The large nozzles have the capacity to spray over a 3.5 m (11.5 ft) width. At slower speeds, the smaller nozzles are used. When the speed of the truck increases, the requirement for liquid volume increases. Therefore the smaller nozzles are closed automatically and the larger nozzles are opened without a disturbance or break in spray pattern. When the truck decreases its speed, the reverse process occurs (TS Online, April 2003).

There are three more stainless steel nozzles that are mounted on the left end of the spray bar. These additional steel nozzles spray liquid to the left lane of the roadway. With the help of the side nozzles, a total width of 7 m (23 ft) can be sprayed with the spray bar to the highway. Each side of the nozzles is pressure regulated for ensuring an even flow at all speeds of the truck (TS Online, April 2003).

The nozzle-type spreader may have problems with the plugging of the nozzles or may dispense a fine mist that it disperses before hitting the surface of the pavement. Several nozzle-type spreader designs incorporate large size (6 mm (0.25 in) or larger) spray nozzles, which increase the reliability of spray equipment. The large size spray nozzles require less liquid filtration and they do not clog so easily. Spinner disks can spray liquid droplets that are very large for uniform coating of the surface of the pavement (U.S. FHWA, June 1996).
2.2.4.2 Spinner-type spreader

Spinner type spreader is shown in Figure 2.2.4.1. This unit is attached to the rear of a vehicle that is equipped with liquid tanks. The unit is powered by the hydraulic system of the truck or by a separate road wheel (U.S. FHWA, June 1996).

In spinner type spreaders, the liquid chemical is pumped through two impeller pumps to a stainless steel spinner. The stainless steel spinner is convex having 10 curved vanes. In addition, the spinner mechanism can be adjusted manually in order to give asymmetric or symmetric spread patterns. The unit has the capacity of applying liquid over a spread width of 2 to 8 m (7 to 26 ft) while traveling at speeds between 10 and 60 km/h (5 and 40 mph) (TS Online, April 2003).

In general, for spinner type spreaders, research has proved that liquid chemicals can be applied successfully at speeds up to 40 to 55 km/h (25 to 35 mph) and at speeds up to 65 to 80 km/h (40 to 50 mph) for spray bar type spreaders. Turbulence generated at the back of the truck prevents a uniform distribution pattern for higher application speeds (TS Online, April 2003).

2.2.4.3 Use and comparison of spreading equipment

Asphalt distributor trucks, liquid fertilizer spreaders, and spreaders used to spray for weed control have been modified and used successfully by several state highway agencies and have provided capital savings. The Nevada Department of Transportation and the Colorado Department of Transportation are two examples that have modified their old spreaders and reused them in their initial anti-icing programs. The California Department of Transportation has been using a spray bar, which can apply 100 L (25 gal)
of chemical solution per lane mile at speeds up to 50 km/h (30 mph) (Better Roads Magazine, April 2001).

The right equipment is needed in order to maximize snow and ice control, even when an active anti-icing program is being used. First the usage requirements should be listed. The treatment operations should begin by deciding on the right equipment to be used. Factors that should be considered include corrosiveness, recirculation, tank material, deicer weight and tank capacity (Better Roads Magazine, June 1998).

All of the equipment must be calibrated before winter maintenance operations start. Although majority of the state agencies do this, they are less likely to check the manufacturer’s calibration on new equipment ordered from the industry. Calibration is a good practice to perform. In addition, most of the state agencies think that calibration is essential only before the winter starts and do not realize that settings may change with the use of the equipment. Changes of the mechanical links and components can occur, and hydraulic systems function differently through time. Comparison between the controller’s application rate setting and the volume remaining in the tank must be made several times during the winter to see if there is any deviation. A dipstick is generally used for the checking of liquid chemical applicators (U.S. FHWA, June 1996).

The application equipment should handle the needed application rate and pattern. It should have desired maximum and minimum volume per area for each application. In other words, the tank capacity should be adequate for the intended use. It should offer a concentrated stream for deicing. The equipment should have the adequate length to cover the desired number of lanes per application. The application equipment that is chosen should travel as fast as the required rate during an application. The conditions should be
safe for the personnel during the period that the solution is applied (Better Roads Magazine, June 1998).

An application that leaves a damp surface is sufficient in most conditions. Since these liquid chemical applications do not result in a flow of liquid on the surface of the pavement, the spread uniformity should be obtained at the time of application. When a nozzle or filter is clogged, the part of the highway will be untreated. Nozzles and filters have to be checked regularly (U.S. FHWA, June 1996).

Speed of the spreader should be controlled for some conditions. The control speed versus volume per area of application should be checked. In addition the ground speed controls should be performed (Better Roads Magazine, June 1998).

The high speed of the spreading truck will cause turbulence, which will affect the uniformity of the spread coverage. It is preferable to have a spreader that travels at speeds close to those of the traveling public in order to reduce the speed differential and improve the safety of the application (Better Roads Magazine, April 2001).

The liquid supplier tanks that are used on spreader trucks must be made of non-corrosive equipment like polyethylene. Several state agencies in the US have used stainless steel tanks. However, this causes the system to be heavier. Some of the highway agencies have installed 11 m$^3$ (3000 gal) vehicle-mounted storage tanks for use on the spreaders but, they found out that they would be able to carry only 7.5m$^3$ (2000 gal) of chemical liquid on their standard sized vehicles because of the weight limitations and density of the liquid. In addition, they experienced some more problems with the liquid sloshing in a tank that does not have any internal baffles. Therefore it is recommended
that truck-mounted tanks that are greater than 5.5 m³ (1500 gal) should be equipped with internal baffles (TS Online, April 2003).

2.3 Economics of anti-icing

In the US, every year approximately $1.5 to $2 billion is spent on highway snow-and ice-control programs (Mergenmeier, Spring 1995; Hyman and Levey, 1999). De-icing, snow and ice control technology, represents approximately one-third of all the winter maintenance costs of the United States (U.S. TRB Special Report 235, 1991).

State highway agencies have applied an average of approximately 10 million tons of road salt each winter since 1970 according to the 1991 TRB report. As time passes it has been experienced that the widespread use of salt and abrasives cause lots of indirect cost impacts. These cost impacts include the damage to motor vehicles, infrastructure and the environment. The use of abrasives increases cleanup costs and can reduce the quality of air. A winter road sanding resulted in air particulate loading as high as 89% in one study (Better Roads, April 2001).

The liquid anti-icers that are used by state agencies are the least expensive alternatives to sanding and dry salting. They are sold for approximately $40 per gallon on the market (MDT Online, April 2003). The cost of sand in today’s figures is approximately $180 per cubic yard (Salt & Highway De-icing, Fall 2001).

Application of liquid anti-icers is much more cost-effective, and it reduces the need for the less environmentally friendly abrasives and salt mixtures. In addition, the application of liquids before precipitation helps to reduce the maintenance costs because the need for plowing and after-storm sweeping lessens (MDOT Online, April 2003).
2.4 Types of anti-icing chemicals and their application proportions

2.4.1 The use of sodium chloride (NaCl) as an anti-icer

Currently, sodium chloride is used in the world as the principal de-icer and anti-icer because it is the most cost effective and the most available anti-icer. It is quite easy to obtain plentiful amounts of sodium chloride (salt) in the earth and from the sea (SI-1 Online, April 2003). Sodium chloride has been used as an ice-control chemical on roads starting from early 20th century. It is produced by three processes. The first process is the mining of rock salt from conventional hard rock with the help of mining equipment and techniques. The second process is the release of solar salt by the evaporation of sea water. Finally the third salt producing process is the release of evaporated or solution of vacuumed salt (which is a very pure form obtained from drying) from the injected water to deep underground deposits (U.S. FHWA, June 1996).

The primary type of salt used currently is rock salt that is mined from the earth (SI-1 Online, April 2003). Most of the salt that is used for roadway applications in the United States is rock salt (U.S. FHWA, June 1996). Solar salt being another type is used quite commonly too (SI-1 Online, April 2003). It is produced in several western states and some of it is imported to the eastern states (U.S. FHWA, June 1996). Approximately 15 million tons of de-icing salt is currently used each year in the United States and about 4-5 million tons in Canada (SI-1 Online, April 2003).

In the 21st century's highly mobile society, it is very essential to remove hazardous and unsafe conditions created by snow and ice as quickly as possible and to keep the roads open 24 hours in order to guarantee essential mobility in winter. This is the reason why an anti-icer is necessary. In some situations, salt is used alone when there
is ice or too little snow to plow and salt is also used in conjunction with snowplows (SI-1 Online, April 2003). However, generally sodium chloride is used to prevent snow and ice from bonding to the pavement and to allow snowplows to remove the accumulations quickly and efficiently. Professional applications of salt are required to assure that the anti-icer also reduces the slipperiness of the roads. Research has shown that using salt as an anti-icer reduces accidents sharply. A study conducted by the Marquette University Department of Civil and Environmental Engineering documented injury accident reduction rate of 88.3%, coinciding with the findings of an earlier German study illustrated in the figure (2.4.1.1) below (SI-1 Online, April 2003).

![Figure 2.4.1.1 Accident rates before and after NaCl spreading (SI-1 Online, April 2003)](image)

**2.4.1.1 Application proportions of NaCl brine solution**

The following table (Table 2.4.1.1.1) shows the sodium chloride mixing proportions for the use in anti-icing and de-icing operations (U.S. FHWA, June 1996).
Table 2.4.1.1 Proportions for preparing sodium chloride solutions

<table>
<thead>
<tr>
<th>% NaCl actual</th>
<th>Weight NaCl per volume solution kg/m³ (lb/gal)</th>
<th>Weight NaCl per volume water kg/m³ (lb/gal)</th>
<th>Crystallization temperature °C (°F)</th>
<th>Weight per unit volume of solution kg/m³ (lb/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>108 (0.9)</td>
<td>96 (0.8)</td>
<td>-6.7 (20)</td>
<td>1072 (8.95)</td>
</tr>
<tr>
<td>15</td>
<td>168 (1.4)</td>
<td>156 (1.3)</td>
<td>-11.1 (12)</td>
<td>1112 (9.28)</td>
</tr>
<tr>
<td>20</td>
<td>228 (1.9)</td>
<td>204 (1.7)</td>
<td>-17.8 (0)</td>
<td>1150 (9.6)</td>
</tr>
<tr>
<td>23*</td>
<td>276 (2.3)</td>
<td>228 (1.9)</td>
<td>-21.1 (-6)</td>
<td>1169 (9.76)</td>
</tr>
<tr>
<td>25</td>
<td>300 (2.5)</td>
<td>252 (2.1)</td>
<td>-8.9 (16)</td>
<td>1234 (10.3)</td>
</tr>
</tbody>
</table>

*Note. This is the "eutectic" point of sodium chloride. Eutectic point is the point where the lowest freezing point of the mixture is reached (Nixon and Williams, October 2001 & U.S. FHWA, June 1996).

2.4.1.2 Methods for preparing NaCl brine solution

Currently, sodium chloride brine manufacturing plants which can operate relatively trouble-free became a necessity with the use of salt brine solutions for anti-icing applications. Highway agencies working with private companies have designed a number of salt brine production plants. Two types of sodium chloride brine solution producing plants are in use nowadays. These saturated brine manufacturing systems are called batch flow and continuous flow units. Simple batch units are for temporary or small scale production and can be assembled using small tanks. Continuous flow units are more efficient and have been developed for high capacity production of sodium chloride brine solutions (U.S. FHWA, June 1996).

There are two methods of mixing that can be used to prepare a certain concentration of liquid sodium chloride. When the volume of the mixing container is...
known, Method 1 is used to prepare desired volume of salt brine. Method 2 is used when the volume of the mixing container is not known. Each of these methods is described below (U.S. FHWA, June 1996).

**Method 1 (The volume of the mixing container is known)**

To start with, the weight in kg (or lb) of solid sodium chloride that is needed to make 1 m$^3$ (or 1 gal) of solution at the required concentration level is determined by using the “per volume solution” column of Table 2.4.1.1.1.

The next step is to fill the container to 2/3 full of water and to add the required dry salt while mixing with a paddle. When salt dissolves completely, water is added to the container in order to bring the level to the working volume and the solution is mixed. Finally, the sodium chloride solution is tested with a hydrometer in order to determine the percentage of concentration. For anti-icing applications, the concentration of the sodium chloride solution should be as close to 23.3% as possible, and it is recommended not to exceed 25% (U.S. FHWA, June 1996).

**Method 2 (The volume of the mixing container is not known)**

Simple batch unit is used for the production of brine solution in this case. To start with, a hopper tank is filled with dry salt and water is let to run through it by gravity action to the bottom of the hopper tank. Water which is passed through a bed of rock salt by gravity will produce a saturated solution at the water temperature. The next step is to discharge the brine solution at the bottom of the hopper tank into a holding tank below the hopper tank. From the holding tank, the brine solution is passed through a 10 µm filter or pumped into a larger storage tank or directly put into a spreader truck. If the brine solution is pumped from the holding tank to a larger storage tank, the mixture in the
larger storage tank is mixed with a mechanical agitator or with an air bubbler. At the same time, the addition of salt and water to the hopper tank is continued until the large storage tank is nearly full. Although the process seems straightforward, salt brine solution production rates are not slow with this process; approximately 8 L/s (600 gal/h). The simple batch plant used by Kansas Department of Transportation is shown below in Figure 2.4.1.2.1 (U.S. FHWA, June 1996).

Figure 2.4.1.2.1 Kansas DOT salt brine production facility (U.S. FHWA, June 1996)

During the production process of salt brine, the percentage of concentration of the salt brine should be checked and determined with using a hydrometer. The hydrometer measures the specific gravity of the brine solution which will increase as the concentration of the solution increases. Figure 2.4.1.2.2 shows the measurement of salt brine concentration with a hydrometer below (U.S. FHWA, June 1996).
Figure 2.4.1.2.2 Salt concentration testing by a hydrometer (U.S. FHWA, June 1996)

Following table (Table 2.4.1.2.1) lists hydrometer readings and the corresponding salt concentrations for a brine solution at a temperature of 15°C (59°F) (SI-2 Online, April 2003).
Table 2.4.1.2.1 Pure salt concentrations and corresponding specific gravity 
(measured by a hydrometer) at 15°C (59°F)

<table>
<thead>
<tr>
<th>Percent salt</th>
<th>Specific gravity at 15°C (59°F)</th>
<th>Percent of saturation</th>
<th>*Weight of salt kg/m³ (lb/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.000</td>
<td>0</td>
<td>0 (0)</td>
</tr>
<tr>
<td>5</td>
<td>1.035</td>
<td>20</td>
<td>51.8 (0.432)</td>
</tr>
<tr>
<td>6</td>
<td>1.043</td>
<td>24</td>
<td>62.7 (0.523)</td>
</tr>
<tr>
<td>7</td>
<td>1.050</td>
<td>28</td>
<td>73.5 (0.613)</td>
</tr>
<tr>
<td>8</td>
<td>1.057</td>
<td>32</td>
<td>84.6 (0.706)</td>
</tr>
<tr>
<td>9</td>
<td>1.065</td>
<td>36</td>
<td>95.9 (0.800)</td>
</tr>
<tr>
<td>10</td>
<td>1.072</td>
<td>40</td>
<td>107.2 (0.895)</td>
</tr>
<tr>
<td>11</td>
<td>1.080</td>
<td>44</td>
<td>118.9 (0.992)</td>
</tr>
<tr>
<td>12</td>
<td>1.087</td>
<td>48</td>
<td>119.8 (1.000)</td>
</tr>
<tr>
<td>13</td>
<td>1.095</td>
<td>52</td>
<td>131.8 (1.100)</td>
</tr>
<tr>
<td>14</td>
<td>1.103</td>
<td>56</td>
<td>154.7 (1.291)</td>
</tr>
<tr>
<td>15</td>
<td>1.111</td>
<td>60</td>
<td>166.8 (1.392)</td>
</tr>
<tr>
<td>16</td>
<td>1.118</td>
<td>63</td>
<td>178.9 (1.493)</td>
</tr>
<tr>
<td>17</td>
<td>1.126</td>
<td>67</td>
<td>191.5 (1.598)</td>
</tr>
<tr>
<td>18</td>
<td>1.134</td>
<td>71</td>
<td>204.3 (1.705)</td>
</tr>
<tr>
<td>19</td>
<td>1.142</td>
<td>75</td>
<td>217.2 (1.813)</td>
</tr>
<tr>
<td>20</td>
<td>1.150</td>
<td>79</td>
<td>230.1 (1.920)</td>
</tr>
<tr>
<td>21</td>
<td>1.158</td>
<td>83</td>
<td>243.4 (2.031)</td>
</tr>
<tr>
<td>22</td>
<td>1.166</td>
<td>87</td>
<td>256.8 (2.143)</td>
</tr>
<tr>
<td>23</td>
<td>1.175</td>
<td>91</td>
<td>270.3 (2.256)</td>
</tr>
<tr>
<td>24</td>
<td>1.183</td>
<td>95</td>
<td>284.1 (2.371)</td>
</tr>
<tr>
<td>25</td>
<td>1.191</td>
<td>99</td>
<td>293.3 (2.448)</td>
</tr>
<tr>
<td>25.2</td>
<td>1.200</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Weight of commercial salt required = (weight of pure NaCl from table) ÷ (purity in percent) (SI-2 Online, April 2003).
2.4.2 Types of and proportions for preparing other commonly used anti-icing chemical solutions

In this section information is presented on the properties of five chemicals used for anti-icing treatments and instructions in order to prepare different liquid concentrations. The most widely used chemicals for anti-icing applications are calcium chloride, magnesium chloride, calcium magnesium acetate, and potassium acetate. They are listed below in Table 2.4.2.1 with their eutectic temperatures and eutectic concentrations and then are explained in detail (U.S. FHWA, June 1996). Eutectic temperature is the lowest freezing temperature obtained by the anti-icer and the eutectic concentration is the concentration of the anti-icer, which depletes the freezing point of the solution to the eutectic temperature.

Table 2.4.2.1 Common anti-icing chemicals with their eutectic temperatures and concentrations

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Eutectic temperature</th>
<th>Eutectic concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Chloride (CaCl2)</td>
<td>-51 (-60)</td>
<td>29.8</td>
</tr>
<tr>
<td>Magnesium Chloride (MgCl2)</td>
<td>-33 (-28)</td>
<td>21.6</td>
</tr>
<tr>
<td>Calcium Magnesium Acetate (CMA)</td>
<td>-27.5 (-17.5)</td>
<td>32.5</td>
</tr>
<tr>
<td>Potassium Acetate (KAc)</td>
<td>-60 (-76)</td>
<td>49</td>
</tr>
</tbody>
</table>

(U.S. FHWA, June 1996).
2.4.2.1 Calcium Chloride (CaCl₂)

CaCl₂ is one of the most widely used anti-icing chemical in the United States. There are two methods that are used to manufacture commercial CaCl₂. The first method is extraction of CaCl₂ from natural brines obtained from deep wells (principally in Michigan), and the second method is by a chemical process called the Solvay process, in which sodium chloride is reacted with calcium carbonate to produce sodium carbonate (soda ash) and calcium chloride (U.S. FHWA, June 1996).

The solid state of calcium chloride dissolves very quickly in water with little mixing required. The following table (2.4.2.1.1) shows the calcium chloride mixing proportions (U.S. FHWA, June 1996).

Table 2.4.2.1.1 Proportions for preparing calcium chloride solutions

<table>
<thead>
<tr>
<th>%CaCl₂ actual</th>
<th>Weight CaCl₂ 77% flake</th>
<th>Crystallization temperature °C (°F)</th>
<th>Weight per unit volume of solution kg/m³ (lb/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per volume solution kg/m³ (lb/gal)</td>
<td>per volume water kg/m³ (lb/gal)</td>
<td>volume per unit</td>
</tr>
<tr>
<td>10</td>
<td>139 (1.16)</td>
<td>146 (1.22)</td>
<td>-5.4 (22.3)</td>
</tr>
<tr>
<td>15</td>
<td>218 (1.82)</td>
<td>238 (1.99)</td>
<td>-10.3 (13.5)</td>
</tr>
<tr>
<td>20</td>
<td>303 (2.53)</td>
<td>344 (2.87)</td>
<td>-18.0 (-0.4)</td>
</tr>
<tr>
<td>25</td>
<td>397 (3.31)</td>
<td>471 (3.93)</td>
<td>-29.4 (-21)</td>
</tr>
<tr>
<td>29.8*</td>
<td>491 (4.1)</td>
<td>621 (5.18)</td>
<td>-55.0 (-67)</td>
</tr>
<tr>
<td>30</td>
<td>498 (4.16)</td>
<td>627 (5.23)</td>
<td>-46.0 (-50.8)</td>
</tr>
</tbody>
</table>
*Note: This is the "eutectic" point of calcium chloride, i.e., the concentration of calcium chloride that results in the lowest temperature (-55°C (67°F)) at which the solution of calcium chloride can exist while remaining completely liquid (U.S. FHWA, June 1996).

### 2.4.2.2 Magnesium Chloride (MgCl₂)

Magnesium chloride is one of the most common ice-control agents and its principal source is the Great Salt Lake in Utah. Although it is easy to obtain it in solid (flake) form, it is generally used in liquid form for anti-icing applications. The eutectic temperature of magnesium chloride is approximately -33°C (-28°F) and eutectic concentration is about 21.6%. Compared to calcium chloride, the ice melting capacity of magnesium chloride is approximately 40% greater than calcium chloride. Proprietary mixtures are available having 20 to 25% magnesium chloride with different corrosion inhibitor additives. Magnesium chloride solutions are effective anti-icing agents when applied at temperatures above -7°C (19°F) (U.S. FHWA, June 1996).

### 2.4.2.3 Calcium Magnesium Acetate (CMA), [CaMg₂(CH₃COO)₂]₆

The anti-icing chemical, calcium magnesium acetate, gets produced when dolomitic limestone is reacted with acetic acid. The costly component of calcium magnesium acetate is acetic acid. Calcium magnesium acetate can be obtained as pellets. The anti-icing chemical is not as soluble in water as sodium chloride and calcium chloride. Solutions of calcium magnesium acetate can be prepared just before the operation for use as a prewetting agent or straight chemical application. Due to its light particle mass and its affinity for water, calcium magnesium acetate is not a very effective anti-icing chemical in solid form. Calcium magnesium acetate is primarily a mixture of calcium and magnesium acetates, obtained with a 3/7 Ca/Mg ratio. The eutectic
The eutectic temperature of calcium magnesium acetate is about -28°C (-18°F) and the eutectic concentration is approximately 32.5% (U.S. FHWA, June 1996).

### 2.4.2.4 Potassium Acetate (KAc), KC₂H₃O₂

The anti-icing chemical potassium acetate is commonly represented as KAc and it gets produced through the reaction of acetic acid with potassium carbonate. The sources of acetic acid are the same as are used in the production of calcium magnesium acetate. Potassium carbonate is from one of the groups of salts which are commercially known as potash. Potassium carbonate used to be obtained from running the water through the wood ashes and boiling the resulting solution in large iron pots. The end product which gets formed was called potash. Potassium carbonate gets produced today through one of several processes that use potassium chloride, which is another salt of the potash family.

The potassium acetate compound is white, crystalline, deliquescent powder and has a saline taste. Potassium acetate is quite soluble in both water and alcohol. Solutions of potassium acetate are alkaline under litmus tests. The dry form of potassium acetate is combustible; however it is used as a dehydrating agent, a reagent in analytical chemistry, and in the production of synthetic flavors, in addition to other uses. The eutectic temperature of a potassium acetate and water solution is approximately -60°C (-76°F) and the eutectic concentration of potassium acetate is about 49%. The commercial form of liquid potassium acetate which contains 50% concentration by weight and has corrosion inhibitors has been used as a prewetting agent with dry salt or as a straight chemical application. Satisfactory results have been obtained with the straight liquid form applications during anti-icing experiments.

(U.S. FHWA, June 1996).
2.4.3 Phase diagrams of commonly used chemical anti-icing solutions and their comparisons (Freezing points)

2.4.3.1 Phase diagrams of NaCl & CaCl₂

The phase diagrams of NaCl and CaCl₂ solutions are shown in Figure 2.4.3.1.1. The freezing-point of the brine solution decreases with increasing concentration until the eutectic composition is reached. The freezing-point of the brine solution will not decrease any more as the concentration is increased after the eutectic composition is reached. Brine solutions that have a concentration less than the eutectic concentration, have a freezing-point lower than the melting temperature of pure ice or 0°C (32°F) (U.S. FHWA, June 1996).

In snow and ice control applications and particularly during anti-icing treatments, it is necessary to operate with brine solutions as close as possible to, but less than, the eutectic concentration. The concentration of the brine solution will decrease as it is diluted with water from either the melting of snow/ice or falling rain/freezing rain. Consequently, it is important to monitor the dilution process so that the solution concentration does not decrease to a value that corresponds to a temperature in the freezing temperature range above the pavement temperature. When this kind of situation occurs, the solution will refreeze (U.S. FHWA, June 1996).

As can be seen from the Figure 2.4.3.1.1, the eutectic temperature of the sodium chloride water system is higher than the eutectic temperature of the calcium chloride water system. The eutectic concentration of the calcium chloride water system is about 30% CaCl₂ and 70H₂O% by weight that depletes the freezing point of the water from 0°C (32°F) to -51°C (-60°F). The eutectic concentration of the sodium chloride water system...
is 23% NaCl and 77% H₂O by weight, that depletes the freezing point of the water from 0°C (32°F) to -21°C (-6°F) (U.S. FHWA, June 1996).

![Phase diagram of NaCl and CaCl₂ solutions](image)

Figure 2.4.3.1.1 Phase diagrams of NaCl and CaCl₂ solutions (U.S. FHWA, June 1996)

The 30% eutectic concentration of calcium chloride (shown in Figure 2.4.3.1.1) at the eutectic temperature is greater than the corresponding concentration of a commercially available pelletized form of calcium chloride (29.6 to 29.8%). It is normal that some differences may occur between individual phase diagrams of commercially available calcium chloride water systems. The reason is because of the presence and amounts of other chemical elements (U.S. FHWA, June 1996).
Some research studies show that anti-icing applications must not be conducted using liquid, prewetted, or dry salt when the temperature of the pavement is at or below approximately -9.5°C (15°F). Some of the state highway agencies also believe that it is not practical to use salt below -9°C (15°F) for most of the snow and ice control applications, except while using calcium chloride as an anti-icer. Results of the research have shown that the action of the salt is very slow when the temperature is below -9.5°C (15°F). The following figure (Figure 2.4.3.1.1) also shows that the phase diagrams of NaCl and CaCl₂ are quite similar between the temperature range of 0°C (32°F) down to -10°C (15°F) or even down to approximately -15°C (5°F). In addition to this, the sodium chloride and the calcium chloride brine solutions have approximately the same freezing (solidification) characteristics between this temperature range. However, calcium chloride has a much lower eutectic temperature compared to sodium chloride (U.S. FHWA, June 1996).

In order to compare the NaCl brine solution with CaCl₂ solution, their combined phase diagrams are presented in the Figure 2.4.3.1.1.

However, Figure 2.4.3.1.1 does not show the best application concentration and temperature range of NaCl brine solution. Therefore, Figure 2.4.3.1.2 is provided to present the best application practices of NaCl brine solution.
Figure 2.4.3.1.2 Phase diagram of NaCl showing the best application temperature and concentration of NaCl brine solution

(SI-2 Online, April 2003)

As can be observed from Figure 2.4.3.1.2, application of salt brine on the dark black region provides the melting of the ice and gives the best application results. However application of brine solution within the light gray regions result either in the presence of too little salt or too much salt, and there is a strong possibility that refreezing will occur. In addition, the application of salt brine at temperatures below the eutectic temperature (-6°F (-21°C)) will not be any use to the pavement because the water would already be in the solid state (SI-2 Online, April 2003).
2.4.3.2 Phase diagrams of CMA, KAc and MgCl₂

The phase diagram curve for calcium magnesium acetate that is shown in Figure 2.4.3.2.1 was determined from preparing different percentage concentration solutions of commercially available calcium magnesium acetate supplied in a dry pellet form. The curve for potassium acetate was determined by using commercially available potassium acetate that is in liquid form. Figure 2.4.3.2.1 presents the eutectic temperature of the calcium magnesium acetate water system which is -27.5°C (-17.5°F) and the eutectic concentration as 32.5%. The same figure also shows the eutectic temperature of the potassium acetate water system as -60°C (-76°F) and the eutectic concentration of the same chemical as 49%. Both of the curves (curves for calcium magnesium acetate and potassium acetate) nearly overlap with each other. At the same time, compared to the other three curves (the phase diagram curves of magnesium chloride, calcium chloride and sodium chloride solutions), they both have flatter slopes. This feature is an important characteristic of both calcium magnesium acetate and potassium acetate solutions. The freezing temperatures of both calcium magnesium acetate and potassium acetate solutions increase slower through dilution compared to the freezing temperatures of either sodium chloride, calcium chloride, or magnesium chloride. This characteristic makes them suitable to be used in a liquid form during anti-icing applications. This feature especially helps while pretreating the bridge decks for anticipation of frosting or pretreating localized icing conditions (U.S. FHWA, June 1996).

The eutectic temperature of the magnesium chloride solution is between the sodium chloride and calcium chloride solutions. The eutectic composition for the magnesium chloride solution, as can be seen from Figure 2.4.3.2.1, is 21.6 percent MgCl₂.
and 78.4 percent H₂O by weight which freezes at about -33°C (-28°F) (U.S. FHWA, June 1996).

It is very important to check the percent concentrations of magnesium chloride solutions before using them for anti-icing treatment operations. The percent concentration of the brine should not be too high above that at the eutectic temperature. If it is, the solution can clog the spreader spray nozzles and/or burn out the electric pumps (U.S. FHWA, June 1996).

![Phase diagrams of five chemical solutions](image)

**Figure 2.4.3.2.1 Phase diagrams of five chemical solutions** (U.S. FHWA, June 1996)

When the chemical solutions are compared with each other, it can be concluded that sodium chloride is the most favorable anti-icing treatment chemical among them. The reason is because a higher concentration of either calcium magnesium acetate or potassium acetate solution is needed compared to the corresponding concentration of
sodium chloride at a given temperature to prevent the solution from refreezing. The concentration of calcium magnesium acetate solution should be approximately 1.41 times higher than the concentration of sodium chloride solution at -9.4°C (15°F) (19% for calcium magnesium acetate versus 13.5% for sodium chloride) to prevent both of the solutions from refreezing. This number rises to 1.54 at -3.9°C (25°F). The concentration of potassium acetate solution should be approximately 1.37 and 1.38 times greater than the sodium chloride solution concentrations at -9.4°C (15°F) and -3.9°C (25°F), respectively. These differences in concentrations required for both calcium magnesium acetate and potassium acetate solutions result in higher costs per application for both chemicals compared to sodium chloride. (U.S. FHWA, June 1996).

A comparison of the freezing points of the three chloride solutions can be made with the help of Figure 2.4.3.2.1. At a pavement temperature under 0°C (32°F) but above the eutectic temperature of sodium chloride, magnesium chloride solution will start freezing at a lower concentration compared to calcium chloride and sodium chloride at that temperature. As an example, the freezing concentration of magnesium chloride at -10°C (15°F) is approximately 11 percent while the freezing concentration of calcium chloride and sodium chloride at that temperature are approximately 12.5 percent and 13.5 percent, respectively. This means that magnesium chloride solutions can be diluted more compared to the calcium chloride and sodium chloride solutions before they start freezing at a given temperature. However, once the dilution starts the refreeze temperature of magnesium chloride increases faster compared to the freezing temperatures of calcium chloride and sodium chloride. The slope of the magnesium chloride curve on the left of its eutectic concentration is steeper compared to the slope of the calcium chloride and
sodium chloride curves till the three brine concentrations reach approximately 5 percent or the temperature of approximately -3°C (27°F). Due to the steep slope of magnesium chloride, it is quite hard to obtain the right amount of eutectic concentration in order to reach the eutectic temperature compared to sodium chloride. That is the reason sodium chloride solution is more preferable for anti-icing applications compared to magnesium chloride. In the range of -3°C (27°F)-0°C (32°F), all three chloride solutions have about the same freezing properties (U.S. FHWA, June 1996).

2.5 Important properties of anti-icing chemicals

This heading summarizes the characteristics of anti-icing chemicals that may affect the extent to which a given chemical prevents ice formation and satisfies the customers. Currently, anti-icing chemicals have eight properties that can be measured and identified. These properties are: freezing point depression, consistency, environmental impact, stability, corrosion, handling, conductivity and documentation. The explanation of each property and the way in which the performance of the property is measured are presented below (Nixon and Williams, October 2001).

2.5.1 Freezing point depression

As described earlier, the most important property of snow-ice prevention chemicals is that when mixed with water, they reduce the freezing point of the mixture below the freezing point of water (0°C (32°F)). As can be seen from the phase diagram of sodium chloride (Figure 2.4.3.1.2), when additional sodium chloride is added, the freezing point of the mixture drops to lower temperatures until the eutectic temperature is reached (SI-1 Online, April 2003).
Although the eutectic temperature is an easy point of comparing the snow-ice prevention chemicals, it does not provide help for the user to identify the performance of the chemicals. Most of the treatment chemicals tend to give good performance till they reach the eutectic temperature. This means that as the concentration of the mixture is increased the freezing depression will be more (Nixon and Williams, October 2001).

2.5.2 Consistency

Operationally it is extremely important for anti-icing chemical to perform consistently from batch to batch and over time. In ideal conditions, each batch of the delivered chemical should be tested for all 8 properties mentioned in this section, which are very important for the agency that is purchasing the chemical. However, in practice, this is not feasible and it is hard to examine each arriving batch one by one. Therefore, at least two properties in particular must be consistent. These properties are the viscosity and the specific gravity of the anti-icing chemical. The measurements of these two properties are relatively easy, and they can also indicate the performance of other properties. The measurements of these two properties are conducted to find out if the values of them are within the allowable ranges (Nixon and Williams, October 2001).

2.5.2.1 Viscosity

Viscosity of a specific anti-icing chemical may be determined easily with an efflux cup by measuring the time it will take for the liquid to flow through a funnel with a certain diameter opening (Nixon and Williams, October 2001).

The high viscosity solutions are preferred rather than the anti-icer solutions that are having a low viscosity. If the viscosity of the solution is high, it will not flow easily and pollute the environment due to the storm water runoff. However, while choosing
highly viscose solutions care should be taken to select the ones that have the tendency to be distributed to the lanes (GPC Online, October 2003).

2.5.2.2 Specific gravity

Specific gravity can be determined quite easily by using a hydrometer. Simple checks on specific gravity can serve as indicators of any problems. Differences in specific gravity values will indicate that the concentration of the anti-icing liquid is not correct (S&IM Online, October 2003). If the operators believe that they are applying a mixture with a eutectic concentration of the salt brine on the road, but in fact they are only applying a 12.5% sodium chloride solution, the freezing will occur sooner and dangerous situations can take place quite unexpectedly (Nixon and Williams, October 2001). The specific gravity readings (measured by using a hydrometer) of different percentage by weight solutions of sodium chloride were presented in Table 2.4.1.2.1 (SI-2, April 2003).

2.5.3 Environmental impact

Regarding the adverse effects of classical anti-icing chemicals to the environment, currently there is an increasing number of concerns in the world. The adverse effects of the anti-icing chemicals on the groundwater, on the vegetation of the roadside and on the nearby streams and rivers, cover the concerns of the environmentalists.

Environmental impacts of the anti-icing chemicals cover: the measurement of the concentration of heavy metals and other chemicals that are in the anti-icing liquid, the toxicity of the anti-icing liquid, the Biological Oxygen Demand (BOD) and the Chemical Oxygen Demand (COD) of the anti-icing liquid. In ideal conditions, all of these five factors must be determined for any type of anti-icing liquid that is applied to the roadway.
However, currently there is only a limited amount of data present for the toxicity, BOD, and COD of the anti-icing liquids (Nixon and Williams, October 2001).

These tests should be applied to the anti-icer in order to be environmentally safe. Otherwise, these chemicals can deplete the oxygen supply needed by aquatic plants and animals (when they reach to streams by runoff), can leach into ground-water and therefore flow to the surface water and can also leach onto ground and change the soil composition (UOM Online, October 2003).

Standard tests for determining the amounts of all of these five factors are readily available. Toxicity may be measured in a number of ways. The Strategic Highway Research Program (SHRP) recommends various amounts of toxicity tests. However the most relevant tests for toxicity determination are: Fathead Minnows (EPA/600/4-85/013) and on seed germination (EPA/560/6-82/002). These tests should be conducted at least initially to determine the toxicity of the anti-icing liquid. In order to find out the nitrogen concentration present in the anti-icing liquid, the standard test entitled the Kjeldahl Method must be conducted. This test is explained briefly in Standard Methods for the Examination of Water and Wastewater, published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation in 1998. The test methods for determining the BOD and COD are explained in the same publication also (Nixon and Williams, October 2001).

In the following table (Table 2.5.3.1), the maximum permissible amounts of some elements determined by the Environmental Protection Agency (EPA) (EPA Online, September 2003) and by the Pacific Northwest Snowfighters (PNS) are presented (Nixon and Williams, October 2001). From the table it can be seen that for some of the chemicals
the permissible limits specified by the PNS are stricter than the EPA’s drinking water standards.

Table 2.5.3.1 Allowable levels of various elements

<table>
<thead>
<tr>
<th>Metal</th>
<th>PNS Requirements (ppm)</th>
<th>Drinking Water Standards (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>25.00</td>
<td>NA</td>
</tr>
<tr>
<td>Cyanide</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Arsenic</td>
<td>5.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Copper</td>
<td>0.20</td>
<td>1.30</td>
</tr>
<tr>
<td>Lead</td>
<td>1.00</td>
<td>0.015</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.05</td>
<td>0.002</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.50</td>
<td>0.10</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.20</td>
<td>0.005</td>
</tr>
<tr>
<td>Barium</td>
<td>10.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Selenium</td>
<td>5.00</td>
<td>0.05</td>
</tr>
<tr>
<td>Zinc</td>
<td>10.00</td>
<td>5.00</td>
</tr>
</tbody>
</table>

(Nixon and Williams, October 2001 and EPA Online, September 2003).

2.5.4 Stability

Stability is also one of the most important characteristics of the anti-icing chemicals. Highway state agencies assume that once an anti-icing chemical is received, it will not undergo any change through time. However, in practice it is experienced that the
chemicals (especially organic liquids) do not stay stable. At the very least, stratification can occur (Nixon and Williams, October 2001). In other circumstances the anti-icing liquid can be either chemically or biologically active and may therefore degrade through time (UOM Online, October 2003).

All of the properties of the anti-icing liquid must be tested regularly in order to obtain a correct determination of the stability of the liquid versus time. However, this is not possible in all of the situations. Therefore, it is recommended that the characteristic of stability be measured in terms of the manufacturer's willingness to warrant the product for a certain amount of time. However, the warranty includes some requirements. For example, it may require that the tanks which store the chemicals should be agitated with mixers which are used regularly, according to a specified schedule (Nixon and Williams, October 2001).

In addition although organic chemicals are preferred for anti-icing applications, they tend to be less stable compared to inorganic chemicals and chosen to be applied due to this reason (Stidger, August 2002).

2.5.5 Corrosion

The corrosive effect of inorganic anti-icing chemicals has caused the users to consider the deterioration of the pavements and to be concerned about the corrosivity of the chemicals which they are using. This concern of corrosivity has two main aspects. First of all, the anti-icing chemicals can corrode the application equipment, like crash barriers, trucks, and signs; secondly, anti-icing chemicals can also infiltrate concrete and corrode reinforcing steel (re-bar) inside the concrete. The second problem is more serious than the first one, because it is very hard to stop it from occurring. Application equipment
and metal surfaces can be washed with water. However, the re-bar within the concrete cannot be washed. The corrosion of the re-bar is problematic in other ways also. The conditions that the steel inside the concrete will undergo are quite complex from a corrosion point of view. There are not any simple experiments which measure how much corrosion is caused by the anti-icing chemical on the re-bar. There is one method in order to measure the corrosivity caused by the chemical to the re-bar. This method is proposed by SHRP and entitled as SHRP H-205.12. However, this test requires several months to conduct and it is not in common usage. The corrosivity effect of the chemical on the re-bar is not only hard to measure but also the corrosion of it poses further difficulties. There are some corrosion inhibitors that stop the corrosivity effect of the anti-icing chemicals. However, these corrosion inhibitors go inside the re-bar and it is an unknown fact how long these inhibitors persist. Inhibitors containing chlorides persist for a long time, but it is possible that corrosion inhibitors merely delay the corrosion of re-bar, instead of providing complete protection. (Nixon and Williams, October 2001).

2.5.6 Handling

There are two aspects that are of concern in regard to handling of the anti-icing chemicals. The first concern is the question, of how easily the anti-icing liquid can be used. Will the anti-icing liquid require special pumps and nozzles, or can gravity flow be used? It is not necessary to use gravity flow all of the time, but handling is much simpler if the anti-icing liquid can be poured down by gravity flow alone instead of requiring special pumps. The second concern is how easily the liquid will be stored. Liquids that have very high specific gravities can require strengthened containers compared to the ones with standard liquid containers. This property of the anti-icing chemicals is not such
a big concern compared to the other properties of the anti-icing chemicals; however, the
users need to be aware if there are special storage concerns (Nixon and Williams,
October 2001).

In addition, organic chemicals require more careful handling compared to the
inorganic chemicals due to the reason of being less stable (Stidger, August 2002).

2.5.7 Conductivity

Conductivity is a property of the materials that determines how easily an electric
current can flow through that material. Some anti-icing liquids have very high
conductivity and can therefore cause hazards for any roadside electronics. This is more of
a concern in the winter maintenance activities that are applied to the airport runways
compared to highways. However, it is included as a category, because it may be
important for some end users (Nixon and Williams, October 2001). In addition, it is very
easy to measure conductivity.

2.5.8 Documentation

The documentation of the anti-icing liquid chemical is very important for an end
user. There are two aspects of documentation, which are of concern. The first one is, the
extent to which an anti-icing liquid can be chemically defined in some degree for the
measure of the quality control of that anti-icing liquid. Anti-icing materials can be
grouped according to the percentages of given chemicals present in the material.
Therefore, a given supply of road salt can be characterized like: NaCl 98.1%, CaCl₂ 0.8%,
Other 1.1%. The guide proposes that anti-icing chemicals must be grouped according to
the percentage of the chemical named “other”. The justification for this is that the
category termed “other” can in fact be anything at all, and it is not in anyway controlled.
Therefore, the less “other” there is in a given chemical, the more confidence there is that the material will perform as it is supposed to do (Nixon and Williams, October 2001).

The other aspect of documentation relates to the simple presentation of sufficient information to the final user to allow them to make an informed decision. The guide proposes that all anti-icing chemicals must be required to provide information in all categories. A given highway state agency does not need to consider all these categories, and therefore may not require information in all categories; however the collection and presentation of this information must be a standard practice in the anti-icing industry (Nixon and Williams, October 2001).

2.6 Types of instrumentation available for salt residual measurement on the field pavement

The salinity testers that are available in the market for the detection of the anti-icer on the road surfaces are summarized in the titles below.

2.6.1. Salt measuring instrument SOBO 20

SOBO 20 is a device used for the quick measurement of the amount of salt on the road surface (BC Online, March 2003). SOBO 20 is built on a conductivity cell and is specifically designed for the quantitative measurement of chloride solutions on roads (Blackburn et al, 1994). The following figure (2.6.1.1) shows how the device looks like.
2.6.2 Non contact pavement condition sensor system

The non contact pavement condition sensor system technology is reported to combine standard weather features such as wind speed, temperature and moisture with cutting edge image recognition. The image recognition provides the device with the
ability to sense ice, snow, water, precipitation and type, and visibility. This information along with video can then be transferred directly into the web. The system is sited to have the ability to determine chemical concentration and identification. It has the capacity to scan a width between 15 to 20 feet, which is approximately three lane widths (W&S Online, May 2003).

The non contact pavement condition sensor system works on the principal of spectral absorption bands in the near infrared region which allows distinguishing the different states of water. However, the device is currently in pre-production stage and deployed at Department of Transportation (DOT) Remote Weather Information Systems (RWIS) sites in the Northeast (W&S Online, May 2003). The following figure (2.6.2.1) shows what the device looks like.

![Non contact pavement condition sensor system](W&S Online, May 2003)

Figure 2.6.2.1 Non contact pavement condition sensor system (W&S Online, May 2003).
2.6.3 Embedded Sensors

These surface sensors are embedded in the pavement. They have the ability to detect the pavement temperature, freeze point, form of moisture (snow/ice), and the amount of anti/de-icing chemical. The sensors also determine air temperature, relative humidity, wind speed and direction, precipitation, and visibility. All sensors connect to a remote processing unit that transmits the data which is collected (Clines, April 2003). The following figure (2.6.3.1) shows what the sensor looks like.

![Embedded pavement sensor](MnDOT Online, October 2003)

2.7 What is black ice formation?

Black ice is the general term for a quite thin coating of very clear, homogeneous and bubble-free ice that forms on a surface with a temperature at or slightly above 0°C (32°F). Black ice forms when the temperature of the air that is in contact with the pavement is below the freezing-point of water. Black ice is in the form of small slightly
super cooled water droplets that deposit on the pavement and coalesce (flow together) before freezing (U.S. FHWA, June 1996).

Blackice forms because of two types of meteorologic events, which are condensation and precipitation (Browning, November 2002). Condensation events such as dew, frost, mist, fog, or super-cooled water vapor (unfrozen in air down to $-40^\circ$C), can cause black ice formation on pavement surfaces (Stull, 2000; Sumner, 1988). In addition, precipitation like rain, drizzle, sleet, and snow can also cause black ice formation when in contact with a cold or cooling surface pavement.

The black ice formation creates very slippery road conditions. Therefore the formation of it must be prevented by applications of anti-icers.

**2.7.1 Salt brine residue levels required to preclude black ice formation**

The following table (Table 2.7.1.1) summarizes the brine application rates required to preclude black ice formation at various temperatures (U.S. FHWA, June 1996).
Table 2.7.1.1 Brine application rates required to preclude black ice (U.S. FHWA, June 1996)

<table>
<thead>
<tr>
<th>PAVEMENT TEMPERATURE RANGE, TREND, AND RELATION TO DEW POINT</th>
<th>TRAFFIC CONDITION</th>
<th>INITIAL OPERATION</th>
<th>SUBSEQUENT OPERATIONS</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dry chemical spread rate, kg/lane-km (lb/lane-mi)</td>
<td>dry chemical spread rate, kg/lane-km (lb/lane-mi)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>liquid</td>
<td>solid or prewetted solid</td>
<td>liquid</td>
</tr>
<tr>
<td>Above 0°C (32°F), steady or rising</td>
<td>Any level</td>
<td>None, see comments</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-2 to 2°C (28 to 35°F), remaining in range or falling to 0°C</td>
<td>Traffic rate less than 100 vehicles per h</td>
<td>Apply prewetted solid chemical</td>
<td>Solid performs well with less traffic</td>
<td>7-18 (25-65)</td>
</tr>
<tr>
<td></td>
<td>Traffic rate greater than 100 vehicles per h</td>
<td>Apply liquid or prewetted solid chemical</td>
<td>7-18 (25-65)</td>
<td>7-18 (25-65)</td>
</tr>
<tr>
<td>-7 to -2°C (20 to 28°F), remaining in range, and equal to or below dew point</td>
<td>Any level</td>
<td>Apply liquid or prewetted solid chemical</td>
<td>18-36 (65-130)</td>
<td>18-36 (65-130)</td>
</tr>
<tr>
<td>-10 to -7°C (15 to 20°F), remaining in range, and equal to or below dew point</td>
<td>Any level</td>
<td>Apply prewetted solid chemical</td>
<td>Liquid chemical will not work for very low T.</td>
<td>36-55 (130-200)</td>
</tr>
<tr>
<td>Below -10°C (15°F), steady or falling</td>
<td>Any level</td>
<td>Apply abrasives</td>
<td>Very low T.</td>
<td>Apply abrasives as needed</td>
</tr>
</tbody>
</table>

Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate
2.8 Parameters that affect the performance of anti-icing treatments

In contrast to prescribing that chemicals are applied or that plow runs are made every hour or two or another decided interval, decisions on anti-icing treatment may be based on a number of information sources that help to increase the performance of the chemicals. The first and most obvious information source is the visual observations of precipitation, weather and pavement conditions from patrols, and from operators. The second information source is an indication or the measurement of sodium chloride concentration on the pavement. The third information source is the measurement of frictional resistance to sliding (U.S. FHWA, June 1996).

The higher the friction coefficient after the salt-brine application, the more effective the anti-icing application is. Measurement of friction was used successfully in the anti-icing projects of the State Highway Research Program (SHRP) and the Federal Highway Administration (FHWA) (U.S. FHWA, June 1996). There are a lot of devices that measure friction coefficient on the roadways. Skid trailers are the ones that are most commonly used for the determination of the coefficient of friction. However, due to various reasons related to safety and equipment deterioration, skid trailers are not normally used on snow covered pavements. Specialized vehicles incorporating a fifth wheel, which measures the increase in force when braked at a controlled slip rate, are available, but high cost has limited their use mainly to airports. A low cost device called Coralba (C-µ) was used by both the SHRP and FHWA test programs. This device can be installed in almost any vehicle and can produce reliable measurements. It gives a direct readout of friction coefficient when the vehicle is hard-braked from the speed of 65 km/h.
(40 mph) (U.S. FHWA, June 1996). The friction coefficient and a corrected friction coefficient are shown on the C-\(\mu\). The vehicles' natural friction due to air resistance and road slope is taken into account when the corrected value is measured. It is also possible to calibrate the friction coefficient for the purpose of comparing values between different vehicles independent of brakes and tires. This information can be used to decide when and where to salt the road in winter (CPT Online, September 2003). In addition this device’s repeatability is acceptable for treatment analysis and decision support purposes, provided the device is operated in accordance with the manufacturer’s specifications. The device requires hard braking; therefore, it is not suitable for use in heavy traffic. In addition, because this device cannot be used in heavy traffic, the measurement of friction coefficient for evaluating the effectiveness of the anti-icing applications is not so common (U.S. FHWA, June 1996).

Another important point while making evaluations of the effectiveness of the salt brine applications is that it is beneficial for the personnel of each maintenance area to conduct a post storm evaluation of the treatment effectiveness. This can help to identify the places needing improvement and determine the changes which can be made in the treatment strategy. A post season review of treatment effectiveness is very helpful. It can help to find out where changes are needed in equipment, material, and route configurations. It can also help the decision makers to begin a process of engineering an anti-icing program and fit the exact needs of a site or state agency. In addition it can also help to identify where changes in personnel procedures and training are needed for an effective winter maintenance program (U.S. FHWA, June 1996).
Obtaining information from Road Weather Information Systems (RWIS) also increases the performance of winter maintenance activities. RWIS are automated weather reporting stations with special sensors embedded in and below the road, and on nearby towers. RWIS collect detailed data on weather conditions at and near the road surface, which can assist weather forecasters to decide on the icing conditions. State highway agencies can use current road weather information in order to decide if the treatment of the highway is necessary, when to treat, what brine solutions to use, and how much to salt (RWIS Online, September 2003). The following table (Table 2.8.1) shows some performance measures of the winter maintenance strategies and the increases in the performance with using anti-icing applications and weather data from RWIS (Boselly, March 2001).
Table 2.8.1 Effects of anti-icing and RWIS to performance measures of winter maintenance

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>The Increases in Performance via Using Road Weather Information System (RWIS) Data</th>
<th>The Increase in Performance with Using Anti-icing</th>
</tr>
</thead>
</table>
| **Mobility**         | • Reduced travel times  
                      • Improved traveler information                                                   | • Reduced number of road closures  
                      • Improved traveler information                                                   |
| **Safety**           | • Reduced accident frequency  
                      • Less disruption of emergency services                                             | • Reduced accident frequency  
                      • Decrease in insurance claims                                                     |
| **Productivity**     | • More efficient response strategies  
                      (right resources, in right place, at right time)  
                      • Reduced maintenance costs (staff, equipment and materials)  
                      • Assisted with crew scheduling  
                      • Facilitated data sharing                                                         | • Less snow/ice bonding facilitated more efficient plowing  
                      • Reduced maintenance costs (overtime pay and materials)  
                      • Reduced time to clear snow/ice from roads  
                      • Less abrasive cleanup required                                                   |
| **Environmental Quality** | • Improved quality as a result of reduced salt usage                             | • Reduced impact on roadside vegetation, aquifers, and watercourses  
                      • Improved air quality as a result of reduced abrasive usage                       |
| **Other / Indirect** | • Reduced infrastructure damage  
                      (roads, bridges, guardrail, etc.)  
                      • Assisted in planning of operations other than winter maintenance (e.g., paving)  
                      • Assisted in avalanche risk assessment                                             | • Reduced asset damage (vehicles, equipment, etc.)                                 |

(Boselly, March 2001).
2.9 Salt dissipation testing techniques from literature

Leggett and Sdoutz performed a research in 1999 to determine the friction coefficient of the anti-icing chemical on the asphalt pavement when it is in solid, liquid or in transition state (liquid ⇔ solid). Their aim was to measure the slipperiness of the road during the transition state of the chemical. The researchers used nine different anti-icing chemicals that are commonly found in the market (CMA, CF7, CMAK, Corguard 2000, Calcium Chloride, Freezgard O, Icestop 2000, Cal Ban and MCP). The chemicals were applied at the rates of 60 L/lane-km and 150 L/lane-km. Considering the fact that the friction coefficient will decrease as the salt dissipates, the researchers measured the friction with a drag sled, equipped with tires, weighing 4.9 kg (10.9 lb). The pull force was measured with a Mettler Toledo load cell with a sensitivity of 0.001 g. The drag sled was pulled across the test surface, using a constant velocity motor, at a velocity at about 1 km/h (0.6 mph). Humidity changes were also obtained and were graphed versus time (3-4 hours) together with friction coefficient values. The decrease in the friction coefficients were showing the salt dissipation. Figure 2.9.1 shows the format which the results of the experiments were shown in (Leggett & Sdoutz, 1999).
Another salt dissipation testing technique was performed by Fonnesbech in 1999 and summarized in his article “Ice Control Technology with 20 Percent Brine on Highways”. %20 of saturated brine was used for ice clearing and to increase the level of drivability and safety. The brine was spreaded from a truck traveling 45 mph (70 km/h) in winter 1998-1999 in Funen County. The residual salt from the spreading of brine and prewet salt were measured using SOBO 20. The salt residual was measured 2, 5 and 10 hours after the liquid application across the road in both low and high traffic periods. Figure 2.9.2 shows the format which the results of the experiments were shown in (Fonnesbech, 1999).
The test techniques that were used in this study are unique for this research and cannot be found in any other literature. They are explained in detail in the following chapter.
Chapter 3 Methodology

3.1 Introduction

The effectiveness of the anti-icing program depends on the successful implementation of the treatment system. The dissipation of the anti-icing chemical through time, exposure to traffic and weather conditions, are important factors for determining the success of the operation. In the data collection phase of this thesis study, tests were conducted to find correlations between dissipation of the salt concentration, weather data and traffic counts and therefore; to be able to guide the maintenance managers for developing a systematic and effective winter maintenance practice for keeping roads in the best condition during winter. Tests were conducted in the laboratory as well as in field conditions in order to verify the salt residual measurements and obtain more accurate test results. The procedures for SOBO 20 calibration tests and the field tests that were conducted for this research study are provided in this section.

3.2 Types of instrumentation used for laboratory measurement of NaCl concentrations of brine solutions

Brine solution can be expressed by the mass of solute divided by the mass of total solution. This has been defined as percent by weight for NaCl, by the following equation.
\[ C(\%) = \frac{W_{NaCl}}{W_{total}} \]

Where:

- \( C(\%) \) = Concentration of NaCl by weight
- \( w_{NaCl} \) = Weight of NaCl in solution
- \( w_{total} \) = Weight of total solution

For laboratory analysis, four methods were used in order to find the concentration (percent by weight) of sodium chloride in the brine solution. The methods that were used are: total dissolved solids, atomic absorption spectrophotometry, ion chromatography, and salimeter. These four methods are described in detail below.

### 3.2.1 Total dissolved solids

Total dissolved solids are determined by using the Standard Methods for Examination of Water and Waste Water, Method 208B. This method follows EPA approved method 160.1 named Filtered Residue (Clesceri and Greenberg, 1998).

Prior to conduction of the analysis, a clean ceramic evaporating dish must be heated in an oven at 180°C for approximately one hour, and then it must be placed in a desiccator for a night. After it cools in the desiccator, the weight of the dish is measured on a four decimal balance just before it is used. The filter funnel apparatus is used in this test, which is from Gelman Sciences (Product No.4205). The filter paper that is used is Whatman (Cat. No. 1827-047) 934-AH Grade - fine porosity, fast flow rate, with a 1.5μm size particle retention. The filters are then cleaned with three rinses of 20 ml of distilled water on a vacuum filtration unit. After they are cleaned, 100 ml of raw sample,
measured by a 100 ml graduate cylinder, is passed through the filter paper. The filtrate is collected in a clean and empty flask, and then the filter is washed with three successive 10 ml portions of distilled water. These last distilled water portions are also added to the filtrate. The total volume of filtrate and rinses are then put into the ceramic evaporation dish and placed in the oven at 180° C for a night. The dish is cooled in the desiccator and then the weight of it is measured. The total dissolved solids are determined by subtracting the weight of the empty dish from the weight of the dish with the dry filtrate. The result is reported per unit volume of sample in units of mg/L. Duplicate total dissolved solid measurements are conducted for each sample in order to assure the quality (Clesceri and Grenberg, 1998).

3.2.2 Atomic absorption spectrophotometry

In order to determine the sodium ion (Na⁺), the Standard Methods for Examination of Water and Waste Water Method 3111B for Atomic Absorption (AA) Spectrophotometry can be used, which follows EPA approved method 273.1 titled Sodium by AA Direct Aspiration (AA Manual, 1996).

Sodium concentrations of 5 mg/L, 20 mg/L and 40 mg/L standard solutions must be prepared before analysis. These standard solutions are prepared from purchased analytical grade standard solution of 1000 mg/L NaCl concentration by diluting. Samples that are collected must be diluted to appropriate concentration in order to be within the calibration range of the atomic absorption spectrophotometer. Brine solution is filtrated through a Whatman filter paper (Cat. No. 1827-047) 934-AH Grade - fine porosity, fast flow rate, with a 1.5 µm size particle retention. The filter funnel apparatus used in this test is from Gelman Sciences (Product No.4205). A 100 ml sample, which is measured by
a 100 ml graduated cylinder, is filtered from the prepared filter paper. The filtrate is then collected in a clean and empty glass vial. The pH of the filtrate is stabilized to a value equal or less than 2, with using nitric acid (HNO₃) (AA Manual, 1996).

In this thesis project, a Perkin Elmer AA Model number AAAnalyst 300 with air supply is used. The atomic absorption spectrophotometer gives three readings for each measurement (with a delay time of 1 second) and then averages them. The equipment makes a calibration curve by measuring the blank and standards for each analysis set. The correlation coefficients are higher than 0.97 for the calibration curves (Mitchell et al., March 2003).

Following figure (3.2.2.1) shows the atomic absorption spectrophotometer used for this thesis project.
3.2.3 Ion chromatography

In order to determine the concentration of chloride ion, Standard Methods for Examination Water and Waste (AWWA, 1998) Method 9056A for Ion Chromatography is followed in this thesis project. A Dionex IC 25 Ion Chromatograph coupled with a Dionex Anion Atlas Electrolytic Suppressor is utilized in order to find out the chloride ion concentration in diluted samples. The Dionex IC 25 is attached by interface to a desktop computer installed with PeakNet software for data storage and analysis purposes (IC Manual CD, 1998).

Standards are developed for seven ions at 1%, 5%, 10%, 50%, and 100% of the Accu Multicomponent Anion Standard, for calibration. The dilution of the samples must be within the range of the standardization curve in order to obtain accurate results. Therefore, the addition of 400 µl of full strength brine solution to two liters of de-ionized water dilutes the solution. Smaller concentrations are diluted proportionally (IC Manual CD, 1998).

The following figure (3.2.3.1) shows the ion chromatograph used for this thesis project.
3.2.4 Salimeter

Another equipment used for determining the NaCl concentration in the field and/or in the lab study was a hydrometer. This equipment, as mentioned earlier, measures the relative density specifically for salt and it is also known as salimeter. The salimeter indicates the salt percentage by weight.

The following figure (3.2.4.1) shows what a salimeter looks like.
3.3 Type of instrumentation used for salt residual measurement on the field pavement

The salt residual measurements on the field study and on some parts of the lab study of this thesis project were made by using SOBO 20, which is manufactured by Boschung Company of Switzerland. A brief description and the operation principle of this salinity tester is given below (Mitchell et al., March 2003).

The operation principle of SOBO 20 is relatively easy. The device determines the weight of salt per unit pavement area by releasing a certain amount of a test solution (consisting of distilled/de-mineralized water and acetone (acetone 15% by weight)) into a small chamber which is pressed to the pavement. A thick rubber gasket surrounding the bottom of the chamber seals the interface to capture the solution, which is forcefully injected and immediately dissolves the salt on the exposed pavement inside the gasket. The conductivity of the absorbed solution is used to determine the quantity of salt inside the chamber. The device looks like a small jackhammer. The test fluid, which is in the
upper portion, is pumped into the chamber by pushing the “T” handle down while holding the instrument perpendicular to the pavement to prevent leakage from the gasket (Mitchell et al., March 2003).

The SOBO 20 shows the readings on a scale with a range of 0 to 45 g/m². The concentrations higher than 15 g/m² can be read by using a “*3” scale multiplier engaged by a switch on the readout box. The area of pavement exposed to the test solution is a circle having a diameter of 5.2 cm, and an area of about 0.002 m².

Laboratory and field experiments were conducted using two SOBO 20s.

3.4 Procedure of SOBO 20 calibration testings under laboratory conditions and on Stocker Parking Lot

Two SOBO 20 devices manufactured by Boschung Mecatronic AG (Switzerland) (BC Online, March 2003) were used in the data collection phase of this thesis study. The calibration tests for the SOBO 20 were conducted under laboratory conditions and on Stocker Parking Lot in order to develop test protocols for the field study. During these calibration tests, experience was gained and the most efficient way of using SOBO 20 was practiced. The detailed explanations of the SOBO 20 calibration tests are provided in the following headings.

3.4.1 SOBO 20 laboratory calibration tests on asphalt, concrete, and plastic specimens

SOBO 20 calibration tests were conducted between the 17-18th September and 19-22nd October, 2002 in the geotechnology laboratory of the Stocker Engineering Building of Ohio University. The calibration tests were performed to compare the SOBO 20 readings with the ideal concentrations and to test the accuracy of the equipment. In
addition, the laboratory tests were conducted to see if both the new and the old SOBO 20 were giving the same results when the same concentration of brine solution was applied to the specimen.

One of the SOBO 20s was purchased for this anti-icing project and the other was previously used by Ohio Department of Transportation (ODOT). However, the old one needed repair. In addition, the old SOBO 20 was calibrated to read concentrations in ounces per square yard. The old SOBO 20 was modified during the repair to read concentrations in units of grams per square meter (g/m²) like the new SOBO 20.

The laboratory study included “100 SOBO 20 punching tests” with the use of the old and new SOBO 20, on concrete, asphalt and plastic specimens. “100 SOBO 20 punching tests” were a series of controlled tests for determining the accuracy of both the units before field experiments. The “100 SOBO 20 punching tests” were conducted on each specimen to prove that the two SOBO 20s were not different from each other. This test was also good at comparing the actual salt concentrations with the readings obtained from SOBO 20. The expectation of the researcher was to get the same 100 readings (that are equal to the applied salt concentration) from the device, for each specimen and for both of the SOBO 20s.

In the procedure of “100 SOBO 20 punching tests”, certain quantities of salt brine solutions having different concentrations (gr/L) were injected with a syringe into a small hole just on top of the SOBO 20’s gasket. The solution was captured inside the SOBO 20 and the device was pressed down preventing leakage from occurring. Next, SOBO 20 was pressed down to perform the reading. The actual concentration of the sodium chloride (g/L) was multiplied by the amount of solution that was being injected through
the hole of the device (ml). By this way, the amount of salt (in grams) that is inside the
gasket of SOBO 20 was calculated. Next, the amount of salt was divided by the area of
the gasket to find the salt density in grams/m² for the comparison with respective SOBO
20 readings.

This procedure was completed 100 times on concrete, asphalt and plastic for both
old and new SOBO 20s. The results were presented statistically (with presentation of
mean, average, and standard deviation of all the 100 readings) for each specimen and
SOBO 20.

3.4.2 SOBO 20 calibration tests on concrete pavement of Stocker Parking Lot

SOBO 20 calibration tests were conducted on the parking lot of the Stocker
Engineering Building of Ohio University. The aim of the application of this test before
the field study was to experiment with SOBO 20 and to become more familiar with the
use of the equipment. In addition, with the background obtained from the test study of the
parking lot, field application procedure for Route 50 East was developed.

The tests were conducted on the 23rd and 25th of September, 2002. The brine
solution was applied by using a plant watering sprayer to 21 m² free space that was
present near the faculty parking lot.

Calculations were made to find the amount of brine volume that should be
sprayed on the 21 m² area which would correspond to ODOT’s application rate. The
calculations showed that 0.5 L of brine solution should be sprayed to the entire area to be
able to keep the same conditions with ODOT application. However, to calibrate the
device more effectively 5 L/21 m² of application was also sprayed as well as 0.5 L/21 m².
Prior to the application of the salt, 9 lines were marked on the pavement using chalk. The lines had 1.3 m of spacing between them. The next step was to place 3 spots on each line with 1 meter distances between them. Then, 23% by weight salt brine solution was applied to the pavement with using a plant watering sprayer. The salt residuals of each line having 3 spots were measured by SOBO 20 at varying intervals. The following figure (Figure 3.4.2.1) shows the schematic figure of the tested area. The figure was not drawn according to scale. Each circled corner represents a spot that was measured at a certain time after the application of the brine.

Figure 3.4.2.1 Schematic figure of the Stocker Parking Lot test area
The following photos (Figure 3.4.2.2) show the application spreader and the measurements of salt residual on the spots using SOBO 20.

Figure 3.4.2.2: Measurement of the spots and the spreader used during Stocker Parking Lot tests
3.4.3 Laboratory ODOT brine analysis by TDS, salimeter, AA and IC methods

Samples of sodium chloride brine solution were collected from the nozzle type spreader truck of ODOT before the application of the liquid to the highway. The brine solution samples were obtained from the spreaders at the five sites and brought to the laboratory in order to verify the concentration of the NaCl, which was reported by ODOT to be 23%. The analyses were conducted by using salimeter, AA (AA Manual, 1996) and IC (IC Manual CD, 1998) instrumentation, and finally by using the TDS Method following the Standard Methods (Clesceri & Greenberg, 1998).

According to the information obtained from ODOT, the flowrate of the applied brine was 40 gallon/lane-mile. However, it was impossible to verify this because the automatic flow control changed the flow rate according to the speed of the truck.

The following figure (3.4.3.1) show how brine solution samples were collected from the distributor of the ODOT’s nozzle type spreader truck for verification under laboratory conditions.

Figure 3.4.3.1 Collection of brine sample from the truck for laboratory analysis
3.5 Methodology followed during the field study portion of the anti-icing project

The methodology followed during the field study portion of this thesis project is summarized below:

1. Select a total of five sites for the application of anti-icing tests. The sites that are chosen are part of the highways of US 50 (both asphalt and concrete pavement), US 33 (asphalt pavement) and US 23 (both asphalt and concrete pavement). These sites are all four lane highways.

2. In order to measure the salt brine residual on the pavements, mark four sections on each of the highways. In each of the sections, also mark sampling locations for the measurement of salt concentration versus time and exposed traffic.

3. Using the nozzle type spreader truck provided by ODOT, apply the sodium chloride brine solution to the highway at the speed of 40 gallon/lane*mile. The application is done by ODOT personnel.

4. Collect samples of sodium chloride brine solution from the hose of the nozzle type spreader truck at each of the five sites. Analyze the collected samples in the laboratory using TDS, AA, IC and the salimeter.

5. Prepare the pavements before the application of the brine by marking the test stations with using a chalk string.

6. Measure the concentration of sodium chloride on the pavement before the application of the brine (blank readings).

7. Measure the salt residual through time and through exposed traffic using SOBO 20 device manufactured by Boschung Mecatronic AG in Switzerland. The measurements
are divided into two tests: “10 nozzle tests” and “diagonal tests”. Continue conducting the
tests till no salt residual remains on the pavement.

8. Measure the pavement temperature using temperature gun in each of the testing
time intervals.

9. Determine the effects of exposed traffic on salt residual and on the efficiency of
the treatment.

10. Determine the effects of time on salt residual and on the efficiency of the
treatment.

11. Determine the effects of weather data (that is obtained from weather stations)
on the salt residual on the pavement.

3.6 Development of brine residue measuring procedures in the field

Based on the need to practice SOBO 20 in the field before the actual testing on
the highway, the first readings in the field were done on the concrete berm of Route 50
East on the 30th of September, 2002 as the 1st pilot study. The test fluid of the SOBO 20
was flooding and diluting the untested areas after each reading was being made by SOBO
20. This issue was generating problems and therefore; more SOBO 20 calibration tests
were conducted in the laboratory to overcome this problem.

The salt brine solution was applied to the highway by the nozzle type spreader
truck, in the form of stream lines through the ten nozzles of the truck. The turbulence,
which was generated at the end of the application vehicle due to the wind and the speed
of the truck, caused the dispersion of the ten nozzle brine trails on the pavement.
However, the ten brine trails were quite visible on the traveled lane. The rest of the
highway (other than the ten brine trails) was completely dry all throughout the anti-icing
application test. Figure 3.6.1 shows the application of the liquid anti-icer and the ten brine trails that were generated on the pavement surface.

Figure 3.6.1 Application of the liquid anti-icer and the formation of ten salt trails

The first test type conducted on the 1st pilot study was called “left, center and right test (LCR test)”. The procedure was to measure the salt brine residual using SOBO 20 in the two wheel paths and between the two points. This test type was not successful in verifying the points with the highest salt concentration and it was impossible to repeat the readings in a completely parallel direction. Therefore, this test did not represent the remaining salt residuals adequately. Overall, this test type was only used for the first field site (in the first two pilot tests) and then it was abandoned.

Next, two new test types were developed in the 1st pilot study, for use in the 2nd pilot study and in the field tests of the five sites. These tests were “diagonal (profile) tests” and “10 nozzle tests”.

The diagonal test was used to measure all the salt residuals along the lane width. Adjacent applications of SOBO 20 were conducted in order not to leave any part of the 12 feet left without being measured. The maximum distance between the two successive readings was 7 cm (twice the gasket width.), as shown in the following figure (3.6.2).

![Figure 3.6.2 Schematic figure of two successive readings of diagonal test and gasket dimensions of SOBO 20](image)

The Figure 3.6.3 shows the SOBO 20 measurements following the diagonal line.

![Figure 3.6.3 SOBO 20 measurements during the diagonal test](image)
In order to minimize the test fluid to flow and dilute the salt concentration of the unmeasured areas, SOBO 20 was laid back and the effluent was released down the slope. The following figure (3.6.4) shows how this situation was established.

![Flow of test fluid down the slope](image)

**Figure 3.6.4 Release of test fluid down from the slope of SOBO 20**

By the inclination of SOBO 20, the dilution of the unmeasured diagonal areas was prevented. However, the test fluid created another risk of flowing down to the unmeasured test sections by the spreading by traffic flow. The diagonal test was leaving large amounts of fluid on the pavement. The disturbance of the downstream test sections by the test fluid was prevented by sweeping the test fluid upstream with a broom after each diagonal test was completed.

The second test type was called the “10 nozzle test”. The first 10 nozzle test was conducted on the concrete shoulder of the Route 50 East in Athens (1st pilot test area). It included the measurement of the salt concentration of each brine trail. Ten readings were
obtained on each sampling location and per traffic exposure period. The following figure (Figure 3.6.5) shows the SOBO 20 measurements during the 10 nozzle test.

![Figure 3.6.5 Measurements with SOBO 20 during 10 nozzle test](image)

The test proved that the 10 nozzle test was better than LCR tests because it provided better prediction of the salt dissipation through time. It was also experienced that, adequate amount of acetone solution would have to be left at each test section in order to save time, since only 25 readings can be made with the reservoir capacity of SOBO 20.

The test sections for the 1st pilot study were marked with 300 feet distances between them. The space was left in order not to let the test fluid (acetone solution) flow downstream and dilute the untested areas.
The 2nd pilot test was conducted on the 2nd and 3rd of October, 2002 on the driving lane of Route 50 East in Athens. This driving lane was just near the shoulder of Route 50 East which was used for the first pilot study. After the salt brine solution was applied by ODOT, LCR tests were conducted for the last time. The procedure of the LCR test was the same as the one conducted in the 1st pilot test. Next, diagonal tests were tried in the 2nd pilot test in order to profile the salt concentration experimentally along a diagonal drawn on the pavement. The purpose of the diagonal test on the 2nd pilot test area was to estimate the amount of salt that is generally on the pavement. Special care was shown in order to maintain minimum spacing between adjacent SOBO 20 measurements (approximately 7 cm). The length of the diagonals in the 2nd pilot test varied and therefore; resulted in the generation of different numbers of SOBO 20 readings per sampling location. Overall, the most important decisions that were made at the end of the second pilot test were to standardize the length of the diagonal and conduct duplicate diagonal tests for each sampling location. This decision was made in order to obtain reliable and consistent data.

3.7 Description of the site locations chosen for data collection

The sites that were chosen for this thesis study to be treated by anti-icing applications were:

- Athens 50 Asphalt Concrete (ATH-50 AC).
- Athens 50 Portland Cement Concrete (ATH-50 PCC).
- Athens 33 Asphalt Concrete (ATH-33 AC).
- Delaware 23 Asphalt Concrete (DEL-23 AC).
- Delaware 23 Portland Cement Concrete (DEL-23 PCC).
All of the test sites listed above are in Ohio and they are adjacent sections of highways having four lanes. Each test site had a weather station close to the highway. By the help of these weather stations air temperature and humidity data was obtained. ODOT applied the NaCl brine solution by the nozzle type spreader truck and also controlled the traffic. In addition, traffic counts were obtained by the traffic counters provided by ODOT each time the lane was closed and opened to traffic.

These five sites had different pavements and had weather stations at close distances. The following table (Table 3.7.1) summarizes the pavement type, average daily traffic (ADT), exposure to traffic hour and to vehicles, and the date of the anti-icing application tests for the five sites studied.

**Table 3.7.1 Characteristics of the sites and dates of the anti-icing tests**

<table>
<thead>
<tr>
<th>Name of the Test Site</th>
<th>Type of Pavement</th>
<th>Dates of the Brine Residual Measurement Tests (2002)</th>
<th>Average Daily Traffic</th>
<th>Exposed Time to Traffic</th>
<th># of Vehicles during Exposed Traffic Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATH-50</td>
<td>PCC</td>
<td>October 8-9</td>
<td>8560</td>
<td>22hr.28min</td>
<td>3082*</td>
</tr>
<tr>
<td>ATH-50</td>
<td>AC</td>
<td>November 25-26</td>
<td>7500</td>
<td>7hr.53min</td>
<td>3855</td>
</tr>
<tr>
<td>DEL-23</td>
<td>PCC</td>
<td>October 31-November 1</td>
<td>26820</td>
<td>16hr.40min</td>
<td>6361</td>
</tr>
<tr>
<td>DEL-23</td>
<td>AC</td>
<td>October 30-31</td>
<td>26820</td>
<td>17hr.9min.</td>
<td>6368</td>
</tr>
<tr>
<td>ATH-33</td>
<td>AC</td>
<td>November 13-15</td>
<td>16730</td>
<td>33hr.55min</td>
<td>11214</td>
</tr>
</tbody>
</table>

* Estimated traffic

**3.7.1 Nozzle brine lines**

The nozzle type spreader truck produced some variability in brine line widths during the application of the solution. The widths of the brine lines were measured at each site as soon as the spreader truck finished the application of the solution. As expected. The following figure (Figure 3.7.1.1) shows the average widths of the brine
lines for each of the tested sites. It is obvious that the average brine line widths for each site are not the same. This could be due to the drip hose length differences of the application equipment, speed of the nozzle type spreader truck, or due to environmental factors like wind speed and wind direction.

### Brine Line Widths at All Sites

![Brine Line Widths Graph](image)

**Figure 3.7.1.1** Widths of the brine lines for the tested five sites (Mitchell et al., March 2003)

The following figure (3.7.1.2) shows how the brine line widths were measured by using a measuring tape.
Figure 3.7.1.2 Measurement of brine line widths
3.7.2 ATH-50 PCC

Route 50 PCC near Athens was the first highway which the anti-icing operations were applied to. The name of the residential area just near the test road was Cannanville. As mentioned above, the two pilot tests were conducted at this site, between the 30th of September and 3rd of October 2002, prior to the 1st field test which was conducted on the 8th and 9th of October 2002. The following figure (Figure 3.7.2.1) presents the map of the test area.

Figure 3.7.2.1 Site location of ATH-50 PCC (Maps Online, June 2003)
Eastbound driving lane of Route 50 was divided into 4 sections and named as A, B, C and D. The sections were separated from each other by 300 feet spacing. This distance was laid out in order to prevent the flowing of the test fluid (acetone solution + salt) to the unmeasured test areas.

For each test section, the pavement was marked as "b", "0", "1", "2", "3", "4", "5", "6" in order to sample easily. Each sample location was approximately 50 feet away from each other. The "b" sampling points were blank readings, and the measurements were conducted at these points before the application of salt. The "0" sampling locations were for the measurements of salt residual just after the application of the brine. The rest of the sampling locations were marked for time elapsed readings and after the sampling locations were exposed to traffic.

During the salt residual measurements at the sampling location, ODOT controlled the traffic and no vehicles passed in the lane during testing. In addition, ODOT also provided a traffic counter, however it malfunctioned during the field study on U.S 50.

Since there were two SOBO 20s available, two groups were formed in order to spend less time. Each group was composed of two people. One group was made responsible for sections A and B, while the other group was made responsible for sections C and D.

After the groups were formed, the lane was closed to traffic, the sample locations were marked out and test fluid containers (acetone solutions) and brooms were dropped near each sampling location. For ATH-50 PCC, spray paints were used to mark the diagonals while chalk strings were used for the rest of the sites. Lines were marked
parallel to the flow of the traffic. The diagonal lengths for ATH-50 PCC were not controlled and they were between 15-25 feet.

As soon as the blank readings were made ODOT's nozzle type spreader truck distributed the brine solution. Next, “0” readings were made for all of the test sections (A,B,C,D) without loosing time. Then the lane was opened to traffic by ODOT for the first time after application of the brine solution. It was observed that (since there was a warm weather condition that day) the brine lines dried immediately and the brine tracks remained just before the lane was opened to traffic for the first time. In order to maintain consistency, the SOBO 20s and the groups were not changed and the groups conducted the readings on their assigned sampling locations throughout the day. The groups conducted duplicate readings on randomly selected diagonals. The duplicate readings were attempted to be made very close to the original diagonal reading.

Based on the presence of grooves on the ATH-50 PCC, the test fluid escaped from SOBO 20 and flowed through the grooves. This situation became a larger issue in the other sites.

According to the experience obtained at the end of the two pilot tests and the 1st field test on the 1st tested site (ATH-50 PCC), it was decided to measure salt residual readings of each brine trail and to make the diagonal tests on a certain diagonal length to maintain consistency for the rest of the sites. There were a total of ten brine nozzles and therefore; the procedure was named as the “10 nozzle test”. In addition, the diagonals were decided to be drawn by chalk strings in 20 (short diagonal) and 30 (long diagonal) feet lengths. The group conducting diagonal readings on the short diagonal, made
duplicate tests while the other group conducted only one test on the long diagonal. This method compensated the work load on the groups and saved time.

The following figure (Figure 3.7.2.2) presents the diagonal and 10 nozzle brine measurements.

![Figure 3.7.2.2 Salt residual measurements on the diagonal pavement and on the ten nozzles (Mitchell et al, March 2003)](image)

For ATH-50 PCC, the diagonal readings and the three parallel “left”, “center” and “right” readings were reported since the 10 nozzle tests were not completed for each section and sampling point. Based on the failure of the traffic counters, the traffic counts were estimated from ODOT Traffic Survey records.

### 3.7.3 ATH-50 AC

Route 50 asphalt pavement of Athens was another highway which the anti-icing operations were applied to. The anti-icing tests were conducted on the 25th and 26th of
November, 2002 for this site. The name of the residential area just near the test road was Coolville. The following figure (Figure 3.7.3.1) presents the map of the tested area.

Figure 3.7.3.1 Site location of ATH-50 AC (Maps Online, June 2003)

The pavement type of ATH-50 AC was “nova chip”. The nova chip type of pavement is the mixture of the hot asphalt with the emulsion asphalt (ASA Online, June 2003).
Only one SOBO 20 was available for use on ATH-50 AC, since one of the SOBO 20s broke down during the use in ATH-33 AC. Therefore, the amount of data obtained was less in ATH-50 AC compared to other sites. The test sections were reduced to A, B and C and the sampling locations were reduced to four ("0", "1", "2", "3"). "0" readings were not conducted for the section C in order to compare the effect of "0" readings. Tests on the sections B and C were conducted during the same time. Brine solution was applied to section A while Section B and C were being tested for the second time period. The length of all the diagonals was 30 feet.

Traffic counts were obtained from ODOT traffic survey records for the corresponding date.

3.7.4 DEL-23 AC and DEL-23 PCC

Route 23 pavement of Delaware was another highway which the anti-icing operations were applied to. The tests were conducted on the 30th and 31st of October, 2002 for the asphalt pavement and on the 31st of October and 1st of November, 2002 for the concrete pavement of DEL-23. The concrete and asphalt pavements of DEL 23 highway were just opposite lanes of the same location. Therefore, only one map is provided below (Figure 3.7.4.1) for the representation of the highway.
The traffic counters and the traffic control were again provided by ODOT and the traffic counters gave successful readings this time. The ten nozzle and diagonals the diagonal tests were conducted on each test section (A, B, C, D) and sampling location ("b", "0", "1", "2", "3", "4").

The sections A, B, C, and D were marked with a chalk string on DEL-23 PCC and DEL-23 AC. The diagonal lengths were 20 feet on sections A and B while they were 30 feet on sections C and D. As decided before, the group that was testing A and B
performed duplicate diagonal tests while the group testing C and D conducted only one diagonal test for each sampling location.

Some parts of the DEL-23 AC’s surface were highly porous while some parts were average porous. The acetone solution (test fluid) was escaping into the cracks due to the porous structure of the pavement. DEL-23 PCC was highly porous too. Based on this reason, the test sections were moved from their initial labeled positions.

3.7.5 ATH-33 AC

Route 33 asphalt pavement of Athens was another highway which the anti-icing operations were applied to. The name of the residential area just near the test road was Nelsonville. The following figure (Figure 3.7.5.1) presents the map of the tested area.

Figure 3.7.5.1 Site location of ATH-33 AC (Maps Online, June 2003)
The tests were conducted between the 13th and 15th of November 2002 on asphalt pavement of Athens-33. The type of the pavement was micro seal asphalt. Micro seal is an economical intermediate material which is used to improve the surface of the highway (DOPW Online, June 2003). Successful traffic control and counts were again provided by ODOT. Just like DEL-23, 20 feet diagonals were marked with chalk strings on test sections A an B, and 30 feet diagonals were marked on C and D.

In ATH-33 AC, the applied brine solution dried very slowly and when the lane was first opened to traffic, there was a liquid solution of brine on the pavement. In addition, one of the nozzles left a very wide trail on ATH-33 AC. One of the reasons that the brine solution did not dry out quickly was because of the pavement being very smooth and nearly impervious. When the lane was first opened to traffic, the traffic helped the brine solution to disperse on the pavement. In order to see the effect of traffic dispersion, a new section (E) was added. The E section was on the far end of the traffic control where the dispersion by traffic occurred immediately at time of application Limited amounts of diagonal and 10 nozzle tests were conducted on section E.

Towards the end of the data collection in this site the old SOBO 20 broke down.
Chapter 4 Results and Discussion

4.1 Introduction

This chapter discusses the results of the laboratory, Stocker Parking Lot and field tests. It presents the results of the SOBO 20 calibration tests conducted in the lab and in the parking lot, shows the decline of salt residual in the field study versus time and traffic, and finally interprets the results of the field study.

4.2 SOBO 20 laboratory calibration test results on asphalt, concrete and plastic specimens and comparison of the results with the ideal readings

As mentioned in Chapter 3 of this thesis study, in order to see if both the old and the new SOBO 20s are giving consistent readings for the application of the same salt concentration, “100 punching tests” were conducted on plastic, concrete and asphalt pavements. The statistical results of these punching tests are summarized in the Figures 4.2.1 and 4.2.2 below.
Statistical Analysis of the Lab Test of SOBO 20 using Asphalt, Concrete and Plastic Pavements for the Application of 10 g/m² Brine Solution (19-22 October, 2002)

Figure 4.2.1 Results of SOBO 20 calibration “100 punching tests” in the laboratory for different specimens and for the application of 10 g/m² salt concentration

Figure 4.2.2 SOBO 20 comparison readings for “100 punching tests”
The Figure 4.2.2 shows the statistical distribution of the SOBO 20 readings. The T shaped lines present the ranges, of the readings and the rectangles show the concentrations that were detected the most. Both of the graphs (Figure 4.2.1 & 4.2.2) present that the old SOBO 20s gave an average reading of about 11.4 g/m² for the application of 10 g/m² brine solution, while the new SOBO 20 gave an average reading of about 11.36 g/m² for all of the specimen types. The range was approximately in between 8-12 g/m². The reason of getting an average of 10% higher readings from the ideal salt concentration was due to the leakage generated from the gasket of the SOBO 20. While performing these calibration tests, it was found out by the researchers that SOBO 20 gives the most accurate result when the device is pushed down perpendicular to the pavement. Therefore, towards the end of the calibration tests the readings were closer to ideal salt concentration of 10 g/m².

Another reason for the completion of “100 punching tests” was to assure that each SOBO 20 was dispensing the same amount of solution to the pavement surface. Theoretically each SOBO 20 must release an acetone solution volume of 40 ml (1000ml/25), since the reservoir capacity of SOBO 20 is 1 liter and 25 readings can be made by this amount of solution. Figure 4.2.3 indicates the average volumes discharged by both of the SOBO 20s.
As can be seen from the above figure (Figure 4.2.3), the average volume of discharges are approximately the same for both of the SOBO 20s. The mean is 40.5 ml for the old and 40.025 ml for the new SOBO 20. The utilization of the two sample T test proved that the two devices are the same at a 95% confidence interval.

4.3 Results of the SOBO 20 calibration tests on concrete pavement of Stocker Parking Lot

The SOBO 20 calibration tests in the Stocker Parking Lot were conducted in order to get familiar with the use of SOBO 20 and to develop protocols for the field application. As mentioned in Chapter 3, the salt concentrations of the three spots on a total of nine lines were measured with SOBO 20. Each line was measured at different times and the readings obtained from the three spots were averaged. This test enabled the
researchers to graph the salt residual dissipation through time. The results of the Stocker Parking Lot test are presented below in Figure 4.3.1.

Figure 4.3.1 Average salt residual versus time for the Stocker Parking Lot test with the application of 23% brine solution at two different application rates

As can be seen from Figure 4.3.1, the salt concentrations decreased with time. This is due to the parking cars that passed (approximately 15 vehicles) through the Stocker Parking Lot and causing the dissipation of the salt residual.

The zero (0) minute readings should correspond to 6.571 g/m² (actual salt concentration) when 0.5 L of brine was applied to 21 m² parking lot area, and as can be seen from the above Figure 4.3.1, the expectation coincided with the reading at zero minute, which was made just after the application of brine. However, 65.71 g/m² (actual salt concentration) did not correspond with the zero (0) minute reading of 5L/21m² brine
application because the SOBO 20 is manufactured to read in the range of 0-45 gr/m². Therefore, the initial salt concentration for 5L/21m² brine application represents a value greater than 45 gr/m².

The salt dissipation equations for both of the brine application rates are summarized in the Table 4.3.1.

Table 4.3.1 Exponential dissipation equations of two application rates of brine solution in the Stocker Parking Lot

<table>
<thead>
<tr>
<th>Application Rate</th>
<th>Dissipation Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5L/21m²</td>
<td>Salt [I]=35.5exp(-0.004*Time)</td>
</tr>
<tr>
<td>5L/21m²</td>
<td>Salt [I]=5.3exp(-0.0074*Time)</td>
</tr>
</tbody>
</table>

4.4 Results of laboratory ODOT brine analysis by TDS, salimeter, AA and IC methods

ODOT reported that the brine solutions provided were at 23.3% concentration. The analyses of brine solutions collected at the five test sites were done in the laboratory in order to verify whether the concentrations are approximately the same as eutectic concentration or not. The results of the laboratory analysis obtained by the use of AA, IC, salimeter and the TDS method are provided in Table 4.4.1.
Table 4.4.1 Analysis of brine solution from dispensing trucks at the five field sites

<table>
<thead>
<tr>
<th>Highway</th>
<th>Date</th>
<th>TDS (g/L)</th>
<th>%NaCl by Weight Obtained from TDS</th>
<th>%NaCl by Weight Obtained from Salinometer</th>
<th>%NaCl by Weight Obtained from IC from IC</th>
<th>%NaCl by Weight Obtained from IC from Salinometer</th>
<th>%NaCl by Weight Obtained from AA from TDS</th>
<th>%NaCl by Weight Obtained from AA from IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample for Lab use</td>
<td>ODOT Garage</td>
<td>275.14</td>
<td>23.35</td>
<td>88.00</td>
<td>23.21</td>
<td>259.67</td>
<td>22.23</td>
<td>321.14</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>9/30/2002 (1st pilot study)</td>
<td>272.31</td>
<td>23.15</td>
<td>89.00</td>
<td>23.48</td>
<td>267.27</td>
<td>22.76</td>
<td>305.60</td>
</tr>
<tr>
<td>DEL 23 AC</td>
<td>10/2/2002 (2nd pilot study)</td>
<td>276.04</td>
<td>23.42</td>
<td>88.00</td>
<td>23.21</td>
<td>298.73</td>
<td>24.34</td>
<td>307.00</td>
</tr>
<tr>
<td>Sample for Lab use</td>
<td>10/8/2002</td>
<td>277.03</td>
<td>23.49</td>
<td>89.00</td>
<td>23.48</td>
<td>291.58</td>
<td>23.82</td>
<td>295.63</td>
</tr>
<tr>
<td>DEL 23 AC</td>
<td>10/30/2002, before</td>
<td>271.62</td>
<td>23.11</td>
<td>86.50</td>
<td>22.82</td>
<td>276.36</td>
<td>23.44</td>
<td>304.96</td>
</tr>
<tr>
<td>DEL 23 AC</td>
<td>10/30/2002, after</td>
<td>277.09</td>
<td>23.49</td>
<td>87.50</td>
<td>23.06</td>
<td>254.56</td>
<td>24.76</td>
<td>309.92</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>10/31/2002</td>
<td>270.94</td>
<td>22.98</td>
<td>85.00</td>
<td>22.42</td>
<td>279.21</td>
<td>23.66</td>
<td>308.14</td>
</tr>
<tr>
<td>Sample for Lab use</td>
<td>11/13/2002</td>
<td>269.62</td>
<td>22.87</td>
<td>89.00</td>
<td>23.48</td>
<td>298.92</td>
<td>24.35</td>
<td>304.76</td>
</tr>
<tr>
<td>ATH-50 AC</td>
<td>11/20/2002</td>
<td>275.36</td>
<td>23.37</td>
<td>89.00</td>
<td>23.48</td>
<td>296.45</td>
<td>25.04</td>
<td>307.58</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>273.92</td>
<td>23.26</td>
<td>87.90</td>
<td>23.19</td>
<td>281.75</td>
<td>23.83</td>
<td>306.00</td>
</tr>
</tbody>
</table>

As can be seen from Table 4.4.1, the averages of the results of the testing methods ranged from 23.19% to 25.59%. The most accurate test methods were the TDS and Salinometer because they give readings closest to the eutectic concentration. In order for the salt concentration to be recognized by the IC and AA machine, the samples were diluted 5000 times and this affected the accuracy of the results. Overall, the average concentration obtained by using the four methods was found to be 23.97%. All of the methods used in the verification of the ODOT brine solution proved that the salt concentration provided by ODOT is at or near eutectic concentration, which is 23.3% salt by weight.

4.5 ATH-50 PCC results

4.5.1 Traffic, time, and weather data for ATH-50 PCC
The concrete pavement of ATH-50 was in good condition and was grooved transversely. Table 4.5.1.1 presents the traffic, time and weather data of ATH-50 PCC.

**Table 4.5.1.1 Traffic, time and weather data for ATH-50 PCC (Mitchell et al., March 2003)**

<table>
<thead>
<tr>
<th>ATH-50 PCC October 8-9, 2002</th>
<th>Data Collection Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Hours</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic #vehicles</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic Hours</td>
<td>0</td>
</tr>
<tr>
<td>Average Air Temperature (°C)</td>
<td>9.66</td>
</tr>
<tr>
<td>Average Pavement Temperature (°C)</td>
<td>15.56</td>
</tr>
<tr>
<td>Maximum Daily Humidity (%)</td>
<td>73.30</td>
</tr>
<tr>
<td>Average Daily Humidity (%)</td>
<td>72.00</td>
</tr>
</tbody>
</table>

Notes: Traffic counter failed. Counts estimated from ODOT Traffic Survey Report using hourly factors, divided by two for one direction of travel, times four-fifths (estimate) for shoulder lane occupancy.

**4.5.2 Graphical profiles of salt concentration across lane width ATH-50 PCC**

Figure 4.5.2.1-4.5.2.4 present the results of the diagonal tests for sections A through D of ATH-50 PCC. These represent diagonals ranging from 14 to 24 feet. It can be easily seen that the brine coverage was concentrated toward the centerline. The positions of the ten brine nozzles can be differentiated in the diagonal profiles since the salt concentrations are higher in these points compared to the other points. The individual presentation of the diagonal profile graphs for each sampling location is presented in Appendix-1 for all of the test sites.
Figure 4.5.2.1 Diagonal profile of ATH-50 PCC for section A

Figure 4.5.2.2 Diagonal profile of ATH-50 PCC for section B
Figure 4.5.2.3 Diagonal profile of ATH-50 PCC for section C

Figure 4.5.2.4 Diagonal profile of ATH-50 PCC for section D
4.5.3 Frequency of occurrence of the diagonal readings for ATH-50 PCC

Figures 4.5.3.1-4.5.3.4 present the frequency of occurrence of the data at sections A-D for ATH-50 PCC. These dot plots show the evolution of the profiles versus time. They illustrate the decline of salt residual. It can be seen from Figure 4.5.3.3 that the salt concentrations that are less than 10 g/m² are more at 7 th sampling period (after 6 hours of salt application) compared to the other sampling periods. This shows that the complete salt dissipation occurred after 6 hours for the C section of ATH-50 PCC. Similarly, for Figure 4.5.3.1-4.5.3.4, there are very few readings between 10-20 g/m² for the last testing period which shows the decline of salt through time.
Figure 4.5.3.1 Frequency of occurrence ATH-50 PCC brine data for section A
Salt Brine Application Study
State Route 50 - Station 168+00
October 8&9, 2002

Figure 4.5.3.2 Frequency of occurrence ATH-50 PCC brine data for section B
Salt Brine Application Study
State Route 50 - Station 174+00
October 8&9, 2002

Figure 4.5.3.3 Frequency of occurrence ATH-50 PCC brine data for section C
Salt Brine Application Study
State Route 50 - Station 180+00
October 8&9, 2002

Figure 4.5.3.4 Frequency of occurrence ATH-50 PCC brine data for section D
4.5.4 Comparison of the accuracy of the data by “ten spot means” and “average of top ten diagonal readings” for ATH-50 PCC

The average of highest ten diagonal readings are assumed to represent the average concentrations that are on the ten nozzle trails. The average of highest ten diagonal readings are graphed to see if they coincide with the graph of the average ten nozzle readings. This is done to check the accuracy of the test results.

The averages of the highest ten diagonal readings for sections A through D of ATH-50 PCC versus traffic exposure are presented in Figure 4.5.4.1. The graph shows that the applied brine concentration varied randomly over 24 hours. Except for a few data from the graph the salt concentration is above 6 g/m² for all of the sections (the average top ten diagonal readings for all the sections are between 6.5-10 g/m²) and even after being exposed to 3500 traffic.

Figure 4.5.4.1 Average of top ten diagonal readings for all sections of ATH-50 PCC
Ten nozzle plots and average ten nozzle readings are not included for ATH-50 PCC because the brine trail measurements were tried for the 1st time on ATH-50 PCC and therefore, the data were not sufficient to report. Extensive nozzle data were collected, and the results are presented for the other four sites (DEL-23 AC, DEL-23 PCC, ATH-33 AC and ATH-50 AC).

4.6 ATH-50 AC results

4.6.1 Traffic, time, and weather data for ATH-50 AC

The asphalt pavement of ATH-50 was not in very good condition and it had lots of grooves. For this test site, only one SOBO 20 was available, and therefore the amount of data collected for this test site was limited and so some short cuts were made. Table 4.6.1.1 and 4.6.1.2 summarize the traffic, time and weather data for ATH-50 AC.

Table 4.6.1.1 Traffic, time and weather data for A section of ATH-50 AC (Mitchell et al., March 2003)

<table>
<thead>
<tr>
<th>ATH-50 AC, Section A November 25-26, 2002</th>
<th>Data Collection Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Hours</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic, # vehicles</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic Hours</td>
<td>0</td>
</tr>
<tr>
<td>Average Air Temperature (°C)</td>
<td>4.50</td>
</tr>
<tr>
<td>Average Pavement Temperature (°C)</td>
<td>8.06</td>
</tr>
<tr>
<td>Maximum Daily Humidity (%)</td>
<td>95.40</td>
</tr>
<tr>
<td>Average Daily Humidity (%)</td>
<td>82.30</td>
</tr>
</tbody>
</table>
Table 4.6.1.2 Traffic, time and weather data for B & C section of ATH-50 AC

(Mitchell et al., March 2003)

<table>
<thead>
<tr>
<th>ATH-50 AC, Section B &amp; C November 25-26, 2002</th>
<th>Data Collection Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Hours</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic, # vehicles</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic Hours</td>
<td>0</td>
</tr>
<tr>
<td>Average Air Temperature (°C)</td>
<td>NA</td>
</tr>
<tr>
<td>Average Pavement Temperature (°C)</td>
<td>NA</td>
</tr>
<tr>
<td>Maximum Daily Humidity (%)</td>
<td>NA</td>
</tr>
<tr>
<td>Average Daily Humidity (%)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4.6.1.3 presents the schedule of operations for ATH-50 AC.

The notations A0, B1, etc., show the SOBO 20 data collection periods used in the graphs and charts. Diagonal tests and ten spot tests were conducted except where there is an asterisk (*) which indicates that only ten spot tests were conducted at that collection period.

Table 4.6.1.3 Schedule of operations for ATH-50 AC (Mitchell et al., March 2003)

<table>
<thead>
<tr>
<th>ATH-50 AC Data Collection Nov. 25-26, 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Section</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>

* Only ten spot tests were conducted

4.6.2 Graphical profiles of salt concentration across lane width ATH-50 AC

Figures 4.6.2.1-4.6.2.3 show the diagonal profiles for sections A through C of ATH-50 AC. The salt concentration profiles for the three sections are quite different from each other. Section C has very low salt concentration compared to the other stations
because diagonal tests were conducted 22.5 hours after the salt solution was spreaded to the test site.

Figure 4.6.2.1 Diagonal profile of ATH-50 AC for section A

Figure 4.6.2.2 Diagonal profile of ATH-50 AC for section B
Figure 4.6.2.3 Diagonal profile of ATH-50 AC for section C
4.6.3 Frequency of occurrence of the diagonal readings for ATH-50 AC

Figures 4.6.3.1-4.6.3.3 present the frequency of occurrence of the data at sections A-C for ATH-50 AC. Figure 4.6.3.1 and 4.6.3.2 show that approximately 50% of salt depletion occurred at the 2nd test trial for Station A and Station B. The complete salt dissipation took place at the last sampling location for all of the stations of ATH-50 AC.

Anti-Icing Brine Application Study
Test Section A
US 50 & 7 Coolville
November 25 & 26, 2002

Each dot represents up to 2 observations.

Figure 4.6.3.1 Frequency of occurrence ATH-50 AC brine data for section A
Figure 4.6.3.2 Frequency of occurrence ATH-50 AC brine data for section B
Figure 4.6.3.3 Frequency of occurrence ATH-50 PCC brine data for section C
4.6.4 Nozzle readings on the ten salt trails for ATH-50 AC

The following three graphs (Figure 4.6.4.1-4.6.4.3) present the results of the ten nozzle tests for sections A-C of ATH-50 AC. The decline of the salt density through time can be observed from these graphs since the test results of each sampling location are included (ten nozzle tests are conducted for each sampling location at different times after the brine application). However, Section C has some salt concentration (ranging between 0-2 g/m²) left on the pavement even after the 3rd sampling period.

![Graph showing nozzle readings for ATH-50 AC (A)](image)

Figure 4.6.4.1 Ten spot readings of ATH-50 AC for section A
Figure 4.6.4.2 Ten spot readings of ATH-50 AC for section B

Figure 4.6.4.3 Ten spot readings of ATH-50 AC for section C
4.6.5 Comparison of the accuracy of the data by “ten spot means” and “average of top ten diagonal readings” for ATH-50 AC

Figures 4.6.5.1 and 4.6.5.2 show the average of the highest ten diagonal readings and the average ten spot readings, respectively, plotted on the same time base according to traffic exposure for ATH-50 AC. The assumption was that the average of the highest ten diagonal readings should match with the average of the ten nozzle readings since the ten nozzles have the highest salt densities on the 12 feet lane. As expected, the two graphs are similar, which indicates that the results of the ten nozzle tests coincided with the results of the diagonal tests for ATH-50 AC.

![Average highest ten diagonal readings vs traffic for ATH-50 AC](image)

Figure 4.6.5.1 Average of top ten diagonal readings for all sections of ATH-50 AC
Figure 4.6.5.2 Average of ten nozzle readings for all sections of ATH-50 AC

Figure 4.6.5.2 does not present C-0 data of Station C because zero hour tests were not conducted in this station due to the limitation of SOBO 20. In addition, figures 4.6.5.1 and 4.6.5.2 show that 0 hour results of Station A do not match with each other. There may have been inaccuracy in SOBO 20 measurements at this station in this time period or the liquid solution may have run into the pores (before being measured) while diagonal test was being conducted.

The evolution of the salt concentration for each nozzle through time is presented in Appendix-2 for each sampling location of each section of the four test sites (DEL-23 AC, DEL-23 PCC, ATH-33 AC and ATH-50 AC).

4.7 DEL-23 PCC results

4.7.1 Traffic, time, and weather data for DEL-23 PCC
The concrete pavement of DEL-23 was in good condition. However, this site had deep transverse grooves which the test fluid ran into before the salt residual was measured. In order to make measurements in areas with less grooves, sections C and D of DEL-23 PCC were moved a few stations away. Table 4.7.1.1 summarizes the time, traffic and weather data of DEL-23 PCC for a 16.5 hours time period.

Table 4.7.1.1 Traffic, time and weather data for DEL-23 PCC (Mitchell et al., March 2003)

<table>
<thead>
<tr>
<th>DEL-23 PCC</th>
<th>October 30-31, 2002</th>
<th>Data Collection Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Hours</td>
<td>0</td>
<td>4:30</td>
</tr>
<tr>
<td>Cumulative Traffic, # vehicles</td>
<td>0</td>
<td>697</td>
</tr>
<tr>
<td>Cumulative Traffic Hours</td>
<td>0</td>
<td>1:15</td>
</tr>
<tr>
<td>Average Air Temperature (°C)</td>
<td>2.22</td>
<td>6.24</td>
</tr>
<tr>
<td>Average Pavement Temperature (°C)</td>
<td>9.86</td>
<td>13.68</td>
</tr>
<tr>
<td>Maximum Humidity (%)</td>
<td>30.10</td>
<td>38.30</td>
</tr>
<tr>
<td>Minimum Humidity (%)</td>
<td>38.75</td>
<td>38.10</td>
</tr>
<tr>
<td>Total Solar Radiation (Watt/m²)</td>
<td>140.33</td>
<td>315.25</td>
</tr>
<tr>
<td>Mean Wind Speed (m/s)</td>
<td>0.35</td>
<td>1.07</td>
</tr>
</tbody>
</table>

4.7.2 Graphical profiles of salt concentration across lane width for DEL-23 PCC

In this section, the diagonal profiles of DEL-23 PCC are presented for each test section. The diagonal graphs of all of the sampling locations are shown in the same figure to consume less space. However, the individual presentation of the diagonal profile graphs for each sampling location is provided in Appendix-1 for all of the test sites.

Figures 4.7.2.1-4.7.2.4 present the diagonals of DEL-23 PCC over 16.5 hours of traffic exposure. The diagonals of sections A and B were 20 feet long, while C and D were 30 feet long. The salt concentrations at the 0 sampling location were quite higher than the salt concentrations at the succeeding measuring times. Salt dissipated approximately 80% after 0 sampling time period for all of the sections (A, B, C and D.
Figure 4.7.2.1 Diagonal profile of DEL-23 PCC for section A

Figure 4.7.2.2 Diagonal profile of DEL-23 PCC for section B
Figure 4.7.2.3 Diagonal profile of DEL-23 PCC for section C

Figure 4.7.2.4 Diagonal profile of DEL-23 PCC for section D
4.7.3 Frequency of occurrence of the diagonal readings for DEL-23 PCC

Figures 4.7.3.1 to 4.7.3.4 present the evolution of the diagonal profiles for test sections A, B, C and D of DEL-23 PCC.

Figure 4.7.3.1 shows that %75-80 reduction of salt concentration is reached just after the first sampling location for Station A. This is mainly due to the porous structure of the pavement. In addition, very high readings are obtained for Station A at the first sampling period compared to other stations for DEL-23 PCC. This can be a cause of inaccurate use of the SOBO 20, since these large concentrations were not expected for the first sampling period.

As can be seen from figures 4.7.3.2 to 4.7.3.4, for the other stations of DEL-23 PCC the average salt concentrations at the first sampling location vary between 7-10 g/m² which are close to what is expected. In addition, the salt concentration shows a similar trend (or decrease very little) between the second and the fourth sampling locations. This may be due to the reason that there is only two hour time between the test periods that are within the second and the fourth sampling locations.
Figure 4.7.3.1 Frequency of occurrence DEL-23 PCC brine data for section A
Figure 4.7.3.2 Frequency of occurrence DEL-23 PCC brine data for section B
Figure 4.7.3.3 Frequency of occurrence DEL-23 PCC brine data for section C
US 23 Brine Study
Portland Cement Concrete
October 31 & November 1, 2002
Station D

Figure 4.7.3.4 Frequency of occurrence DEL-23 PCC brine data for section D
4.7.4 Nozzle readings on the ten salt trails for DEL-23 PCC

In this section, the decay of the salt concentration for DEL-23 PCC versus sampling locations for all of the nozzle numbers is shown. Figures 4.7.4.1 to 4.7.4.4 present the bar graphs of the ten nozzle tests for DEL-23 PCC. As can be seen from these four figures, total salt dissipation took place at the 4th sampling location (after 22.5 hours) for all of the stations according to the ten nozzle tests. The highest percentage of salt deduction occurred at Station A and D just after the 0 hour sampling period. This is again can be explained by the porous pavement structure of DEL-23 PCC.
Figure 4.7.4.1 Ten spot readings of DEL-23 PCC for section A

Figure 4.7.4.2 Ten spot readings of DEL-23 PCC for section B
Figure 4.7.4.3 Ten spot readings of DEL-23 PCC for section C

Figure 4.7.4.4 Ten spot readings of DEL-23 PCC for section D
The evolution of the salt concentration for each nozzle through time is presented in Appendix-2 for each sampling location of each section of the four test sites (DEL-23 AC, DEL-23 PCC, ATH-33 AC and ATH-50 AC).

4.7.5 Comparison of the accuracy of the data by “ten spot means” and “average of top ten diagonal readings” for DEL-23 PCC

The averages of the top ten diagonal readings and the ten nozzle readings of DEL-23 PCC for sections A through D versus time are presented in Figures 4.7.5.1 and 4.7.5.2, respectively. It can be seen from both of these figures that the average overall concentration is greater than 5 \( \text{g/m}^2 \) up to 2000 cumulative traffic. As expected, the trends of both of the graphs are similar except for the 0 hour readings of section C and A. Generally, the trends of the average ten nozzle and average top ten diagonal graphs did not coincide the most on the first sampling location (at 0 hour sampling period). This is mainly due to the reason that the crew (that is using the SOBO 20) did not practice how to use the SOBO 20 early in the morning (while starting the first sampling location measurements) and this caused some inaccuracy in the early morning data till the researchers adopted how to use the equipment correctly (without generating any leakage from the gasket of the equipment) through time.
Figure 4.7.5.1 Average of top ten diagonal readings for all sections of DEL-23 PCC

Figure 4.7.5.2 Average of ten nozzle readings for all sections of DEL-23 PCC
4.8 DEL-23 AC results

4.8.1 Traffic, time, and weather data for DEL-23 AC

The asphalt pavement of DEL-23 was open-graded. The brine solution and the test fluid flowed into the gaps very quickly. Table 4.8.1.1 summarizes the time, traffic and weather data of DEL-23 PCC for 17 hours time period.

**Table 4.8.1.1 Traffic, time and weather data for DEL-23 AC (Mitchell et al., March 2003)**

<table>
<thead>
<tr>
<th>DEL-23 AC October 30-31, 2002</th>
<th>Data Collection Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Hours</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic, # vehicles</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic Hours</td>
<td>0</td>
</tr>
<tr>
<td>Average Air Temperature (°C)</td>
<td>2.68</td>
</tr>
<tr>
<td>Average Pavement Temperature (°C)</td>
<td>6.94</td>
</tr>
<tr>
<td>Maximum Humidity (%)</td>
<td>38.84</td>
</tr>
<tr>
<td>Minimum Humidity (%)</td>
<td>38.77</td>
</tr>
<tr>
<td>Total Solar Radiation (Watts/m²)</td>
<td>17.50</td>
</tr>
<tr>
<td>Mean Wind Speed (m/s)</td>
<td>2.95</td>
</tr>
</tbody>
</table>

4.8.2. Graphical profiles of salt concentration across lane width for DEL-23 AC

Figures 4.8.2.1 to 4.8.2.4 present the diagonal profiles of DEL-23 AC over 17 hours of traffic exposure. Just like DEL-23 PCC, the diagonals of sections A and B were 20 feet long, while C and D were 30 feet long for DEL-23 AC. It can be observed from the figures (4.8.2.1-4.8.2.4) that the measured salt residuals were almost the same for the 1st four sampling periods. The salt dissipation through time followed parallel trend as the result of the diagonal tests. This can be seen mainly in Station D in Figure 4.8.2.4 clearly. Total salt dissipation occurred 23 hours after the brine solution application. However, the salt concentrations were very low for DEL-23 AC compared to DEL-23 PCC.
DEL-23 AC(A)

Figure 4.8.2.1 Diagonal profile of DEL-23 AC for section A

DEL-23 AC(B)

Figure 4.8.2.2 Diagonal profile of DEL-23 AC for section B
Figure 4.8.2.3 Diagonal profile of DEL-23 AC for section C

Figure 4.8.2.4 Diagonal profile of DEL-23 AC for section D
4.8.3 Frequency of occurrence of the diagonal readings for DEL-23 AC

Figures 4.8.3.1 to 4.8.3.4 present the evolution of the diagonal profiles for test sections A, B, C and D of DEL-23 AC. As can be seen from the figures (4.7.3.1-4.7.3.4 & 4.8.3.1-4.8.3.4), the concrete pavement of DEL-23 has higher initial salt concentrations compared to DEL-23 AC. In addition, figures 4.8.3.1 to 4.8.3.4 prove that there is very little amount of salt dissipation till the end of the third sampling period for Stations A, B, C and D of DEL-23 AC.

Anti-Icing Brine Application Study
DEL - 23 AC at Station A
October 30 & 31, 2002

Figure 4.8.3.1 Frequency of occurrence DEL-23 AC brine data for section A
Anti-Icing Brine Application Study
DEL - 23 AC at Station B
October 30 & 31, 2002

Figure 4.8.3.2 Frequency of occurrence DEL-23 AC brine data for section B
Anti-Icing Brine Application Study
DEL - 23 AC at Station C
October 30 & 31, 2002

Figure 4.8.3.3 Frequency of occurrence DEL-23 AC brine data for section C
Anti-Icing Brine Application Study
DEL - 23 AC at Station D
October 30 & 31, 2002

Figure 4.8.3.4 Frequency of occurrence DEL-23 AC brine data for section D
4.8.4 Nozzle readings on the ten salt trails for DEL-23 AC

In this section, the decay of the salt concentration for DEL-23 AC versus sampling locations for all of the nozzle numbers is shown. The figures 4.8.4.1-4.8.4.4 present the bar graphs of the ten nozzle tests for DEL-23 AC.

All of the bar graphs for DEL-23 AC (4.8.4.1-4.8.4.4) of the ten nozzle tests show the dissipation of salt residual at the end of 17 hours of time exposure. In addition, sections B&C showed a complete salt dissipation at the 4th sampling location. However, the B section of DEL-23 AC gives inaccurate results for the initial testing period. The initial sampling period of DEL-23 AC(B) had salt concentrations varying between 0-7 g/m². The zero (0) concentration readings that were obtained just after the application of the salt brine were not expected.

![Figure 4.8.4.1 Ten spot readings of DEL-23 AC for section A](image)
Figure 4.8.4.2 Ten spot readings of DEL-23 AC for section B

Figure 4.8.4.3 Ten spot readings of DEL-23 AC for section C
4.8.4.4 Ten spot readings of DEL-23 AC for section D

4.8.5 Comparison of the accuracy of the data by “ten spot means” and “average of top ten diagonal readings” for DEL-23 AC

The averages of the top ten diagonal readings and the ten nozzle readings of DEL-23 AC for sections A through D versus time are presented in Figures 4.8.5.1 and 4.8.5.2 respectively. Both of the graphs present that the initial SOBO 20 readings are quite low compared to DEL-23 PCC; approximately 75% less than the initial readings of DEL-23 PCC.

The salt concentrations are all less than 7 g/m² even immediately after the salt brine application.

The trends of both of the graphs differ for section D and the 1st three readings of section C, which means that the results did not coincide with what was expected. The readings of SOBO 20 may have differed between the diagonal and the ten nozzle test.
because of the porosity of DEL-23 AC, which had allowed the brine solution to run into them before the readings were made.

Figure 4.8.5.1 Average of top ten diagonal readings for all sections of DEL-23 AC

Figure 4.8.5.2 Average of ten nozzle readings for all sections of DEL-23 AC
4.9 ATH-33 AC results

4.9.1 Traffic, time, and weather data for ATH-33 AC

The asphalt pavement of ATH-33 was micro graded and it was in excellent condition. Table 4.9.1.1 summarizes the time, traffic and weather data of ATH-33 AC for 48 hours time period.

Table 4.9.1.1 Traffic, time and weather data for ATH-33 AC (Mitchell et al., March 2003)

<table>
<thead>
<tr>
<th>ATH33 AC November 13-15 2002</th>
<th>Data Collection Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Hrs</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic #vehicles</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative Traffic Hrs</td>
<td>0</td>
</tr>
<tr>
<td>Average Air Temperature (°C)</td>
<td>6.25</td>
</tr>
<tr>
<td>Average Pavement Temperature (°C)</td>
<td>10.83</td>
</tr>
<tr>
<td>Maximum Daily Humidity (%)</td>
<td>96.50</td>
</tr>
<tr>
<td>Average Daily Humidity (%)</td>
<td>69.29</td>
</tr>
</tbody>
</table>

4.9.2 Graphical profiles of salt concentration across lane width for ATH-33 AC

In this section, the diagonal profiles of ATH-33 AC are presented for each test section. The diagonal graphs of all of the sampling locations are shown in the same figure to consume less space. However, the individual presentation of the diagonal profile graphs for each sampling location is provided in Appendix-1 for all of the test sites. The following representative charts (Figures 4.9.2.1-4.9.2.5) describe the test sections A-E of ATH-33 AC. They present the nine diagonal profiles made for all of the test sections except E (section E has five profiles) over 48 hours of traffic exposure. The diagonals were 20 feet long for sections A and B, while they were 30 feet long for sections C, D and E.
As can be seen from the diagonal profiles of five of the sections (Figures 4.9.2.1-4.9.2.5) salt dissipated very slowly for this test site. Based on this reason, the tests were run for a 48 hour time period till the SOBO 20 could not detect any salt on the pavement. ATH-33 AC was the test site, which the tests were conducted for the longest time.

The places of the ten nozzle salt trails can be easily determined from Figures 4.9.2.1-4.9.2.5 for the zero (0) hour sampling period (since the highest salt densities on the diagonal profile graphs are the salt trails where the brine was applied to). In addition, the distances between each salt trail can be seen from the same figures for the 0 hour sampling period.

Figure 4.9.2.1 Diagonal profile of ATH-33 AC for section A
Figure 4.9.2.2 Diagonal profile of ATH-33 AC for section B

Figure 4.9.2.3 Diagonal profile of ATH-33 AC for section C
Figure 4.9.2.4 Diagonal profile of ATH-33 AC for section D

Figure 4.9.2.5 Diagonal profile of ATH-33 AC for section E
4.9.3 Frequency of occurrence of the diagonal readings for ATH-33 AC

The frequency of occurrence dot plots that show the evolution of the profiles for test sections A, B, C and D versus time are presented in the following figures (Figure 4.9.3.1-4.9.3.4). As can be seen from the figures, nine sampling periods were used because of the slow dissipation of the salt residual due to the smooth surface of ATH-33 AC. The tests would have taken even more time (even 10-12 sampling periods would be used), however; rain started during the ninth sampling period and washed all of the salt away. The complete salt dissipation can be observed from the ninth sampling period of the following dot plots (Figures 4.9.3.1-4.9.3.4).

Figures 4.9.3.1-4.9.3.4 present that there is a large amount of salt concentration decrease between the 4th and the 5th sampling period due to 15 hour time difference between these two test periods. In addition, figures 4.9.3.1 to 4.9.3.4 show that the salt concentrations on the 6th, 7th and 8th sampling periods are larger compared to the readings obtained in the 5th sampling period. This is due to the process called hydrogroscopicity which allowed the salt absorb the humid air all throughout the night and this diluted the concentration of the salt on the pavement. Through time, the salt trails dried out and higher readings were obtained for the rest of the sampling periods.

The salt dissipation occurred rather slowly in ATH-33 AC compared to the other test sites. This can be explained by the excellent pavement condition of this test site.

Based on the reason that the tests were not conducted on all of the sampling locations for section E of ATH-33 AC, the frequency of occurrence graph was not drawn.
Anti-Icing Brine Application Study
Test Section A
US 33 - Micro Seal Asphalt
November 13 & 14, 2002

Figure 4.9.3.1 Frequency of occurrence ATH-33 AC brine data for section A
Figure 4.9.3.2 Frequency of occurrence ATH-33 AC brine data for section B
Figure 4.9.3.3 Frequency of occurrence ATH-33 AC brine data for section C
Figure 4.9.3.4 Frequency of occurrence ATH-33 AC brine data for section D
4.9.4 Nozzle readings on the ten salt trails for ATH-33 AC

In this section, the decay of the salt concentration of ATH-33 AC versus sampling locations for all of the nozzle numbers is shown. The figures 4.9.4.1-4.9.4.5 present the bar graphs of the ten nozzle tests for ATH-33 AC.

Similar to frequency of occurrence graphs, the nozzle bar charts (4.9.4.1-4.9.4.5), also show that the salt concentration on the brine trails decreased a certain amount during the fifth sampling period compared to the previous sampling period because of the 15 hours of traffic exposure overnight. As mentioned earlier, another reason of the salt depletion is because overnight, the crystallized salt drew moisture from the humid night air. Sodium chloride absorbed the water under cool humid conditions due to hygroscopicity, which helped to dilute the salt concentration of the pavement (SU Online, October 2003). The brine lines were visually white in the daytime but they were dark black in the morning during the fifth sampling period due to hygroscopicity.

Figures 4.9.4.1 to 4.9.4.5 present that total salt dissipation did not occur even at the last sampling location. Smooth surface structure of the pavement is responsible for this. Tests were planning to be conducted for one more sampling location, however, rain event prevented the researchers to continue.
Figure 4.9.4.1 Ten spot readings of ATH-33 AC for section A

Figure 4.9.4.2 Ten spot readings of ATH-33 AC for section B
Figure 4.9.4.3 Ten spot readings of ATH-33 AC for section C

Figure 4.9.4.4 Ten spot readings of ATH-33 AC for section D
4.9.4.5 Ten spot readings of ATH-33 AC for section E

The evolution of the salt concentration for each nozzle through time is presented in Appendix-2 for each sampling location of each section of the four test sites (DEL-23 AC, DEL-23 PCC, ATH-33 AC and ATH-50 AC).

4.9.5 Comparison of the accuracy of the data by “ten spot means” and “average of top ten diagonal readings” for ATH-33 AC

The averages of the top ten diagonal readings and the ten nozzle readings of ATH-33 AC for sections A through D versus time are presented in Figures 4.9.5.1 and 4.9.5.2, respectively. It can be seen from both of these figures that the average overall concentration is greater than 7 g/m² up to 2000 cumulative traffic for the air temperatures between 5-10°C. This means that ice prevention is effective till the fifth sampling period. The pavement surface must be responsible for the salt concentration to stay on the surface for this long.
As expected, the trends of both of the graphs are very similar. The concentrations of all of the sections (A-D) for all of the sampling periods coincided, which proves the accuracy of the tests and the SOBO 20.

Based on the reason that the tests were not conducted on all of the sampling locations for section E of ATH-33 AC, the average diagonal and nozzle readings of it were not included in the figures 4.9.5.1 and 4.9.5.2.

Figure 4.9.5.1 Average of top ten diagonal readings for all sections of ATH-33 AC
4.1.0 Interpretation of results for field study

4.1.0.1 Theoretical and actual sodium chloride (NaCl) concentrations

The theoretical salt concentration that should be on the pavement just after the brine application is calculated in this section. The calculation is done based on the 40 gallon/lane\*mile application rate of ODOT. The average salt concentration used was 23.97\%, which corresponded to 278 gram of salt per liter of solution and therefore, 42 kg of salt per 40 gallons of solution. The following calculation was done as an example to show how to find the theoretical salt density based on each brine line.

\[
(42 \text{ kg/lane*mile}) \times (1000 \text{ gr/1 kg}) \times (1 \text{ lane/12 feet}) \times (\text{ total nozzle width in feet} / 0.3048 \text{ m}) \times (1 \text{ mile/1.609 kilometer}) \times (1 \text{ km/1000meter}) = \text{ actual salt concentration just after brine application (gr/m}^2\text{)}
\]

Figure 4.9.5.2 Average of ten nozzle readings for all sections of ATH-33 AC
Table 4.10.1.1 presents the average line widths at each individual field pavement site and for average line width at all sites. In addition, it also shows the theoretical salt concentration on each of the test sites just after the application of the brine solution.

Table 4.10.1.1 Theoretical NaCl concentration on each of the test sites

<table>
<thead>
<tr>
<th>Sites</th>
<th>Total nozzle length (cm)</th>
<th>Total nozzle length (feet)</th>
<th>Theoretical salt concentration (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-23 AC</td>
<td>31.5</td>
<td>1.03</td>
<td>7.38</td>
</tr>
<tr>
<td>DEL-23 PCC</td>
<td>41.5</td>
<td>1.36</td>
<td>9.72</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>35.5</td>
<td>1.16</td>
<td>8.31</td>
</tr>
<tr>
<td>ATH-50 AC</td>
<td>26</td>
<td>0.85</td>
<td>6.09</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>23</td>
<td>0.75</td>
<td>5.39</td>
</tr>
<tr>
<td>Average nozzle length</td>
<td>31.5</td>
<td>1.03</td>
<td>7.38</td>
</tr>
</tbody>
</table>

Therefore, the brine application should have resulted in a salt concentration of approximately 7.38 g/m² if the brine solution was applied uniformly on the 12 feet lanes.

In this study, the results of the nozzle and diagonal tests indicate that many of the salt trails survived fairly well based on the 7 g/m² criterion.

4.10.2 Variability of the pavements of the studied sites

As mentioned in the methodology part of this thesis study, the concrete pavements of ATH-50 and DEL-23 were transversely grooved portland cement concrete. The asphalt pavement of ATH-50 was nova chip bituminous asphalt cement concrete while the asphalt pavement of DEL-23 was highly porous crushed limestone aggregate bituminous asphalt cement concrete. In addition, the asphalt pavement of ATH-33 was microseal bituminous asphalt cement concrete.

For all of the studied sites, the salt concentration declined through time and traffic, however; pavement variability affected the variability of the data.
Figure 4.10.2.1 indicates the initial difference found between the very porous asphalt and the concrete pavements of DEL-23 just after the brine application. As can be seen from Figure 4.10.2.1, all initial salt concentrations for the asphalt pavement of DEL-23 were below 11 g/m² while the salt residuals outside the mean concentrations were up to 35 g/m² for the concrete pavement of DEL-23. In addition, the average of the initial concentrations of the DEL-23 PCC were approximately twice that of the average initial concentrations of DEL-23 AC, as shown by Figure 4.10.2.1. The porosity of the asphalt pavement was attributed to creating variability in the measurements of the salt density throughout the tests conducted at DEL-23 AC.

US 23 Brine Study Initial Concentrations
Asphalt Cement and Portland Cement Concrete Comparison

Figure 4.10.2.1 Variation in initial salt densities on DEL-23 AC and DEL-23 PCC prior to traffic (Mitchell et al., March 2003)
Figure 4.10.2.2 presents the comparison of the average initial salt densities for all sections of each test site. The differences of the average initial salt concentrations prove the significance of the pavement type. DEL-23 PCC and ATH-33 AC both had initial average brine concentrations of approximately 18 g/m². ATH-50 PCC and the ATH-50 AC had average initial brine concentrations of 8 and 7 gr/m² respectively and therefore, were next in order of average initial salt density. In addition, the average salt concentrations of ATH-50 PCC and ATH-50 AC were approximately 60% less than the average salt concentrations of DEL-23 PCC and ATH-33 AC. The lowest average initial salt residual concentration was measured on the DEL-23 AC and it was approximately 4.5 g/m².

Anti-Icing Brine Study
Variation in Initial Concentration
As Represented by Top 10 Diagonal Concentrations

Figure 4.10.2.2 Variation in average initial salt densities for all of the studied five sites prior to traffic (Mitchell et al., March 2003)
4.10.3 Comparisons of the results of the five test sites

This section compares the salt dissipation of the studied test sites versus exposed time and traffic. Figures 4.10.3.1 and 4.10.3.2 present the average ten nozzle data and the average highest ten diagonal data versus cumulative traffic for all sites except ATH-50 PCC. ATH-50 PCC was not included in these graphs due to the lack of nozzle data.

As can be seen from figures 4.10.3.1 and 4.10.3.2, the salt concentrations measured just after the application of brine solution were highest for ATH-33 AC and DEL-23 PCC (approximately 18 g/m²). Both of the average initial concentrations dropped around 65% when exposed to 2000 traffic. ATH-50 AC had initial average salt concentration of approximately 6.5-7 g/m² according to Figures 4.10.3.1 and 4.10.3.2. In addition, ATH-50 AC showed a rapid decline of approximately 50% when exposed to 1000 cumulative traffic. DEL-23 AC was the site which had the lowest average initial salt density of around 4 g/m² according to Figures 4.10.3.1 and 4.10.3.2. However, average salt concentration of DEL-23 AC remained the same till about 2000 cumulative traffic and showed a rapid decline of around 80% between 2000 and 6000 cumulative traffic. Overall, only ATH-33 AC maintained salt concentrations of around 7 g/m² throughout the study, even after being exposed to 12,000 cumulative traffic. Therefore, ATH-33 AC was successful in keeping the required salt density that can preclude ice formation for the entire testing period.
Figure 4.10.3.1 Average of ten nozzle readings for all sections of the studied test sites as a function of cumulative traffic.

Average highest 10 diagonal readings vs traffic for all of the test sites

Figure 4.10.3.2 Average of top ten diagonal readings for all sections of the studied test sites as a function of cumulative traffic.
The following figures (Figure 4.10.3.3 & 4.10.3.4) present the average ten nozzle data and the average highest ten diagonal data versus cumulative time for the entire test sites.

Similar to the results obtained from Figures 4.10.3.1 and 4.10.3.2, Figures 4.10.3.3 and 4.10.3.4 also show that ATH-33 AC keeps a salt residual of around 7 g/m² all throughout the study. In addition, Figures 4.10.3.3 and 4.10.3.4 present that DEL-23 PCC maintained a salt residual of at least 10 g/m² till six hours of time exposure while ATH-50 PCC maintained at least 6 g/m². Moreover, even after being exposed to 24 hours time, the salt residual of ATH-50 PCC was 7 g/m² (complete salt dissipation was not measured for ATH-50 PCC due to the failure of the traffic control). It can be observed from the figures (4.10.3.3 & 4.10.3.4) that the salt residual of DEL-23 PCC showed a rapid decline after the initial salt measurement till the end of the test study (from 0 hours to 17 hours of traffic exposure). Similar to the results obtained from Figures 4.10.3.1 and 4.10.3.2, Figures 4.10.3.3 & 4.10.3.4 also show that the minimum of the average initial salt concentration was for DEL-23 AC. Del-23 AC maintained the same salt level till 8 hours and decreased around 80% at 20 hours of time exposure.
Average highest 10 diagonal readings vs traffic for all of the test sites

![Graph showing average of top ten diagonal readings for all sections of the studied test sites as a function of cumulative time.]

Figure 4.10.3.3 Average of top ten diagonal readings for all sections of the studied test sites as a function of cumulative time

Average ten nozzle readings vs traffic for all of the test sites

![Graph showing average of ten nozzle readings for all sections of the studied test sites as a function of cumulative time.]

Figure 4.10.3.4 Average of ten nozzle readings for all sections of the studied test sites as a function of cumulative time
4.10.4 Estimation of decline of salt residual versus time and traffic on the test sites

For DEL-23 PCC, Figures 4.10.4.1 – 4.10.4.4 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of time and traffic, respectively. According to these graphs (Figures 4.10.4.1 – 4.10.4.4), a total decline in salt concentration occurred after about six hours of traffic and corresponding cumulative traffic of about 1700.

Figure 4.10.4.1 DEL-23 PCC Cumulative time vs. average highest ten diagonal readings for all sections and sampling locations
Average Highest Ten Diagonal Readings vs Cumulative Traffic for DEL-23 PCC

Figure 4.10.4.2 DEL-23 PCC Cumulative traffic vs. average highest ten diagonal readings for all sections and sampling locations

Average Ten Nozzle Readings vs Cumulative Time for DEL-23 PCC

Figure 4.10.4.3 DEL-23 PCC Cumulative time vs. average ten nozzle readings for all sections and sampling locations
Figure 4.10.4.4 DEL-23 PCC Cumulative traffic vs. average ten nozzle readings for all sections and sampling locations

For DEL-23 AC, Figures 4.10.4.5 – 4.10.4.8 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of time and traffic, respectively. According to these graphs (Figures 4.27.4.5 – 4.27.4.8), the initial salt concentrations were very low for this test site and a rapid decline of brine occurred at two hours which corresponds to approximately 1800 cumulative traffic. However, as mentioned earlier, because of the high porosity of the asphalt pavement of DEL-23 AC, there is variability in the salt residual readings for this site.
Figure 4.10.4.5 DEL-23 AC Cumulative time vs. average highest ten diagonal readings for all sections and sampling locations

Figure 4.10.4.6 DEL-23 AC Cumulative traffic vs. average highest ten diagonal readings for all sections and sampling locations
Figure 4.10.4.7 DEL-23 AC Cumulative time vs. average ten nozzle readings for all sections and sampling locations

Figure 4.10.4.8 DEL-23 AC Cumulative traffic vs. average ten nozzle readings for all sections and sampling locations
For ATH-33 AC, Figures 4.10.4.9 – 4.10.4.12 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of time and traffic, respectively. According to these graphs (Figures 4.10.4.9 – 4.10.4.12), the salt dissipation occurred slowly and the salt concentration remained more than approximately 6.5 g/m² till 48 hours and 11,214 vehicles.

![Graph of Average Highest Ten Diagonal Readings vs Cumulative Time for ATH-33 AC](image)

Figure 4.10.4.9 ATH-33 AC Cumulative time vs. average highest ten diagonal readings for all sections and sampling locations
Figure 4.10.4.10 ATH-33 AC Cumulative traffic vs. average highest ten diagonal readings for all sections and sampling locations

Figure 4.10.4.11 ATH-33 AC Cumulative time vs. average ten nozzle readings for all sections and sampling locations
Figure 4.10.4.12 ATH-33 AC Cumulative traffic vs. average ten nozzle readings for all sections and sampling locations

For ATH-50 PCC, Figures 4.10.4.13 and 4.10.4.14 present the equations of best fit for the averages of the highest ten diagonal concentrations as a function of time and traffic, respectively. Average ten nozzle readings versus time and traffic are not included for ATH-50 PCC due to lack of data. According to these graphs (Figures 4.10.4.13 and 4.10.4.14), the salt concentration varied randomly over 24 hours time exposure. In addition, it can easily seen from these graphs (Figures 4.10.4.13 and 4.10.4.14) that the salt concentration is above 6.5 g/m² even after being exposed to 3500 cumulative traffic and 24 hours cumulative time.
Figure 4.10.4.13 ATH-50 PCC Cumulative time vs. average highest ten diagonal readings for all sections and sampling locations

Figure 4.10.4.14 ATH-50 PCC Cumulative traffic vs. average highest ten diagonal readings for all sections and sampling locations
For ATH-50 AC, Figures 4.10.4.15 – 4.10.4.18 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of time and traffic, respectively. According to these graphs (Figures 4.10.4.15 – 4.10.4.18), the mean salt concentrations obtained from the top ten diagonal and the ten nozzle tests showed a very rapid decline. The average salt residuals dropped to 1-2 g/m² in less than 5 hours and 1000 cumulative traffic.

![Graph showing average highest ten diagonal readings vs cumulative time for ATH-50 AC](image)

**Figure 4.10.4.15** ATH-50 AC Cumulative time vs. average highest ten diagonal readings for all sections and sampling locations
Average Highest Ten Diagonal Readings vs Cumulative Traffic for ATH-50 AC

\[ y = -1510.1 \ln(x) + 1954.2 \]

\[ y = -1726.3 \ln(x) + 1765.3 \]

Figure 4.10.4.16 ATH-50 AC Cumulative traffic vs. average highest ten diagonal readings for all sections and sampling locations

Average Ten Nozzle Readings vs Cumulative Time for ATH-50 AC

\[ y = -7.6858 \ln(x) + 11.524 \]

\[ y = -5.1445 \ln(x) + 7.1389 \]

Figure 4.10.4.17 ATH-50 AC Cumulative time vs. average ten nozzle readings for all sections and sampling locations
Finally, Table 4.10.4.1 summarizes the best fit salt dissipation equations as a function of time and traffic. It lists all the equations that are obtained from figures 4.10.4.1 to 4.10.4.18. The equations were calculated by Microsoft Excel Computer Program by drawing a best fit trendline of the cumulative time (or cumulative traffic) versus concentration data. As can be seen from Table 4.10.4.1, the equations obtained using top ten diagonals and ten nozzle methods are similar to each other. This means that the results coincided with what was being expected.
Table 4.10.4.1 Salt dissipation equations as a function of time and traffic

<table>
<thead>
<tr>
<th>Test type</th>
<th>Test Site</th>
<th>SOBO 20 Reading (Salt Concentration, g/m²) Decay Equation as a Function of Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Ten Diagonal Tests</td>
<td>DEL-23 PCC</td>
<td>Time = -6.8 * Ln (Concentration) + 14.9</td>
</tr>
<tr>
<td></td>
<td>DEL-23 AC</td>
<td>Time = -9.3 * Ln (Concentration) + 12.3</td>
</tr>
<tr>
<td></td>
<td>ATH-33 AC</td>
<td>Time = -23.1 * Ln (Concentration) + 59</td>
</tr>
<tr>
<td></td>
<td>ATH-50 PCC</td>
<td>Time = -18.77 * Ln (Concentration) + 42.6</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (A)</td>
<td>Time = -9.6 * Ln (Concentration) + 9.8</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (B)</td>
<td>Time = -7.8 * Ln (Concentration) + 9.9</td>
</tr>
<tr>
<td>Ten Nozzle Tests</td>
<td>DEL-23 PCC</td>
<td>Time = -5.75 * Ln (Concentration) + 15.44</td>
</tr>
<tr>
<td></td>
<td>DEL-23 AC</td>
<td>Time = -6.6 * Ln (Concentration) + 11.3</td>
</tr>
<tr>
<td></td>
<td>ATH-33 AC</td>
<td>Time = -23 * Ln (Concentration) + 65.75</td>
</tr>
<tr>
<td></td>
<td>ATH-50 PCC</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (A)</td>
<td>Time = -7.7 * Ln (Concentration) + 11.5</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (B)</td>
<td>Time = -5.14 * Ln (Concentration) + 7.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test type</th>
<th>Test Site</th>
<th>SOBO 20 Reading (Salt Concentration, g/m²) Decay Equation as a Function of Traffic (# of vehicles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Ten Diagonal Tests</td>
<td>DEL-23 PCC</td>
<td>Traffic = -2547 * Ln (Concentration) + 5919</td>
</tr>
<tr>
<td></td>
<td>DEL-23 AC</td>
<td>Traffic = -3385 * Ln (Concentration) + 4623</td>
</tr>
<tr>
<td></td>
<td>ATH-33 AC</td>
<td>Traffic = -5755 * Ln (Concentration) + 14852</td>
</tr>
<tr>
<td></td>
<td>ATH-50 PCC</td>
<td>Traffic = -1913.9 * Ln (Concentration) + 4685</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (A)</td>
<td>Traffic = -1726 * Ln (Concentration) + 1765</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (B)</td>
<td>Traffic = -1510 * Ln (Concentration) + 1954</td>
</tr>
<tr>
<td>Ten Nozzle Tests</td>
<td>DEL-23 PCC</td>
<td>Traffic = -2123 * Ln (Concentration) + 6082</td>
</tr>
<tr>
<td></td>
<td>DEL-23 AC</td>
<td>Traffic = -2389 * Ln (Concentration) + 4260</td>
</tr>
<tr>
<td></td>
<td>ATH-33 AC</td>
<td>Traffic = -5806 * Ln (Concentration) + 16537</td>
</tr>
<tr>
<td></td>
<td>ATH-50 PCC</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (A)</td>
<td>Traffic = -1385 * Ln (Concentration) + 2076</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (B)</td>
<td>Traffic = -1022 * Ln (Concentration) + 1475</td>
</tr>
</tbody>
</table>

Two examples of the use of the salt dissipation equations are shown below.

**Example 1:** What will be the residual salt concentration in DEL-23 PCC 20 hours after the brine application?

**Answer:**

According to “Top Ten diagonal Test Equation”

\[
\text{Salt Residual concentration (g/m}^2\text{)} = \exp \left\{ \frac{(20-14.9)}{-6.8} \right\}
\]

\[
= 0.472 \text{g/m}^2
\]
According to “Ten Nozzle Test Equation”

Salt Residual concentration (g/m$^2$) = \( \exp \{(20-15.44)/-5.75\} \)

\[ = 0.452 \text{ g/m}^2 \]

**Example 2:** What will be the residual salt concentration in DEL-23 PCC after 7000 vehicles of traffic exposure just after the brine application?

**Answer:**

According to “Top Ten diagonal Test Equation”

Salt Residual concentration (g/m$^2$) = \( \exp \{(7000-5919)/-2547\} \)

\[ = 0.654 \text{ g/m}^2 \]

According to “Ten Nozzle Test Equation”

Salt Residual concentration (g/m$^2$) = \( \exp \{(7000-6082)/-2123\} \)

\[ = 0.649 \text{ g/m}^2 \]
4.10.5 Estimation of decline of salt residual versus temperature on the test sites

For DEL-23 PCC, Figures 4.10.5.1 and 4.10.5.2 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of pavement temperature. According to these graphs (Figures 4.10.5.1 – 4.10.4.2), a total decline in salt concentration occurred at pavement temperature of around 5°C for DEL-23 PCC.

Figure 4.10.5.1 DEL-23 PCC Temperature vs. average highest ten diagonal readings for all sections and sampling locations
Figure 4.10.5.2 DEL-23 PCC Temperature vs. average ten nozzle readings for all sections and sampling locations

For DEL-23 AC, Figures 4.10.5.3 and 4.10.5.4 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of pavement temperature. According to these graphs (Figures 4.10.5.3 – 4.10.5.4), a total decline in salt concentration occurred at pavement temperature of around 3°C. As mentioned earlier, the salt concentrations are low for this test site. Due to the high porosity of the asphalt pavement of DEL-23 AC, there is variability in the salt residual readings.
Figure 4.10.5.3 DEL-23 AC Temperature vs. average highest ten diagonal readings for all sections and sampling locations

Figure 4.10.5.4 DEL-23 AC Temperature vs. average ten nozzle readings for all sections and sampling locations
For ATH-33 AC, Figures 4.10.5.5 and 4.10.5.6 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of pavement temperature. According to these graphs (Figures 4.10.5.5 – 4.10.5.6), a total decline in salt concentration occurred very slowly and at pavement temperature of around 4.5°C for ATH-33 AC.

Figure 4.10.5.5 ATH-33 AC Temperature vs. average highest ten diagonal readings for all sections and sampling locations
Figure 4.10.5.6 ATH-33 AC Temperature vs. average ten nozzle readings for all sections and sampling locations

For ATH-50 PCC, Figure 4.10.5.7 presents the equation of best fit for the averages of the highest ten diagonal concentrations as a function of pavement temperature. Average ten nozzle readings versus pavement temperature are not included for ATH-50 PCC due to lack of data. According to this graph (Figures 4.10.5.7), the salt concentration varied randomly and a total decline in salt concentration occurred at a pavement temperature of around 12°C. As can be seen, in this test site (ATH-50 PCC), the temperature which the salt has dissipated is higher compared to the other test sites.
Figure 4.10.5.7 ATH-50 PCC Temperature vs. average highest ten diagonal readings for all sections and sampling locations

For ATH-50 AC, Figures 4.10.5.8 and 4.10.5.9 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of pavement temperature. According to these graphs (Figures 4.10.5.8 – 4.10.5.9), a total decline in salt concentration occurred at pavement temperature of between 4-7°C for Station A and at around 0°C for Stations B and C. As can be seen, the graphs of temperature vs. average ten nozzle readings and temperature vs. average top ten diagonal readings are not very similar for this test site (ATH-50 AC). This may be due to the incorrect use of the temperature gun in this test site or sudden changes in the weather temperature.
Figure 4.10.5.8 ATH-50 AC Temperature vs. average highest ten diagonal readings for all sections and sampling locations

Average Highest Ten Diagonal Readings vs Pavement Temperature for ATH-50 AC

\[ y = 2.2661 \ln(x) + 5.543 \]

\[ y = -7.3429 \ln(x) + 12.47 \]

Figure 4.10.5.9 ATH-50 AC Temperature vs. average ten nozzle readings for all sections and sampling locations

Average Ten Nozzle Readings vs Pavement Temperature for ATH-50 AC

\[ y = 1.9858 \ln(x) + 5.0187 \]

\[ y = -3.5716 \ln(x) + 8.1773 \]
Figure 4.10.5.10 and 4.10.5.11 summarizes data for concrete and asphalt pavements by presenting the average concentrations of “Ten Nozzle Test” and “Top Ten Diagonal” test readings versus average pavement temperature. Figure 4.10.5.10 shows that the average pavement temperature readings were higher for ATH-50 PCC compared to DEL-23 PCC. Figure 4.10.5.11 shows that DEL-23 AC and ATH-50 AC-A has parallel decay equation trendlines which means their salt decay trends are similar to each other and their graphs would have overlapped if the pavement temperature for both of them were the same.
SUMMARY GRAPH for PCC

Average of "Ten Nozzle Test" and "Top Ten Diagonal Test" NaCl Concentrations versus Pavement Temperature for PCC

Figure 4.10.5.10 Summary graph of PCC for pavement temperature

\[ y = 2.2401 \ln(x) + 6.4589 \]

\[ y = 3.8584 \ln(x) + 12.812 \]
SUMMARY GRAPH for AC
Average of "Ten Nozzle Test" and "Top Ten Diagonal Test" NaCl Concentrations versus Pavement Temperature for AC

\[
y = -2.5918 \ln(x) + 13.949 \\
y = 6.1172 \ln(x) + 1.2434 \\
y = 3.1396 \ln(x) + 5.4215 \\
y = 2.3838 \ln(x) + 5.0347
\]

Figure 4.10.5.11 Summary graph of AC for pavement temperature
Finally, Table 4.10.5.1 summarizes the best fit salt dissipation equations as a function of pavement temperature. It lists all the equations that are obtained from figures 4.10.5.1 to 4.10.5.9.

**Table 4.10.5.1 Salt dissipation equations as a function of pavement temperature**

<table>
<thead>
<tr>
<th>Test type</th>
<th>Test Site</th>
<th>SOBO 20 Reading (Salt Concentration, g/m²) Decay Equation as a Function of Pavement Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Top Ten Diagonal Tests</strong></td>
<td>DEL-23 PCC</td>
<td>Temperature = 2.4 * Ln (Concentration) + 6.7</td>
</tr>
<tr>
<td></td>
<td>DEL-23 AC</td>
<td>Temperature = 3.66 * Ln (Concentration) + 5.3</td>
</tr>
<tr>
<td></td>
<td>ATH-33 AC</td>
<td>Temperature = 5.6 * Ln (Concentration) + 3.16</td>
</tr>
<tr>
<td></td>
<td>ATH-50 PCC</td>
<td>Temperature = 2.1 * Ln (Concentration) + 14.9</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (A)</td>
<td>Temperature = 2.27 * Ln (Concentration) + 5.54</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (B&amp;C)</td>
<td>Temperature = 7.4 * Ln (Concentration) + 12.47</td>
</tr>
<tr>
<td><strong>Ten Nozzle Tests</strong></td>
<td>DEL-23 PCC</td>
<td>Temperature = 2.1 * Ln (Concentration) + 6.32</td>
</tr>
<tr>
<td></td>
<td>DEL-23 AC</td>
<td>Temperature = 2.711 * Ln (Concentration) + 5.6</td>
</tr>
<tr>
<td></td>
<td>ATH-33 AC</td>
<td>Temperature = 6.5 * Ln (Concentration) - 0.35</td>
</tr>
<tr>
<td></td>
<td>ATH-50 PCC</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (A)</td>
<td>Temperature = 1.98 * Ln (Concentration) + 5.02</td>
</tr>
<tr>
<td></td>
<td>ATH-50 AC (B&amp;C)</td>
<td>Temperature = -3.57 * Ln (Concentration) + 8.18</td>
</tr>
</tbody>
</table>

An example on the use of the salt dissipation equations is shown below.

**Example:** What will be the residual salt concentration in DEL-23 PCC when the pavement temperature is 10°C?

**Answer:**

According to “Top Ten diagonal Test Equation”

Salt Residual concentration (g/m²) = \( \exp \left\{ \frac{(10-6.7)}{2.4} \right\} \)

\[ = \frac{3.96}{g/m^2} \]

According to “Ten Nozzle Test Equation”

Salt Residual concentration (g/m²) = \( \exp \left\{ \frac{(10-6.32)}{2.1} \right\} \)

\[ = \frac{5.77}{g/m^2} \]
4.10.6 Estimation of decline of salt residual versus humidity on the test sites

For DEL-23 PCC, Figures 4.10.6.1 and 4.10.6.2 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of average humidity. According to these graphs (Figures 4.10.6.1 – 4.10.6.2), a total decline in salt concentration occurred at average humidity of around %39.1 for DEL-23 PCC.

Figure 4.10.6.1 DEL-23 PCC Humidity vs. average highest ten diagonal readings for all sections and sampling locations
Figure 4.10.6.2 DEL-23 PCC Humidity vs. average ten nozzle readings for all sections and sampling locations

For DEL-23 AC, Figures 4.10.5.3 and 4.10.5.4 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of average humidity. According to these graphs (Figures 4.10.6.3 – 4.10.6.4), a total decline in salt concentration occurred also at average humidity of around % 39.
Average Highest Ten Diagonal Readings vs Humidity for DEL-23 AC

![Graph showing the relationship between average highest ten diagonal readings and average humidity for DEL-23 AC.]

\[ y = -0.8123 \ln(x) + 39.343 \]

Figure 4.10.6.3 DEL-23 AC Humidity vs. average highest ten diagonal readings for all sections and sampling locations

Average Ten Nozzle Readings vs Humidity for DEL-23 AC

![Graph showing the relationship between average ten nozzle readings and average humidity for DEL-23 AC.]

\[ y = -0.5887 \ln(x) + 39.272 \]

Figure 4.10.6.4 DEL-23 AC Humidity vs. average ten nozzle readings for all sections and sampling locations
For ATH-33 AC, Figures 4.10.5.5 and 4.10.5.6 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of average humidity. According to these graphs (Figures 4.10.6.5 - 4.10.6.6), a total decline in salt concentration occurred very slowly and at average humidity of around 84% for ATH-33 AC.

**Average Highest Ten Diagonal Readings vs Humidity for ATH-33 AC**

![Graph showing the relationship between average humidity and average highest ten diagonal readings for ATH-33 AC. The equation is \( y = -5.9808 \ln(x) + 83.395 \).]

Figure 4.10.6.5 ATH-33 AC Humidity vs. average highest ten diagonal readings for all sections and sampling locations
Average Ten Nozzle Readings vs Humidity for ATH-33 AC

![Graph showing the relationship between average concentration and average humidity.](image)

\[ y = -5.961 \ln(x) + 84.988 \]

Figure 4.10.6.6 ATH-33 AC Humidity vs. average ten nozzle readings for all sections and sampling locations

For ATH-50 PCC, Figure 4.10.6.7 presents the equation of best fit for the averages of the highest ten diagonal concentrations as a function of average humidity. Average ten nozzle readings versus pavement temperature are not included for ATH-50 PCC due to lack of data. According to this graph (Figures 4.10.6.7), the salt concentration varied randomly and a total decline in salt concentration occurred at an average humidity of around 96%. As can be seen, in this test site (ATH-50 PCC), the average humidity which the salt has dissipated is higher compared to the other test sites.
Figure 4.10.6.7 ATH-50 PCC Humidity vs. average highest ten diagonal readings for all sections and sampling locations

For ATH-50 AC, Figures 4.10.6.8 and 4.10.6.9 present the equations of best fit for the averages of the highest ten diagonal concentrations and the averages of the ten nozzle concentrations as a function of average humidity. According to these graphs (Figures 4.10.6.8 – 4.10.6.9), a total decline in salt concentration occurred at average humidity of %79.23 for Station A and at %82.3 for Stations B and C. As can be seen, the graphs of average humidity vs. average ten nozzle readings and average humidity vs. average top ten diagonal readings are a horizontal line for Station B and C of this test site (ATH-50 AC). This shows that the humidity of the environment stayed the same (%82.3) throughout the test time for B&C Stations of ATH-50 AC.
Figure 4.10.6.8 ATH-50 AC Humidity vs. average highest ten diagonal readings for all sections and sampling locations

Figure 4.10.6.9 ATH-50 AC Humidity vs. average ten nozzle readings for all sections and sampling locations
Figure 4.10.6.10 and 4.10.6.11 summarizes data for concrete and asphalt pavements by presenting the average concentrations of “Ten Nozzle Test” and “Top Ten Diagonal” test readings versus average humidity. Figure 4.10.6.10 shows that the average humidity readings were higher for ATH-50 PCC compared to DEL-23 PCC. Figure 4.10.6.11 shows that ATH-50 AC-A had lower humidity percentages compared to ATH-50-B&C. DEL-23 AC was the test site where the humidity was the lowest compared to other asphalt test sites. The highest top ten diagonal test decay equation was presented for ATH-50 PCC and it was not combined with the ten nozzle test decay equation. This is due to the reason that ten nozzle tests were not conducted for ATH-50 PCC.
SUMMARY GRAPH for PCC
Average of "Ten Nozzle Test" and "Top Ten Diagonal Test" NaCl
Concentrations versus Humidity for PCC

\[ y = -12.492 \ln(x) + 94.216 \]
\[ y = -0.2715 \ln(x) + 39.131 \]

Figure 4.10.6.10 Summary graph of PCC for humidity
SUMMARY GRAPH for AC
Average of "Ten Nozzle Test" and "Top Ten Diagonal Test" NaCl Concentrations versus Humidity for AC

\[ y = -1E-14 \ln(x) + 82.3 \]
\[ y = 2.9142 \ln(x) + 78.91 \]
\[ y = -6.0086 \ln(x) + 84.329 \]
\[ y = -0.6864 \ln(x) + 39.315 \]

- DEL-23 AC
- ATH-33 AC
- ATH-50 AC-A
- ATH-50 AC-B&C

Figure 4.10.6.11 Summary graph of AC for humidity
Finally, Table 4.10.6.1 summarizes the best fit salt dissipation equations as a function of average humidity.

**Table 4.10.6.1 Salt dissipation equations as a function of average humidity**

<table>
<thead>
<tr>
<th>Test Site</th>
<th>SOBO 20 Reading (Salt Concentration, g/m²) Decay Equation as a Function of Average Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-23 PCC</td>
<td>Humidity = -0.2847 * Ln (Concentration) + 39.04</td>
</tr>
<tr>
<td>DEL-23 AC</td>
<td>Humidity = -0.8123 * Ln (Concentration) + 39.343</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>Humidity = -5.908 * Ln (Concentration) + 83.4</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>Humidity = -11.268 * Ln (Concentration) + 95.907</td>
</tr>
<tr>
<td>ATH-50 AC (A)</td>
<td>Humidity = 2.96 * Ln (Concentration) + 79.5</td>
</tr>
<tr>
<td>ATH-50 AC (B&amp;C)</td>
<td>Humidity = 82.3</td>
</tr>
<tr>
<td>DEL-23 PCC</td>
<td>Humidity = -0.2599 * Ln (Concentration) + 39.154</td>
</tr>
<tr>
<td>DEL-23 AC</td>
<td>Humidity = -0.5887 * Ln (Concentration) + 39.272</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>Humidity = -5.961 * Ln (Concentration) + 85</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>NA</td>
</tr>
<tr>
<td>ATH-50 AC (A)</td>
<td>Humidity = 2.2184 * Ln (Concentration) + 79.035</td>
</tr>
<tr>
<td>ATH-50 AC (B&amp;C)</td>
<td>Humidity = 82.3</td>
</tr>
</tbody>
</table>

An example on the use of the salt dissipation equations is shown below.

**Example:** What will be the residual salt concentration in DEL-23 PCC when the average humidity is 39%?

**Answer:**

According to “Top Ten diagonal Test Equation”

Salt Residual concentration (g/m²) = \( \exp \left\{ (39-39.04)/-0.287 \right\} \)

\[ = 1.15 \text{ g/m}^2 \]

According to “Ten Nozzle Test Equation”

Salt Residual concentration (g/m²) = \( \exp \left\{ (39-39.154)/-0.2599 \right\} \)

\[ = 1.81 \text{ g/m}^2 \]
4.10.6.1 Average humidity versus cumulative time for all the test sites

In order to see the humidity change, average humidity versus cumulative time graphs are drawn for all of the test sites. By the help of the graphs from 4.10.6.1.1 to 4.10.6.1.6, the humidity values that had an effect on hydroscopicity can be obtained.

As can be seen from the figures 4.10.6.1.1 to 4.10.6.1.6, the average humidity did not fluctuate very much through time for all of the test sites. For DEL-23 PCC, the average humidity values were between %38-%39.5 through 16.6 hours. The average humidity increased through night time (when no measurements were made) from %38.47 to %39.37. Hydroscopicity took place when the average humidity value was around %39 for DEL-23 PCC.

For DEL-23 AC, the average humidity values were between %38-%40 through 17 hours. The average humidity increased through night time (when no measurements were made) from %38.25 to %39.73. Hydroscopicity took place when the average humidity value was around %39.7 for DEL-23 AC.

For ATH-33 AC, the average humidity values were between %68-%82 through 48.15 hours. The average humidity values were higher at this test site compared to DEL-23 AC and DEL-23 PCC. Since the total testing period was around 48 hours for this test site, hydroscopicity took place two times (since there passed two overnights and tests were not conducted during night time). During the first night, the humidity increased from %68.3 to %71.6, and during the second night, the humidity increased from %71.6 to %81.9. First hydroscopicity took place when the average humidity was around %71.5 and second hydroscopicity took place when the average humidity was around %81.9 for ATH-33 AC.
For ATH-50 PCC, the average humidity values were between %72-%81.5 through 22.5 hours. The average humidity increased through night time (when no measurements were made) from %72 to %81.4. Hydrogroscopicity took place when the average humidity value was around %81 for ATH-50 PCC.

For ATH-50 AC (Station A) the average humidity values were between %77-%83.5 through 17.15 hours. The average humidity decreased through night time (when no measurements were made) from %83.5 to %77.1. Hydrogroscopicity took place when the average humidity value was around %77 for ATH-50 AC (Station A).

For ATH-50 AC (Station B &C) the average humidity percentage was %82.3 for 20 hours. The average humidity did not change at all. Therefore, it can be said that the hydrogroscopicity took place when the average humidity values was around %82.3 for ATH-50 AC (Station B&C).

![Graph showing average humidity versus cumulative time for DEL-23 PCC](image)

**Figure 4.10.6.1.1** Average humidity versus cumulative time for DEL-23 PCC
Figure 4.10.6.1.2 Average humidity versus cumulative time for DEL-23 AC

Figure 4.10.6.1.3 Average humidity versus cumulative time for ATH-33 AC
Figure 4.10.6.1.4 Average humidity versus cumulative time for ATH-50 PCC

Figure 4.10.6.1.5 Average humidity versus cumulative time for ATH-50 AC (A)
Figure 4.10.6.1.6 Average humidity versus cumulative time for ATH-50 AC (B&C)

4.10.7 Summary tables of decay equations for asphalt and concrete pavements together with $R^2$ values

Tables 4.10.7.1 to 4.10.7.3 summarizes the decay equations obtained by using the “ten nozzle” and “highest top ten diagonal readings” tests’ results.

Table 4.10.7.4 shows the summary of the $R^2$ values for the decay equations of the “Average top ten diagonal graphs” and “Average 10 nozzle graphs”. The cells that are in color show the decay equations that yielded accurate correlations. All of the four parameters (time, traffic, weather and humidity) gave similar average $R^2$ values as can be seen from Table 4.10.7.5. Time and traffic parameters correlated very closely giving an average $R^2$ value of 0.665 while average $R^2$ for weather and humidity were around 0.55 and 0.6 respectively.
## Table 4.10.7.1 Summary of the decay equations for concrete pavement

<table>
<thead>
<tr>
<th>Name of the Concrete Test Area</th>
<th>DEL-23 PCC</th>
<th>ATH-50 PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay Equation of Avg. 10 Nozzle Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration (g/m²) vs Time (hr)</td>
<td>$\text{Time} = -5.75 \times \ln(\text{Concentration}) + 15.44$</td>
<td>NA</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Traffic (# of vehicles)</td>
<td>$\text{Traffic} = -2123 \times \ln(\text{Concentration}) + 6082$</td>
<td>NA</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Weather (°C)</td>
<td>$\text{Temperature} = 2.4 \times \ln(\text{Concentration}) + 6.7$</td>
<td>NA</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Humidity (%)</td>
<td>$\text{Humidity} = -0.2847 \times \ln(\text{Concentration}) + 39.04$</td>
<td>NA</td>
</tr>
<tr>
<td>Decay Equation of Avg. Top 10 Diagonal Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration (g/m²) vs Time (hr)</td>
<td>$\text{Time} = -6.8 \times \ln(\text{Concentration}) + 14.9$</td>
<td>$\text{Time} = -18.77 \times \ln(\text{Concentration}) + 42.6$</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Traffic (# of vehicles)</td>
<td>$\text{Traffic} = -2547 \times \ln(\text{Concentration}) + 59.9$</td>
<td>$\text{Traffic} = -1913.9 \times \ln(\text{Concentration}) + 4685$</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Weather (°C)</td>
<td>$\text{Temperature} = -2.1 \times \ln(\text{Concentration}) + 6.32$</td>
<td>$\text{Temperature} = 2.1 \times \ln(\text{Concentration}) + 14.9$</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Humidity (%)</td>
<td>$\text{Humidity} = -0.2599 \times \ln(\text{Concentration}) + 39.154$</td>
<td>$\text{Humidity} = -11.268 \times \ln(\text{Concentration}) + 95.907$</td>
</tr>
</tbody>
</table>
Table 4.10.7.2 Summary of the decay equations for asphalt pavements of DEL-23 and ATH-33

<table>
<thead>
<tr>
<th>SUMMARY OF ASPHALT PAVEMENT</th>
<th>Name of the Asphalt Test Area</th>
<th>DEL-23 AC</th>
<th>ATH-33 AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay Equation of Avg. 10 Nozzle Test</td>
<td></td>
<td>Time = -6.6 * Ln (Concentration) + 11.3</td>
<td>Time = -23 * Ln (Concentration) + 65.75</td>
</tr>
<tr>
<td>Concentration (g/m³) vs Time (hr)</td>
<td></td>
<td>Time = -2389 * Ln (Concentration) + 4260</td>
<td>Traffic = -5806 * Ln (Concentration) + 16537</td>
</tr>
<tr>
<td>Concentration (g/m³) vs Traffic (# of vehicles)</td>
<td></td>
<td>Temperature = -2.711 * Ln (Concentration) + 5.6</td>
<td>Temperature = -6.5 * Ln (Concentration) - 0.35</td>
</tr>
<tr>
<td>Concentration (g/m³) vs Weather (°C)</td>
<td></td>
<td>Humidity = -0.5887 * Ln (Concentration) + 39.272</td>
<td>Humidity = -5.908 * Ln (Concentration) + 83.4</td>
</tr>
<tr>
<td>Decay Equation of Avg. Top 10 Diagonal Test</td>
<td></td>
<td>Time = -9.3 * Ln (Concentration) + 12.3</td>
<td>Time = -23.1 * Ln (Concentration) + 59</td>
</tr>
<tr>
<td>Concentration (g/m³) vs Time (hr)</td>
<td></td>
<td>Time = -3385 * Ln (Concentration) + 4623</td>
<td>Traffic = -5755 * Ln (Concentration) + 14852</td>
</tr>
<tr>
<td>Concentration (g/m³) vs Traffic (# of vehicles)</td>
<td></td>
<td>Temperature = 3.66 * Ln (Concentration) + 5.3</td>
<td>Temperature = 5.6 * Ln (Concentration) + 3.16</td>
</tr>
<tr>
<td>Concentration (g/m³) vs Weather (°C)</td>
<td></td>
<td>Humidity = -0.8123 * Ln (Concentration) + 39.343</td>
<td>Humidity = -5.908 * Ln (Concentration) + 83.4</td>
</tr>
</tbody>
</table>
Table 4.10.7.3 Summary of the decay equations for asphalt pavement of ATH-50

<table>
<thead>
<tr>
<th>SUMARY OF ASPHALT PAVEMENT</th>
<th>Name of the Asphalt Test Area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Decay Equation of Avg. 10 Nozzle Test</strong></td>
<td><strong>ATH-50 AC (A)</strong></td>
</tr>
<tr>
<td>Concentration (g/m²) vs Time (hr)</td>
<td>Time = -7.7 * Ln (Concentration) + 11.5</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Traffic (# of vehicles)</td>
<td>Traffic = -1385 * Ln (Concentration) + 2076</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Weather (°C)</td>
<td>Temperature = 1.98 * Ln (Concentration) + 5.02</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Humidity (%)</td>
<td>Humidity = 2.2184 * Ln (Concentration) + 79.035</td>
</tr>
<tr>
<td><strong>Decay Equation of Avg. Top 10 Diagonal Test</strong></td>
<td><strong>ATH-50 AC (B&amp;C)</strong></td>
</tr>
<tr>
<td>Concentration (g/m²) vs Time (hr)</td>
<td>Time = -5.14 * Ln (Concentration) + 7.1</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Traffic (# of vehicles)</td>
<td>Traffic = -1022 * Ln (Concentration) + 1475</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Weather (°C)</td>
<td>Temperature = -3.57 * Ln (Concentration) + 8.18</td>
</tr>
<tr>
<td>Concentration (g/m²) vs Humidity (%)</td>
<td>Humidity = 82.3</td>
</tr>
<tr>
<td><strong>ATH-50 AC (B&amp;C)</strong></td>
<td>Humidity = 82.3</td>
</tr>
</tbody>
</table>

ATH-50 AC (B&C)

- Time = -9.6 * Ln (Concentration) + 9.8
- Traffic = -1726 * Ln (Concentration) + 1765
- Temperature = 2.27 * Ln (Concentration) + 5.54
- Humidity = 2.96 * Ln (Concentration) + 79.5
### Table 4.10.7.4 Summary of the $R^2$ values for the decay equations

<table>
<thead>
<tr>
<th>R² for Time</th>
<th>Average Top 10 Diagonal Graphs</th>
<th>Average 10 Nozzles Graphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-23 PCC</td>
<td>0.94</td>
<td>0.9688</td>
</tr>
<tr>
<td>DEL-23 AC</td>
<td>0.9267</td>
<td>0.9224</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>0.4079</td>
<td>0.3642</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>0.1874</td>
<td>---</td>
</tr>
<tr>
<td>ATH-50 AC-A</td>
<td>0.9516</td>
<td>0.4709</td>
</tr>
<tr>
<td>ATH-50 AC-B&amp;C</td>
<td>0.6635</td>
<td>0.487</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R² for Traffic</th>
<th>Average Top 10 Diagonal Graphs</th>
<th>Average 10 Nozzles Graphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-23 PCC</td>
<td>0.9571</td>
<td>0.9675</td>
</tr>
<tr>
<td>DEL-23 AC</td>
<td>0.8761</td>
<td>0.8765</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>0.4672</td>
<td>0.4201</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>0.1223</td>
<td>---</td>
</tr>
<tr>
<td>ATH-50 AC-A</td>
<td>0.9514</td>
<td>0.4705</td>
</tr>
<tr>
<td>ATH-50 AC-B&amp;C</td>
<td>0.6949</td>
<td>0.5451</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R² for Weather</th>
<th>Average Top 10 Diagonal Graphs</th>
<th>Average 10 Nozzles Graphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-23 PCC</td>
<td>0.5011</td>
<td>0.5614</td>
</tr>
<tr>
<td>DEL-23 AC</td>
<td>0.7341</td>
<td>0.8073</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>0.2601</td>
<td>0.3115</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>0.0149</td>
<td>---</td>
</tr>
<tr>
<td>ATH-50 AC-A</td>
<td>0.9881</td>
<td>0.583</td>
</tr>
<tr>
<td>ATH-50 AC-B&amp;C</td>
<td>0.9663</td>
<td>0.2736</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R² for Humidity</th>
<th>Average Top 10 Diagonal Graphs</th>
<th>Average 10 Nozzles Graphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-23 PCC</td>
<td>0.33</td>
<td>0.4019</td>
</tr>
<tr>
<td>DEL-23 AC</td>
<td>0.8654</td>
<td>0.913</td>
</tr>
<tr>
<td>ATH-33 AC</td>
<td>0.2651</td>
<td>0.2326</td>
</tr>
<tr>
<td>ATH-50 PCC</td>
<td>0.2644</td>
<td>---</td>
</tr>
<tr>
<td>ATH-50 AC-A</td>
<td>0.9122</td>
<td>0.3927</td>
</tr>
<tr>
<td>ATH-50 AC-B&amp;C</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 4.10.7.5 Average R² values for time, traffic, weather and humidity parameters

<table>
<thead>
<tr>
<th>R² for Time</th>
<th>Average Top 10 Diagonal Graphs</th>
<th>0.67951667</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average 10 Nozzles Graphs</td>
<td>0.64266</td>
</tr>
<tr>
<td>R² for Traffic</td>
<td>Average Top 10 Diagonal Graphs</td>
<td>0.67816667</td>
</tr>
<tr>
<td></td>
<td>Average 10 Nozzles Graphs</td>
<td>0.65594</td>
</tr>
<tr>
<td>R² for Weather</td>
<td>Average Top 10 Diagonal Graphs</td>
<td>0.57743333</td>
</tr>
<tr>
<td></td>
<td>Average 10 Nozzles Graphs</td>
<td>0.50736</td>
</tr>
<tr>
<td>R² for Humidity</td>
<td>Average Top 10 Diagonal Graphs</td>
<td>0.60618333</td>
</tr>
<tr>
<td></td>
<td>Average 10 Nozzles Graphs</td>
<td>0.58804</td>
</tr>
</tbody>
</table>

### 4.10.8 Correction Factor for SOBO 20

As mentioned earlier, only one SOBO 20 reading per applied area was made using SOBO 20 due to the reason that the acetone spoiled the tested area and prevented the 2⁻ⁿᵈ reading from being accurate. The second reading in the same area was assumed to be zero. However, to find the SOBO 20 correction factor, several punches on the same area was done and cumulative readings were obtained in the lab, till the salt dissipated and zero readings were obtained. Concrete and asphalt samples were used and 2.93 ml of 23% salt was applied to the 5 inch diameter specimens. The ideal reading that was expected from SOBO 20 at the first punch was 98 g/m². Since the range of SOBO 20 is between 0-45 g/m², mostly 45 g/m² readings were obtained for the first punches instead of 98 g/m². This was one of the limitations of this lab test. The addition of the concentrations of all the punches was assumed to give the ideal reading. The tests were applied on both dry and wet pavements. The results are summarized in the Table 4.10.8.1 below.
Table 4.10.8.1 Results of the cumulative punching tests on the same test area for the testing of undissolved salt

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Volume of Brine Applied (ml)</th>
<th>% Brine</th>
<th>Pavement Condition</th>
<th>1st punch</th>
<th>2nd punch</th>
<th>3rd punch</th>
<th>4th punch</th>
<th>5th punch</th>
<th>6th punch</th>
<th>Total Reading (g/m²)</th>
<th>Theoretical SOBO 20 Reading (g/m²)</th>
<th>Average SOBO 20 Reading (g/m²)</th>
<th>% Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>2.93ml</td>
<td>23</td>
<td>Dry</td>
<td>30</td>
<td>27</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>65</td>
<td></td>
<td>82.8</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wet</td>
<td>&gt;45</td>
<td>36</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td></td>
<td>92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33</td>
<td>21</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
<td>39</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td></td>
<td>91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>13</td>
<td>3</td>
<td>1</td>
<td></td>
<td>107</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCC</td>
<td>2.93ml</td>
<td>23</td>
<td>Dry</td>
<td>30</td>
<td>24</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td></td>
<td>67</td>
<td></td>
<td>79.2</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wet</td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>12</td>
<td>1</td>
<td></td>
<td></td>
<td>103</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>12</td>
<td>2</td>
<td></td>
<td></td>
<td>59</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42</td>
<td>39</td>
<td>8</td>
<td>1</td>
<td></td>
<td></td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;45</td>
<td>27</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>24</td>
<td>4</td>
<td>1</td>
<td></td>
<td>74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>33</td>
<td>5</td>
<td>1</td>
<td></td>
<td>84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>33</td>
<td>5</td>
<td>1</td>
<td></td>
<td>84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>39</td>
<td>10</td>
<td>1</td>
<td></td>
<td>95</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>&gt;45</td>
<td>&gt;45</td>
<td>36</td>
<td>7</td>
<td>1</td>
<td></td>
<td>89</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As can be seen from the same table (Table 4.10.8.1), the average of the total of all the cumulative readings of SOBO 20 readings differ from the theoretical reading by 15.2% for dry asphalt and by 6.3% for wet asphalt. In addition, the average of total SOBO 20 readings differ from the theoretical reading by 18.8% for dry concrete and by 13.75% for wet concrete. Table 4.10.8.2 shows the correction factor of SOBO 20 according to the results shown in Table 4.10.8.1.

### 4.10.8.2 Correction factor of SOBO 20

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Pavement Condition</th>
<th>% Deviation</th>
<th>%Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Dry</td>
<td>15.2</td>
<td>84.8</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>6.3</td>
<td>93.7</td>
</tr>
<tr>
<td>PCC</td>
<td>Dry</td>
<td>18.8</td>
<td>81.2</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>13.75</td>
<td>86.25</td>
</tr>
</tbody>
</table>

The correction factors from Table 4.10.8.2 can be used to correct the concentrations that are obtained in the field by SOBO 20 or to correct the concentrations that are obtained from the salt dissipation equations presented in sections 4.10.4 to 4.10.6. However, these correction factor percentages are quite inaccurate due to the limitation that 1st punching results were not obtained accurately because of the 0-45 g/m² limit of the SOBO 20. Therefore, all throughout the field tests of this test study, these percentages were not used as correction factors and only one punch per area was conducted.
Chapter 5 Conclusions and Recommendations

The aim of this thesis study was to determine the factors that are affecting the effectiveness of the anti-icing application such as traffic, time, pavement temperature and humidity. In addition, another aim of the study was to analyze the decrease rate of the salt brine density for asphalt and concrete pavements under field conditions. The influencing factors were identified in this thesis study in order to correlate data and recommend decay equations of salt dissipation versus time, traffic, pavement temperature and humidity.

A series of field and laboratory tests were conducted to test the accuracy of the SOBO 20 and to try different pavement types for the anti-icing applications. The major problem during these lab and field studies was the need for a reliable device to measure salt residual. The limitations of this research study are summarized below.

Limitations for the field study

The test sites, where the field study was conducted, had less average daily traffic (ADT) compared to the interstate system. These sites with less ADT were chosen in order to provide safety for the researchers to conduct the field tests during the rush hours. The experimentation with the anti-icing application in the interstate system would have allowed better results in the identification of salt dissipation versus traffic.
The salt residual measurement device, SOBO 20 also provided some limitations to the study. SOBO 20 had the disadvantage of spoiling the area (where the measurements were made) with acetone solution. In addition, laboratory studies showed that the SOBO 20 readings were ± %10 different from the actual concentrations. The device was reading values 9 to 11 g/m² when 10 g/m² salt solution was applied. One of the SOBO 20s failed during the use on the 4th test site (ATH-33 AC).

Another limitation of the thesis study was the different characteristics of the test sites. The porosity of the pavement surfaces, especially for DEL-23 AC test site, was a big variability and caused the brine solution to dissipate very quickly. The places on the same highway that have less grooves could have been chosen to overcome this limitation.

All of the tests, which were conducted on the field sites, were made during daylight hours in order to provide safety for the researchers. However, this created a big time gap between the evening and the early morning data.

Salt dissipation data for the test sites provided sudden increases in the NaCl concentration through time. These enabled the concentration graphs have humps. This situation was not expected. The early morning data (after the salt was applied from the previous day) had very low salt concentrations compared to the data at the other times of the day. This situation was explained by hydroscopocity. This process allowed the salt absorb the humid air all throughout the night and dilute the salt concentration on the pavement. Therefore, very low concentrations of salt were being obtained in the early morning data. Since sunlight allowed the moisture to evaporate from the pavement towards the afternoon, higher concentration readings were obtained through time.
Moreover, the anti-icing application tests in the field were conducted in fall rather than in winter temperatures. This was a limitation for the investigation of anti-icing application protocols in winter weather conditions. In addition, a rain event caused the dissipation of the salt residual at one of the test sites (ATH-33 AC).

Another limitation was the lack of the available method to measure the salt application rate of the nozzle type spreader truck. It was provided by ODOT that the application rate was 40 gallons/lane-mile. Therefore, each nozzle was assumed to distribute 4 gallons/lane-mile.

Finally, only one application concentration (eutectic) and application rate of brine solution was used by ODOT. Different application rates and concentrations would have been useful to find out the trends of salt dissipation for different conditions.

**Limitations of the laboratory study**

The salt residual on the asphalt and concrete specimens were only measured with the SOBO 20 device which gave ±%10 deviation from the ideal readings. It would have been more accurate to conduct laboratory tests with at least one other salt residual measuring device like embedded sensors.

**5.1 Conclusions**

Three of the field test sites were asphalt, while the other two sites were concrete. Decay equations of salt dissipation versus time, traffic, pavement temperature and humidity were obtained at the end of this study for all of the test sites. However, out of these five test sites, only ATH-33 AC, ATH-50 PCC and DEL-23 PCC provided the most reliable data for determining the decay equation of the salt concentration. The use of the decay equation is necessary for the development of the anti-icing application protocols.
before snow/ice events. The field sites yielded decay equations that can provide an estimate of salt residual dissipation versus time, traffic and weather for the type of pavement surfaces that were used in this thesis study. These decay equations can give the residual salt concentration of the treated pavement at a given time, traffic and weather condition. The salt density can be easily calculated by plugging in the known parameters into the decay equations as shown in the examples under the Tables 4.27.4.1 and 4.27.5.1.

ATH-33 AC was the test site where the salt dissipation occurred the slowest due to its almost impervious pavement type. In addition, for concrete pavement, DEL-23 PCC was the test site where the salt dissipation took place the slowest because it was the test site which had more smoother surface compared to the other concrete test area. Therefore, it can be concluded that if the pavement condition is good and it does not have deep grooves, the salt dissipation occurs after around 50 hours, at around 5 °C and 6500 traffic exposure for asphalt pavement and after 22.5 hours, between 4-5.5 °C and 11,250 vehicles for concrete pavement.

5.2 Recommendations

Recommendations for future researchers are provided below:

- Different application rates and concentrations of brine solution must be applied to broaden the data and for the comparison of the decay equations for different conditions.
- Different types of anti-icing chemicals should be tested in order to come up with more effective liquid solutions that are as cost effective as sodium chloride.
- A study on the impacts of pavement porosity on the effectiveness of the anti-icing applications should be conducted.

- More advanced salt residual measurement devices (that do not spoil the measured pavements) should be used.

- More advanced brine solution application devices should be used for pilot studies instead of a plant-watering sprayer in order to provide uniform distribution.

- Salt dissipation versus weather conditions must be developed to come up with better anti-icing application procedures prior to storm events.

- Studies should be conducted under winter weather conditions in order to come up with better pretreatment procedures.

- A computer software program must be developed which may be used as a decision making tool for ODOT personnel before a snow/ice event.
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SOBO 20 READINGS (G/M²)

INCHES
Diagonal profiles of DEL-23 PCC(A)

SOBO 20 READINGS (G/M²)

INCHES
Diagonal profiles of DEL-23 PCC(B)

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Station A - Nozzle #2

Station A - Nozzle #3

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Appendix 3: Glossary of Terms

**Dry chemical spread rate:** Application rate of the chemical. It is simply the weight of the chemical applied per lane kilometer (or mile) for solid applications. It is the weight of the dry chemical in solution applied per lane kilometer (or mile) for liquid applications (U.S. FHWA, June 1996).

**Freezing rain:** Is the supercooled droplets of liquid precipitation that are falling on an area whose temperature is below or slightly above the freezing point, resulting in a hard, slick, generally thick coating of ice generally called glaze or clear ice. Non-supercooled raindrops that are falling on an area whose temperature is very much below the freezing point will also result in glaze (U.S. FHWA, June 1996).

**Frost:** Frost is also called hoarfrost. Frost is the ice crystal, which are in the forms of scales, needles, feathers or fans deposited on areas that are cooled by either radiation or by other processes. The deposited frost can be composed of the drops of dew frozen just after deposition of ice, which are formed directly from water vapor at a temperature below 0°C (32°F) (sublimation) (U.S. FHWA, June 1996).

**Light snow:** Light snow is the kind of snow, which is falling at the rate of less than 12 mm (0.5 inch) per hour. The visibility is not affected adversely that much (U.S. FHWA, June 1996).

**Liquid chemical:** The chemical solution applied to roadways for anti-icing strategies. The weight of the dry chemical in solution is applied per lane kilometer (or mile) and the
amount applied is called the chemical application rate or the dry chemical spread rate (U.S. FHWA, June 1996).

**Moderate or heavy snow:** The type of snow that is falling at a rate of 12 mm (1/2 in) per hour or greater. The visibility can be adversely affected and can be reduced (U.S. FHWA, June 1996).

**Sleet:** Sleet is the mixture of rain and snow which has been melted partially by falling through an atmosphere with a temperature a little bit above freezing (U.S. FHWA, June 1996).

**Slush:** Slush is the accumulation of snow that lies on an impervious base. Slush is saturated with water in excess of its freely drained capacity. It cannot support any weight when stepped or driven on but will "squish" till the support of the surface is reached. (U.S. FHWA, June 1996).

**Eutectic temperature:** The eutectic temperature is the temperature on which co-crystallization of more than one phase occurs. Eutectic temperature is the lowest possible liquidus temperature in a system that contains two stable phases. The liquidus curve will form a singularity at eutectic temperature in the melting diagram of the heterogeneous multicomponent system (GMELIN Online, April 2003).