ESTABLISHING BEST PRACTICES FOR REMOVING SNOW AND ICE FROM CALIFORNIA ROADWAYS

Final Project Report

by

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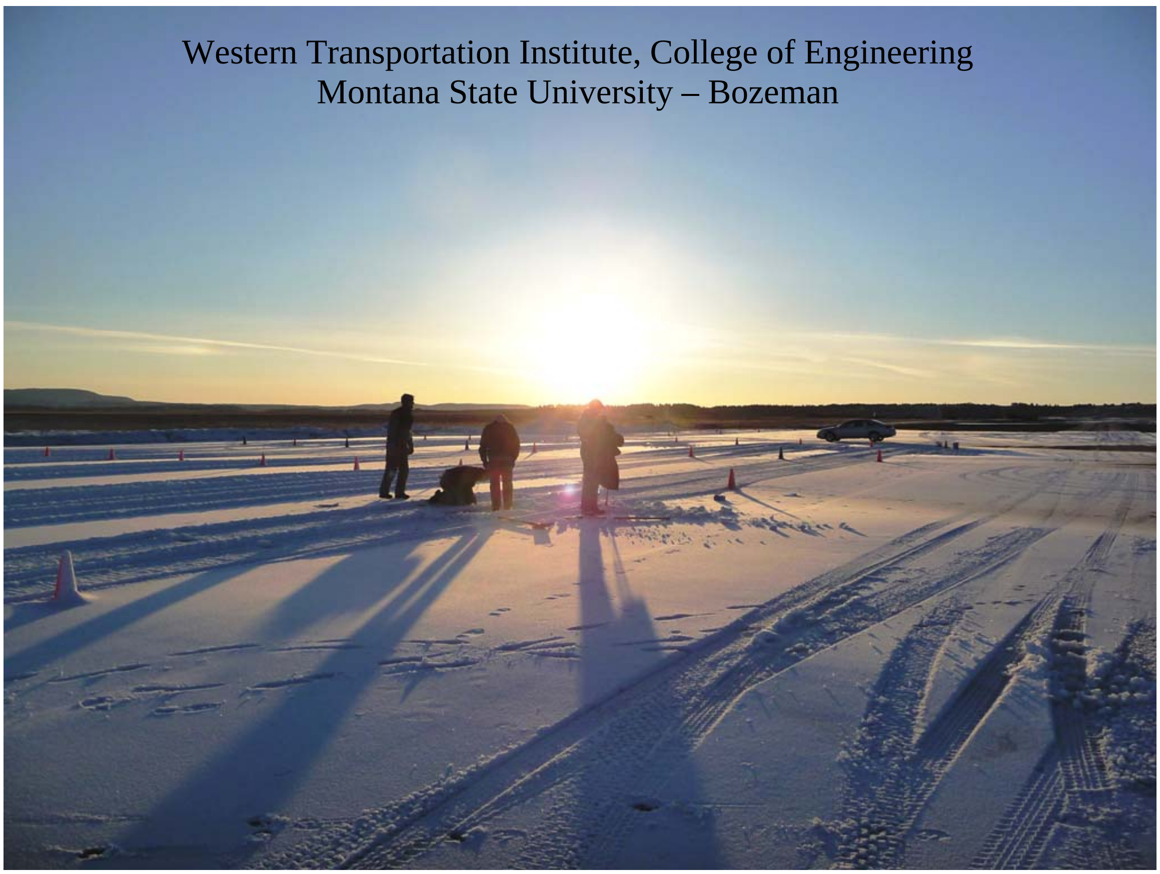

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16. Abstract

Departments of transportation use a variety of strategies to effectively maintain roadways during winter while considering a number of factors such as level of service, cost, infrastructure and environmental impacts, equipment, and weather. Impacts to infrastructure, vehicles and the environment have motivated the state of California to reduce salt usage on highways. Anti-icing, a winter maintenance strategy based on timely application of winter maintenance chemicals before the onset of a storm, typically uses less chemical to achieve effective results. A lack of established dispersal rates, laboratory studies to verify field studies, and an understanding of the science associated with anti-icing principles have slowed full implementation of anti-icing strategies in California. This research effort focused on synthesizing available information regarding winter maintenance best practices and establishing a set of preliminary guidelines to implement anti-icing strategies in California. A qualitative and quantitative evaluation of the performance of five typical anti-icing chemicals was conducted. Performance measures included temperature at which the snow–pavement bond failed, friction of the pavement surface after snow removal, and snow–pavement bond strength. In general, anti-icing methods employed in the laboratory and in full-scale controlled field tests improved the ability of the plow to remove snow from the pavement surface, lowered the temperature at which the snow–pavement bond failed, weakened the bond between compacted snow and pavement, and improved pavement surface friction after plowing when compared to untreated pavements. A set of guidelines was developed to initiate implementation of anti-icing practices in California. Further assessments are necessary to optimize this methodology based on specific temperature scenarios, storm types, precipitation levels, and application methods.

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EXECUTIVE SUMMARY

Departments of transportation use a variety of strategies to maintain roadways during the winter in the most effective manner possible while considering a number of factors such as level of service, cost, infrastructure and environmental impacts, equipment, and weather. Maintenance divisions have historically relied heavily on the use of salt to keep roadways clear. However, the impacts to infrastructure, vehicles and the environment resulting from salt usage have motivated the California legislature to mandate a reduction in salt usage on the highways. The California Department of Transportation (Caltrans) is responsible for maintaining the same level of service on highways while using salt and other winter maintenance chemicals more efficiently. Anti-icing is a winter maintenance strategy that is based on the timely application of a winter maintenance chemical before the onset of a storm to weaken or prevent the bond between compacted snow and the pavement surface from forming in order to improve removal efforts.

Some Caltrans districts currently use anti-icing techniques to a limited extent, but there are three major limitations that have slowed full implementation of this methodology: 1) lack of established chemical application rates, 2) lack of laboratory studies to verify field studies, and 3) lack of understanding of the science associated with anti-icing principles. These limitations may lead to inefficient or inappropriate chemical use, which may have economic, environmental or safety repercussions. Transportation agencies must determine how to apply the right amount and type of chemicals in the right place at the right time to balance cost, effectiveness, safety, infrastructure service life and environmental stewardship considerations.

The objective of this research was to develop guidelines for optimal snow and ice removal operations designed specifically for California's typical highway environments. This research effort focused on: 1) synthesizing available information regarding winter maintenance best practices, and 2) establishing a set of preliminary guidelines to implement anti-icing strategies in California. Preliminary guidelines were established through laboratory investigations and field tests to predict and/or verify the viability of select chemicals under various road and weather conditions. Caltrans winter maintenance personnel were surveyed to identify winter maintenance strategies currently used within the state. A review of literature was conducted to summarize current and state-of-the-art winter maintenance practices in the United States and abroad. Results from this review identified five commonly available chemical types, which were selected to be used during laboratory and field testing. These chemicals were sodium chloride, magnesium chloride, calcium chloride, potassium acetate, and a chemical made from agricultural byproducts.

Performance of each of the selected chemicals was studied in a laboratory setting by applying each chemical to concrete and asphalt pavement specimens at four application rates and under three temperature scenarios. Natural, harvested snow was applied to the treated pavement surfaces and compacted. Performance was evaluated based on 1) the temperature at which the

snow–pavement bond failed, 2) pavement surface friction after snow removal, and 3) the snow–pavement bond shear strength. Chemical application rates used in the laboratory tests were lower than typical field application rates, but because of the controlled method of chemical application, bonds between the snow and the pavement surface did not occur at rates higher than 15 gallons per lane-mile. Overall, the presence of anti-icing chemicals significantly reduced the temperature at which the bond between the snow and the pavement debonded, reduced bond strength and improved friction for all chemicals, application rates, and temperature regimes when compared to untreated pavements. Temperatures at which the snow–pavement bonds failed were lower, bond strengths on treated pavements were reduced to less than a fifth of the bond strength on untreated pavements regardless of chemical or application rate, and friction of the pavement surface was slightly higher on treated pavements than on untreated pavements after snow removal.

Chemical performance was also evaluated using a series of full-scale field tests at the TRANSCEND research facility in Lewistown, Montana. Chemicals were applied to various pavements at the site from 5 to 40 gallons per lane-mile. Man-made snow was applied to the pavements using a state-of-the-art snowmaking system and compacted. Qualitative and quantitative evaluations were conducted, which included measures of the ease of snow removal from the surface using a plow truck, friction of the surface after snow removal, and snow–pavement bond strength. Generally, improvements in performance were observed for most chemicals through reduction or elimination of the snow–pavement bond or improved plowability. Friction measurements in the field were inconclusive. While these results are thought to pertain to anti-icing practices in general, other external factors such as wetness of snow, traffic, wind, etc. may influence how a particular chemical performs.

Anti-icing is a viable, proactive methodology that can be effectively used in conjunction with traditional deicing strategies to maintain roadways during winter storms. Anti-icing generally uses less chemical to maintain a safe driving surface during winter maintenance efforts, which saves money and reduces impacts to the environment and infrastructure. Successful implementation of anti-icing in California requires proper equipment, training personnel, selection of appropriate chemicals, and accurate forecasting. This strategy is most effective when tailored to specific regions or stretches of roadways. Optimization of this procedure by assessing the effects of traffic, temperature, storm type, precipitation levels, application methods and equipment is recommended.

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1 INTRODUCTION

Many state departments of transportation (DOTs) are faced with the difficult task of providing and maintaining transportation infrastructure while allowing for economic development, emergency management, environmental stewardship, motorist safety and more. Maintaining and operating roadways during the winter season can make balancing these priorities complicated for some states. The California Department of Transportation (Caltrans) must operate and maintain roadways in seven snow districts located primarily in the mountainous regions of the state. Legislation to reduce the use of salt has led Caltrans to alter its winter maintenance practices. Though Caltrans has reduced its overall salt usage, an insufficient amount of research is available to establish the best practices for winter maintenance using alternative chemicals in the state.

Much effort has been directed toward the development and testing of alternative anti-icing and deicing chemicals. While many departments use deicing techniques to control roadway snow and ice during or after a storm, the practice of applying anti-icing chemicals before a snowfall is a technique that is gaining favor worldwide. However, three major limitations have slowed implementation of anti-icing methods: 1) lack of established effective rates of dispersal, 2) lack of laboratory studies to verify field studies, and 3) incomplete understanding of the science associated with anti-icing principles. These limitations may lead to inefficient or inappropriate use which may result in economic, environmental or safety repercussions. To ensure an appropriate balance between cost, safety, effectiveness, infrastructure service life, and environmental stewardship, transportation agencies must determine how to apply the right amount and type of chemicals in the right place at the right time.

1.1 Objectives

The objective of this research was to develop guidelines for optimal snow and ice removal operations for California's typical highway environments. In particular, the research 1) synthesized the information on best practices of anti-icing and deicing in other states and other countries, 2) identified commonly used chemicals for winter maintenance purposes, and 3) investigated the effective working temperature and appropriate application rate of a variety of chemicals under various road weather scenarios. The chemicals were investigated in controlled laboratory and field environments to ensure uniformity and repeatability.

1.2 Caltrans Current Practices

A simple questionnaire was used to determine Caltrans' current snow and ice control practices (Appendix A). This questionnaire was sent to several Caltrans winter maintenance personnel using contacts provided by David Frame (Caltrans). The survey inquired about current practices including types of equipment used, products commonly used, typical application rates, strategies or governing policy for responding to winter storms, and availability of RWIS within the snow districts. Follow-up telephone interviews were conducted to elicit more information and allow participants to suggest techniques and/or materials that they would like to see evaluated in lab and field tests.

Districts indicated that liquid products are rarely used for deicing because it is ineffective at removing snow and ice from roadways. Most personnel agreed that anti-icing is appropriate at certain times and in certain places, but lack of knowledge has hindered their ability to more widely implement these practices. One district reported using anti-icing during drier, colder weather, frost, and in shaded areas. The majority of districts reported using deicing practices with solid chemicals rather than anti-icing. One common reason is because it is believed that anti-icing chemicals will be washed away during wet snow events or during storms in which rain turns into snow. Another common reason for not using an anti-icing strategy was because forecasting algorithms have not been extensively implemented into their winter maintenance practices.

Sodium chloride (solid and liquid) and magnesium chloride are the most commonly used products by Caltrans. Other materials being used by the department include Ice Slicer® and NC-3000 (now known as Ice Clear RDF®). Magnesium chloride was preferred by many respondents, but sodium chloride is more commonly used because it is less expensive. Respondents indicated a desire to implement a more effective, environmentally friendly and affordable chemical for winter maintenance practices.

2 LITERATURE REVIEW

Winter weather events present a variety of weather and pavement conditions that require different management strategies. Three main strategies are: 1) mechanical removal with or without friction enhancements, 2) deicing, and 3) anti-icing. While these strategies can be used individually, they are more often used in combination with one another (Blackburn et al., 2004).

Over the past two decades, approaches to snow and ice control have shifted from reactive methods to a more proactive strategy. Treatments to prevent or weaken the bond between the pavement and snow prior to a storm are gaining favor, but the classic methodology of plowing with chemical follow-up and abrasives remains a mainstay in winter operations. Chemical applications usually involve chlorides, but alternatives such as acetates have undergone extensive research as agencies seek to reduce environmental impacts and corrosion to vehicles and infrastructure (Boselly, 2001).

A comprehensive literature review was conducted to summarize current practices and recent advances in winter operations used by a number of states and countries. The review looked at findings from recent publications and reports on snow and ice control materials and methods including abrasives, freeze-point-depressant chemicals, plowing, deicing, prewetting, anti-icing, and technologies such as Road Weather Information Systems, instrumented plows, etc.

2.1 Winter Maintenance Chemicals and Traction Materials

Agencies must consider factors such as performance, cost, availability, ease of use, corrosion impacts, environmental impacts, and health effects when selecting an appropriate chemical for snow and ice control operations. The Pacific Northwest Snowfighters (PNS) association was formed to develop standards and specifications for winter maintenance chemicals. In order for products to be placed on the PNS Qualified Product List, they must pass stringent friction, toxicology and corrosion testing. For example, products containing corrosion inhibitors must prove to be 70 percent less corrosive to mild steel than sodium chloride (Fay et al., 2008). Standardized chemical specifications and stringent quality control guidelines will help transportation agencies identify the best products available. PNS-approved chemicals should pose no significant damage to human health, vehicles or the environment when used correctly (O'Keefe and Shi, 2005).

The most common chemical products used for winter maintenance activities are sodium chloride ($NaCl$), magnesium chloride ($MgCl_2$, abbreviated as MgCl in this report), calcium chloride ($CaCl_2$, abbreviated as CaCl in this report), calcium magnesium acetate (*CMA*), and potassium acetate (CH_3CO_2K, abbreviated as KAce in this report). Each year the United States uses approximately 8 to 12 million tons of chloride salts for winter maintenance operations (Fischel, 2001). NaCl has been the chemical of choice since the early 20th century because it is inexpensive, abundant and effective. Harmful effects to the environment and corrosion of highway structures have been recognized, but the benefits of traveler safety have kept chlorides in use.

Based on an analysis by Fischel (2001), the use of NaCl has decreased each year since 1995 as the use of alternative chemicals has increased. Agencies are making an effort to use chemical alternatives that are less harmful, such as acetates. CMA and KAce are the types most commonly used. Even though acetates are minimally corrosive to highway structures, relatively environmentally benign and perform well, their high cost has slowed more widespread use (O'Keefe and Shi, 2005; Perchanok, 2008; and Warrington, 1998).

Byproducts from the agricultural industry and are often used as additives to inorganic (e.g., chloride-based) winter maintenance chemicals. Some ag-based products are produced by the fermentation and processing of cane or beet sugar syrup, corn barley, or other carbohydrates and milk (Fay et al., 2008; Fischel, 2001; and O'Keefe and Shi, 2005). Research in recent years shows that adding a variety of organic compounds to common winter maintenance chemicals can significantly decrease the freezing point (Koefod, 2008). Nixon suggests that ag-based products can be combined with winter maintenance materials to act as corrosion inhibitors and increase melting capacity (Nixon and Williams, 2001). Ag-based products have low eutectic and effective temperatures and are relatively benign to the environment and highway infrastructure.

Abrasives create temporary traction, allowing roads to remain operable when other means to remove snow and ice from the roadway are unsuccessful. Typically, abrasives are used at lower pavement temperatures, below 12.2°F (-11°C), and on roads with low traffic and relatively low levels of service (Blackburn et al., 2004). Because they do not lower the freezing point of water, abrasives are not used for deicing or anti-icing operations. Even though the Montana DOT uses abrasives in its winter maintenance operations, it says that "abrasives are costly to purchase, store, use and clean up. Additionally, they are poor in performance, have a short beneficial life, and are hard on the environment as well as human health, and cause wear to pavement markings" (Williams, 2001). Due to these concerns, snow and ice control operations in Montana are shifting away from abrasives, and toward the use of winter maintenance chemicals to maintain desired levels of service.

2.1.1 Chemical Performance

The performance of a winter maintenance chemical is measured by its ability to penetrate, undercut and break the bond between the ice and the pavement, or to prevent the ice–pavement bond from forming. The chemical's ability to do so is determined by the eutectic and effective temperatures. The eutectic temperature is the lowest temperature at which ice melts. Because the function of a deicer is to lower the freezing point of water, eutectic measurements and the effect of liquid deicers on freezing points are frequently used to predict the effectiveness of a given chemical (Blackburn et al., 1994). The lowest *effective* temperature for a deicer is defined as the temperature at which the deicer will "melt" a reasonable amount of ice within a reasonable amount of time. A Federal Highway Administration (FHWA) study conducted by Ketcham at al. (1996) found the eutectic temperatures for several types of chemical, shown in Table 1.

Table 1: Eutectic Temperatures (from Ketcham et al., 1996)

Chemical	Concentration	Eutectic Temperature	
		°C	°F
Sodium chloride	23%	-21	-5.8
Calcium chloride	29.8%	-51	-59.8
Magnesium chloride	21.6%	-33	-27.4
Calcium magnesium acetate	32.5%	-27	-16.6
Potassium acetate	49%	-60	-76

Various ice-melting attributes have been studied for CaCl, MgCl, CMA and KAce, often in comparison to NaCl. A study by Chang et al. (1994) showed that CaCl works twice as fast as NaCl, and Cheng and Guthrie (1998) found that when its effectiveness is compared to NaCl, "calcium chloride tends to adhere to the roads better, dissolve more rapidly, and melt at lower ambient temperatures." Warrington (1998) agrees that CaCl is a more effective chemical at lower temperatures because of its ability to attract moisture and stay on the road longer. The Ontario Ministry of Transportation chooses not to use CaCl because the wet solution left on the road creates a slippery driving surface, and the solution may become diluted and refreeze (Perchanok et al., 1991). In contrast to other researchers, Blackburn (1994) asserts "the fact that calcium chloride has a much lower eutectic temperature than sodium chloride is not of importance for anti-icing operations" because research shows that at temperatures below 14°F (-10°C) chemicals work too slowly and should not be used. Thus, in the effective working range, CaCl and NaCl exhibit similar freezing characteristics (Ketcham et al., 1996).

Experience and lab tests show that MgCl melts ice more quickly and at colder temperatures than NaCl. Furthermore, less MgCl is required than NaCl or CaCl. According to a FHWA publication, the melting capacity of MgCl is 40 percent greater than CaCl (Ketcham et al., 1996). The Montana Department of Transportation found that MgCl will keep 30 percent more water from freezing at -0.4°F (-18°C) than will CaCl (Williams, 2001).

Lab and field studies have provided promising results about the performance of acetates. Fay et al. (2008) performed lab tests on the ice melting capacity of various freeze-depressant chemicals and found that CMA was the only chemical still melting after 30 minutes. The Washington Department of Transportation found that when applied before a storm CMA provided residual benefit for up to 24 hours under certain conditions, and areas treated four or five times with a sand–chloride mix could be treated once with 60 gallons per lane mile of CMA (Wyant, 1998).

Field trials by multiple agencies found CMA to be acceptable as a winter maintenance chemical at certain temperatures but not as consistent or effective as NaCl when applied in equal amounts (Fischel, 2001). To obtain equivalent deicing results, CMA has to be applied at rates between 1.4 and 2.6 times as much as NaCl (Perchanok et al., 1991; Fischel, 2001). However, reports from California, Wisconsin, Alberta, and Ontario indicated that CMA remained on the highway longer than NaCl, thus reducing the number of applications required (Perchanok et al., 1991). Reports from Minnesota showed CMA to be non-corrosive and non-polluting, but a higher concentration of CMA was needed compared to NaCl. At 15°F (-9.4°C), 1.41 times higher concentrations were necessary to keep the roads from freezing, which translated into higher costs (Ketcham et al., 1996).

A common conclusion among studies is that acetates, while they are freeze-point depressants, do not provide effective snow melting capabilities; however, they are effective at preventing ice from forming on the pavement surface. A trial study accompanied efforts to incorporate CMA in parts of New Zealand, where only abrasives had been used for 20 years. Five years of field monitoring in central North Island showed a reduction in road closure duration and a reduction in maintenance vehicle operation costs and occupation time. Field observations also showed a reduction in crashes, a decrease in travel time, increased skid resistance by 24 percent, and reduced numbers of applications (Burkett and Gurr, 2004).

KAce is used at most U.S. airports and, according to Fischel (2004), is the most effective acetate at low temperatures. It is the most common chemical used in fixed automated deicing systems because it is non-corrosive to steel rebar, bridge structures, and concrete (Beckwith, 2007). Applications of the chemical on bridges also have been shown to reduce the number and severity of crashes (Fay et al., 2008).

In a recent survey of highway agencies, ag-based products were ranked as the "most advantageous" snow and ice control chemical and were said to perform well at low temperatures. Lab tests found ag-based products effective at 23°F (-5°C) (Fay et al., 2008). Another study indicated that such products melt snow faster and at lower temperatures and provide more consistent, longer-lasting residuals than MgCl (Fischel, 2001).

2.1.2 Corrosion Impacts

Vehicle and structural damage resulting from chemical corrosion is an area of concern in snow and ice control operations. Chlorides are considered to be the most corrosive of winter maintenance chemicals (Fay et al., 2008). Chlorides penetrate concrete to the reinforcing steel on highway structures, which may result in deterioration and reduced strength, serviceability, and aesthetics. Transportation Canada reported that the chloride ion (Cl^-) migrates into concrete causing major damage to structures by corroding the steel structure (O'Keefe and Shi, 2005). Research by Mends and Carter (2002) determined the diffusion coefficients through concrete of MgCl to be two to three times greater than NaCl, which meant the time required to initiate corrosion of the concrete-embedded reinforcing steel was 10 to 15 years less (O'Keefe and Shi, 2005). The Colorado DOT switched from primarily using a salt–sand mix to MgCl and found improved deicing performance; however, some portions of the state switched back to salt–sand because research has shown MgCl to have a greater impact to infrastructure and roadside vegetation than originally thought (Fay et al., 2008).

Motorists and the trucking industry are concerned about chloride use because of vehicular corrosion. Chlorides damage vehicle and equipment chrome, tractor and trailer bodies, aluminum parts, wheels, hoses, and electrical parts (Fischel, 2001). The National Bureau of Standards and Batelle Laboratories estimate automobile corrosion costs from NaCl use exceed $1.2 billion a year (Blackburn et al., 1994). A FHWA-funded study estimated the cost of corrosion to vehicles to be $2.3 billion annually (Salt Institute, 2004).

Long-term use of chlorides does not result in strength loss in the cement paste matrix (Fay et al., 2008). A study on the effect of chemicals on pavement condition deterioration found that although chlorides can worsen scaling problems when cement goes through freeze/thaw cycles, using properly cured, air-entrained Portland cement concrete will help prevent scaling. The study also showed that chlorides have few negative effects on asphalt pavement (Lee et al., 2000).

Acetates are less corrosive to metals than chlorides. Electrochemical and weight-loss tests over a 14- to 17-month period indicated that bridge structural metals, including steel, cast iron, aluminum and galvanized steel, endured significantly less corrosion with CMA than with NaCl (Fay et al., 2008). KAce is commonly used at airports because it is less corrosive than NaCl (Shi et al., 2009). While acetates are less corrosive to steel than chlorides, research has shown they have a greater effect on concrete and asphalt. Ongoing research by the Innovative Pavement Research Foundation has found that acetates could “induce increased levels of expansion in concrete with ASR [alkali-silica reactivity] susceptible aggregates” (Lee et al., 2000). Lab studies for the Colorado DOT found that acetates can cause significant emulsification of asphalt resulting in strength loss. Because of these findings and the environmental impacts, Colorado no longer uses acetates (Fay et al., 2008).

A maintenance garage in Michigan DOT found that using ag-based products reduced maintenance to equipment by minimizing rusting on truck hoppers, spinners and other parts (Kahl, 2004). A corrosion specialist with Michigan DOT claims that ag-based products perform better, are more environmentally friendly, and are less corrosive than conventional materials. In a statewide evaluation of ag-based products on test roadways it was concluded that using ag-based products for winter maintenance showed promising results. Highlights from the study included reduced maintenance and equipment hours and an overall decrease in material cost. Accidents were reduced on I-94 compared to the previous year, and bare pavements were maintained longer. The agency said that “when ABP [agricultural by-products] are used appropriately for anti-icing, they can be a powerful tool in providing safer roads to the traveling public at less cost” (Kahl, 2004).

2.1.3 Environmental Impacts

Studies by FHWA, the Strategic Highway Research Program (SHRP), National Cooperative Highway Research Program (NCHRP), Canadian Strategic Highway Research Program, state agencies and private research firms have found that winter maintenance chemicals can adversely affect air quality, soil, roadside vegetation, and surface and groundwater.

Acetates are organic and affect the environment in different ways than chloride-based chemicals (Fischel, 2001). Research has consistently found that acetates do not severely impact soil, vegetation, wildlife or human health but can adversely affect nearby water by elevating biochemical oxygen demand levels, which causes anoxic conditions and stimulates growth of bacteria and algae (Fay et al., 2008, and Fischel, 2001). Oxygen depletion will most likely occur in slow-moving streams and small ponds because the 100 to 500-fold dilution of deicers from roadways will reduce impacts to most waterways. As demonstrated in lab tests, an acetate concentration of 100 ppm would completely deplete the dissolved oxygen in field ponds in two days (Fischel, 2001). In contrast, environmental monitoring over a five-year period in North Island, New Zealand, where CMA is the primary chemical used, indicates no negative impacts on soil, vegetation or streams (Burkett and Gurr, 2004).

Organic corrosion inhibitors contain high concentrations of phosphorus, sulfate, ammonia and nitrate, which adversely affect water quality and can result in the growth of unwanted aquatic vegetation (Fischel, 2001). Another concern is the oxygen depletion of the water (Nixon and Williams, 2001). Soil microorganisms break down the organic material, which temporarily creates anoxic conditions in soil that can kill vegetation. Some ag-based products lower the pH level of the soil and cause leaching of metals from the soil into ground water (Fischel, 2001).

2.1.4 Cost

According to a Colorado DOT study, abrasives are the least expensive snow and ice control material, with prices ranging from $6 to $16 per ton (Fischel, 2001). When surveyed, highway agencies reported using abrasives because of cost considerations. However, the overall cost of the use of abrasives is higher than the material cost because of the need for frequent applications and the cost of cleanup (Fay et al., 2008).

Many agencies prefer to use chlorides because of the low initial material cost. Depending on the quantities and location, solid NaCl can be purchased for $20 to $60 per ton and liquid NaCl can be produced at a cost as low as $0.03 per gallon (Fischel, 2001; Shi et al., 2009; Boselly, 2001). MgCl ranges from $0.25 to $0.78 per gallon and CaCl is typically around $0.50 per gallon (Fischel, 2001). While MgCl and CaCl usually cost more than NaCl, typically less quantity is needed to achieve the same result (Fischel, 2001; Williams and Linebarger, 2000). However, one state agency reported that it costs approximately 4.5 times more to melt ice and six times more to debond ice using CaCl than it does using NaCl because of the greater unit cost for CaCl (Perchanok et al., 1991).

According to Fischel (2004), adding ag-based products increases the cost of winter maintenance materials by $142 per ton. When Colorado DOT used a corn-based product added to MgCl as an anti-icing material, the cost increased from $0.34 per gallon to $0.60 per gallon (O'Keefe and Shi, 2005).

The high cost of acetates is their principal disadvantage. In New Zealand using CMA is five times more expensive than using chlorides, but agencies report that the greater cost is offset by the increased benefits to road users (Burkett and Gurr, 2004). According to researchers at the Ontario Ministry of Transportation, CMA costs 30 times more than NaCl, and higher application rates are required making their use 45 times more expensive (Perchanok et al., 1991). A cost analysis performed by Montana Department of Transportation indicated that, compared to MgCl, CMA would cost 5 times more and KAce would cost 12 times more (Williams 2001). The EPA estimates the cost of using acetates to be 10 to 20 times higher than salts (Environmental Protection Agency, 1999).

While NaCl may be inexpensive to purchase, the corrosion effects and environmental impacts may make its true cost much higher. One study estimates that the indirect costs associated with corrosion and environmental impacts of NaCl are $5 billion per year (Blackburn et al., 2004). A Transportation Research Board study found bridge decks were deteriorating prematurely due to chloride use, and a FHWA study showed the remediation of concrete bridges damaged by chlorides could cost $5 billion per year (O'Keefe and Shi, 2005). A Transportation Research Board study found that corrosion and environmental effects of NaCl may cost ten times more than its initial material cost (Blackburn et al., 1994). An economic assessment of the social costs of salting estimates the cost of NaCl to be $800 per ton "including costs of repair and maintenance of roads and bridges, vehicle corrosion costs and loss of aesthetic values through roadside tree damage" (Vitaliano, 1992).

Many studies have evaluated the performance, corrosion impacts, environmental impacts, and initial costs of winter maintenance materials. Table 2 summarizes the main findings of these studies for common winter maintenance chemicals and traction materials.

Table 2: Summary of Current Winter Maintenance Materials (Fischel et al., 2001)

		Abrasives	Sodium Chloride	Calcium Chloride	Magnesium Chloride	Calcium Magnesium Acetate	Potassium Acetate
Performance	Eutectic Temperature	NA	-21°C @ 23%	-51°C @ 29.8%	-33°C @ 21.6%	-27°C @ 32.5%	-60°C @ 49%
	General	< 11°C	Effectively depresses the freeze point of water	Effective at low temperatures; melts ice faster than NaCl	Effective at low temperatures; melts ice faster than NaCl	Effective as a liquid anti-icer; melts longer than NaCl	Effective as a liquid anti-icer; effective at low temperatures
Corrosion Impacts	Highway Structures	Non-corrosive	Corrosive	Moderately corrosive	Moderately corrosive	Non-corrosive	Non-corrosive
	Asphalt Concrete	Non-corrosive	Slightly corrosive	Slightly corrosive	Slightly corrosive	Moderately corrosive	Moderately corrosive
Environmental Impacts	Air Quality	Fine particulate material increases air pollution	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives
	Vegetation	Can smother roadside vegetation causing mortality	Inhibits water and nutrient uptake; vegetation and damage mortality	Inhibits water and nutrient uptake; vegetation and damage mortality	Inhibits water and nutrient uptake; vegetation and damage mortality	Potential mortality from oxygen depletion in soil	Potential mortality from oxygen depletion in soil
	Soil	Little effect on soil expected	Increases salinity; decreases soil stability and permeability	Increases soil salinity; improves soil structure	Increases soil salinity; improves soil structure and permeability	Potential oxygen depletion from breakdown of acetate; improves soil structure	Potential oxygen depletion from breakdown of acetate
	Surface / Ground Water	Increases turbidity; inhibits photosynthesis in aquatic plants	Potential increase in water salinity; slight increase in metals	Potential increase in water salinity; slight increase in metals	Potential increase in water salinity; slight increase in metals	Potential oxygen depletion	Potential oxygen depletion
Cost	Initial	Low cost	Low cost	Relatively low cost	Relatively low cost	High cost	High cost
	Associated	High cost	High cost	High cost	High cost	Low cost	Low cost

2.2 Winter Maintenance Strategies and Technologies

Winter maintenance on roads is accomplished by a variety of strategies, such as forecasting, plowing, deicing, etc. The frequency and use of the various strategies can be dependent on historical preferences, geography, conditions during winter storms, etc. This section of the literature review provides information about the various methods and technologies widely used in winter maintenance.

2.2.1 Plowing

Plowing is the most important tool in snow removal (Blackburn et al., 1994) and is used in almost all snow and ice removal strategies. Advances in snowplow technology have reduced the amount of energy needed to remove snow and ice (Epps and Ardila-Coulson, 1997). Most states use the same basic type of equipment: dump trucks with plows, rotary plows and loaders (Williams and Linebarger, 2000). Some common types of plows are one-way front plows, reversible plows, deformable mold board plows, underbody plows, and side-wing plows. Some plows can be shifted from side to side using hydraulics, allowing the plow to extend to the side by 9 to 12 feet (Ketcham et al., 1996).

Nixon and Chung (1992) conducted lab tests that examined snow blade geometry and the mechanics of scraping snow and ice. The study concluded that fairly minor changes in the cutting edge geometry provided substantially improved ice cutting. A prototype of the preferred blade geometry from laboratory experiments was tested in the field and found to outperform conventional blades (Nixon, 1993).

Another study looked at the effectiveness of serrated blades for scraping. Compared to classic blades, serrated blades require smaller forces to remove a given ice thickness but they remove less ice overall (Nixon et al., 1996). Nixon and Potter (1997) found that trucks with underbody plow blades are the best for snow removal because of the ability to vary download forces on the cutting edge or plow blade. Front-mounted blades provide the download force only through their self weight.

2.2.2 Deicing

Deicing is a reactive snow and ice control strategy that seeks to break the bond between snow/ice and the pavement by chemical and mechanical means. This traditional strategy is widely used today. Using the deicing approach, chemicals are applied during or after a winter storm when snow or ice has already bonded to the pavement. The chemicals melt channels through the snow and ice to the pavement. A thin layer of the chemical solution spreads at the interface between the ice and pavement and the ice–pavement bond is eventually weakened so that it can be mechanically removed. Blackburn et al. (2004) reported that deicing is a suitable strategy for most weather, locations, and traffic conditions. Solid chemicals were found to be the most effective for thicker snow accumulations. The Montana DOT reported that deicing typically produced bare and wet road conditions over time, associated with increased traction and safer roads (Bergstrom, 2002). According to the SHRP Project H-332, the effectiveness of deicing depends on the chemical and mechanical equipment used (Chappelow et al., 1992). Deicing allows for higher traffic speed and volume, reduces the need for abrasives (thus improving air quality), and saves on fuel consumption compared to plowing alone (Fischel, 2001). It is still the favored practice of most departments of transportation because it is effective and relatively inexpensive (Williams and Linebarger, 2000).

One concern about deicing is the increased potential for accidents due to poor road conditions prior and during maintenance activities. Also alarming is the large quantity of materials and labor hours required to maintain the desired level of service (O'Keefe and Shi, 2005). While proactive preventive strategies are increasingly used, deicing is a mainstay in winter operations and still appropriate for treatment throughout long lasting storms.

2.2.3 Anti-Icing

The FHWA defines anti-icing as "the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freeze-point depressant" (Ketcham and Minsk, 1996). State agencies are faced with the task of providing a high level of service during storms while protecting the environment, all with limited financial and staffing resources. Agencies are therefore shifting towards anti-icing strategies, which are considered more cost effective than traditional methods. Five times more energy is needed to remove ice and snow once the ice–pavement bond has formed (Boselly, 2001). Anti-icing is not limited to the pretreatment of chemical at the onset of a storm; regularly scheduled treatments, such as biweekly treatments on bridge decks, can also be employed (Boselly, 2001).

Anti-icing is suitable for most weather conditions, locations and traffic conditions; however, anti-icing should not be used when the pavement temperature is less than the effective temperature of the chemical or during blowing snow and rain (Nixon, 2002). If anti-icing is used in windy conditions, the liquid chemicals can cause snow to adhere to the pavement (Adams et al., 1991), and if used during rainy conditions they can be diluted or washed away.

The key to an effective anti-icing program is to "apply the right type and amount of material in the right place at the right time" (Federal Highway Administration, 1996). Anti-icing provides a higher level of service with the same or lesser amount of chemicals, but the chemical treatment should be scheduled using weather data from road weather information systems. The "Manual of Practice for an Effective Anti-icing Program" provides a summary of recommended methods (Blackburn et al., 2004).

Nixon (2002) estimates anti-icing creates a savings of 10 to 20 percent of the typical winter maintenance budget, and the cost per lane mile is reduced by up to 50 percent. Savings result from lower material and labor costs, higher levels of service, fewer environmental impacts, and improved safety. The reduced amount of chemicals used on the roadways also helps decrease indirect costs from corrosion to vehicles and highway infrastructure (Boon and Cluett, 2002; Canadian Strategic Highway Research Program, 2000; and Nixon, 2002). Using anti-icing techniques, the Colorado DOT reduced sand use by 55 percent and the cost of winter operations went from \$5,200 per lane mile to \$2,500 per lane mile. In freezing rain conditions, Oregon DOT reduced the costs per lane mile from \$94 to \$24 (Nixon, 2002). The higher level of service provided by anti-icing leads to safer travel and a reduction in insurance claims, accidents, and road closures (Alger et al., 2004; Blackburn et al., 1994; Boon and Cluett, 2002; Canadian Strategic Highway Research Program, 2000; and Nixon, 2002).

In 2000, Montana DOT performed a case study on a storm that affected two road sections of State Highway 200 located in different maintenance divisions where an anti-icing strategy was used on one and deicing on the other. The anti-icing section required 44 percent less sand and labor costs were reduced by 52 percent. Although more chemicals were applied, the overall cost was 37 percent less per lane mile compared to the deicing section (Goodwin, 2003). A case study in Idaho found that years of anti-icing with liquid MgCl on U.S. Highway 12 reduced accidents by 83 percent, abrasive use by 83 percent, and labor hours by 62 percent. Because of these successes, Idaho expanded its anti-icing operations throughout the state (Breen, 2001).

2.2.4 Prewetting

A more innovative strategy in winter maintenance that is becoming more popular is the practice of prewetting, where solid chemicals are coated with a liquid prior to being spread on the road (Conger, 2005). Prewetted solid chemicals are used in both anti-icing and deicing strategies. Blackburn et al. (2004) explain that prewetting accelerates the deicing process and reduces bounce and scatter because more chemical adheres better to the road surface. Improved adhesion means fewer materials are wasted, and the chemicals have a longer-lasting effect (Ketcham et al., 1996). A field evaluation in Michigan monitored the placement of dry salt versus prewetted salt. Ninety-six percent of the prewetted material was retained on the road surface compared to only 70 percent of the dry salt because of reduced bounce and scatter (O’Keefe and Shi, 2005). Overall, this strategy decreases maintenance costs, improves roadway safety, and lowers the accident rate (O’Keefe and Shi, 2005).

Prewetted salt was also found to be effective at temperatures below 14°F (-10°C) when dry salt was not (Luker et al., 2004). The British Columbia Ministry of Transportation and Infrastructure also found that the effective temperature range of sodium chloride increased by prewetting with MgCl and CaCl, making it more effective at colder temperatures. The Virginia DOT prewetted salt and sand with MgCl and CaCl and found that it accelerated the ice melting process but also accelerated corrosion of the equipment (Roosevelt, 1997). The Illinois DOT reported success using a variation of prewetting in which dry NaCl applications were immediately followed by liquid NaCl or CaCl (Blackburn et al., 2004). Williams (2001) found that prewetting decreased the amount of abrasives needed by approximately 50 percent in cold temperatures (O’Keefe and Shi, 2005). The Washington DOT conducted a field observation study in an area near threatened fish habitat. When the agency used MgCl to prewet sand it found that the amount of abrasives needed to provide the desired level of service was not detrimental to the streambeds and that although the chloride levels increased overall, they did not reach toxic levels. In addition to the environmental benefit, the agency found prewetting also reduced labor and spring cleanup costs. Limitations to widespread adoption of prewetting include lack of experience, training and equipment (O'Keefe and Shi, 2005).

2.2.5 Road Weather Information Systems

RWIS provide agencies with weather information and real-time pavement conditions, which can be used to make winter maintenance decisions related to the appropriate type of treatment, materials, and application rates. Accurate and reliable weather forecasting are crucial to implementation of successful, cost-effective anti-icing programs.

Ketchum (1996) describes RWIS as a "network of data-gathering and road condition monitoring systems and their associated communications, processing, and display facilities which provide decision information to maintenance managers." The sensors provide real-time, accurate and site-specific pavement surface conditions such as pavement temperature and the presence of water, ice, and chemical, and weather data such as ambient temperature, relative humidity, solar radiation, wind speed and direction, precipitation and other climatic conditions (Blackburn et al., 1994; Boselly, 2001; Canadian Strategic Highway Research Program, 2000). This information can be used with available algorithms to allow agencies to reasonably predict pavement conditions for the next 24 hours over a network of roads (Blackburn et al., 1994).

Using these forecasts, agencies can maximize the effectiveness of deicing and plowing efforts. A survey of Washington DOT maintenance personnel reported improved employee satisfaction and increased productivity by eliminating most regularly scheduled night shifts, and more efficient allocation of labor by employing RWIS data (Boon and Cluett, 2002). RWIS can reduce the use of routine patrols, provide travelers better information, provide a cost-effective and higher level of service and increase environmental quality by reducing the amount of unnecessary chemical applications (Boon and Cluett, 2001; Boselly, 2001; Environmental Protection Agency, 1999). Virginia estimated a $48,000 cost savings in salaries and equipment the first year a RWIS was used (Wyant, 1998). A $4.5 million system in Maryland was projected to pay for itself in five to seven years through reduced maintenance personnel stand-by time (Boselly, 2001). Researchers estimated a 300 percent return on a 26-sensor RWIS network on a joint project between Nevada and California near Lake Tahoe (Wyant, 1998). Massachusetts saved $53,000 in the first year by using a network of nine sensors in the Boston area (Boselly, 2001).

One limitation of RWIS is that it lacks spatial coverage because it only provides measurements at fixed locations. One solution is the use of infrared thermometers mounted on patrol vehicles to measure pavement temperatures between sensor locations (Wisconsin Department of Transportation, 2007). Many agencies recommend installing sensors at typical rather than extreme locations to most accurately predict storm events. Pavement temperature prediction models require additional instrumentation and data, especially in mountainous regions (Sato et al., 2004).

Barriers to employing a RWIS are lack of experience, lack of confidence in the system, lack of training, resistance to change, equipment reliability, long-term maintenance concerns, cost, and limitations of existing technology (Boon and Cluett, 2002). To overcome some of the barriers, the Wisconsin DOT schedules annual training including regional workshops (Wisconsin Department of Transportation, 2007). A survey of Montana DOT RWIS users indicated that even though RWIS are being used, more confidence in the information, improved ease of use and additional RWIS sites are still needed (Ballard, 2003). Many researchers and agencies predict better deployment and utilization of RWIS as the cost is reduced and better training becomes available.

2.2.6 In-Place Anti-Icing System

In-place anti-icing systems apply "timely, localized, and repeated treatments of optimum amount of chemical without the deployment of typical maintenance equipment and personnel" (Walderman, 2004). In-place systems are intended for remote locations, high traffic roads where a plow could cause congestion, and segments of roadway that are particularly prone to accidents, such as bridge decks (Bell et al., 2006). Application of chemicals can be triggered manually or automatically. Automatic systems, known as Fixed Automated Spray Technology (FAST), use algorithms to determine when poor road conditions warrant the application of chemicals. RWIS plays a key role in the functioning of these systems.

In-place anti-icing systems are used extensively in Europe on tunnel entrances, steep roads, hazardous intersections, bridges, and on/off ramps (Wyant, 1998). Including capital, interest and depreciation costs, material costs, savings due to accidents avoided, and reduced crew time, Switzerland reports a benefit–cost ratio of 1.45. Germany reported an even greater ratio of 1.9 with its system, which has been in use since 1983. European countries generally view in-place systems as "a proven technology" (Bell et al., 2006).

The United States also utilizes in-place systems. A pilot system installed at a bridge in Virginia in the late 90s provided needed information for Virginia DOT about the construction, maintenance, and operational issues of FAST systems. The test concluded that the system was not a substitute for plowing snow but it did provide vehicle traction and a uniform spread of chemical (Bell et al., 2006). In New York, an automated fixed system is in place on a portion of the Brooklyn Bridge. The New York DOT found that the bridge section treated by the in-place anti-icing system had a higher level of service than segments treated by snowplows and truck-mounted chemical sprayers. However, it was determined that embedding the spray nozzles in the road surface increased the corrosion of the steel grid members in the concrete bridge deck. The nozzles are now mounted on roadside barriers and warning signs are displayed to alert drivers when the system is spraying (Goodwin, 2003). The Utah DOT reported a significant reduction in accidents was seen after an in-place system was installed on an I-215 overpass in Salt Lake City (Bell et al., 2006). The Maryland DOT considers the automatic system on a bridge on I-68 to be a “major success.” Accident rates on the bridge were reduced by 40 percent from previous winters. The Colorado DOT reported a benefit–cost ratio of 2.36 and a 60 percent accident reduction with its FAST system (Bell et al., 2006).

2.3 Emerging Technologies

Winter operations now include not only the traditional methods of mechanical plowing and deicing and the proactive approach of anti-icing, but there is also research, testing and implementation of the following newer technologies: heated bridge decks, surface overlays, and improvements with information technology and equipment. Conger (2005) reports that strategies have changed and will continue to evolve as new technologies emerge and are proven.

2.3.1 Heated Bridge Deck

Another innovative snow and ice control technology is heated bridge decks. According to a FHWA report, three heating technologies are commonly used in the United States: hydronic, heat pipe, and electric. In a hydronically heated system, heated fluid is pumped through tubing embedded in pavement. In a heat pipe system, a working fluid contained in steel pipes vaporizes and condenses resulting in a passive transfer of heat. In an electrically heated system, heat is generated by electrical resistance cables buried in the pavement near the surface in (Minsk, 1999). According to Conger (2005), the operating costs of a heat pipe system are lower than electrical or hydronic systems. A NCHRP synthesis report concluded that heated pavement technologies are feasible, do not pose construction problems, and do not appear to have adverse effects on the durability of a bridge. But the report cautioned that the failure of a single sensor can result in the failure of an entire system and that selecting a proper working fluid for the heat pipes is critical (Conger, 2005).

A study on the prevention of the ice–pavement bond found that “local heating of the ice-substrate interface (without heating the bulk ice) coupled with an extremely small shear load easily debonds ice, even through a rough substrate. With an economical means to heat only the interface to near the melting temperature, ice could easily be removed mechanically with very little effort” (Penn and Meyerson, 2002). Research projects at Oklahoma State University looked at ground source heat pumps as a means of providing the necessary heat to bridge decks (Spitler and Ramamoorthy, 2000).

2.3.2 Surface Overlay

Special bonded surface overlays that retain anti-icing chemicals and gradually releases them onto the surface are a relatively new technology that primarily are used to protect bridges against frost and ice formation. Nixon (2006) explained that one such product “uses a special aggregate that acts, together with an adhesive, in a sponge-like manner such that when anti-icing liquid is applied to the surface, it is retained for a significant portion of time (typically several days) and remains effective as an anti-icing chemical during those times.” During the 2005–2006 winter season, Nixon studied the performance of a pavement overlay product, Safelane®, which was installed in eight locations in the United States. In a number of instances the test section containing Safelane® was clear of snow and ice, while the control test section (i.e., no Safelane®) was not. The test section required fewer chemicals to keep it clear, which resulted in cost, environmental, and safety benefits. At a bridge in Wisconsin, crashes during the previous two years were reduced from 49 to zero after the installation of an overlay. Nixon cautioned that the study period was too short to substantiate this level of improvement (Nixon, 2006).

The Wisconsin DOT performed an evaluation of its surface overlay, which consists of a thin layer of epoxy covered with a layer of absorptive aggregate. Results from the evaluation showed that the overlay produced friction values similar to dry pavement and appeared to be preventing accidents. Monitoring of the long term performance of the surface overlay was recommended (Martinelli, 2007).

In Alaska, Wyant (1998) reported working and experimenting with rubber asphaltic mixes trying to produce a pliable mix that would flex and break the ice as the temperature changed, although little benefit was observed.

The University of Nebraska–Lincoln and Western Michigan University studied a conductive concrete overlay on a bridge in Nebraska. The researchers designed and applied a concrete overlay to achieve high electrical conductivity and high mechanical strength. Because of electrical resistance and impedance, a thin overlay can generate enough heat to prevent ice formation when connected to a power source. The first field test averaged 500 W/m^2 (0.062 hp/ft^2), which generated enough heat to raise the surface temperature 16°F (9°C) above the ambient temperature (Tuan and Yehia, 2004).

2.3.3 Information Technology

A FHWA program developed a winter road maintenance decision support system (MDSS) “to provide objective guidance to winter control decisions concerning appropriate strategies” (Petty et al., 2008). A MDSS uses environmental and road condition information provided by RWIS to recommend proper treatment of roadways during winter maintenance activities. Currently, six versions of MDSS prototypes are available and lessons from recent field tests are being used to improve and refine MDSS algorithms (Hart et al., 2008, and Petty et al., 2008).

The 2003 American Meteorological Society Forum of Weather and Highways recognized the benefits of a denser network of RWIS sites but also realized the cost limitations agencies face. The Society introduced non-invasive road temperature and condition sensors to compensate for limited funding. Over 300 sensors have been installed in more than a dozen countries including 50 states in the United States. The ease of use and low cost of the sensors promote the growth of RWIS networks (Bridge, 2008).

An innovative weather observation technology is being developed by FHWA in conjunction with the IntelliDrive initiative. It utilizes passenger vehicles as weather probes by having automobile manufactures equip cars with onboard units and receivers than can collect data such as windshield wiper state or outside air temperature, and transmit the data to a national communication station (Pisano et al., 2008).

2.3.4 Equipment

In 2002, the Virginia DOT performed a pilot test on automatic vehicle location (AVL) technologies. The tests found AVL systems could be used to track winter maintenance operations in a timely and satisfactory way (Conger, 2005). AVL systems consist of onboard computer systems, pavement sensing devices, multiple material distribution systems, increased horsepower, automated activity reporting, and a friction measuring device (Andrel, 2002).

The Highway Maintenance Concept Vehicle (HMCV) was designed by incorporating applications from other industries in highway maintenance vehicles. The HMCV is capable of applying a precise amount of material at a given time and uses a friction meter to adjust the chemical rate (Andrel, 2002).

The Swedish Road Administration tested a high speed environmental plow that goes faster than traditional plows and is cheaper to use because fewer chemicals are needed. The plow has been evaluated in the lab but not objectively and scientifically tested in the field. The high speed environmental plow is equipped with flexible cutting edges, uses a plow angle of 55° rather than the typical 90°, and can plow at speeds up to 43 miles per hour (Gruhs, 2008).

Global information systems (GIS) and artificial intelligent techniques are being used for an intelligent snow removal asset management system. In an Iowa case study, GIS was used to access and manage road data with normal snow removal. That data was then used to prioritize snowplowing routes, improving snowplowing time by 1.9 percent for a moderate snowfall (Conger, 2005).

2.4 Summary

The literature review provided information about current and emerging practices, materials and technologies. The most common chemical used for deicing and anti-icing is still NaCl because it is abundant, performs relatively well and is inexpensive. While CaCl and MgCl generally perform better than NaCl in colder conditions, the higher cost and possibly greater impacts to infrastructure limit their use. Acetates cost even more, but are less corrosive to metals. The performance of CMA compared to NaCl has not yet been established regarding higher application rates and the benefits of a residual effect. KAce is considered a good choice on bridge decks where corrosion is more of a concern. Ag-based products are gaining favor but, because of higher costs, are more often added to other chemicals to improve performance and reduce corrosion.

Various combinations of technologies and strategies can be used to respond to winter storm events. Technologies such as RWIS and FAST provide information to agencies about current road conditions and can provide localized treatments prior to deploying maintenance personnel. Analyses of RWIS have demonstrated overall cost savings related mostly to more efficient use of equipment and personnel. Successful anti-icing programs are dependent on adequate forecasts, but have been shown to be successful with reduced chemical applications and to provide a better level of service during storms. Deicing is still a widely used and appropriate treatment strategy for winter maintenance. Prewetting solid chemicals or abrasives can improve performance by reducing bounce and scatter, and has been incorporated into deicing, anti-icing, and plowing strategies.

Additional technologies are continually being developed to improve winter maintenance practices (e.g., MDSS, IntelliDrive) and improve transportation infrastructure (e.g., heated bridge decks and special surface overlays). Further development and implementation of these concepts and techniques will continue to advance the state-of-the-practice of winter maintenance.

3 LABORATORY EXPERIMENT

The purpose of the laboratory experiment was to examine the ability of various anti-icing chemicals under different meteorological conditions on a variety of road surface types to mitigate the bonding of snow to the pavement during a winter storm event. A set of experiments was used to determine the optimum application rates for specific hypothetical precipitation scenarios using selected chemical types. This section begins with a discussion of the variables tested and descriptions of the equipment and test procedure methodology. An analysis of the results from the general experiment follows. Additionally, the results of laboratory experiments to evaluate bond strength between the snow and the pavement are presented.

3.1 Methodology

The methodology employed for the laboratory experiments in this study was designed to evaluate the anti-icing performance of chemicals under a variety of conditions. Throughout the development of the experiment, care was taken to ensure the testing conditions were as repeatable and realistic as possible. For instance, the pavement specimens were fabricated and conditioned to ensure uniformity, the anti-icing chemical was applied with a precision-calibrated nozzle, and the same source of naturally harvested snow was used throughout the experiment. The following subsections describe the experiment parameters considered in the laboratory experiments, the proposed matrix of laboratory experiments, and a description of the test procedures and laboratory equipment.

3.1.1 Experiment Parameters

The design of the laboratory experiment was developed to evaluate how several liquid anti-icing chemicals affect the bond between compacted snow and pavements under various conditions. Undoubtedly, there are several variables that affect this bond; however, the laboratory tests were designed to evaluate the effect of only the following four items:

- pavement type,
- anti-icing chemical type,
- chemical application rate, and
- pavement and air temperature (referred to as storm scenario, in this project).

Pavement Types

Two pavement types were used to represent common road surfaces in California: Portland cement concrete and asphalt concrete. Pavement samples were manufactured for the experiments based on mix designs provided by Caltrans.

Chemical Types

Five liquid chemicals were used for the laboratory experiment (referred to throughout this report using the abbreviations that follow in parentheses): 1) sodium chloride (NaCl), 2) calcium chloride (CaCl), 3) magnesium chloride (MgCl), 4) potassium acetate (KAce), and 5) an ag-based product (Agri). These chemicals were selected based on results from the literature review and discussions with Caltrans maintenance personnel.

Sodium chloride is generally the preferred material used on roads during winter storms because it is inexpensive, readily available (brines can often be produced locally), and is effective over a wide range of temperatures. Typical application rates for anti-icing range from 20 to 50 gallons per lane mile (gal/lm). Corrosion inhibitors are commonly added to reduce the corrosion effects of chloride-based products. For this project a solution of 23 percent NaCl brine (manufactured and provided by the Montana Department of Transportation in Helena, MT) was treated with five percent Shield GLT—a commercially available corrosion inhibitor manufactured by Redmond Minerals (Redmond, UT) that has been approved by the Pacific Northwest Snowfighters (PNS) association.

Calcium Chloride with Boost, manufactured by America West Environmental (Pasco, WA), was the commercially available corrosion-inhibited CaCl product used. It was a 30 percent solution of CaCl treated with Geomelt C®—a corrosion inhibitor made of sugar beet-based organic material. The product is PNS approved and has been found to be 84 percent less corrosive than sodium chloride. It is typically applied at rates of 20 to 40 gal/lm during anti-icing operations.

The commercially available corrosion-inhibited magnesium chloride product was Freezgard CI Plus®, made by North American Salt Company (Overland Parks, KS). CI Plus® is a proprietary corrosion inhibitor mixed with a 30 percent magnesium chloride solution; Freezgard CI Plus is a PNS-qualified product. The anti-icing application rates for magnesium chloride are reported to be between 20 and 50 gal/lm.

The potassium acetate used was manufactured by Cryotech Deicing Technology (San Diego, CA) and sold as CF-7®. It is a corrosion-inhibited solution with 50 percent potassium acetate. It is PNS approved and is essentially non-corrosive to vehicles and highway infrastructure. The advantages reported are that it is non-corrosive, causes minimal damage to roadside vegetation, is effective at low temperatures, and does not attract wildlife. The main disadvantages are its high cost and its potential for oxygen depletion of soil and water. Typical application rates are from 25 to 60 gal/lm.

The ag-based product selected was Ice Clear RDF, formally sold as NC-3000. It is a non-chloride agricultural-byproduct-based chemical manufactured by Glacial Technologies (Malvern, OH). Ice Clear RDF is composed primarily of materials derived from the processing of starches and sugars. It is nontoxic and non-hazardous to plant and animal life, making it an ideal alternative for use in sensitive areas. Ice Clear RDF is approved by PNS, and Glacial Technologies suggests the chemical be applied as a pretreatment at approximately 20 to 40 gal/lm.

Application Rates

Typical field application rates range from 10 to 60 gal/lm for most anti-icing operations. Chemical application rates used in the laboratory were determined by applying a specific amount of anti-icing chemicals to a pavement sample, compacting snow to the treated surface, and reducing the rate until a bond between the snow and pavement surface was formed. Generally, bonds between the snow and the pavement formed at very low application rates (2.5 to 15 gal/lm) as compared to typical field application rates. Application rates below 2.5 gal/lm could not be accurately applied in the laboratory. For asphalt pavement specimens, the application rates were 2.5, 5 and 10 gal/lm. Because the snow bonded better to the concrete pavement specimens, slightly higher application rates were used (5, 10 and 15 gal/lm). Two main factors contributed to the lower rates: 1) the sprayer used to apply the chemical had a smooth continuous fan pattern in contrast to the solid streams generally used in the field, and 2) there was no loss of chemical by traffic. Control samples were also included in the experiment in which no chemical was applied to the pavement specimens (i.e., 0 gal/lm).

Storm Scenarios

Three temperature-related storm scenarios were used. Storm scenarios were characterized by the initial temperatures of the air, snow, and pavement. Pavement temperature was controlled using a, temperature-controlled table, air temperature was controlled using a specially designed environmental chamber, and snow temperature was the same as the air temperature. The storm scenarios and respective temperatures for the three storm scenarios are shown in Table 3. Storm scenario I represents the coldest conditions, storm scenario II consists of cool atmospheric conditions on warmer pavement, and storm scenario III represents the warmest conditions.

Table 3: Temperatures for Storm Scenarios

Storm Scenarios	Initial Conditions		
	Pavement Temperature °F (°C)	Snow Temperature °F (°C)	Air Temperature °F (°C)
I (P14–SA14)*	14 (-10)	14 (-10)	14 (-10)
II (P32–SA23)*	32 (0)	23 (-5)	23 (-5)
III (P32–SA30)*	32 (0)	30 (-1)	30 (-1)

*P = Pavement temperature and SA = snow and air temperature in degrees Fahrenheit

3.1.2 Matrix of Laboratory Experiments

The equipment and methodology used for the laboratory experiments accommodated four pavement specimens during an experiment. For a single experiment conducted in the lab, four pavement samples were treated with one of the five chemicals at four application rates (control, low, medium and high). The combination of all the variables (two pavement types, five chemicals, four application rates, and three storm scenarios) results in 120 combinations that were tested in 30 separate experiments. The matrix of experiments that were run is shown in Table 4. Alternately shaded areas of the table indicate a single test run.

Table 4: Matrix of Experiments Run with Specified Variables

Chemical	Asphalt			Concrete		
	P14-SA14	P32-SA23	P32-SA30	P14-SA14	P32-SA23	P32-SA30
NaCl	2.5 gal/lm	2.5 gal/lm	2.5 gal/lm	5 gal/lm	5 gal/lm	5 gal/lm
	5 gal/lm	5 gal/lm	5 gal/lm	10 gal/lm	10 gal/lm	10 gal/lm
	10 gal/lm	10 gal/lm	10 gal/lm	15 gal/lm	15 gal/lm	15 gal/lm
	Control	Control	Control	Control	Control	Control
CaCl	2.5 gal/lm	2.5 gal/lm	2.5 gal/lm	5 gal/lm	5 gal/lm	5 gal/lm
	5 gal/lm	5 gal/lm	5 gal/lm	10 gal/lm	10 gal/lm	10 gal/lm
	10 gal/lm	10 gal/lm	10 gal/lm	15 gal/lm	15 gal/lm	15 gal/lm
	Control	Control	Control	Control	Control	Control
MgCl	2.5 gal/lm	2.5 gal/lm	2.5 gal/lm	5 gal/lm	5 gal/lm	5 gal/lm
	5 gal/lm	5 gal/lm	5 gal/lm	10 gal/lm	10 gal/lm	10 gal/lm
	10 gal/lm	10 gal/lm	10 gal/lm	15 gal/lm	15 gal/lm	15 gal/lm
	Control	Control	Control	Control	Control	Control
Kace	2.5 gal/lm	2.5 gal/lm	2.5 gal/lm	5 gal/lm	5 gal/lm	5 gal/lm
	5 gal/lm	5 gal/lm	5 gal/lm	10 gal/lm	10 gal/lm	10 gal/lm
	10 gal/lm	10 gal/lm	10 gal/lm	15 gal/lm	15 gal/lm	15 gal/lm
	Control	Control	Control	Control	Control	Control
Agri	2.5 gal/lm	2.5 gal/lm	2.5 gal/lm	5 gal/lm	5 gal/lm	5 gal/lm
	5 gal/lm	5 gal/lm	5 gal/lm	10 gal/lm	10 gal/lm	10 gal/lm
	10 gal/lm	10 gal/lm	10 gal/lm	15 gal/lm	15 gal/lm	15 gal/lm
	Control	Control	Control	Control	Control	Control

3.1.3 Description of Test Procedures and Equipment

The laboratory experiment consisted of eight main steps, as listed below. Each step was conducted sequentially and consistently. Equipment designed and constructed for these experiments is described in more detail in the following subsections. The fundamental pieces of equipment include a walk-in environmental chamber, temperature-controlled table, chemical applicator, snow compactor, plow mechanism, friction tester, thermocouple sensors, and data acquisition system. Laboratory equipment was designed to resemble in-field conditions as much as possible, while maintaining repeatability between individual tests.

Step 1: Manufacture pavement substrates

Step 2: Condition, instrument and clean pavement specimens

Step 3: Apply anti-icing chemicals

Step 4: Apply snow to pavement surface

Step 5: Induce simulated traffic load (compaction)

Step 6: Prepare individual test samples on pavement substrates

Step 7: Shear individual test samples from pavement

Step 8: Measure parameters of interest

The testing chamber used for this experiment is one of seven specialized laboratories in the Montana State University Subzero Science and Engineering Research Facility. A facility map is shown in Figure 1. The cold structures testing chamber was chosen because of its large size (12 ft. by 20 ft.), which provided adequate workspace to set up and execute the laboratory experiments. The fully programmable chamber was capable of precise temperature control of -40 to +50°F.

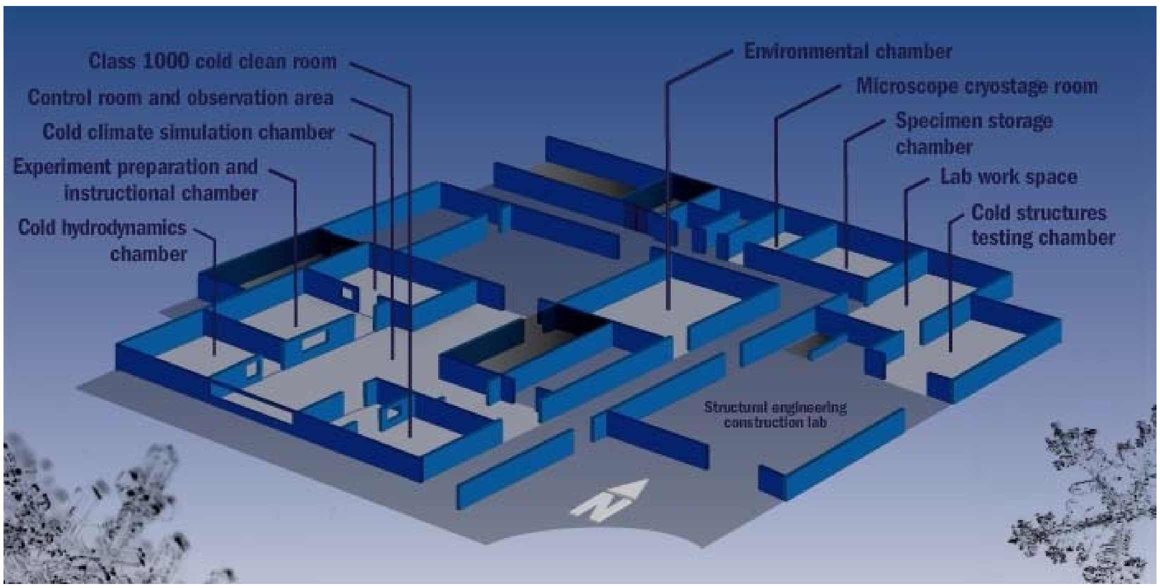

Figure 1: MSU Subzero facility map (MSU Subzero Science and Engineering Research Facility, 2010).

Step 1: Manufacture Pavement Substrates

Two types of pavement substrates representative of California road surfaces were manufactured. These road surface types were selected in consultation with Caltrans personnel. The size of each pavement substrate was 20 in. long, 9 in. wide, and 1 in. thick.

Portland cement concrete samples were manufactured using a mix design provided by Caltrans (provided in Appendix B). The maximum aggregate size in the concrete mix was ¾ in. because the samples were 1 in. thick. Type II Portland cement was used and all substrates were made from a single batch of concrete. Once the mix was ready, it was poured into wood forms and finished using hand tools. The samples were allowed to cure for 60 days in a moist cure room after removal from the forms.

Asphalt concrete pavement substrates were manufactured using full-size construction equipment at the TRANSCEND research facility in Lewistown, Montana. A 1-inch-thick section of asphalt was placed and compacted in a large plywood form so that thickness and surface roughness could be carefully controlled. After the asphalt was placed in the form, the material was leveled using a wooden screed and compacted with a pneumatic smooth-drum roller (Figure 2). Once the asphalt had cooled, individual pavement sections were cut to 9 in. by 20 in. using a wet diamond saw. A Montana Department of Transportation mix design that closely resembled the Caltrans mix design was used (both are included in Appendix B). Maximum aggregate size was less than ½ in. and a PG64-28 asphalt binder was used.

Figure 2: Screeding (left) and compacting (right) asphalt in plywood form.

Step 2: Condition, Instrument and Clean Pavement Specimens

The surfaces of each pavement sample were lightly ground using an angle grinder with a diamond concrete grinding wheel to make surface roughness, texture and aggregate exposure similar for all pavement samples and, thus, all individual experiments. The surfaces of the samples after being conditioned are shown in Figure 3.

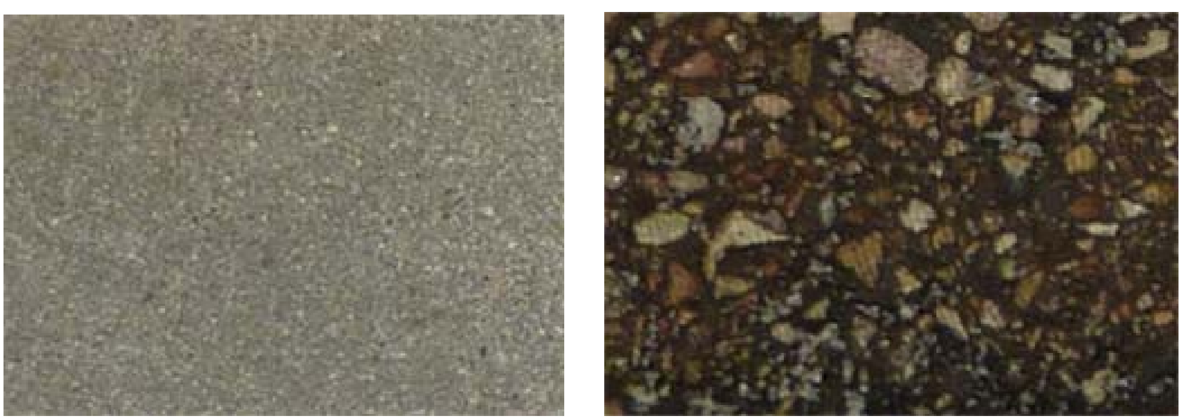

Figure 3: Surface of concrete (left) and asphalt (right) sample after grinding.

After conditioning, individual pavement samples were instrumented with three thermocouples. Small holes were drilled through the pavement in the center of each of the three areas where snow samples would be positioned during the shearing sequence (Step 7). A single thermocouple was inserted into each hole so that its welded end was flush with the surface of the pavement. Bondo® was used to fill the hole, restore the surface of the asphalt, and hold the thermocouple in place. The thermocouple wires were routed in a groove cut on the underside of the pavement to keep the top surface free from obstructions. Each pavement sample was brushed and washed in water to clean the surface, and allowed to dry. Pavement specimens were moved to a temperature-controlled table in the environmental chamber to acclimate them to the initial temperature associated with a particular storm scenario.

Step 3: Apply Anti-Icing Chemicals

Anti-icing chemicals were applied to the pavement surface at the desired application rate using an atomizing spray nozzle. The nozzle was mounted to a custom-built stand with a linear guide block and rail so that it could be moved smoothly across the pavement substrate at a constant speed as the chemical was applied to the pavement surface. Compressed air was used to siphon the anti-icing chemical from a container attached to the stand. Regulated air pressure, siphon height and nozzle speed across the substrate were calibrated to control the rate of chemical applied to the pavement surface.

The spray nozzle was initially calibrated using water at room temperature and then verified with each of the chemicals at colder temperatures. The siphon height and air pressure were adjusted along with the speed of travel across the substrate until the desired application rate was obtained. A metronome was used to maintain consistent rate of travel across the entire sample. Aluminum shields were placed around the substrates to protect the substrates from overspray and wind from the cooling fans in the environmental chamber. A photo of the chemical application setup is shown in Figure 4. Treated pavement samples were stored in the environmental chambers until Step 4 (approximately 1 to 2 hours).

Figure 4: Chemical applicator.

Step 4: Apply Snow to Pavement Surface

Three temperature-related winter storm scenarios were used when the snow was applied to the pavement. Storm events were characterized by the initial temperatures of the air, snow, and pavement. The air and snow temperatures were controlled by programming the MSU Subzero chamber. Temperature of the pavement was controlled using a temperature-controlled table. The temperature-controlled table was specially built to control its temperature to approximately ±1.2°F. The table was constructed using copper tubing and aluminum materials. A Neslab® 740-R recirculating chiller with heating and cooling capabilities was used to circulate fluid through the tubing to control the temperature of the table. Rigid foam insulation was installed under the tubing to reduce heat loss, and a layer of glycol-soaked felt was placed on top of the table to increase thermal conductivity between the table and the pavement substrates. A diagram of the table is shown in Figure 5. Using this equipment, consistent pavement temperatures were maintained in the pavement samples separately from the ambient temperature of the environmental chamber.

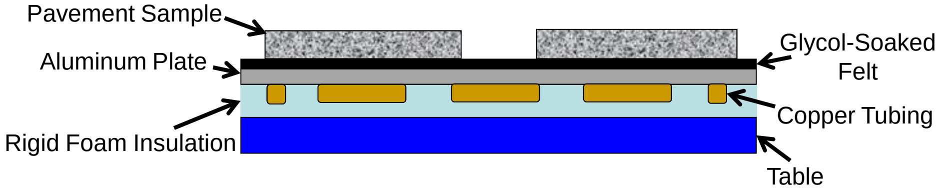

Figure 5: Side view of the temperature-controlled table supporting two pavement specimens.

Snow for the experiments was harvested from the mountains near Bozeman, Montana, and stored in the cold specimen storage chamber at the MSU Subzero Facility at -22°F. Prior to each test, the snow was allowed to acclimate to the air temperature specified by each storm scenario. Before applying the snow to the pavement, the pavement specimen was quickly moved from the temperature-controlled table to the compactor box (Figure 6) and covered with a 1-mm sieve. Snow was grated and sifted through the sieve until the snow was about 1 inch deep on the entire pavement surface (Figure 7, left). A straight edge was used to ensure a uniform depth of snow on the pavement substrate (Figure 7, right).

Figure 6: Pavement sample in the compaction box.

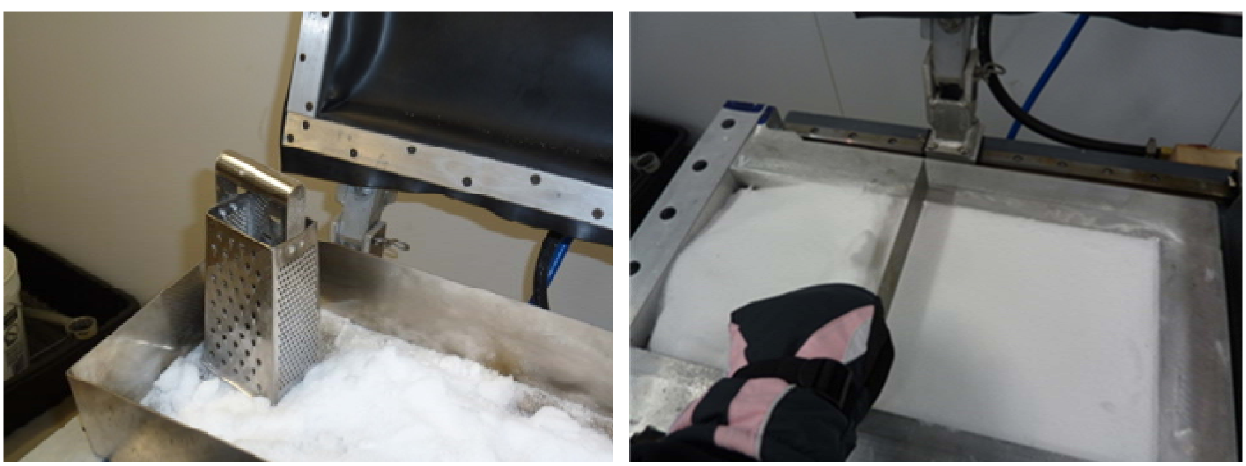

Figure 7: Grated snow is sieved onto the pavement sample (left) and leveled with a screed (right).

Step 5: Induce Simulated Traffic Load

The snow was compacted onto the pavement substrate to simulate traffic loading using a specially designed and constructed compaction box (Figure 8). The lid to the box was fitted with a flexible and soft rubber bladder to apply a uniform compactive stress directly to the surface of the snow. A foam-core board was placed under the concrete samples to prevent them from cracking during compaction. The bladder assembly was filled with compressed air at 80 psi for 5 minutes during compaction. A photograph of a pavement specimen with the compacted snow is shown in Figure 9.

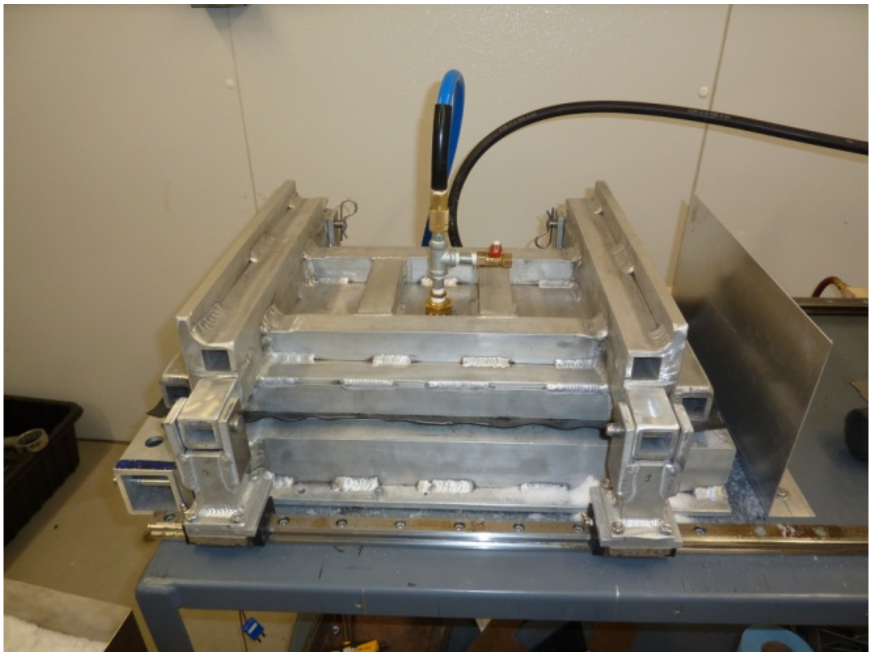

Figure 8: Compaction box with lid closed.

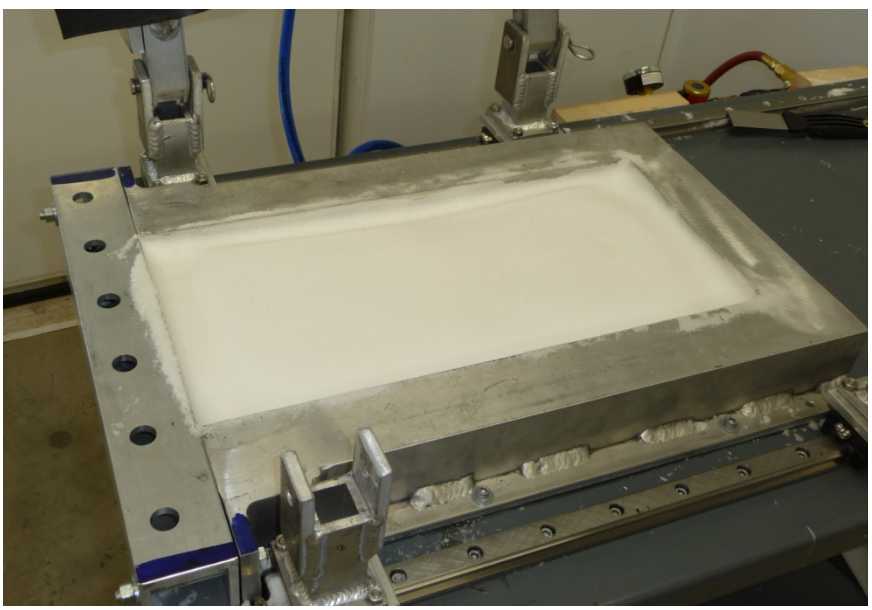

Figure 9: Compacted snow on pavement sample in the compaction box.

Step 6: Prepare Individual Test Samples on Pavement Substrates

Each pavement specimen accommodated three individual samples to assess the bond between the snow and the pavement. Samples were isolated from surrounding snow by pushing thin, metal, square cutters (later utilized as plow boxes) through the depth of the snow at three specific locations using the same compaction device described above. A 1 in. by 2 in. thin, metal box was also positioned on the snow surface to cut out a sample for snow density measurements. A Teflon® cutting guide was used to ensure proper placement of the cutters (Figure 10). A rigid Teflon sheet was positioned over the plow boxes to protect the bladder from damage as it was inflated to 60 psi to drive the plow boxes through the compacted snow.

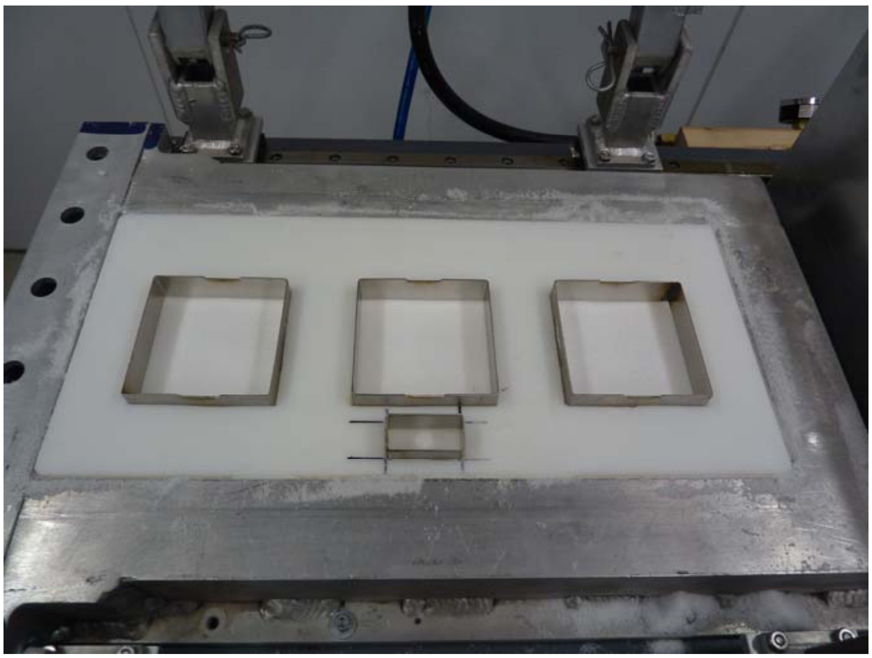

Figure 10: Plow boxes and cutting guide before being pressed into compacted snow.

The snow surrounding the three test samples was removed to isolate the three samples on the pavement surface. Snow samples prepared and ready for testing are shown in Figure 11. Each sample was 4 in. by 4 in. and approximately 0.75 in. thick after compaction. The final layout and dimensions of the pavement specimen and test samples is shown in Figure 12. The temperature-controlled table was built to accommodate four pavement specimens. Each pavement substrate was placed on the temperature-controlled table to maintain its temperature while the other samples were prepared.

Figure 11: Fully prepared sample ready for shearing.

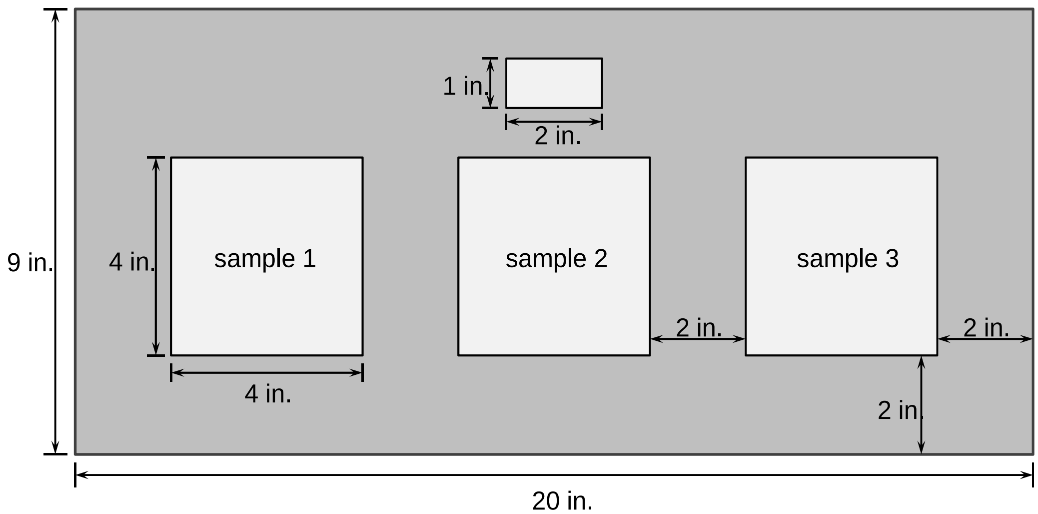

Figure 12: Individual pavement specimen layout.

Snow density measurements of all compacted snow samples were taken to monitor consistency. Snow density varied slightly between the different storm scenarios but was consistent between samples collected within any given storm scenario, as seen in the small standard deviations in Table 5. At 32°F the unit weight of ice is about 57.2 lb/ft^3 and the unit weight of water is 62.4 lb/ft^3. A spring snow pack in the Rocky Mountain region typically has a unit weight of about 50 percent of water (31.2 lb/ft^3) (Thut, 2007). The unit weight of compacted snow measured in the lab was approximately 51 percent higher than springtime snow packs, or about 17 percent less than ice.

Table 5: Unit Weight of Snow in Laboratory Tests

Storm Scenario	Average Unit Weight (lb/ft^3)	Standard Deviation (lb/ft^3)
I (P14-SA14)	48.1	0.05
II (P32-SA23)	46.9	0.07
III (P32-SA30)	46.6	0.04

Step 7: Shear Individual Test Samples from Pavement

Snow was horizontally sheared from the pavement specimen using a plow assembly that consisted of a plow box (inserted in Step 6), hitch, pulley and weight. After excess snow was cleared around the snow samples, a hitch was attached to the plow box. The hitch was used to connect the plow boxes to the pulling force. A string was connected to the hitch that was strung over a pulley where the weight was attached, as illustrated in Figure 13. A constant force of 1.38 lbs was established during proof tests to be large enough to easily remove unbonded snow from the pavement surface, but small enough to keep from shearing lightly bonded snow. Guards were constructed to block wind from the circulation fans in the environmental chamber and keep the weights from swinging. Ramps were positioned along the edge of the pavement specimens to catch the debonded snow from falling off the side of the table and disturbing other samples (Figure 14). In some cases the application rate of the anti-icing chemical was sufficiently high to prevent a bond between the snow and pavement from forming. When this occurred, this step was omitted for these pavement specimens.

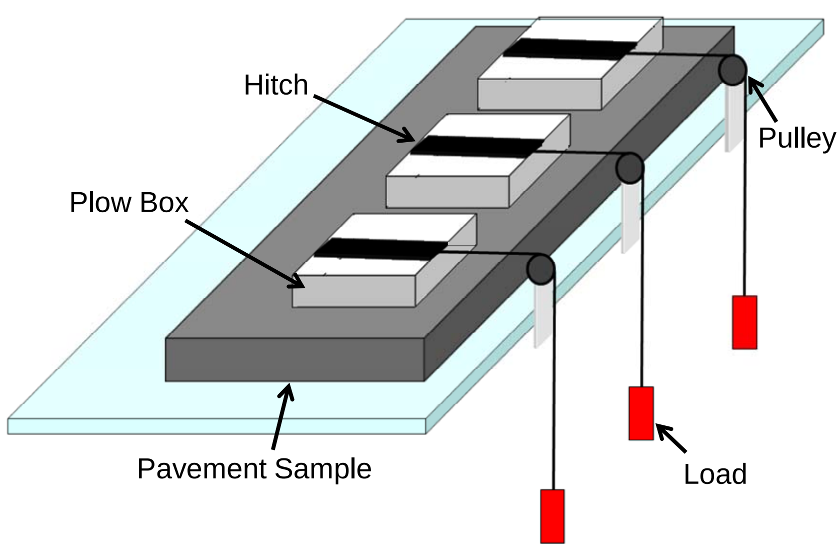

Figure 13: Plow box attached to load with the hitch and pulley.

Figure 14: Ramps on the temperature-controlled table.

Because this test procedure applied a constant shear force to the samples, the bond was weakened between the snow and the pavement by gradually increasing the temperature of the pavement using the thermal table. In this regard, the parameter of interest was the temperature at which the samples debonded, an indirect measure of a particular chemical's ability to weaken this bond or suppress the freezing temperature of the ice crystals at the snow–pavement interface. As the surface temperature increased, the bond between the snow and ice weakened and the sample eventually debonded from the substrate. Three separate samples were debonded from each pavement substrate to measure the variability of the experiment.

Step 8: Measure Parameters of Interest

The two main parameters of interest were 1) the temperature at which the snow–pavement bond failed, and 2) the friction of the pavement surface immediately after shearing had taken place. Temperature at the top of the pavement surface under the center of each sample was measured using the thermocouples and recorded throughout the experiment at five-second intervals using a data acquisition system. The data acquisition system was equipped with special switches so that the exact time and temperature were recorded when each sample was debonded.

Friction measurements were made immediately after the bond between the snow and the pavement surface broke in each of the three samples using a custom-made friction tester. Friction measurements were compared to baseline values collected from samples that were treated at each of the four chemical application rates before snow was applied. This data was used to determine relative friction values between the various chemical treatments. The friction tester was constructed out of steel, weighed 4.9 lbs, and had a 4 in. by 4 in. contact surface. A smooth pad of ¼-in.-thick neoprene rubber (durometer rating of 30A) was used for the friction wear surface. The apparatus was pulled across the pavement surface and the force needed to overcome static friction was measured with a spring scale. The friction tester and spring scale are shown in Figure 15.

Figure 15: Friction tester and spring scale.

3.2 Results and Analyses

The purpose of the laboratory experiments was to determine the optimum application rates for various anti-icing chemicals on a road surface to mitigate bonding of ice and/or snow to the pavement surface during a winter storm event. Temperature and friction data collected during the laboratory experiments was used to compare the performance of the five chemicals relative to pavement type, application rate, and storm scenarios.

Statistical analyses were employed to assess differences in the pavement temperature at which shearing occurred and in the coefficient of friction (COF) after shearing. Individual values of temperature or friction from a single experiment (i.e., three measurements on a single substrate, at a single application rate, using a single storm scenario) were averaged. These average values were used in various combinations to evaluate differences between temperature and friction with respect to chemical type, pavement type, application rate and storm scenario.

A two-sided t-test was used to make quantitative comparisons of the data. This test evaluates the statistical significance of the difference between the means of two sample populations (e.g., the difference in mean shearing temperature of CaCl to MgCl on concrete for storm scenario I). The results of this test can be expressed in a variety of forms, and the decision was made to cite the p-value for each comparison. The p-value ranges between zero and one; values approaching zero indicate a greater likelihood that the sample means are different, while values approaching one indicate a greater likelihood that the means are the same. Another way to consider the p-value is by multiplying it by 100 to generate a percent. This percentage indicates the likelihood that the two means are equal when a random sample is chosen from each of the sample populations. For example, a p-value of 0.42 indicates that there is a 42 percent chance that the means are equal to one another. Detailed comparisons from a variety of combinations based on pavement type, application rate, and storm scenario are presented in Appendix C for debonding temperature and Appendix D for friction.

3.2.1 Debonding Temperature

Winter maintenance chemicals are used because they depress the freezing point of snow and ice. To assess the effectiveness of the chemicals tested, the pavement surface temperature was recorded when the snow sample was debonded from the pavement. Ideally, chemicals that are more efficient at depressing the freezing point of water will more effectively interrupt the bond between the snow and pavement, thereby causing the compacted snow samples to shear from the pavement at lower temperatures.

On asphalt substrates, bonds formed with all chemicals only at the lower application rates (0 and 2.5 gal/lm), but not at 5 or 10 gal/lm. On concrete pavement specimens, bonds formed with all chemicals at 0, 5 gal/lm and 10 gal/lm, but not at 15 gal/lm. These results indicate that the bond between the snow and the pavement is interrupted due to the presence of anti-icing chemicals, as expected. Debonding temperatures for storm scenarios I, II, and III are shown in Figure 16, Figure 17, and Figure 18, respectively. The data presented in these figures indicates that the compacted snow samples debonded at temperatures warmer than 32°F—higher than expected, and greater than the freezing point of water (discussed in greater detail below). Nevertheless, based on this data, presence of chemical generally reduces the temperature at which the snow samples debonded, regardless of chemical type, application rate or storm scenario. This amount of reduction seems to be related in some way to the storm type. As is evident from tests performed on concrete substrates, pavement temperature at debonding decreases as application rate increases. Debonding temperatures were relatively consistent for each chemical type for a particular pavement and application rate. A more detailed and comprehensive statistical analysis of the resulting debonding temperatures is included in Appendix C, although these comparisons did not offer consistent reasons for differences in performance between the anti-icing chemicals.

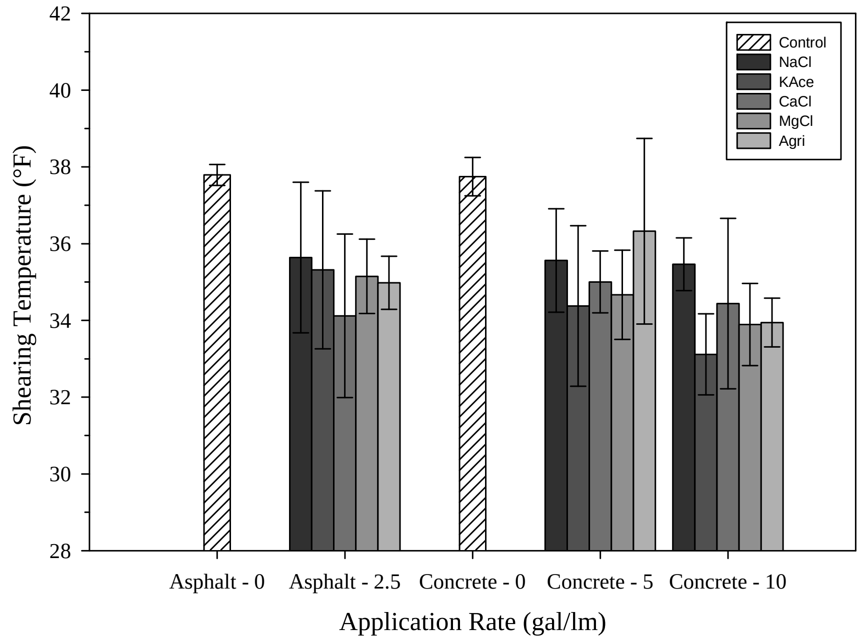

Figure 16: Debonding temperature for storm scenario I (P14–SA14) with 95% confidence error bars.

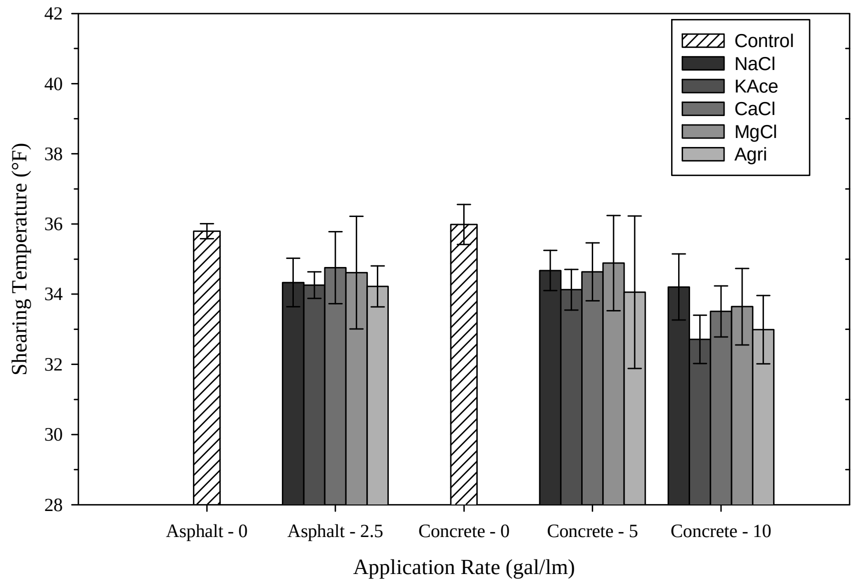

Figure 17: Debonding temperature for storm scenario II (P32–SA23) with 95% confidence error bars.

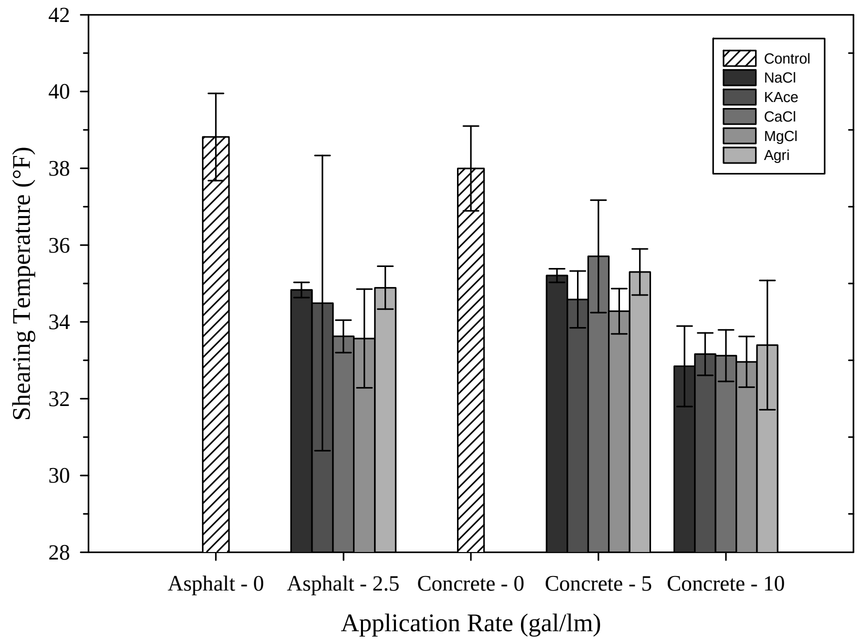

Figure 18: Debonding temperature for storm scenario III (P32–SA30) with 95% confidence error bars.

There are several possible reasons why measured temperatures associated with snow–pavement debonding were higher than expected: rate of change of the pavement temperature, plowing force, method of isolating the snow sample, and placement of the thermocouple. As the temperature of the pavement substrate was increased from the heated table, ice at the pavement–snow surface gradually melted. In the protocol used to examine the bond between the snow and pavement in these experiments, the pavement temperature was raised at a rate of approximately 1°F every 4 minutes. Temperatures measured at different locations during a test setup are provided in Figure 19 (for storm scenario I: P14–SA14), which show the differences between the pavement, chiller (i.e., temperature-controlled table) and the air. At slower rates, the pavement temperature associated with the snow–pavement bond failure would likely be lower because more time would have been available to deteriorate the snow–pavement bond at a particular temperature. Similarly, if shear force applied to the snow sample was increased, less deterioration (and therefore less time) would be necessary to debond the snow from the pavement, thereby decreasing the temperature at which the bond ultimately failed. Conversely, however, if too low a shear force is applied, it would increase the temperature at which the snow–pavement bond failed. Further work is needed to substantiate the effect that rate of change of the pavement temperature and shear force has on debonding temperature.

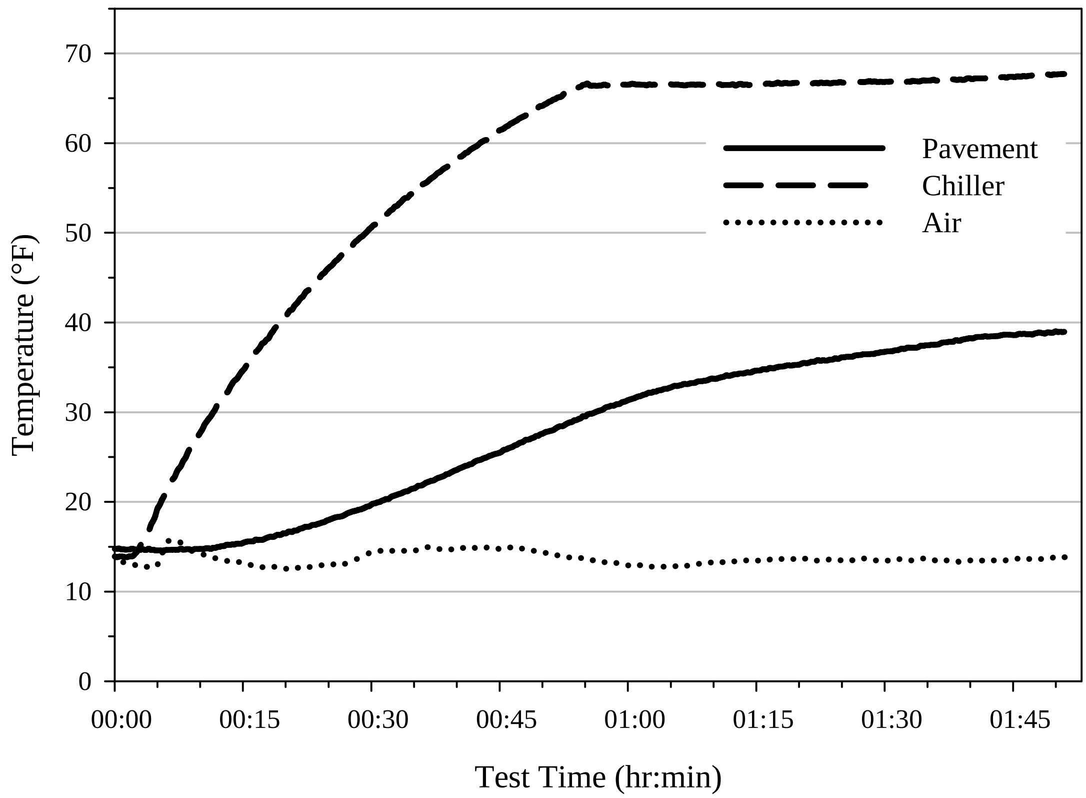

Figure 19: Storm scenario I (P14–SA14) temperature comparisons of air, pavement and chiller.

The method of isolating the snow sample was further investigated and it was found that pushing the plow boxes downward through the thickness of the compacted snow to isolate the test area was causing the snow samples to buckle. This buckling effect likely disrupted the snow–pavement bond. Additional experiments were conducted to evaluate differences between snow samples isolated using the plow boxes and snow samples isolated by cutting the sample out with a saw. These additional experiments were conducted on asphalt and concrete pavement specimens without anti-icing chemicals and using the same shearing assembly to evaluate its effect on the temperature at which the snow–pavement bond failed. The results showed that snow–pavement bonds could be achieved at higher application rates: at least 15 gal/lm on asphalt compared to 2.5 gal/lm using the original snow isolation method.

The thermocouple wire was routed along the bottom of the pavement, then turned vertically to pass through hole drilled in the pavement, with the thermocouple sensing end at the pavement–snow interface. Heat from the temperature-controlled table (which was warmer than the top of the pavement) may have been conducted along the length of the wire and into the sensing element located at the surface. Placement of the thermocouple was investigated by making several additional thermocouple measurements at various positions around a snow sample bonded to the pavement. Storm scenario I (P14–SA14) was utilized for these experiments, as was the original method of pressing the plow boxes through the snow to isolate the sample. Additional thermocouples were installed on and around the pavement substrates as shown in the schematic in Figure 20 and the photo in Figure 21. Thermocouples were positioned under the snow as shown in Figure 22, such that they were routed on the top surface of the pavement instead of in a groove along the underside. Samples were not loaded with the shearing force, but were allowed to remain on the pavement surface so that temperature measurements could be monitored for a longer period of time.

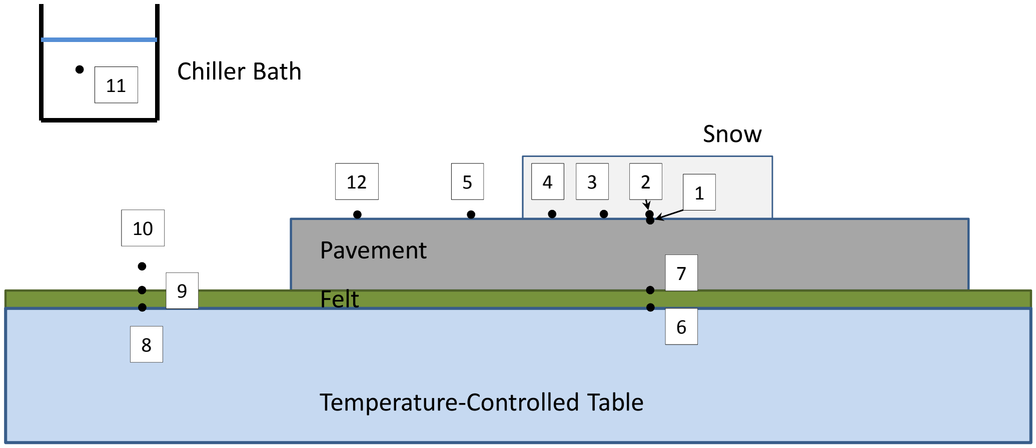

Figure 20: Locations of 12 thermocouples installed in test setup.

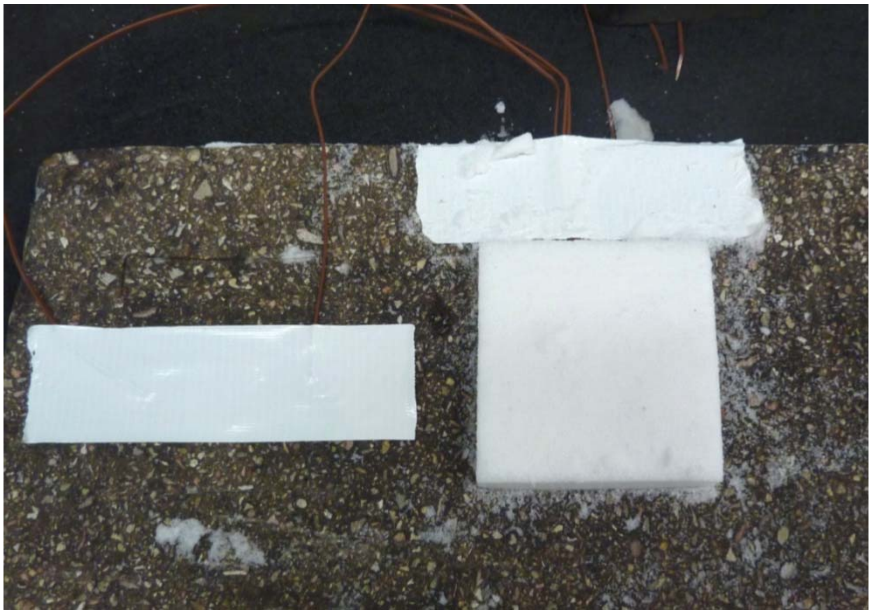

Figure 21: Additional thermocouples installed in test setup.

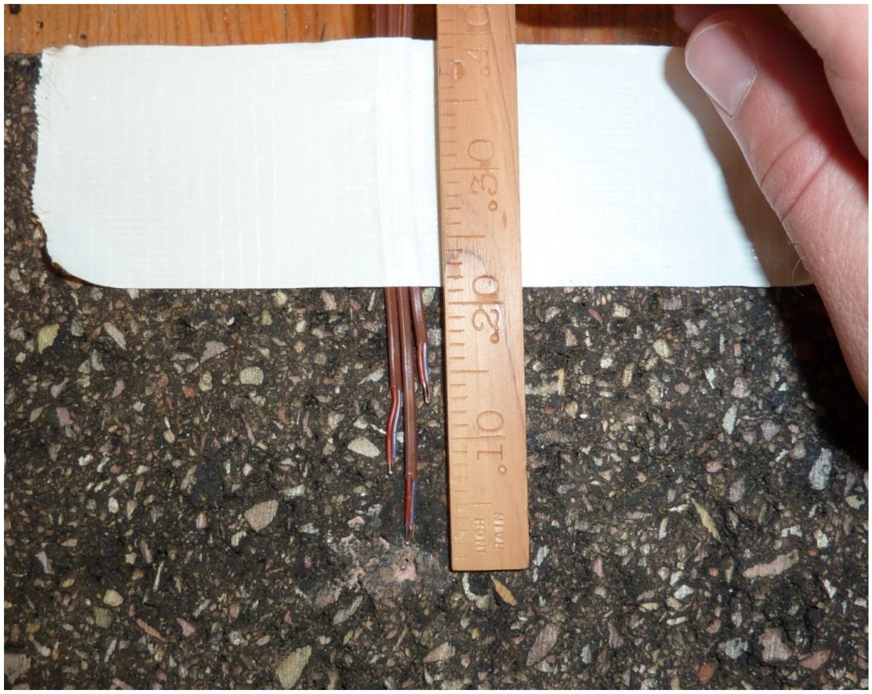

Figure 22: Positioning of thermocouples under the snow sample.

Temperature was monitored for more than one hour after the pavement sample equilibrated to 14°F on the temperature-controlled table, consistent with storm scenario I protocol. The temperature at several locations during this time is shown in Figure 23 for an asphalt pavement and in Figure 24 for a concrete pavement. The temperatures at the center of the snow sample were approximately 4 degrees higher for thermocouples routed along the bottom of the pavement than for thermocouples installed along the top surface of the pavement (thermocouple Location 1 versus Location 2) revealing that the snow–pavement interface temperature was sensitive to the thermocouple installation method. This experiment also revealed that the temperatures under the snow (thermocouple Locations 2, 3 and 4) may not always be uniform, suggesting that the snow melts unevenly. An example of this is shown in Figure 25 and Figure 26, for measurements taken on asphalt and concrete substrates, respectively. Temperatures measured using thermocouples installed on the surface of the asphalt substrate are very uniform under the snow sample; however, the same measurements made on the concrete substrate are slightly different from one another.

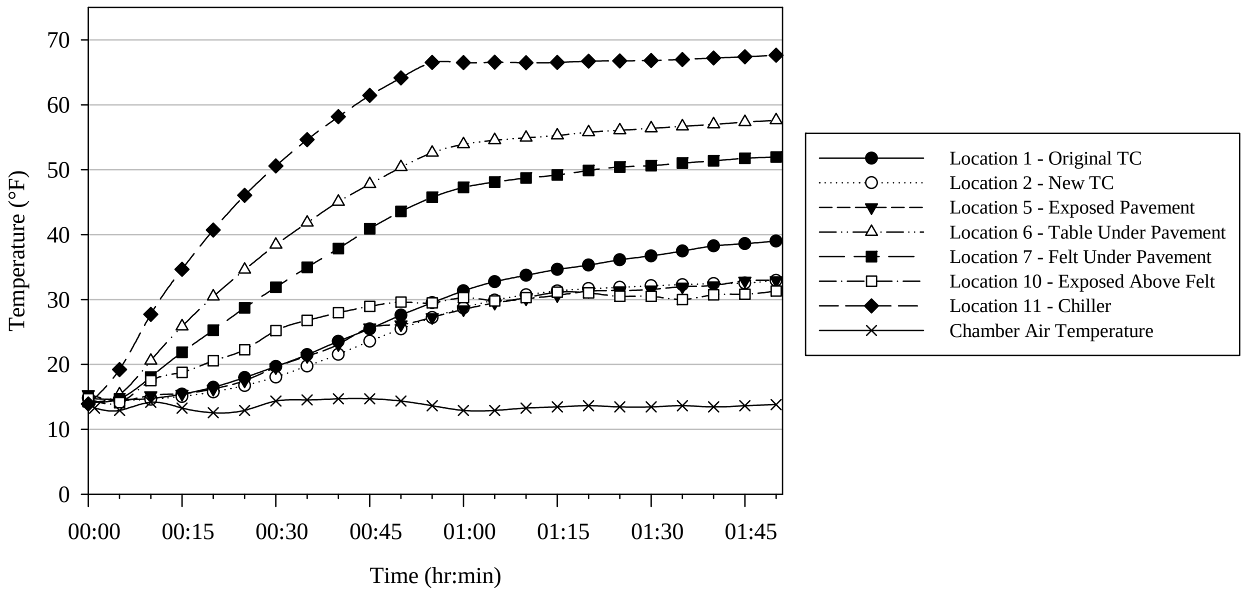

Figure 23: Select transient temperature profiles on asphalt pavement substrates

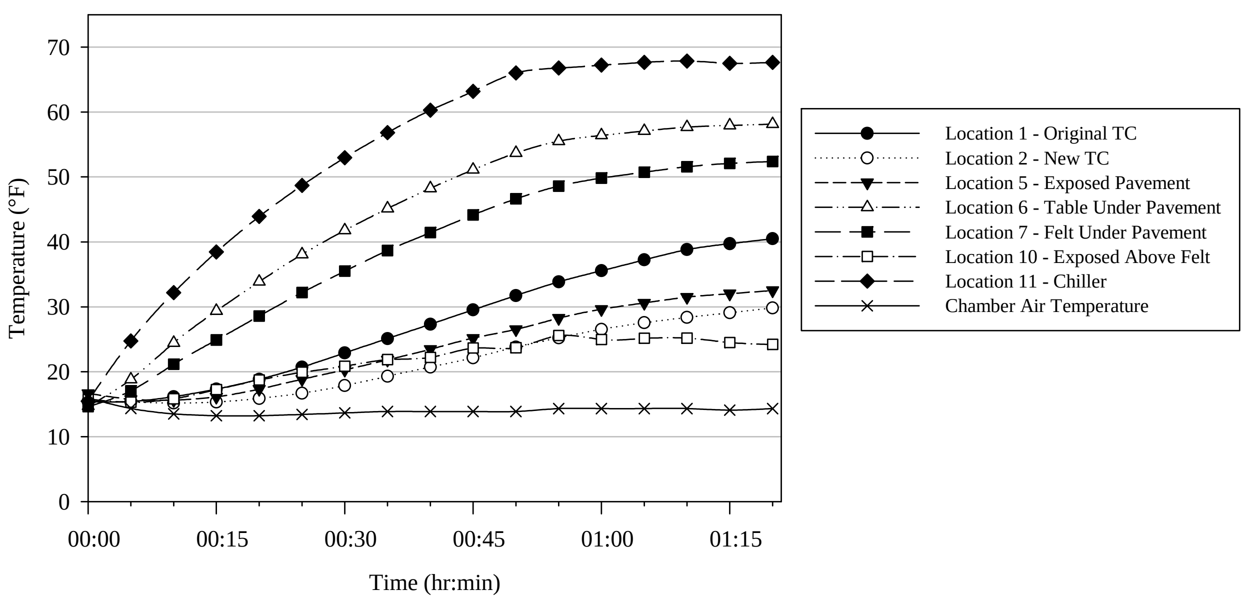

Figure 24: Select transient temperature profiles on concrete pavement substrates

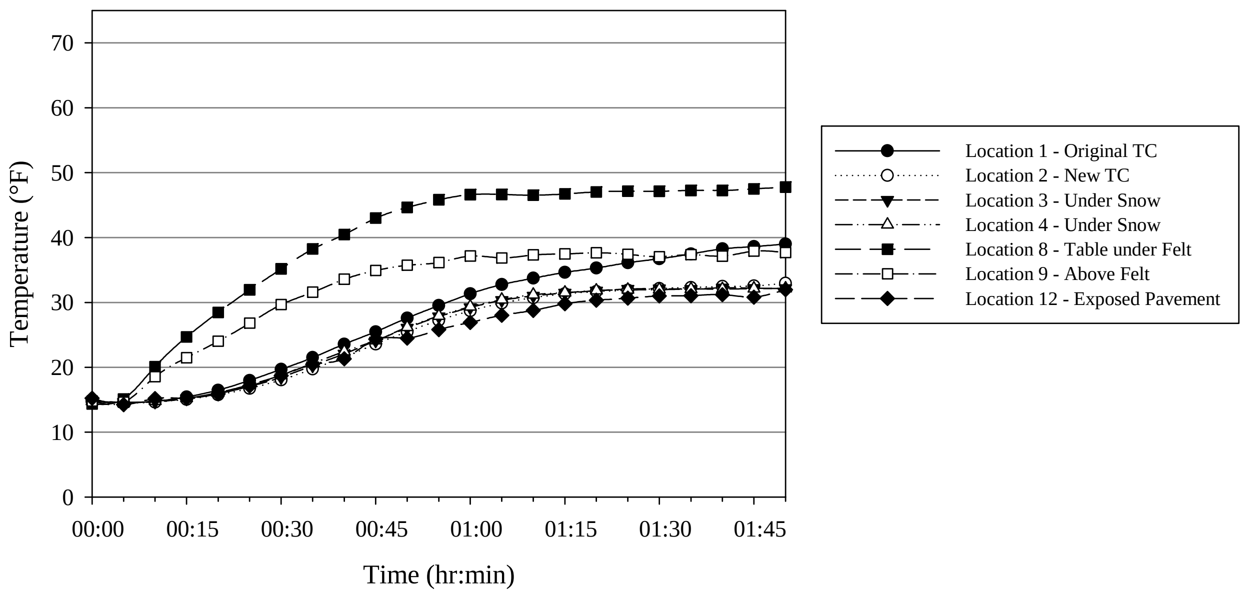

Figure 25: Additional transient temperature profiles on asphalt pavement substrates.

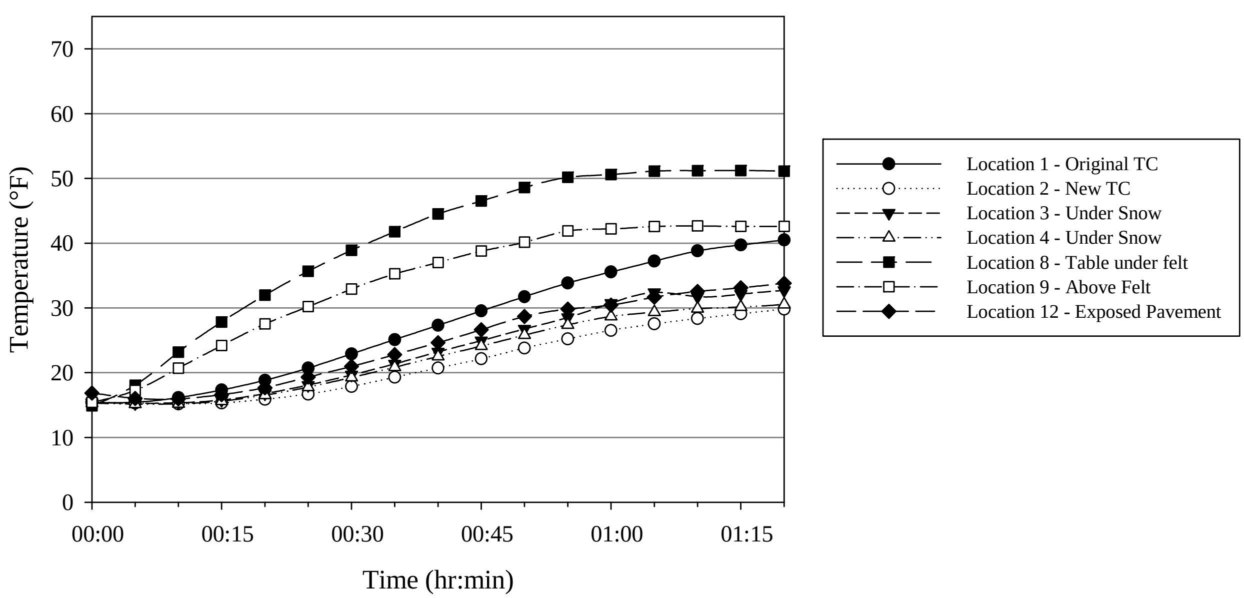

Figure 26: Additional transient temperature profiles on concrete pavement substrates.

New experiments were conducted using thermocouples fastened to the top of the pavement surface with epoxy, as shown in Figure 27. Snow samples were isolated by sawing them out. Debonding temperatures collected from these experiments were compared to results derived from the original thermocouple placement. The measured debonding temperatures are lower than previously measured, as presented in Table 6, revealing a difference of about 6.9 degrees for asphalt and 3.6 degrees for concrete, but still slightly greater than expected.

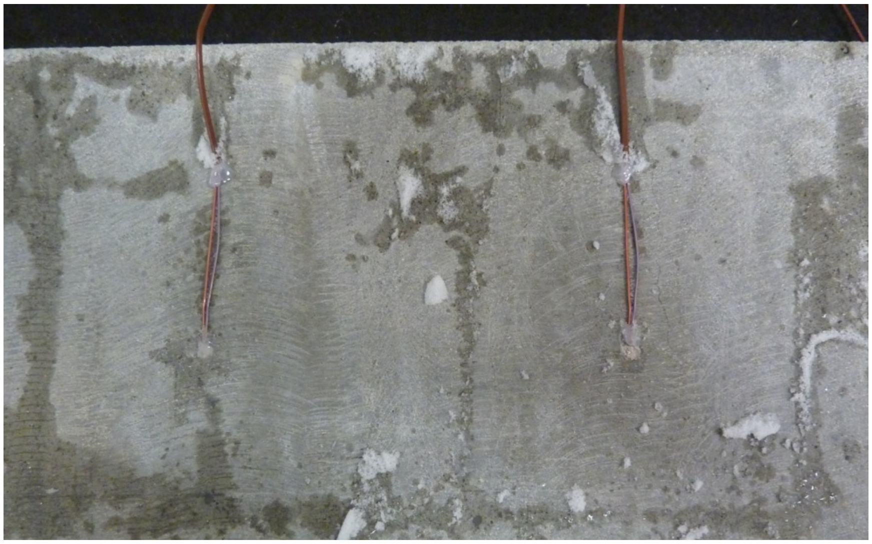

Figure 27: Thermocouples epoxied to a concrete pavement substrate (photograph taken after snow samples debonded).

Table 6: Debonding Temperatures for Different Thermocouple Installations

Pavement Type		Debonding temperature from thermocouples routed along: bottom surface	Debonding temperature from thermocouples routed along: top surface
Asphalt	Average (°F)	41.5	34.6
	Std. Dev. (°F)	1.3	1.1
Concrete	Average (°F)	35.2	31.6
	Std. Dev. (°F)	4.0	1.5

3.2.2 Friction

Prior to its use, the friction tester was tested at three different locations of dry, conditioned concrete and asphalt pavement specimens to evaluate its precision. The mean values, standard deviations, and coefficients of variation (COV) for these tests are shown in Table 7. The COV of multiple friction measurements taken from a single location were low, which implies that the friction tester functions consistently. However, mean values measured at different locations were not always similar to each other (e.g., locations 2 and 3 on asphalt and locations 1 and 3 on concrete), indicating that the friction depended on the location of the measurement. Despite this limitation, the friction tester was used to determine the coefficient of friction (COF) of the pavement after each snow sample debonded.

Table 7: Friction Tester Variability on Dry Pavement

Pavement Type	Location	Average COF	Std. Dev.	COV
Asphalt	1	0.65	0.016	2.4
Asphalt	2	0.61	0.044	7.3
Asphalt	3	0.71	0.016	2.2
Concrete	1	0.96	0.017	1.8
Concrete	2	0.88	0.052	5.9
Concrete	3	0.82	0.035	4.3

Friction of the pavement surface was measured in the location of the three individual snow samples regardless of whether a bond formed to evaluate the relative slipperiness of each pavement specimen after debonding. The average COF values for asphalt and concrete for each particular chemical and application rate are shown in (Figure 27). Averages are based on data from storm scenarios I and III. Friction data was not collected during storm scenario I (P14-SA14) for KAce, MgCl and CaCl or during storm scenario II (P32-SA23) because the friction tester had not yet been manufactured. As evident from the results and further statistical analysis (as detailed in Appendix D), friction of the pavement after debonding was relatively similar between treated samples regardless of pavement type, chemical type, application rate, and storm scenario. However, these friction values were generally higher compared to the untreated (control) substrates. Friction values taken on dry pavement (i.e., before applications of chemical or snow) are much higher than friction values taken after the storm events and debonding (control and treated). Dry friction is greater on concrete than on asphalt, but after-storm friction values are similar, indicating that friction loss is more pronounced on concrete than on asphalt.

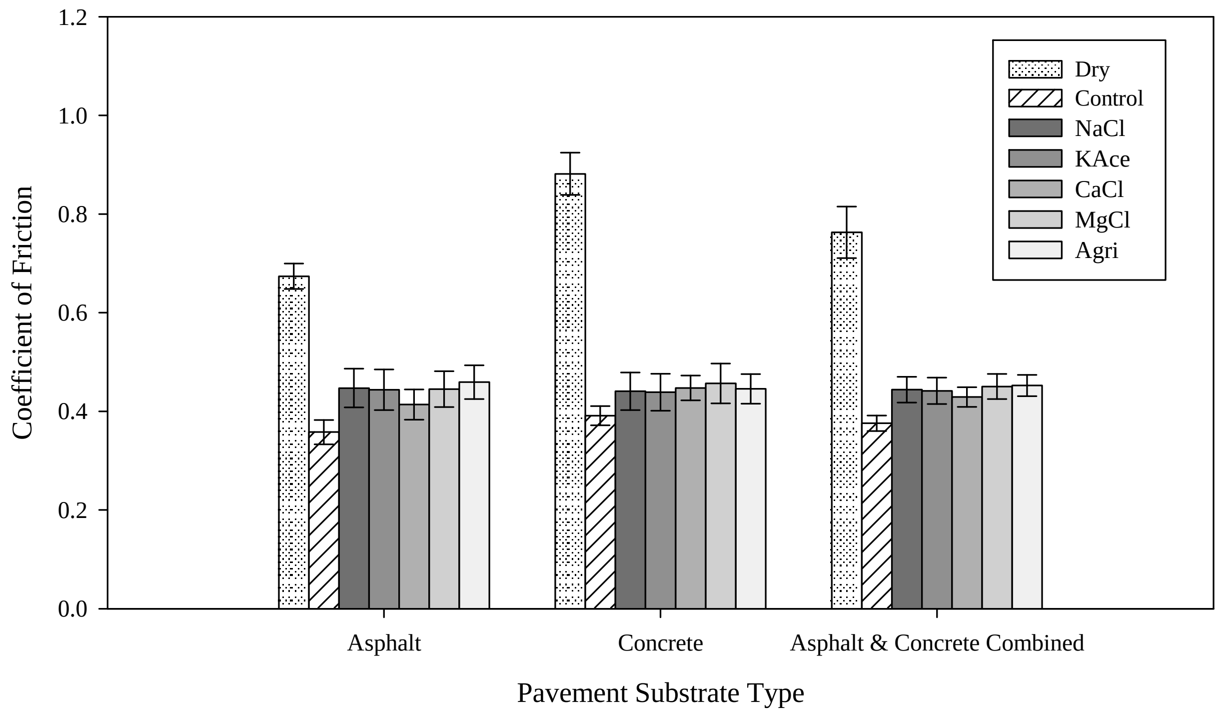

Figure 28: COF as a function of chemical type and application rate with 95% confidence intervals.

3.2.3 Bond Shear Strength

Performance of the various anti-icing chemicals was evaluated based on their ability to weaken the bond between compacted snow and the pavement surface, as described above. This was assessed by the temperature at which the bond between the snow and the pavement failed under constant shear stress. An alternate method to evaluate performance of the anti-icing chemicals, based on a direct measure of the bond strength, was also employed. This method measures the shear force necessary to remove a bonded sample from the pavement substrate as the performance measure. Pavement temperature was held constant and the shearing force was gradually increased by slowly pouring sand into a container connected to the plow hitch. Bond strength was determined by measuring the weight of the sand and bucket at failure. These experiments were conducted on asphalt samples only. Sample preparation was similar to the procedure described in Section 3.1.3 with the following differences:

1. Snow samples were isolated by sawing them out.
2. Chemical application rates on the asphalt substrates were 5, 10 and 15 gallons per lane mile (instead of 2.5, 5, and 10).
3. The same pavement specimens were used for a particular application rate so that performance of different chemicals at the same application rate were not influenced by any differences in the pavement surface condition.

Substrates were washed between tests by soaking in warm water, followed by thorough scrubbing and rinsing with water.

Bond strength was calculated as the force required to shear the snow divided by the contact area (16 in^2). Percent improvement attributed to the anti-icer was calculated as the difference in the bond strength between the control (no anti-icer) and the treated sample, normalized by the bond strength of the control. Bond strengths on asphalt using this procedure are shown in Figure 29. The results showed that the presence of chemical dramatically and consistently reduces the bond shear strength when compared to untreated pavement, translating into about an 80 percent improvement (Figure 30). However, differences in performance between chemicals at a particular application rate or between application rates of the same chemical were not statistically evident from either the bond strength or percent improvement. Thus, while this methodology provided measurable reductions in bond strength between treated and untreated pavement, it could not be determined whether particular chemicals performed better than others. A larger number of samples must be tested in order to statistically identify differences between chemicals. In conclusion, information obtained from the bond strength testing was similar to that from the original experiment design—presence of anti-icing chemicals significantly influenced the snow pavement bond, and anti-icing chemicals performed similarly to one another in most cases.

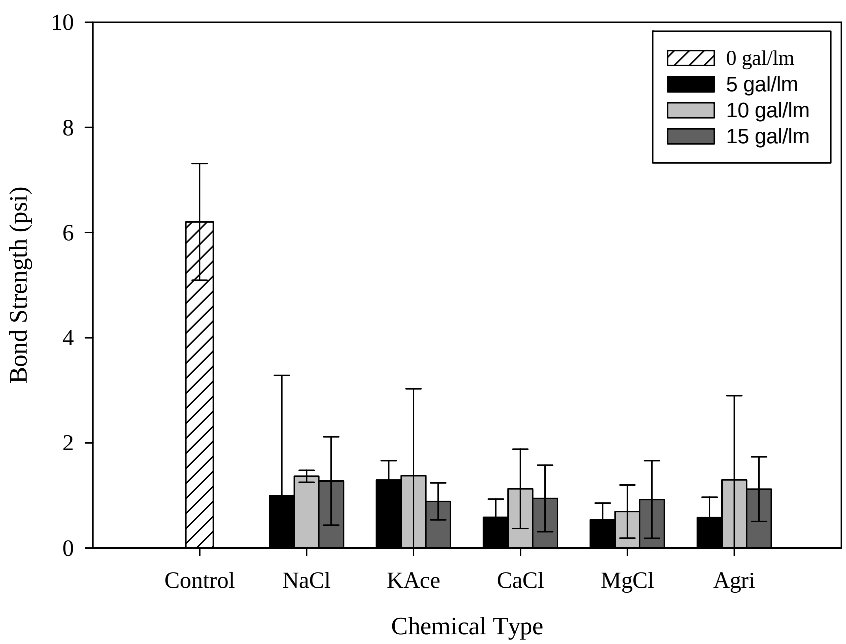

Figure 29: Bond strength of treated asphalt substrates with 95% confidence error bars.

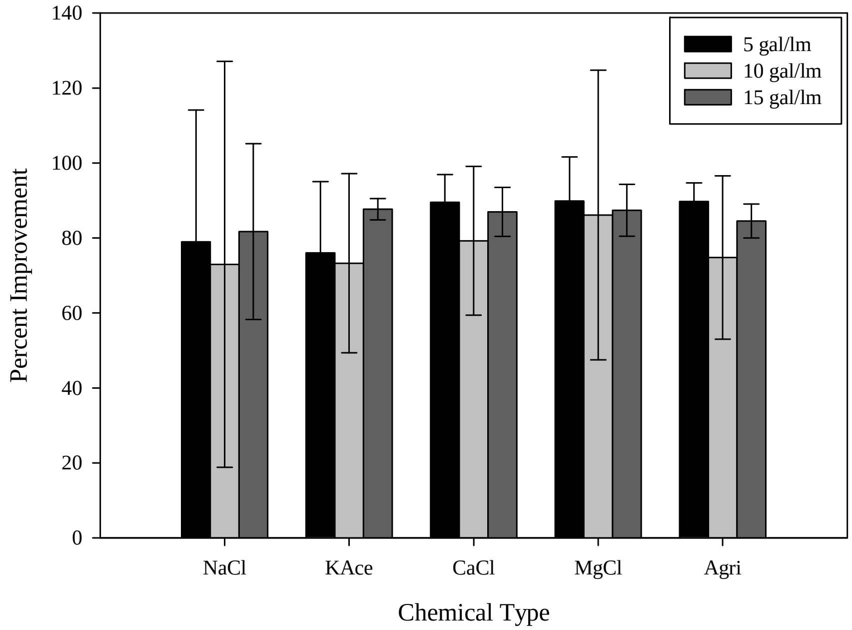

Figure 30: Percent improvement of chemical treatments on asphalt substrates with 95% confidence intervals.

3.3 Summary of Laboratory Testing Results

The performance of the anti-icing chemicals was measured in the laboratory using the temperature at which the snow debonded from the pavement, friction and bond strength. Overall, the debonding temperature and bond strength measurements taken during the laboratory study indicated that pretreatment of pavements with anti-icing chemicals reduced the bond strength between compacted snow and the pavement and improved friction after snow removal, thereby helping winter maintenance personnel maintain the condition of highways during the winter season. In addition, chemical treatments allowed snow to be more easily removed from the pavement at colder pavement temperatures than when the pavement was left untreated, possibly resulting in decreased time to clear roads rather than waiting for the weather to change. Friction measurements indicated that anti-icing slightly improves friction on treated pavements as compared to untreated pavements; however, residual liquid and ice on the pavement after plowing resulted in lower pavement friction values when compared to dry pavements. While improvements were noticed between treated and untreated samples, it was difficult to discern differences in performance between individual chemicals based on temperature, friction and bond strength data.

Overall, each chemical generally performed similarly based on temperature and friction results. Therefore, other factors such as cost, corrosiveness to equipment and infrastructure, availability, storage considerations or environmental concerns are, perhaps, equally important when deciding among chemical types. Even though application rates in the laboratory were lower than typical field applications, under these conditions, the presence of anti-icing chemicals on the pavement surface was effective at reducing the bond between snow and pavement. Further research is needed to refine these test methods to more precisely evaluate differences between individual anti-icing chemicals.

4 FIELD TESTING

Controlled field testing was conducted as a part of this project to further the body of knowledge regarding the performance of anti-icing chemicals. While laboratory tests offer the greatest level of control of the experiment, field testing offers a more realistic evaluation because it is done in a realistic setting and at a larger scale. Three field tests were conducted at the TRANSCEND research facility in Lewistown, Montana. These tests were designed to compare the in-field performances of the five winter maintenance chemicals used in the laboratory portion of this study. The TRANSCEND research facility was chosen for this field work because the experiments could be set up and run in a controlled manner and without risks associated with winter traffic. Furthermore, TRANSCEND offers ample space to treat a variety of pavements in one location without risk or interruption to the travelling public. An additional advantage is the ability to produce man-made snow at TRANSCEND using a large-scale snowmaking system.

Each field test was performed during a two-day period with forecasts that were somewhat similar to conditions used during laboratory testing and with weather conditions that permitted snowmaking. In general, weather conditions that permit snowmaking for a field test include very low winds, no precipitation, and overnight lows between 10 and 25°F. Windy conditions make it difficult to cover test sections evenly with snow and air temperatures must be cold enough to freeze water distributed by the snow making equipment. The ground temperature must be below freezing so that the snow does not melt on contact. Clear skies help melt natural snow residue after plowing the test area or evaporate water left after washing.

During the first day, snow on the test area was plowed and the test sections swept (Figure 31). Once the test sections were dry, chemicals were applied, as specified in each of the field test descriptions below. The chemicals were applied to the pavement at least one hour before making snow. Once air and pavement temperatures were within range (usually late in the evening or after dark) snow was applied to the test sections using the TRANSCEND snowmaking system (Figure 32). Snow was applied as evenly as possible, but was mainly dictated by wind and snowgun placement. The snow was then compacted and allowed to stabilize for at least one hour after a sufficient depth of snow was made across the entire test area. Data was then collected from the test sections according to the protocol for the particular field test. Finally, snow and anti-icing chemicals were removed from the test area by plowing and washing. The following subsections further describe the equipment and facilities used to conduct the field experiments.

Figure 31: Plowing and sweeping in preparation for a field test.

Figure 32: TRANSCEND snowmaking system in operation.

4.1 Equipment and Facilities

Equipment and facilities necessary to conduct the field experiments is described in detail below. Major equipment consists of the snowmaking system at TRANSCEND, the custom anti-icing chemical applicator, compacting and plowing equipment, snow–pavement bond strength tester, and friction tester.

4.1.1 TRANSCEND Snowmaking System

The TRANSCEND snowmaking system is capable of producing 65,000 cubic feet of snow in eight hours under the proper conditions. The fan guns can be adjusted to produce snow with water contents between 30 and 50 percent. The TRANSCEND snowmaking equipment requires that the air temperature be below 27°F wet bulb for the water droplets from the fan guns to freeze sufficiently before they land on the ground. The pavement temperature also must be below freezing to keep the snow from melting when it contacts the pavement. In order to have sufficient time to make enough snow to cover test sections, an overnight low of less than 25°F was required, however, temperatures below 10°F cause nozzles and water lines to freeze and plug, making snowmaking more difficult. Like natural snow, man-made snow is easily carried by the wind, so attention must be paid to wind speed and direction to ensure snow accumulates in the desired areas.

Field tests were scheduled based on regional and local weather forecasts. Attempts were made to capture temperatures similar to the storm scenarios of the laboratory testing. The actual weather conditions (air temperature, relative humidity, and wind speed) measured by a weather station located at TRANSCEND during test events are provided in Appendix E.

4.1.2 Chemical Applicator

The chemicals used for the field test were the same used in the laboratory experiment (NaCl, CaCl, MgCl, KAce, and Agri). A trailer was outfitted with a gas-powered pump, five polymer tanks, flat spray nozzles and appropriate plumbing to apply chemical to pavement at rates from 5 gallons per lane mile to over 100 gallons per lane mile (Figure 33). Thirteen nozzles were used to cover a 12-foot-wide lane. The application rate was adjusted by changing the nozzle size and the speed of the vehicle pulling the trailer. A pressure gage on the outlet of the pump was used to ensure that the pump throttle was set correctly and application was consistent. The chemicals are filtered with one inline screen and screens at each nozzle. Because flow through the pump and nozzle is dependent on properties of the fluid being pumped, the chemical applicator was calibrated for each chemical. The five chemicals were tested at three different application rates in each of the field experiments.

Figure 33: Applying chemical to a test section with the anti-icing trailer.

4.1.3 Compacting and Plowing Equipment

The snow was compacted using an 8,000 lb smooth drum, vibrating compactor. The drum was 54 inches wide and 28 inches in diameter (Figure 40). The snowplow used for winter testing operations was a 1993 International single axle dump truck with a single direction snowplow blade (Figure 34).

Figure 34: TRANSCEND snowplow.

4.1.4 Bond Shear Strength Tester

Similar to the laboratory tests a device was designed and constructed prior to the second and third field tests to measure the shear strength of the bond between the snow and pavement. Initially this device consisted of a 12 in. by 12 in. plow box and a 50 lb. spring scale used to measure the load applied to the snow specimen in the box (Figure 35); however, based on the experience gained from the second field test, the size of the box was reduced to 6 in. by 6 in. and the capacity of the scale was increased to 100 lb. Also, the design of the pulling mechanism was modified so that load could be more consistently applied to the snow samples (Figure 36).

Figure 35: Plow box used in Field Test II.

Figure 36. Measuring bond shear strength during Field Test III with the new plow box.

To measure bond shear strength, a snow sample that was approximately the same size as the plow box was isolated by cutting it out and removing surrounding snow using a saw. The sample was then loaded by pulling on the scale. If the load exceeded the capacity of the scale without debonding the snow from the pavement, a portion of the snow sample was cut away and dimensions and bond strength were measured again. This process was repeated until the snow debonded from the pavement (as illustrated in Figure 37). Dimensions of the debonded sample were measured to determine the area of the sample in contact with the pavement. A normal (downward) force of approximately 5 lb. was placed on top of the plow box to prevent it from lifting up over the snow sample during debonding.

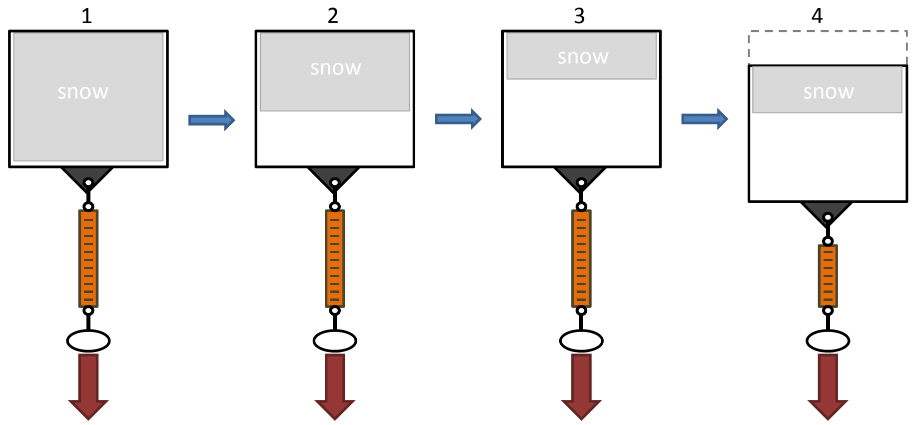

Figure 37: Process to measure bond shear strength.

4.1.5 Friction Tester

Friction was measured in the field using the same friction tester used in the laboratory (described in Section 3.1.3). When friction was measured in the field, normal force was adjusted so that the friction force was less than 6 lb. Measurements were taken in areas clear of snow after plowing (Field Test I) or on the exact area where bond strength was measured (Field Tests II and III). Friction was never measured twice on exactly the same location because the friction tester disturbed any residual snow or ice left on the pavement after plowing/shearing.

4.2 Pavement Surfaces and Test Layout

The chemicals were applied to the pavement at TRANSCEND, and on two special sections of pavement, one asphalt and one concrete, with characteristics similar to the pavements used in the laboratory study. The special asphalt section at TRANSCEND was constructed with full-scale paving equipment and used the same batch of asphalt as the laboratory samples. The special concrete section at TRANSCEND was constructed using a mix design similar to the concrete samples used in the laboratory, and had a broom-finished surface. The special asphalt and concrete pavement sections were relatively small (about 120 ft long and 12 ft wide) and could only accommodate a few test sections per experiment. Therefore, the treatment of the special pavement sections varied for each field test. A large section of asphalt pavement 600 ft long and 200 ft wide, known as the Monster Pad, was used for 15 test sections that consisted of a matrix of five anti-icers and three application rates. Each test section was 50 ft long and 12 ft wide, and was separated from adjacent test sections by buffer zones (12 ft by 50 ft). A schematic of the test section layout is shown in Figure 38. The paved surface of the Monster Pad had been recently fog sealed during the fall preceding the winter testing.

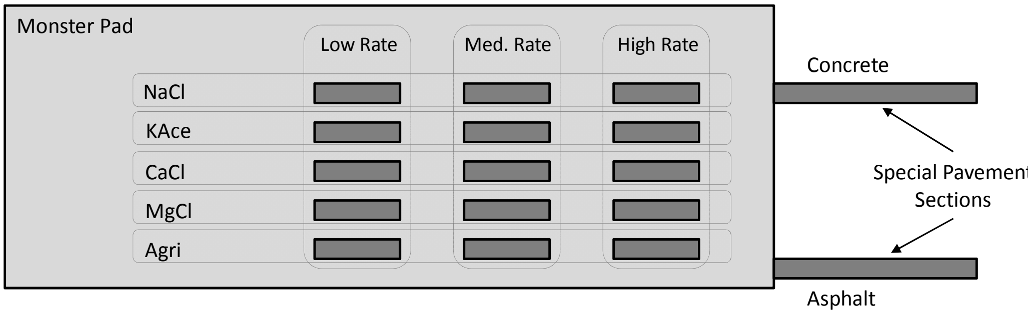

Figure 38: Pavement and test section layout.

4.3 Field Test Trial – December 30–31, 2009

A field trial was attempted to practice the snowmaking procedures, test the equipment, and refine the methodology of the experiment prior to actual field tests. The forecast for this event called for cold overnight lows between 10 and 15°F with little wind and a slight chance of snow. Due to challenges with equipment and weather, chemicals were not applied until well after dark and at temperatures nearing 0°F, which is 15 to 20 degrees below ideal temperatures for anti-icing applications. Chemical application rates used during this experiment (Table 8) were based on results from the laboratory experiments, the literature review, and manufacturers' recommendations. Because of delays associated with equipment and uncooperative weather conditions (including a natural snow event during the night), man-made snow was not produced. Nevertheless, this event provided a good opportunity to observe chemical behavior during natural snowfall and cold, windy conditions.

Table 8: Chemical Application Rates for Field Test Trial

Chemical	Low (gal/lm)	Medium (gal/lm)	High (gal/lm)
NaCl	5	20	40
KAce	5	20	40
CaCl	5	15	30
MgCl	5	20	30
Agri	5	15	25

Special Concrete	
KAce	25

Special Asphalt	
MgCl	20

Falling and blowing snow stuck to all treated areas, with accumulation of snow increasing with higher application rates. Accumulation varied little between different chemicals applied at similar rates (Figure 39). Snow did not accumulate on untreated areas until winds calmed. Test sections treated with NaCl and KAce were drier than the remaining test sections. Wet applications of anti-icing chemicals may cause blowing snow to accumulate on pavements when it might otherwise blow across the dry surface without accumulating. When ambient conditions are predicted to be colder with wind, it may be appropriate to consider the implications of snow accumulation prior to chemical treatment. Approximately 2 inches of snow accumulated on the test area overnight. Snow was easily brushed off of treated and untreated areas alike, indicating that compaction of the snow is important to evaluate anti-icing performance.

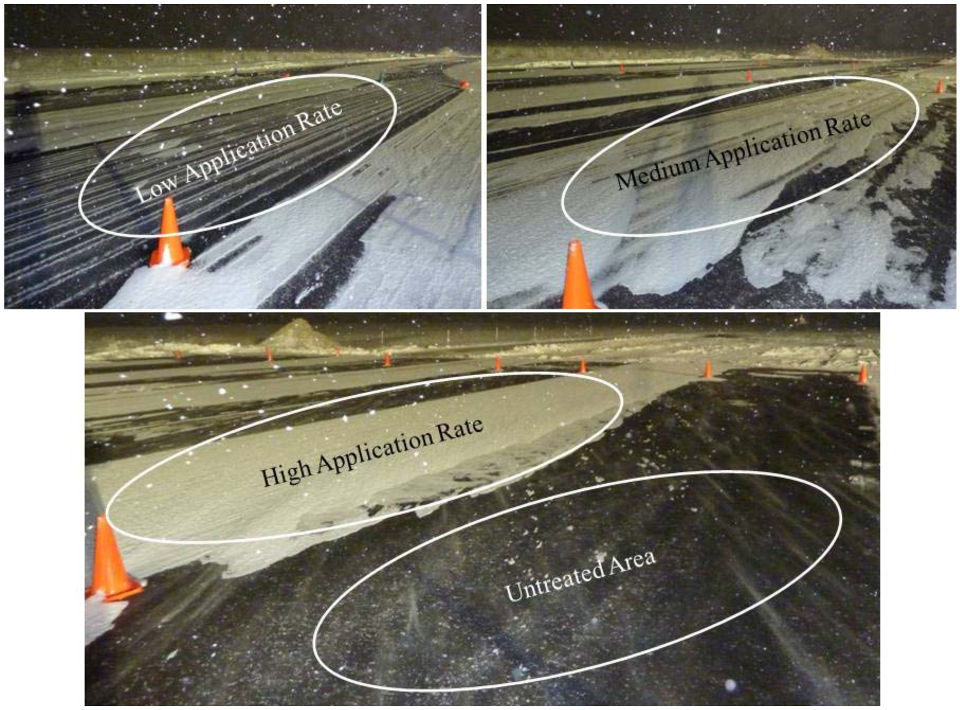

Figure 39: Natural snow accumulation on test sections during field test trial.

4.4 Field Test I – January 26–27, 2010

The forecast for this event was for a low around 15°F with light wind and mostly clear skies. The pavement was cleared and ready by late afternoon. Anti-icing chemicals were applied to the test area late in the afternoon with temperatures in the single digits. Chemical application rates are included in Table 9. Friction in each of the test sections was measured immediately after chemical application. The forecast for the night predicted warmer temperatures; however, because the sky was clear and calm, the temperatures dropped lower and faster than expected after sunset and remained in the single digits all night.

Table 9: Chemical Application Rates for Field Test I

Chemical	Low (gal/lm)	Medium (gal/lm)	High (gal/lm)
NaCl	5	20	40
KAce	5	20	40
CaCl	5	15	30
MgCl	5	20	30
Agri	5	15	25

Special Concrete	
KAce	25

Special Asphalt	
MgCl	20

As during the field trial, applications of NaCl dried relatively quickly. KAce also eventually dried before the man-made snow was applied. Other chemicals remained wet. Winds were calm during snow production so snow coverage was relatively even at a depth of about 1 to 2 inches. The test sections were compacted with two passes of the smooth-drum compactor with vibration on immediately after snowmaking was complete (Figure 40). The snow was allowed to rest until shortly after dawn (about five hours after compaction).

Figure 40: Compacting test sections with a smooth-drum compactor.

Test sections were evaluated early the next morning by plowing the test section with the snow plow at about 5 to 10 mph, followed by photographs, visual observations, and friction measurements. Data collection took approximately two hours. Friction was measured in areas of the test sections with minimal snow on the pavement surface after plowing. Snow in NaCl and KAce test sections at high application rates (Figure 41) was very slushy due to a malfunctioning snowmaking gun. Even though the gun was disabled as quickly as possible, the test sections had already been affected. During plowing, it was evident that the snow in these two areas was very icy compared to other areas where snowmaking equipment operated properly (Figure 42). The plow was not able to remove the ice from the pavement in these areas.

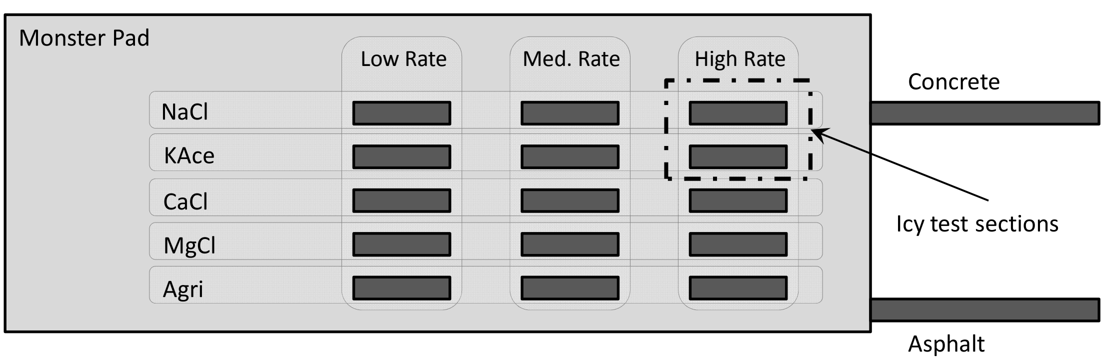

Figure 41: Locations of icy test sections during Field Test I.

Figure 42: Icy test sections after two attempts at plowing.

In general, most sections treated with anti-icing chemicals and control sections (no chemical) appeared to perform similarly, making it difficult to visually differentiate between test sections. A typical plowed section is shown in Figure 43. Unevenness in the pavement surface allowed some snow to remain on the pavement after plowing (Figure 44). This remaining snow was loose and could be easily swept off the paved surface. Alternatively, on the special asphalt section, snow removal on the portion of pavement treated with MgCl was significantly more effective than snow removal on the untreated area of the same pavement, as clearly evident in Figure 45. Plowing was attempted twice on these test sections and snow on the untreated portion of the special asphalt could not be removed. Under the conditions present during this test, the presence of anti-icing chemicals reduced snow removal effort on the special asphalt test section. The difference in results between the special asphalt pavement and the asphalt on the Monster Pad was due, in part, to the surface characteristics of the Monster Pad pavement which had been fog sealed during fall 2009 to protect the asphalt surface.

Figure 43: A typical test section after plowing.

Figure 44: Snow remaining on test section due to uneven asphalt surface.

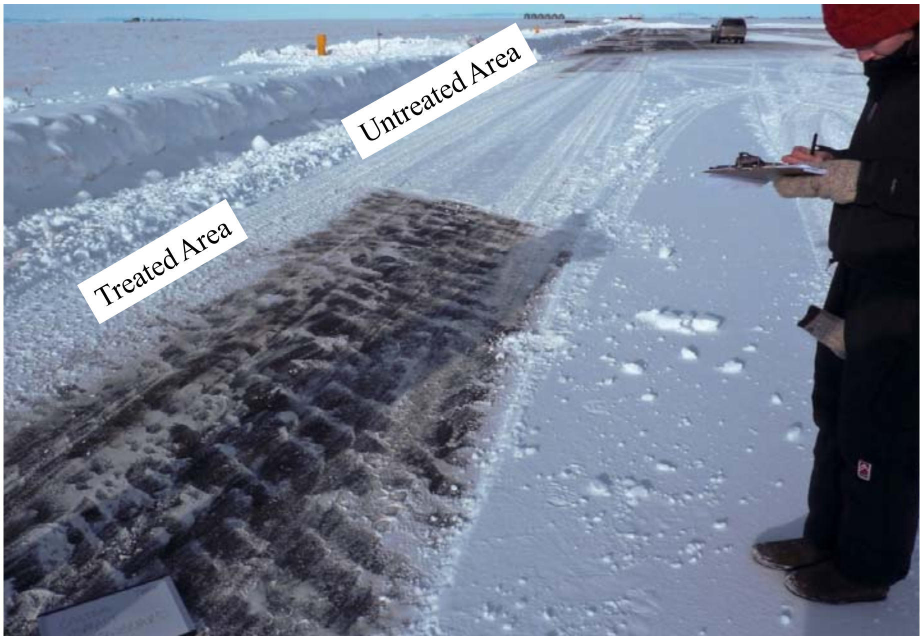

Figure 45: Treated and untreated areas of special asphalt section (MgCl).

Ten measurements of friction were made in each test section. The COF of plowed test sections were mostly similar to one another, as shown in Figure 46. This was most likely due to small amounts of loose snow left on the pavement after the plowing, but may also indicate the inability of the friction device to accurately measure the friction under these conditions. Generally, there were no significant differences between test sections based only on post-plowing friction measurements. Even the icy sections (NaCl and KAce at high application rates) did not yield significantly lower friction values.

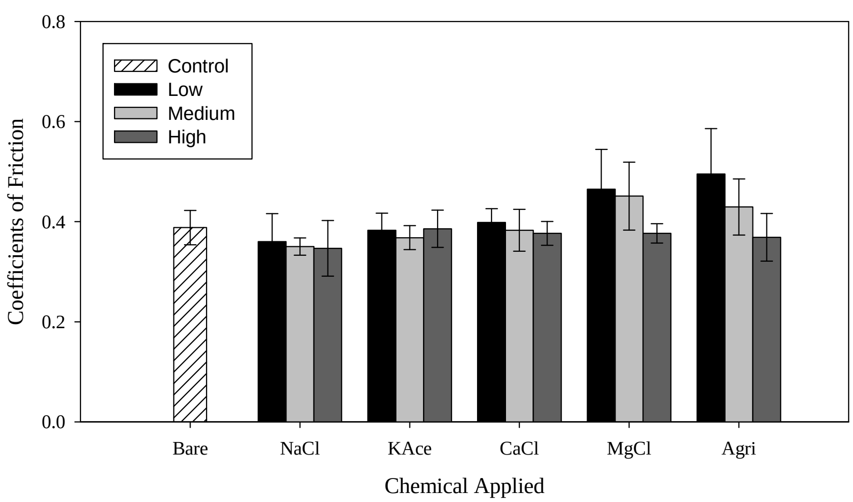

Figure 46: Friction coefficients after plowing during Field Test I.

Plowing and visual observations of snow removal were generally not sensitive enough to evaluate the relative performance of different winter maintenance chemicals. This is especially evident when irrelevant factors such as slight variations in pavement elevation affect the appearance of the test sections. However, matching the testing methodology that was used in the laboratory (i.e., increasing the pavement temperature until the snow can be debonded) was not feasible in the field. In some cases, it was possible to identify differences in performance between pavements treated with chemical and pavements left untreated, either visually or from friction measurements, but this was unusual. Instead, bond shear strength between the snow and pavement would be measured within each test section during subsequent field tests.

4.5 Field Test II – February 22–23, 2010

The second field test was conducted February 22–23 in favorable field conditions. Chemicals were applied late in the afternoon with temperatures below 15°F, using the application rates summarized in Table 10. The forecast was for temperatures in the low twenties, but clear skies overnight helped temperatures fall quickly and lower than forecast. Man-made snow was applied at an air temperature of about 10°F and compacted immediately after snow making. Snow depths were highly variable between 0.75 and 6 inches due to shifting winds. An attempt was made to compact snow with the smooth-drum compactor, but compaction was not consistent in the deeper snow. Instead, the plow truck was used to compact the snow because the tires were able to penetrate the deep snow more effectively (Figure 47). Snow was compacted with four passes of the plow truck immediately after snow application. The snow was allowed to rest until the next morning (approximately eight hours after compaction).

Table 10: Chemical Application Rates for Field Test II.

Chemical	Low (gal/lm)	Medium (gal/lm)	High (gal/lm)
NaCl	5	20	40
KAce	5	20	40
CaCl	5	15	30
MgCl	5	15	30
Agri	5	15	25

Special Concrete	Low	High
NaCl	10	20

Special Asphalt		
MgCl.	10	20

Figure 47: Deep snow compacted using the plow truck.

Evaluations of the test sections began early the next morning just before sunrise in the following order: 1) test sections treated at high application rates, 2) test sections with low application rates, 3) special concrete and asphalt pavements, and 4) the medium-rate test sections. Temperatures ranging from approximately 18°F to 40°F and clear skies made it necessary to collect data in this order so that the test sections with the greatest difference in chemical application rate were sampled with the least amount of interference from the sun and other environmental factors. Test sections on the special pavements were evaluated close in time to one another to eliminate any differences in results due to rapidly changing environmental conditions.

Performance of the anti-icing chemicals was evaluated by measuring bond shear strength and friction in each of the test sections. Lower bond strength and greater friction indicated better performance. Snow density measurements were also taken to evaluate the effect of density on the test results. The 12 in. by 12 in., steel plow box and 50 lb scale were used to shear the compacted snow from the pavement in each test section. Three to four bond strength measurements were made by clearing an area around a patch of compacted snow and carefully cutting the patch of snow to fit within the plow box (Figure 48). As described earlier, the snow was horizontally sheared from the pavement using the plow assembly. Shear force was measured using the spring scale, and the final area of the debonded sample was measured to calculate the shear stress required to induce failure. Three to four friction measurements were immediately made in the area coincident with the removed snow sample. Bond strength, friction and density measurements were also taken in four untreated areas, which were the control test sections. The data collection process was time consuming and sampling the entire area took approximately nine hours. By mid-afternoon, the sun and the increased air temperatures were significantly different than when data collection commenced that morning.

Figure 48: Cutting a snow sample for bond strength testing.

Average bond strengths in test sections with low, medium and high application rates are shown in Figure 49. In test sections treated with low application rates, bond strengths in test sections treated with CaCl and Agri seem to be higher than other test sections. While this result is somewhat consistent with subsequent testing, it may also indicate inconsistencies in pavement texture or compaction from the snow plow. Also, the statistical variance is relatively high for much of the data presented in Figure 49, making it difficult to conclude whether true differences exist. In the NaCl and KAce test sections with high application rates, the snow surface against the pavement appeared to be wet, despite being sampled earlier in the morning. Consequently, there was no bond between the snow and the pavement in these areas. No bond was measured in the medium-rate NaCl test section because the snow was thin and melting during sampling. Direct comparisons with the control sections and between different application rates of the same chemical were difficult to make with this data because of the length of time that passed during the data collection process. While time and temperature may have contributed to differences in bond strength, other factors such as pavement roughness (which could not be accurately evaluated using the friction measurements) and snow density were also thought to affect the relative performance of the test sections.

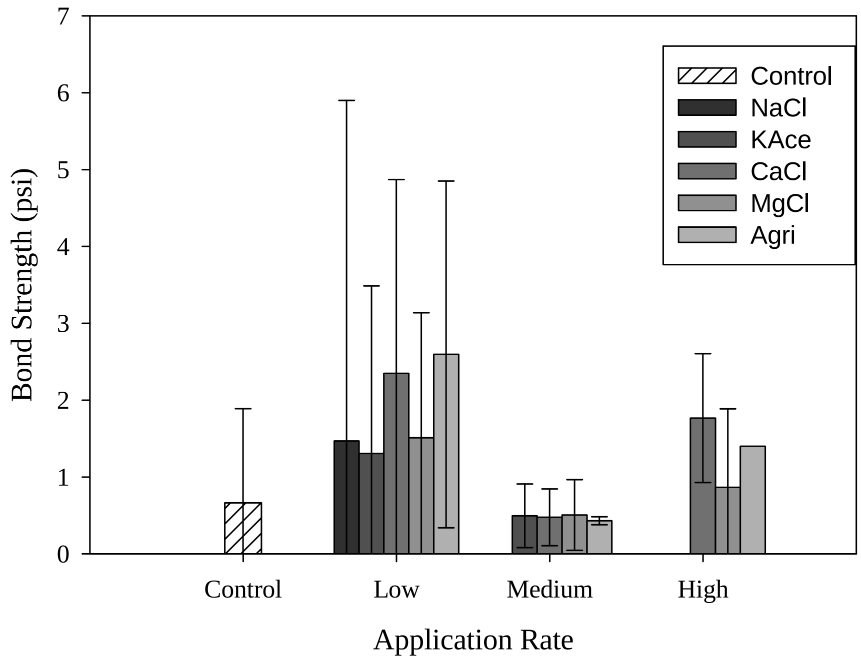

Figure 49: Bond strengths in treated and untreated test sections on the Monster Pad with 95% confidence error bars.

A noticeable reduction in bond strength was observed on the special concrete treated with NaCl and the special asphalt treated with MgCl, as shown in Figure 50. Bond strengths on treated areas of the special concrete were fairly consistent regardless of application rate; however, the reduction of bond strength on the special asphalt with increasing application is difficult to determine with certainty due to variability in the data.

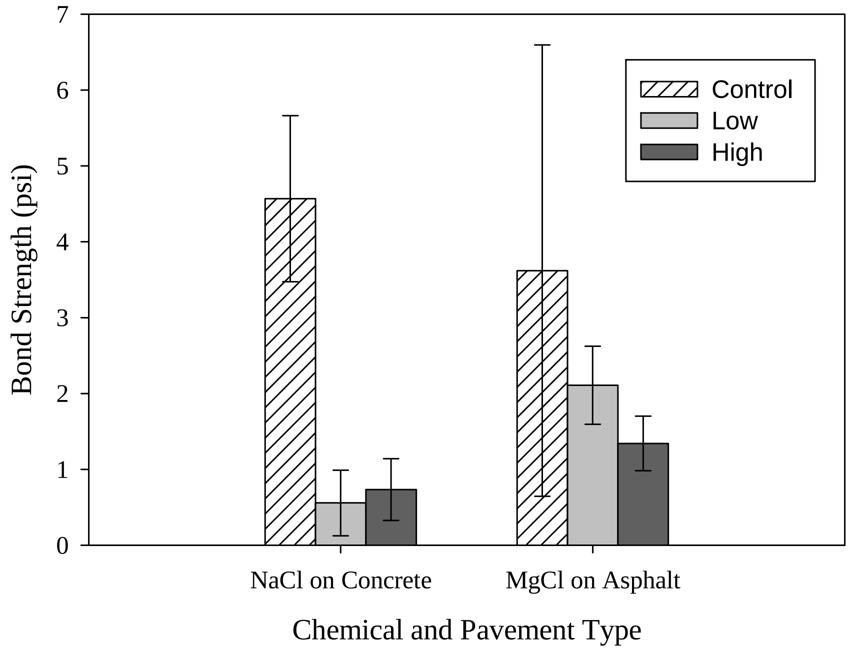

Figure 50: Bond strengths in treated and untreated test sections on special pavements with 95% confidence error bars.

Friction measurements taken after chemical application indicate relatively consistent coefficients of friction on the Monster Pad after chemicals were applied, and slightly higher coefficients than on bare pavement (Figure 51). Ten measurements were taken in each test section. Friction was also measured after bond strength testing on the exact locations the bond strength was tested. Friction was measured once for each location, and the variability in the data can be seen in Figure 52. Friction was not measured where the snow quality had diminished due to exposure to sun and warmer temperatures. Variability can be attributed to varying amounts of snow or liquid left on the pavement surface after debonding and changing snow conditions.

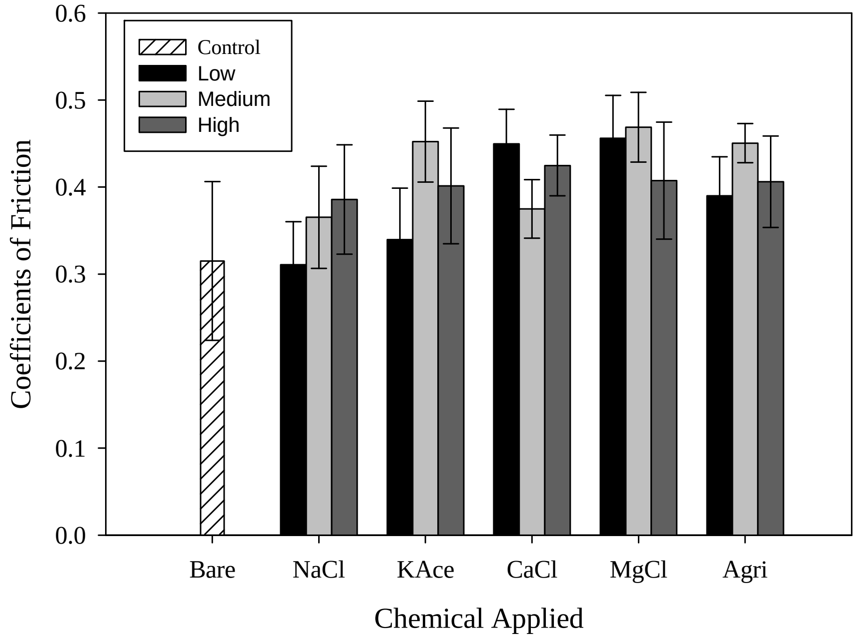

Figure 51: Friction coefficients on the Monster Pad taken after chemical application with 95% confidence error bars.

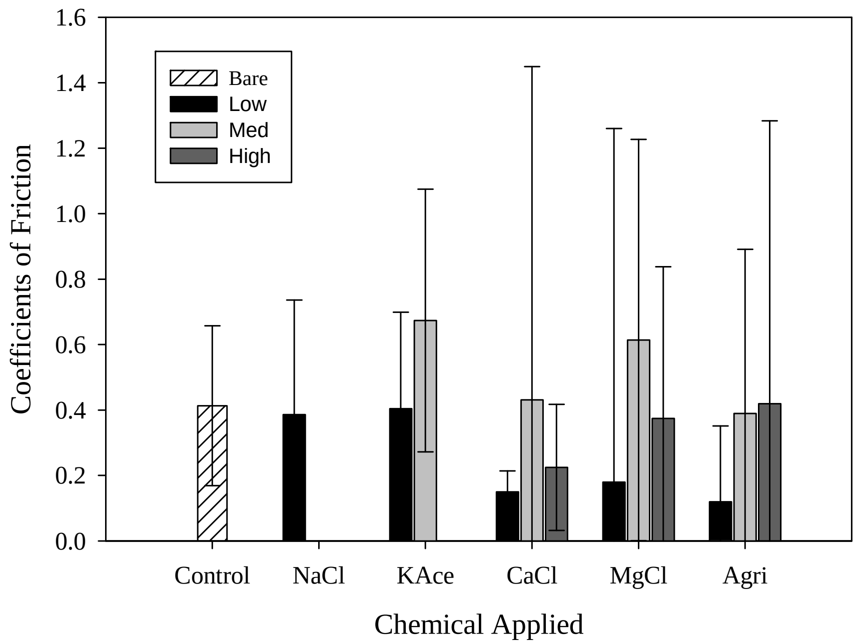

Figure 52: Friction coefficients after bond strength testing with 95% confidence intervals.

4.6 Field Test III – March 10–11, 2010

The final field test was held in the early spring under warmer temperatures. Chemicals were applied in the afternoon with temperatures around 30°F. The application rates for this field test are shown in Table 11. Each chemical was applied at the same low, medium and high rates for more direct comparison between test sections. Also, MgCl was applied to both special pavements at the same rates to facilitate more direct comparisons between pavement types.

Table 11: Chemical Application Rates for Field Test III

Chemical	Low	Medium	High
NaCl	5	15	30
KAce	5	15	30
CaCl	5	15	30
MgCl	5	15	30
Agri	5	15	30

Special Concrete	Low	High
MgCl	15	30

Special Asphalt		
MgCl	15	30

Snowmaking began at about 10:00 PM, when the pavement had cooled sufficiently. The overnight low was about 22°F. Wind was somewhat fast but blew in a favorable direction most of the night. Man-made snow was applied at depths between 1.5 and 2.5 inches, except for two test sections that had very thin coverage before the wind picked up (approximately 0.75 inches deep). During snowmaking it was observed that, according to a diagnostic panel on one of the snowmaking guns, slightly more water was flowing out of one fan gun than the others (difference of about 5 to 10 gallons per minute). This is not unusual and a difference in snow quality between the guns was not observed. However, during sampling, the test sections directly in front of the slightly wetter gun developed a very strong, icy layer close to the pavement when compared to the other test sections. Thin and icy sections are shown in Figure 53; circled numbers in Figure 53 indicate where control measurements were made. Snow was compacted with the smooth drum compactor, and then allowed to sit for approximately two hours.

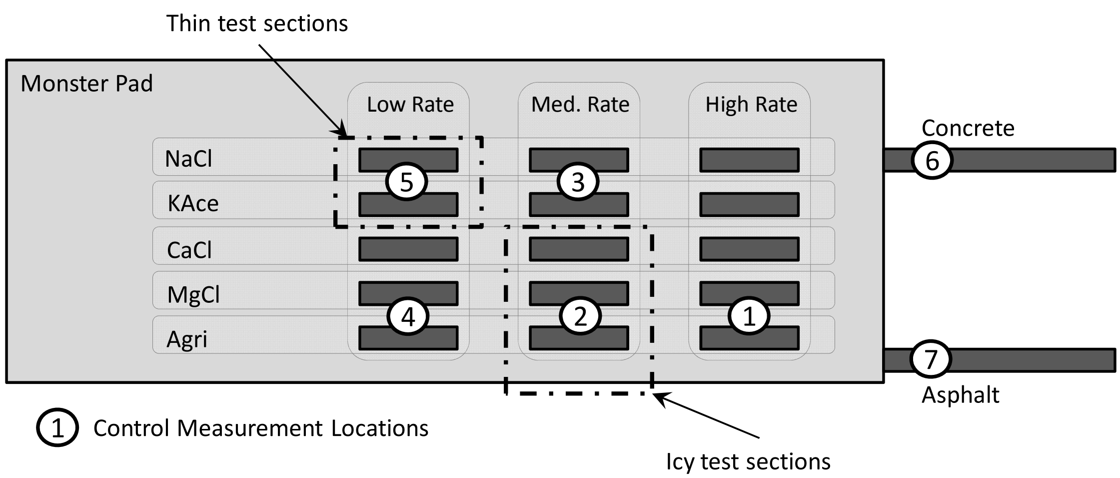

Figure 53: Test section layout for Field Test III, showing locations of anomalies and control measurements.

Test section evaluations started just before dawn and were completed in about five hours under relatively similar weather conditions. Test sections were evaluated by measuring snow density, bond shear strength with the improved plow box, and pavement roughness using ASTM

E965 after the pavement had been cleared and dried. Pavement roughness was measured in precisely the same locations that bond strength was measured. For each test section, three to four bond strength and roughness measurements were taken as well as one density measurement. Measurements were also taken in seven other untreated areas (controls) for comparison to nearby treated areas (as shown in Figure 53). These measurements were taken either immediately before or just after nearby treated test sections were evaluated. By comparing test sections to nearby control sections, the relative effect of some environmental factors can be reduced and all test sections could be compared to one another. Test sections with high chemical application rates were sampled first, followed by medium application rates, low application rates and, finally, the special pavement test sections.

Average bond strength for test sections on the Monster Pad and special pavements are shown in Figure 54 and Figure 55, respectively. The average bond strength is determined by averaging all bond strength measurements made in a single test section. Bond strengths are relatively consistent across the three application rates with two exceptions: 1) icy test sections (in part of the medium application rate area) have higher bond strengths, and 2) the thin test sections (in part of the low application rate area) have lower bond strengths. It is unclear why the bond strengths in these areas differ, but it may be related to environmental factors in addition to chemical performance. Bond strengths of control sections are included in Figure 54 between the particular test sections where they were sampled. For example, the average bond strength of Control Section 5 is shown in Figure 54 in the "Low" rate group between the NaCl column and the KAce column, and the bond strength of Control Section 1 is reported in the "High" rate group between the MgCl and Agri columns. It is important to note, relative to further discussion, that bond strengths in Control Section 2, (icy snow) were essentially the same as bond strengths in every other control section except for the Control Section 5 (thin snow area).

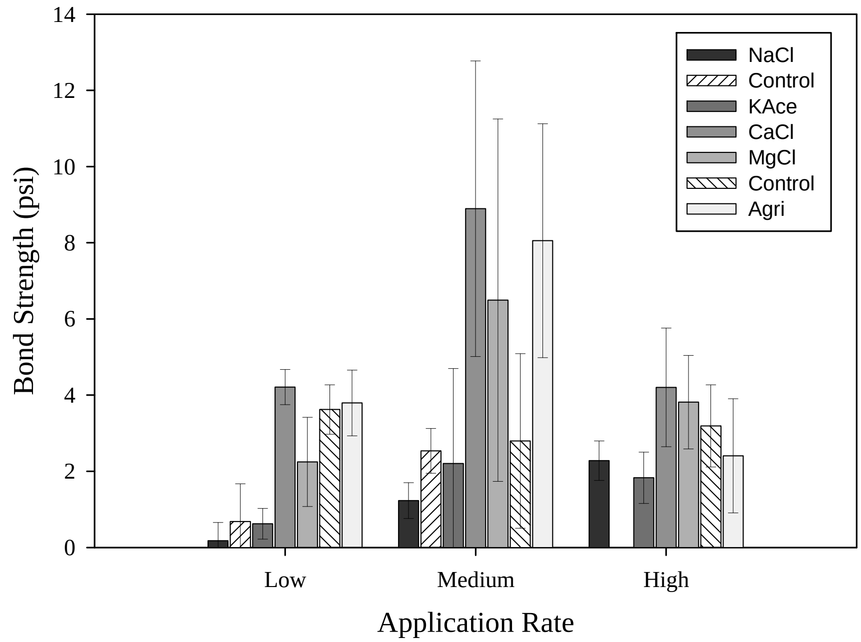

Figure 54: Average bond strengths in control and test sections on the Monster Pad with 95% confidence intervals.

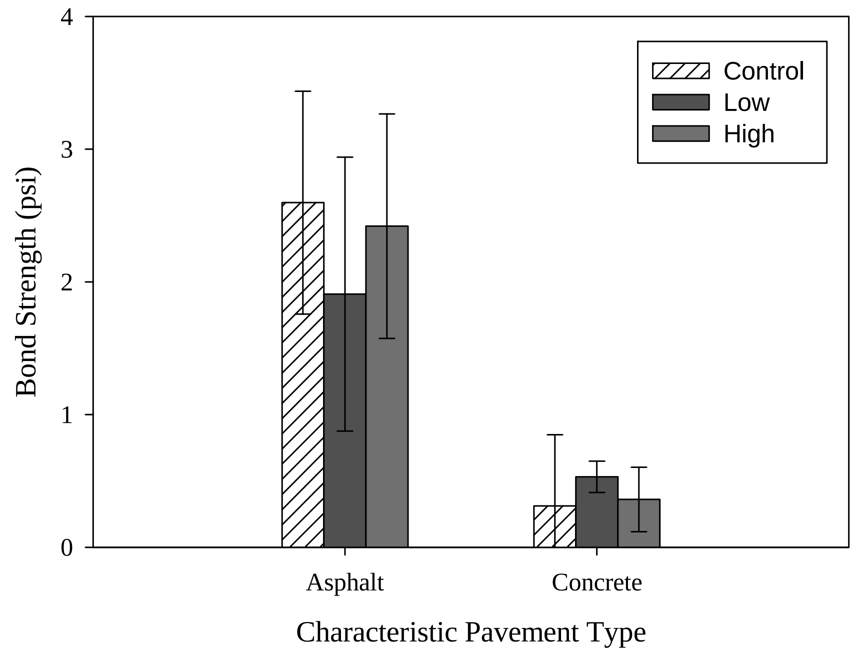

Figure 55: Average bond strengths in control and test sections on characteristic pavements treated with MgCl with 95% confidence intervals.

Data from this field test was further analyzed with respect to snow quality and pavement texture to determine whether the bond strength between snow and pavement at a particular location was affected by any of these factors.

Pavement texture was quantified with the standard test method ASTM E965, in which a known volume of uniformly graded sand is spread in a circular pattern over the pavement surface. The mean texture depth (in inches) is calculated based on the diameter of the circle of sand and the volume of sand. Based on measurements collected in the control sections, there appears to be a loose relationship between pavement texture and bond strength (Figure 56). Additional data is necessary to establish a better relationship between pavement roughness and bond strength.

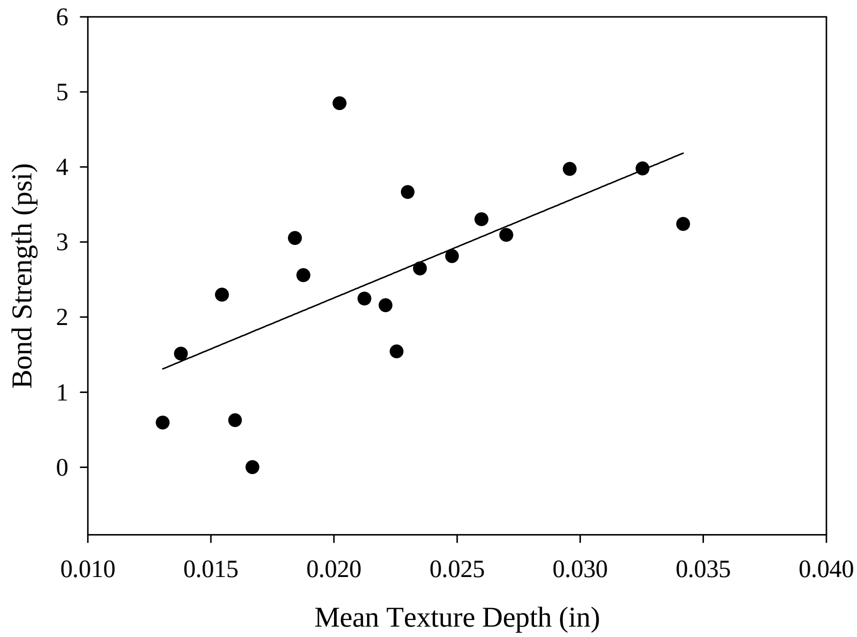

Figure 56: Bond strength plotted with respect to pavement roughness.

Snow density was compared to bond strength in the control test areas to identify a possible relationship between these two measured parameters. The comparison (shown in Figure 57) revealed that there is no relationship between these two parameters. Measurements of snow wetness may provide a more meaningful correlation with the snow–pavement bond strength. Based on the lack of a significant relationship between pavement roughness and snow density, the treated sections were compared to the nearest control section by calculating percent improvement in bond shear strength.

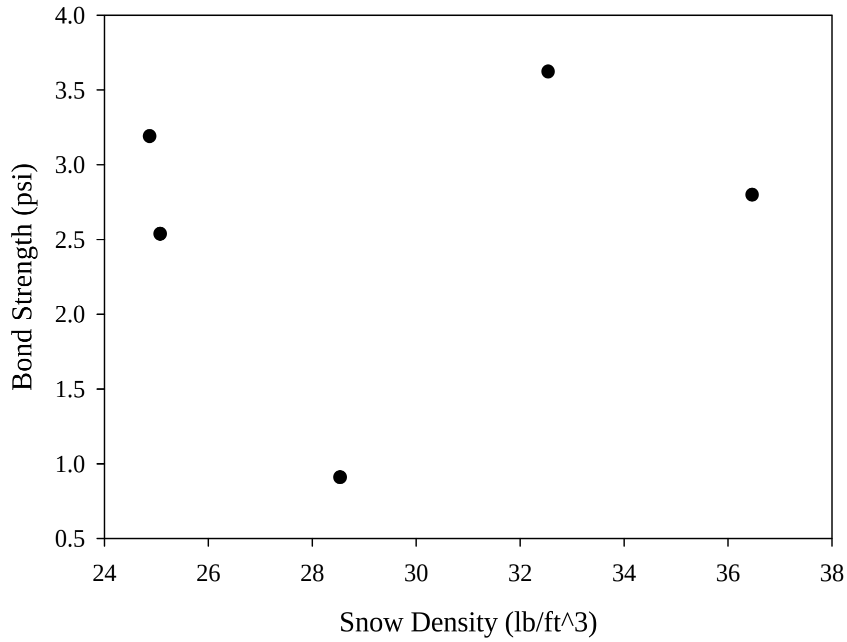

Figure 57: Bond strengths versus density in control sections.

The average bond strength in a treated section was subtracted from the average bond strength in the nearby control section to directly compare results between test sections and adjacent untreated test sections. The results of this analysis method are shown in Figure 58. Values greater than zero indicate that the snow–pavement bond strength in the treated section was lower than the bond strength in the untreated test section. Conversely, values less than zero indicate that the snow–pavement bond strength in the treated section was greater than the bond strength in the untreated section. Results indicated that NaCl and KAce performed favorably at all application rates.

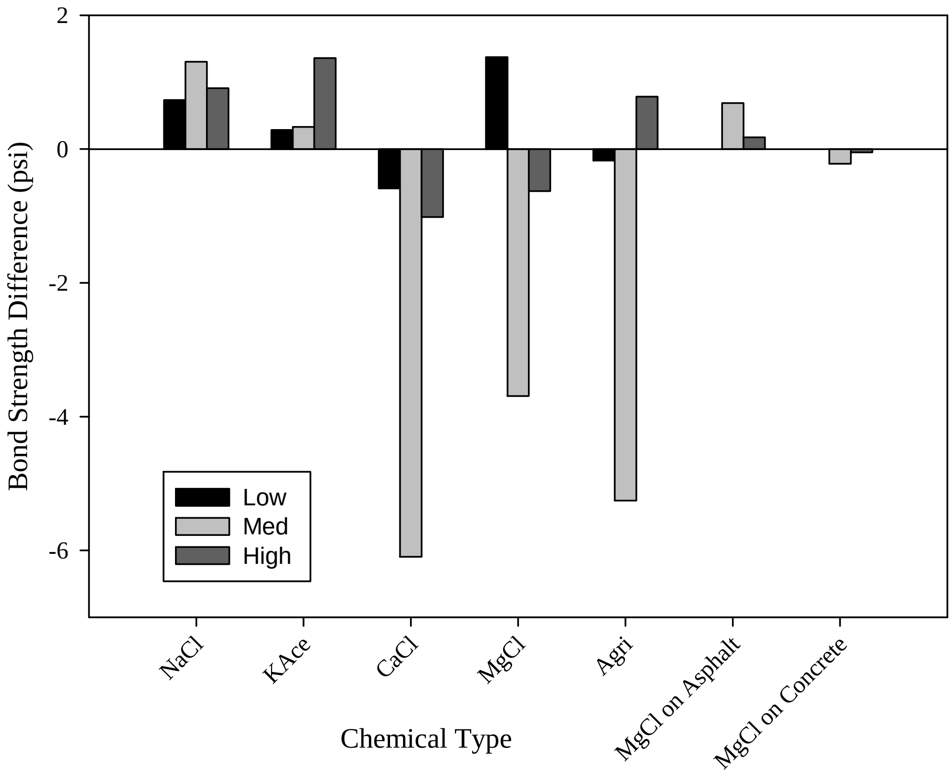

Figure 58: Difference in bond strength between nearby control sections and treated test sections.

Measurements in each test section were compared to one another by calculating percent improvement of treated sections over nearby control sections using Equation 1, where *PI* is percent improvement for a particular test section, BS_c is the average bond strength in the control area nearest the test section in question and BS_t is the average bond strength in the test section. Using this equation, positive values of percent improvement indicate a decrease in bond strength in the test section relative to the control section. Likewise, negative values of percent improvement indicate an increase in bond strength in the test section relative to the control section. Percent improvement values were normalized by the magnitude of the bond strength in the control section, so the relative performance of each control section can be compared.

$$PI = \frac{BS_c - BS_t}{BS_c}(100\%) \qquad \text{Equation 1}$$

Values for percent improvement are shown in Figure 59 for each test section. NaCl and KAce performed favorably at all application rates. Applications of NaCl and KAce also dried the quickest, while applications of MgCl, CaCl and Agri remained wet. The presence of CaCl increased bond strengths regardless of application rate. MgCl and Agri show promise under certain conditions to reduce the bond strength, but increase it under other conditions. In the icy areas, snow in treated areas was much more difficult to remove than in any other region of the test area. The poor anti-icing performance was more noticeable in this area relative to other areas, and it was unclear whether NaCl and KAce would have had the same effect on bond strength because this particular quality of snow did not reach test areas treated with those chemicals. If the results from the icy test sections are ignored, the performance of NaCl, CaCl and MgCl decreases with increasing application rate, while the performance of KAce and Agri generally increase with increasing application rate. On the special asphalt pavement, MgCl reduced the bond strength at both application rates, but seemed to perform best at the lower rate. Both application rates of MgCl increased bond strength on the special concrete test section with respect to the control sections. However, the magnitudes of the bond strengths on this pavement were very small and there was no significant difference in performance between test sections.

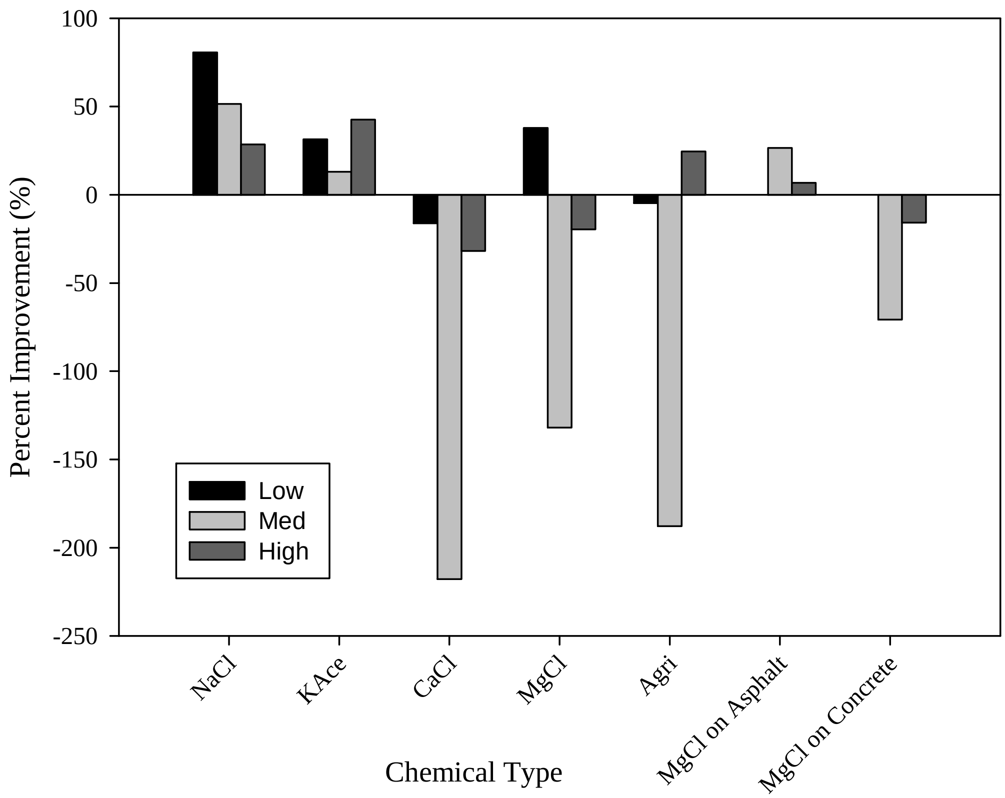

Figure 59: Percent improvement of treated test sections over nearby control sections.

4.7 Summary of Field Tests

The performance of anti-icing chemicals and application rates were tested at the TRANSCEND research facility on the Monster Pad (which was fog sealed during fall 2009), special asphalt and special concrete pavements. Man-made snow was produced using the snowmaking system at TRANSCEND during the three field tests. Quantitative and qualitative assessments were used to evaluate anti-icing performance. General parameters of interest included the ease of snow removal from the paved surface and the friction of the surface after snow was removed. Snow removal effort was quantified using visual observations and bond strength tests, and friction was measured using a hand-held friction tester.

Initially, anti-icing performance was anticipated to be evaluated by plowing test sections and noting visual differences between pavement surfaces. During the first field test, differences in performance were noted on the special asphalt section treated with MgCl. In this case, it was clear that the anti-icing strategy, specifically with MgCl at 20 gal/lm, weakened the bond between the pavement and the compacted snow. On the Monster Pad, however, it was difficult to discern differences between treated and untreated test sections or between the treated test sections because the snow was easily debonded from the pavement surface on all test sections. Snow wetness seemed to be a factor in anti-icier performance.

During subsequent field tests, the snow–pavement bond strength was quantified using the bond strength tests; however, these measurements were highly variable as a result of the small number of measurements that could be made in a reasonable amount of time, and the changing conditions of the snow as the test days progressed. Nevertheless, some general trends were observed. First, field anti-icing applications were successful at relatively low application rates, even as low as 5 gal/lm. Additionally, bond strengths measured on test sections treated with NaCl and KAce were routinely lower than test sections treated with other chemicals. Test sections treated with CaCl regularly had the highest bond strengths, and were usually higher than untreated sections. MgCl and Agri often reduced bond strengths when compared to untreated sections, but higher bond strengths were occasionally recorded. Measurements of pavement roughness and snow density were used to further characterize bond strength measurements, but were not useful in discerning differences.

Friction measurements failed to identify significant differences between various anti-icing chemicals or between anti-icing chemicals and control sections. The presence of liquid, solid or frozen material on the pavement surface hindered the ability to make repeatable measurements with the friction tester. Pavement surface roughness was measured during the third field test to better understand the relationship between surface texture and bond strength, but significant trends were not revealed.

Other qualitative observations were made during field testing to evaluate the behavior of anti-icing chemicals on the pavement. One such observation was related to the hygroscopic nature of the chemicals (i.e., the ability of a chemical to draw moisture from its surroundings). Though somewhat hygroscopic, applications of NaCl usually dried well before applications of snow, regardless of temperature. Applications of KAce also dried, but not as quickly as NaCl, and MgCl, CaCl and Agri never dried. This phenomenon may be significant depending on the weather conditions when anti-icing is used.

5 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this work was to improve California Department of Transportation's winter maintenance practices based on information obtained from an extensive literature review, laboratory experiments and a series of full-scale field tests. This effort was initiated to optimize salt usage on highways in the State of California to minimize corrosion to infrastructure and vehicles and damage to vegetation, and to preserve water quality. The following sections synthesize data collected from all of the project tasks and provide recommendations for implementing anti-icing strategies.

5.1 Conclusions

In this work, anti-icing strategies were shown to be successful at reducing the effort required to clear snow from the roadway. A variety of chemicals, representing a broad range of anti-icing chemicals available commercially, were applied to concrete and asphalt pavements in the laboratory and field under various meteorological conditions to verify this conclusion. Those applications were evaluated by measuring debonding temperature, friction, and snow–pavement bond shear strength. Overall, these laboratory and field experiments demonstrated that these anti-icing chemicals, when properly applied, interrupted the bond between compacted snow and pavement, but that differences between individual chemicals was less apparent. There are several other important factors to consider when selecting an appropriate anti-icing chemical: chemical effectiveness, cost, corrosiveness, environmental impact, availability, etc. The relative importance of each of these factors must be determined on a case-by-case basis.

This study evaluated the effectiveness of a variety of chemicals (temperature at which snow debonded from pavement, pavement surface friction after plowing, and bond strength) and concluded:

- Based on the temperature at which snow debonded from pavement, chemical performance on treated specimens was improved over pavement specimens tested without any chemical application. Differences in performance between chemicals do not seem to follow any obvious trend.
- The use of anti-icing chemicals generally helped maintain friction of the road surface after plowing. The friction coefficients measured during the laboratory experiments were slightly higher on treated pavements than on untreated pavements; however, it was not possible to discern performance differences between chemicals. In the field, friction measurements made on treated pavements were consistent with measurements made on untreated pavements before the application of snow. After snow was applied and removed, friction measurements either remained consistent or were highly variable depending on the particular field test.

- Bond strength measurements in the lab were significantly reduced by the presence of chemical, regardless of chemical type or application rate. Differences in performance between chemicals were more variable in the field tests, and seemed to be related to the wetness of the man-made snow. Poorer performance was coincident with wetter snow.

5.2 Recommendations

The following sections include recommendations for implementing anti-icing strategies into a winter maintenance program and for additional research.

5.2.1 Implementation of Anti-Icing Strategy

Anti-icing is a proven method of efficiently and effectively maintaining roadways. The key to this method is the timely application of chemicals to the pavement surface to weaken or prevent the bond between pavement and compacted snow. The following five tasks should be followed to effectively implement anti-icing practices.

1. Identify priority areas and plan routes
2. Prepare equipment and personnel
3. Obtain appropriate chemicals
4. Forecast the storm, prescribe an application rate, and execute plan
5. Monitor and record results

Identify Priority Areas and Plan Routes

Anti-icing is most frequently used where well-maintained roads are required or expected. Routes should be identified and prioritized before the winter season. Because anti-icing can reduce the effort required to clear a roadway, it is in these areas that the most economic, ecological and safety benefits can be realized. Winter maintenance efforts should be designed to match personnel and equipment resources, and clear performance criteria should be established (e.g., clear lane or restoration of traction in a certain amount of time) when developing these plans.

Prepare Equipment and Personnel

Anti-icing requires special equipment and training. Vehicles should be outfitted with chemical tanks of sufficient size to efficiently complete an entire route. Spray bars on the trucks should be designed to apply chemical at rates between 10 gal/lm and 100 gal/lm and to minimize waste from chemical that is blown away before it reaches the road. Pump controls on the trucks should be set up to compensate for vehicle speed so that uniform and efficient applications are made. When anti-icing, significantly less chemical is used when compared to traditional reactive strategies. Personnel must be trained to recognize the appearance of prescribed anti-icing application rates so that chemical is not wasted.

Obtain Appropriate Chemicals

Selection of an appropriate anti-icing chemical depends on many factors. The relative importance of each of these factors is determined on a case-by-case basis. Factors may include:

- Cost
- Corrosion—corrosive nature of product, need for inhibitors
- Performance—freezepoint depression, longevity, shelf-life, bond interruption, friction, hygroscopicity
- Environment impacts—animal attractant, vegetation, soil, aquatics
- Availability—delivery, storage

Forecast the Storm, Prescribe an Application Rate, and Execute Plan

Knowing when a storm will arrive and what type of precipitation is expected is crucial to determining whether anti-icing is an appropriate response to a particular storm. Forecasting technologies (e.g., RWIS, MDSS, etc.) should be employed to effectively anticipate a winter storm. Timely anti-icing applications are applied before snow accumulates. Storms that transition from rain to snow and high wind with blowing snow are examples of weather that is not conducive to anti-icing. Depending on the storm severity and pavement condition, more or less chemical can be used to treat the roadways. Application rates ranging from 2.5 to 15 gal/lm were used in the laboratory. Application rates used during the field ranged from 5 to 40 gal/lm based on laboratory studies, information from the literature review and field equipment capability. Actual rates may vary and are dependent on traffic levels, type of storm, pavement condition, rate of snowfall, etc.

Monitor and Record Results

Monitoring and recording results of successful and unsuccessful treatment strategies will help improve future decisions. Regularly scheduled discussions between all parties will help facilitate ways to improve practices based on lessons learned and provide an opportunity to introduce new technologies or methods.

5.2.2 Recommendations for Additional Research

The following research items are recommended to refine best practices of maintaining roadways during winter storm events.

- Evaluate the field performance of anti-icing strategies on California roadways by monitoring the performance of a variety of chemicals during several real storm events on actual highways. Performance could be measured by friction, presence of snow accumulation on the road surface, cost–benefit analyses, traffic speed/flow, etc.

- Develop a robust method to measure friction in the laboratory and field to better monitor performance.
- Investigate more efficient methods of chemical application to reduce waste and improve effectiveness.
- Further develop and implement appropriate combinations of liquid and solid chemical treatment strategies.
- Develop a standard laboratory test protocol to evaluate performance of anti-icing chemicals.

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APPENDIX A: SURVEY OF CALTRANS WINTER MAINTENANCE STAFF

Establishing Best Practices of Removing Snow and Ice from California Roadways

This questionnaire was designed to learn about current snow and ice control practices in California. You have been selected to participate in this effort because of your experience or expertise in removing snow and ice on California roadways. The information gathered in this survey will be used to develop a comprehensive description of the state-of-the-practice of snow and ice removal at Caltrans, and to suggest alternative technologies to improve the efficiency and cost-effectiveness of snow and ice removal on California roads.

Thank you for taking the time to complete this questionnaire!

Name: ____
Job Title: __________________________
District: ___________________________
E-mail:____
Phone: ____

Methods

1. What percentage of the time does your district use:
   Anti-Icing:________
   De-Icing:________
   Snowplowing: _______
   Sanding: _______

2. What do you see as the best method of snow removal for maintaining safe winter road conditions?
3. What experience does your district have with anti-icing?
4. Do you utilize weather forecasts to aid you in your winter road maintenance activities?
5. How many vehicles do you currently have equipped for liquid chemical application?
6. What percentage of your total fleet does this represent?

Materials

1. What snow and ice control chemicals does your district currently use? Please indicate any trade names and describe any added corrosion inhibitors.
2. What snow and ice control chemicals would you like to see Caltrans use for snow and ice control operations?
3. What application rates do you use for your current practice?
4. What is your strategy and/or policy governing your snow and ice control maintenance? Timing of applications? How often do you reapply? Different strategies for different storm scenarios.
   Please include any additional comments.

APPENDIX B: ASPHALT AND PORTLAND CEMENT CONCRETE MIX DESIGNS FOR PAVEMENT SAMPLES

Caltrans provided WTI with several asphalt mix designs, which were the basis for the manufacturing of pavement samples used in the laboratory experiments. These are provided first, followed by the MDT mix design used to manufacture the pavement specimens for the laboratory experiment.

May 17 07 01:35p Eagle Peak 530-233-4918 p.1

CGi Technical Services, Inc.

FAX TO: 265-3165

Asphalt Concrete Mix-Design Hveem Method

Project Name: Annual Design
Client: Eagle Peak
Aggregate Source: Hogsback Quarry
Oil Supplier: Albina

Project No.: 06-1068.18
Lab No.: 0
EA:
Oil Grade: PG64-22

Date Sampled:
Date Received: 28-Sep-06
Date Started: 2-Oct-06
Date Verified: n/a

Description of Mix: 12.5mm Maximum Medium
Mix Type: Type A
Asphalt Specific Gravity: 1.018

Specific Gravity	Apparent	Bulk	Bulk SSD	Absorption
Coarse		2.67		1.12
Fine	2.68			

Specific Gravity (CTM 206 and CTM 208):
Specific Gravity (CTM 206 and CTM 207):

Asphalt Concrete Data

Asphalt Content	Compacted Unit Weight (CTM 308)	Compacted Unit Weight (pcf)	Maximum Unit Weight (CTM 367)	Maximum Unit Weight (CTM 309)	Percent Air Voids (CTM 367)	Percent Air Voids (CTM 309)	Stability S-Value (CTM 366)	% Voids in Mineral Aggregate
Mix Design								
5	2.29	142.9	2.48		7.8		40	
5.5	2.29	142.9	2.47		7.2		38	
6	2.30	143.5	2.45		6.1		36	
6.5	2.32	144.8	2.43		4.7		36	
Target								

Sieve Analysis Data

Sieve Size (standard)	Sieve Size (mm)	Bin #1 - 3/4" 0% % passing	Bin #2 - 1/2" 20% % passing	Bin #3 - 3/8" 20% % passing	Bin #4 - Dust 60% % passing	Bin #5 - Sand 0% % passing	Combined	Target Value	Specifications Low	Specifications High
1	25		100	100	100		100			
3/4	19		100	100	100		100			
1/2	12.5		80	100	100		96		95	100
3/8	9.5		29	96	100		85		80	95
#4	4.75		2	25	97		64	62	57	67
#8	2.36		0	4	73		45	43	38	48
#16	1.18		0	1	46		28			
#30	0.6		0	1	32		19	22	17	27
#50	0.3		0	1	18		11			
#100	0.15		0	1	11		7			
#200	0.075		0	0.4	7.5		4.6		3.0	8.0

Aggregate Quality

Fine Aggregate	Value	Specs	Coarse Aggregate	Value	Specs
% Crushed (CTM 205)	100	70	% Crushed (CTM 205)	100	90 max
Sand Equivalent (CTM 217)	57	47 min	LAR Loss @ 100 revs (CTM 211)	2	-
KF Factor (CTM 303)	1.0	1.7 max	LAR Loss @ 500 revs (CTM 211)	9	25 max
Fine Durability (CTM 229)	69	50 min	KC Factor (CTM 303)	0.9	1.7 max
			Coarse Durability (CTM 229)	78	65 min
			Cleanness Value (CTM 229)	n/a	

Optimal Mixture Properties	
Optimum Bitumen Content	5.5
Recommended Range	5.2-5.5
Air Voids (CAL 367)	
S-Value (CAL 366)	>37
Swell (CAL 305)	<0.76
Density (CAL 308)	2.30

Submitted By:

Cliff D. Curry, President/C.E.O.

AAP AASHTO PI8

Figure 60: Caltrans asphalt mix design.

SAMPLE # D71932

% of #4	65		
FSG	2.71	FSG =	23.99
100 - #4	35		
CSG	2.64	CSG =	13.26

CONSTANT 37.24

* Sp. Gravity * 1.02

SP. GRAVITY*
AR 1000 = 1.004
AR 2000 = 1.012
AR 4000 = 1.021
AR 8000 = 1.021
AR 16000 = 1.021
ASPHALT RUBBER = 1.04

AIR VOIDS DETERMINATION

		A	B	C	D	E		
							COMPTD	
A	100 + % Asph.	105.5	105.8	106.1	106.4	106.7	CHKD	
B	% of Asph. / Sp. Gr. Asph.*	5.39	5.69	5.98	6.27	6.57	Sp. Gr. Asph. = Paving Grade 1.02 (AR4000 & above) Sp. Gr. Asph. = Liquid Grade = 0.96	
C	Constant **	37.24	37.24	37.24	37.24	37.24	= % Fine / Sp. Gr. Fines + % Coarse / Sp. Gr. Coarse	
D	B + C	42.63	42.93	43.22	43.52	43.81	Air Voids Determination	
E	Sp. Gr. Briquette	2.29	2.31	2.32	2.34	2.33	Determined from stability of bricket	
F	Max. Theo. Sp. Gr. (A) / (D)	2.47	2.46	2.45	2.45	2.44	Max.Theo. Sp. Gr.= Item **"A"** divided by Item "D"	
G	Rel. Density (E) / (F) x 100	92.7	93.9	94.7	95.5	95.5	Rel. Density = Sp. Gr. Brick devided by Max. Theo. Sp. Gr. X 100	
H	Voids = 100 - G	7.3	6.1	5.3	4.5	4.5	% VOIDS = 100 - Rel. Density (G)	
I	Stability	44	43	43	42	HF		
J	Rice						% Percent of Asphalt	
K	Rice Voids	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		

Figure 61: Caltrans asphalt mix design (continued).

EAGLE PEAK
ROCK & PAVING
P.O. BOX 879
ALTURAS, CA 96101
(530) 233-4568
FAX (530) 233-4918

April 30, 2007

Jerome Tuholski
Caltrans – District 2
4300 Caterpillar Road
P.O. Box 496073
Redding, CA 96049-6073

Re: Contract 02-3C4204

Dear Mr. Tuholski:

Below is our proposed mix design for the subject project 12.5mm PBA 6a Asphalt concrete.

EAGLE PEAK ROCK & PAVING'S, BIN % AND X FACTORS

MIX TYPE	BIN PERCENTAGES #1	#2	#3	X FACTORS #4	#8	#30
*12.5mm Max, Med.	55	25	20	62	43	22
Lime %	1.6	0.8	0.6	Combined Lime % = 1.200		

#1 Bin = Fines
#2 Bin = 3/8" Rock
#3 Bin = 1/2" Rock

*** Type A, PBA 6a**

Asphalt Oil Supplier: Albina Asphalt

Contract No. 02-3C4204

Please call if you have any questions.

Sincerely;

Tony Cruse

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Figure 62: Caltrans asphalt mix design (continued).

ASPHALTIC CONCRETE MIX DESIGN SUMMARY

1392 13th Ave S.W. • P.O. Box 3269 • Great Falls, MT 59403-3269 • 406-453-5400

Revised: March 27, 2008

	Percent Passing						
	Cr. Coarse	Inter.	Cr. Fines		Blend*	Design Blend	Target Values
Sieve	108828	108829	108830				
3/4"	100				100	100	100
1/2"	57				80	82	83
3/8"	22	100	100		64	68	68
No.4	2[illegible] See Attached			Sheet		for 46	1/2" gradations
No.10	1	2	52		26	27	28
No.20	1	2	36		18	18	
No.40	1	2	27		13	14	15
No.80	1	2	16		8	9	
No.100	1	2	14		7	7	
No.200	0.6	1.3	9.3		4.9	4.7	4.7

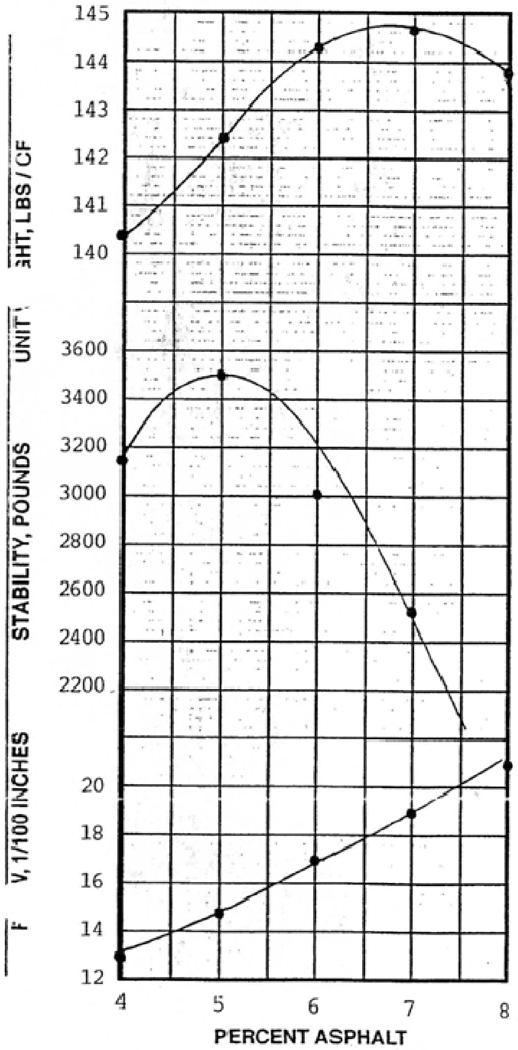
Hydrated Lime 1.4%

Component Aggregate		SP.GR.	% Blend
1	Coase Aggregate (+ No.4)	2.582	53
2	Fine Aggregate (-No.4)	2.590	47
3	Rice Specific Gravity	2.400	@ 5.6%
Asphalt Cement: Montana Refining		PG 64-28	1.0277 Sp G
Mix Property		Asphalt Content, %	Design Limits
Unit Weight, pcf 143.7		5.6	
Stablity, Lbs. 3500		5.6	1800 Min.
Flow, 0.001 in. 16		5.6	8-16
3.8 % Voids - Total Mix		5.6	2-4
15.7 % Voids in Mineral Agg (VMA)		5.6	13 Min.
75.8 % Voids - Filled w/A.C.		5.6	
Recommended Design Value: *		5.6	% Asphalt
This Mix Design is based upon Marshall Test Methods using 75 blows on each end. Three specimens were perpared for each asphalt content.			
Client: United Materials, Inc.			
Project: 2nd Ave. So. 7th to 9th		Great Falls, MT	Drawn By: KS
STPU 5236 (2)		MDOT Grade D Commerial	Checked By: KDM

*47% Lab No. 108828

5% Lab No. 108829

48% Lab No. 108830



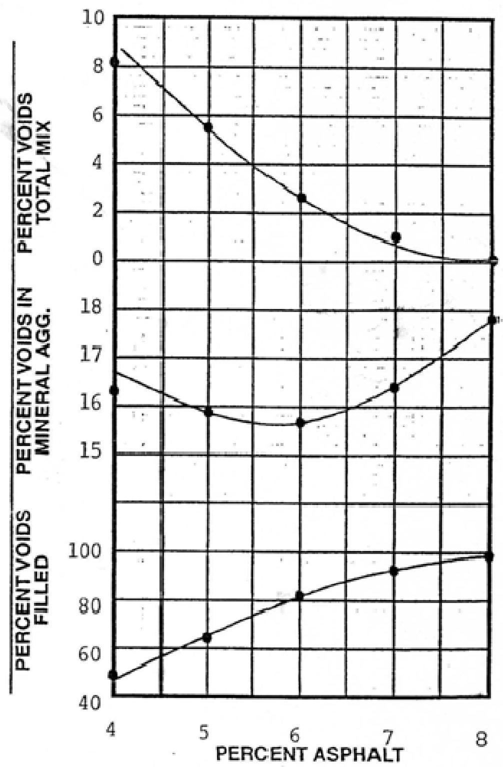


Figure 63: MDT asphalt mix design.

United Materials Inc.
Job No.: C4091103

March 24, 2009
Page 2

2009 Mix Designs
-1/2" Plant Mix

DESIGN BLEND

Screen or Sieve Size	Blend 45% Lab No. 110566 55% Lab No. 110567	Actual Design Blend	Target Values	MT Public Works Type C Specification
	Percent Passing Screen or Sieve Size Shown			
1/2"	100	100	100	100
3/8"	93	93	93	91 - 93
No.4	58	57	57	51 - 71
No.10	37	37	36	34 - 46
No.20	25	24		
No.40	18	18	19	16 - 26
No.80	11	11		
No.100	10	10		
No.200	6.2	6.2	6.2	5 – 9

AGGREGATE TEST RESULTS

		Specifications
Fracture Faces 1 or more, %	98.6	50 Min.
Liquid Limit, %	Granular	25 Max.
Plasticity Index, %	Non-Plastic	6 Max.

Figure 64: MDT asphalt mix design (continued).

Caltrans also provided the following concrete mix designs.

Page 1

08-448504

	source	lab #	%abs	SSD Sg	Sg x 62.4	Quantity
Rock	**Cemex Rialto**		0.90	2.67	166.86	62 % by vol
sand	**Cemex Rialto**		1.50	2.64	164.74	38 % by vol
Cement	**special blend**			3.15	196.56	**375 kg/m3**
Min admix				**2.4**		
Design for 1 cubic yard						
design air (%)	**5.5**	w/c (kg/kg)	**0.42**			
	Absolute Volu	SD weight				
cement	0.1196	375				
Min Admix	0.0000	0				
water	0.1575	158				
air	0.0550					
volume of pas	0.3321					
volume of agg	0.6679					
Rock	0.4141	1102				
Sand	0.2538	667				
totals	1.0000	2301				
theoretical unit weight		2301				
batch size	**0.048 m3**		cement	18.00	18.00	
aggregate quantities			min admix	0.00		
size	11/2 x 1	1X3/4	3/4X3/8	3/8 x #4	0	sand
SSD	21.37	11.07	12.77	7.66	0.00	32.00
DRY	21.21	10.96	12.65	7.59	0.00	31.53
Moist Content	**0.3**	**0.3**	**0.3**	**0.3**	**0**	**0.27**
Batch weight	21.28	10.99	12.69	7.61	0.00	31.61
	21.30	11.00	12.70	7.60		31.60
	.09	.08	.08	.05		.39

110.7

84.2

.69

375kg

Figure 65: Caltrans concrete mix design.

08-448504 Page 1

Edit bold text as required for gradation and mix design calculations
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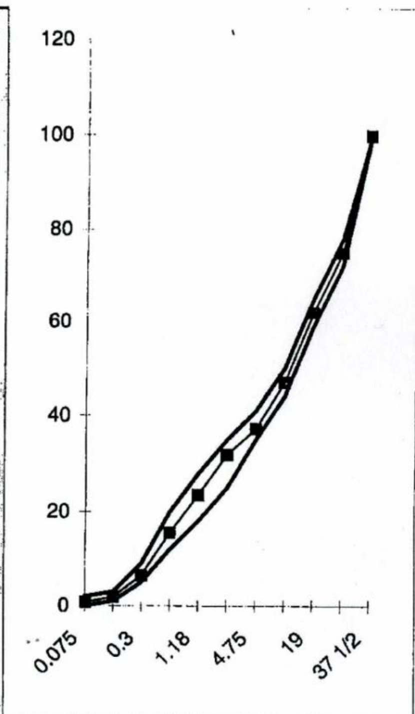
before printing **in J2->**
(box above column 'I')

CONTRACT NO. xx-xxxxx4
C/F Combined Grading Calculations

Sieve Size	11/2 x 1	1X3/4	3/4X3/8	3/8 x #4	sand	11/2 x 1	1X3/4	3/4X3/8	3/8 x #4	0	sand	Final Grading	Grading Test Mt	Grading Specs
						25.0	**13.0**	**15.0**	**9.0**	**0.0**	**38.0**			
2"	100	100	100	100	100	25.0	13.0	15.0	9.0	0.0	38.0	100	100	100
1 1/2"	**100**	**100**	**100**	**100**	**100**	25.0	13.0	15.0	9.0	0.0	38.0	100	100	90-100
1"		**100**	**100**	**100**	**100**	0.0	13.0	15.0	9.0	0.0	38.0	75	72-78	50-86
3/4"			**100**	**100**	**100**	0.0	0.0	15.0	9.0	0.0	38.0	62	59-65	45-75
1/2"				**100**	**100**	0.0	0.0	0.0	9.0	0.0	38.0	47		-----
3/8"				**100**	**100**	0.0	0.0	0.0	9.0	0.0	38.0	47	44-50	38-55
No. 4				**0**	**98**	0.0	0.0	0.0	0.0	0.0	37.2	37	35-41	30-45
No. 8					**84**				0.0	0.0	31.9	32	25-35	23-38
No. 16					**62**					0.0	23.6	24	18-28	17-33
No. 30					**41**					0.0	15.6	16	12--20	10--22
No. 50					**17**					0.0	6.5	6	5--9	4--10
No. 100					**5**					0.0	1.9	2	1--3	1--6
No. 200					**2**					0.0	0.8	1	0--2	0--3
Sp. G - Fine					**2.64**	Avg.Sp.G. Fines					2.64			
Absorb.-Fine					**1.5**	Avg. Abs. Fines					1.50			
Sp. G - Coarse	**2.68**	**2.67**	**2.67**	**2.67**		Avg.Sp.G. Coarse					2.67			
Absorb.-Coarse	**0.75**	**1**	**1**	**1**		Avg. Abs. Coarse					0.90			



Gradation

Figure 66: Caltrans concrete mix design (continued).

CONCRETE MIX WORKSHEET

CHARGE NUMBER 08-448504 **DATE** 10-30-03

SOURCE CEMEX RIALTO

MIX NO.	RD III		
SLUMP (ASTM C143)	2.75	2.5	2.5
KELLY BALL (CTM 533)			
AIR % (CTM 504)	5.5	5.0	5.5
GROSS WEIGHT (lbs)	21.10	21.20	21.15
TARE WEIGHT (lbs)	4.80	4.80	4.80
"F" FACTOR (Unit Wt calibration)	141.65	141.65	141.65
NET WEIGHT (lbs) (Gross Wt-Tare Wt)	16.30	16.40	16.35
UNIT WEIGHT(CTM 518) (Net Wt X "F" factor)	2309	2323	2316
CEMENT (lbs)	16.80	18.00	19.20
INITIAL WATER WT.(lbs)	12.00	12.10	11.65
FINAL WATER WT.(lbs)	3.80	3.60	3.15
NET WATER WT.(lbs)	8.20	8.50	8.50
AIR ENTRAINMENT AGENT	.45ML/LB 16.7	.45ML/LB 17.9	.45ML/LB 19.0

Figure 67: Caltrans concrete mix design (continued).

APPENDIX C: DETAILED STATISTICAL ANALYSIS OF DEBONDING TEMPERATURE RESULTS OF LABORATORY EXPERIMENT

Visual comparisons between the temperatures at which the snow debonded from the pavement, based on the laboratory experiments, did not conclusively indicate whether some chemicals perform better in certain scenarios. Thus statistical analyses were utilized to compare these temperature results. Variables that were investigated with respect to their influence on debonding temperature were chemical type, application rate, pavement type, and storm scenario. The mean debonding temperatures for all combinations of experiment parameters are shown in Table 12. Recall that only experiments in which a bond formed between snow and pavement were considered in the analysis. Statistical methods require the mean and standard deviation of a sample population. A mean and standard deviation were calculated for each combination of the experiment parameters. Equations 2 and 3 were used to calculate a combined mean (μ_T) and combined standard deviation (S_T) of a sorted group, respectively.

$$\boldsymbol{\mu_T = \frac{\sum_i^k x_i}{N}} \qquad \text{Equation 2}$$

$$\boldsymbol{S_T^2 = \frac{\sum_i^k (x_i - \mu_T)^2}{N-1}} \qquad \text{Equation 3}$$

where:
μ_T = combined mean
S_T = combined standard deviation
N = number of samples
x_i = debonding temperature of an individual sample

Table 12: Mean Debonding Temperatures from All Experiments

Storm Scenario	Application Rates	Pavement Type	Chemical	Mean (°F)	Std. Dev. (°F)	COV (%)	N
I (P14-SA14)	Medium	Concrete	NaCl	35.5	0.3	0.8	3
			CaCl	34.4	0.9	2.6	3
			MgCl	33.9	0.4	1.3	3
			Kace	33.1	0.4	1.3	3
			Agri	33.9	0.3	0.8	3
			Control	na	na	na	na
	Low	Asphalt	NaCl	35.6	0.8	2.2	3
			CaCl	34.1	0.9	2.5	3
			MgCl	35.1	0.4	1.1	3
			Kace	35.3	0.8	2.4	3
			Agri	35.0	0.3	0.8	3
			Control*	37.8	0.4	0.9	9
		Concrete	NaCl	35.6	0.5	1.5	3
			CaCl	35.0	0.3	0.9	3
			MgCl	34.7	0.5	1.4	3
			Kace	34.4	0.8	2.5	3
			Agri	36.3	1.0	2.7	3
			Control*	37.7	0.6	1.7	9
II (P32-SA23)	Medium	Concrete	NaCl	34.2	0.4	1.1	3
			CaCl	33.5	0.3	0.9	3
			MgCl	33.6	0.7	2.0	4
			Kace	32.7	0.3	0.8	3
			Agri	33.0	0.4	1.2	3
			Control	na	na	na	na
	Low	Asphalt	NaCl	34.3	0.3	0.8	3
			CaCl	34.8	0.4	1.2	3
			MgCl	34.6	0.6	1.9	3
			Kace	34.3	0.2	0.4	3
			Agri	34.2	0.2	0.7	3
			Control*	35.8	0.3	0.9	12
		Concrete	NaCl	34.7	0.4	1.0	4
			CaCl	34.6	0.5	1.5	4
			MgCl	34.9	0.5	1.6	3
			Kace	34.1	0.4	1.1	4
			Agri	34.1	0.9	2.6	3
			Control*	36.0	0.7	1.9	8
III (P32-SA30)	Medium	Concrete	NaCl	32.8	0.4	1.3	3
			CaCl	33.1	0.3	0.8	3
			MgCl	33.0	0.3	0.8	3
			Kace	33.2	0.2	0.7	3
			Agri	33.4	0.7	2.0	3
			Control	na	na	na	na
	Low	Asphalt	NaCl	34.8	0.1	0.2	3
			CaCl	33.6	0.2	0.5	3
			MgCl	33.6	0.5	1.5	3
			Kace	34.5	1.6	4.5	3
			Agri	34.9	0.2	0.6	3
			Control*	38.8	1.1	2.8	9
		Concrete	NaCl	35.2	0.1	0.2	3
			CaCl	35.7	0.6	1.7	3
			MgCl	34.3	0.2	0.7	3
			Kace	34.6	0.3	0.9	3
			Agri	35.3	0.2	0.7	4
			Control*	38.0	1.2	3.1	10

* Average control value for the storm scenario

To make quantitative comparisons between chemical behaviors, a two-sided t-test was used to evaluate the statistical significance of the difference in the means of two sample populations (e.g., the mean debonding temperature of a specific chemical on asphalt as compared to the mean debonding temperature of the same chemical on concrete). The results of this test can be expressed in a variety of forms. In this case, the p-value was used to express the result of each comparison.

The p-value for a particular comparison ranges between zero and one, with values approaching one indicating a greater likelihood that the means are the same. A confidence interval of 85 percent was used in the analysis, which means that p-values less than 0.15 indicate the means being compared are considered statistically different, and p-values greater than 0.85 indicate the means are considered statistically similar. P-values between 0.15 and 0.85 were considered ambiguous and the relationship between the means was considered inconclusive. It was recognized that confidence intervals greater than 85 percent are typically used; however, the purpose of this analysis is simply to identify general trends in the data, which were less evident when a larger confidence interval was used.

Table 13 provides a summary of the p-values resulting from every combination of the experiment parameters. The columns on the left indicate which storm scenarios and application rates were used to determine the composite mean values being compared. Italicized values are for concrete pavements and non-italicized values are for asphalt pavements. For example, the p-value to determine whether the debonding temperature is the same between KAce and NaCl on asphalt pavement, considering all applications but only storm scenario I (P14–SA14), is 0.66. This essentially indicates that when values of debonding temperature are randomly sampled from the entire data set, the means are equal 66 percent of the time. Since 0.66 is between 0.15 and 0.85, it is considered inconclusive.

Table 13: P-values for Debonding Temperature for All Combinations of Experiment Variables

Storm Scenario			Application Rate				Concrete					
III	II	I	Medium	Low			NaCl	CaCl	MgCl	Kace	Agri	Control
					Asphalt	NaCl	0.41	0.45	0.04	0.00	0.38	0.00
						CaCl	0.03	0.45	0.19	0.02	0.83	0.00
						MgCl	0.20	0.45	0.23	0.21	0.38	0.00
						Kace	0.56	0.22	0.58	0.02	0.08	0.00
						Agri	0.40	0.07	0.43	0.98	0.00	0.00
						Control	0.00	0.00	0.00	0.00	0.00	0.77
					Asphalt	NaCl	0.64	0.38	0.49	0.03	0.05	0.00
						CaCl	0.24	0.15	0.96	0.15	0.18	0.00
						MgCl	0.56	0.77	0.42	0.18	0.20	0.00
						Kace	0.71	0.19	0.45	0.06	1.00	0.00
						Agri	0.63	0.15	0.43	0.84	0.11	0.00
						Control	0.00	0.06	0.09	0.00	0.00	0.48
					Asphalt	NaCl	0.82	0.04	0.00	0.00	0.57	0.00
						CaCl	0.11	0.37	0.26	0.07	0.55	0.00
						MgCl	0.44	0.20	0.04	0.26	0.23	0.00
						Kace	0.66	0.18	0.78	0.06	0.08	0.00
						Agri	0.31	0.24	0.59	0.57	0.81	0.01
						Control	0.05	0.02	0.00	0.04	0.00	0.86
					Asphalt	NaCl	0.20	0.64	0.53	0.82	0.64	0.00
						CaCl	0.01	0.25	0.28	0.46	0.93	0.00
						MgCl	0.05	0.88	0.91	0.59	0.17	0.00
						Kace	0.74	0.44	0.43	0.59	0.38	0.00
						Agri	0.71	0.08	0.06	0.70	0.23	0.00
						Control	0.00	0.00	0.00	0.05	0.00	0.74
					Asphalt	NaCl	-	0.32	0.16	0.02	0.13	na
						CaCl	-	-	0.59	0.03	0.46	na
						MgCl	-	-	-	0.04	0.80	na
						Kace	-	-	-	-	0.07	na
						Agri	-	-	-	-	-	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.79	0.96	0.33	0.16	0.96	na
						CaCl	0.29	0.19	0.43	0.23	0.94	na
						MgCl	0.53	0.72	0.81	0.59	0.56	na
						Kace	0.78	0.55	0.79	0.67	0.39	na
						Agri	0.69	0.37	0.71	0.99	0.62	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.23	0.91	0.60	0.09	0.37	na
						CaCl	0.24	0.75	0.58	0.17	0.38	na
						MgCl	0.56	0.77	0.62	0.13	0.26	na
						Kace	0.71	0.19	0.45	0.56	0.90	na
						Agri	0.63	0.15	0.43	0.84	0.78	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.90	0.22	0.12	0.13	0.32	na
						CaCl	0.11	0.24	0.39	0.35	0.16	na
						MgCl	0.44	0.20	0.27	0.64	0.12	na
						Kace	0.66	0.18	0.78	0.26	0.08	na
						Agri	0.31	0.24	0.59	0.57	0.15	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.01	0.28	0.02	0.07	0.62	na
						CaCl	0.01	0.03	0.06	0.10	0.21	na
						MgCl	0.05	0.88	0.16	0.26	0.05	na
						Kace	0.74	0.44	0.43	0.92	0.20	na
						Agri	0.71	0.00	0.06	0.70	0.57	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	-	0.09	0.24	0.01	0.03	na
						CaCl	-	-	0.74	0.04	0.16	na
						MgCl	-	-	-	0.07	0.19	na
						Kace	-	-	-	-	0.39	na
						Agri	-	-	-	-	-	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	-	0.20	0.01	0.00	0.01	na
						CaCl	-	-	0.44	0.15	0.46	na
						MgCl	-	-	-	0.11	0.87	na
						Kace	-	-	-	-	0.06	na
						Agri	-	-	-	-	-	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	-	0.41	0.72	0.49	0.32	na
						CaCl	-	-	0.52	0.99	0.58	na
						MgCl	-	-	-	0.59	0.32	na
						Kace	-	-	-	-	0.59	na
						Agri	-	-	-	-	-	na
						Control	na	na	na	na	na	na

Summary of Debonding Temperature Values

Based on the preceding analyses of the results of the temperature at debonding and the attendant comparisons between the results of the control and various chemicals, several conclusions were reached.

1. The presence of chemical reduced the debonding temperature for all pavement types, application rates, and storm scenarios.
2. On asphalt samples for all application rates and storm scenarios, CaCl reduced the debonding temperature more than NaCl or Agri.
3. KAce reduced the temperature more than the other chemicals except MgCl on concrete samples for all storm scenarios and application rates.
4. Lower application rates were more effective on asphalt samples than concrete samples.
5. The more chemical applied, the lower the debonding temperature.

APPENDIX D: DETAILED STATISTICAL ANALYSIS OF FRICTION RESULTS FROM LABORATORY EXPERIMENT

A similar statistical analysis was performed with the friction results as with the debonding temperature results (refer to Appendix C for details). Table 14 provides the mean coefficient of friction from all experiments and Table 15 shows the p-values from all combinations of comparisons.

Table 14: Mean Friction from All Experiments

Storm Scenario	Application Rates	Pavement Type	Chemical	Mean (COF)	Std. Dev. (COF)	COV (%)	N
I (P14-SA14)	High	Asphalt	NaCl+GLT	0.37	0.08	21	3
			CCB	0.39	0.08	20	3
			FG	0.43	0.03	8	3
			KA	0.41	0.01	3	3
			ICR	0.40	0.03	9	3
		Concrete	NaCl+GLT	0.46	0.04	9	3
			CCB	0.43	0.06	14	3
			FG	0.43	0.07	15	3
			KA	0.48	0.03	5	3
			ICR	0.48	0.09	20	3
	Medium	Asphalt	NaCl+GLT	0.43	0.09	20	3
			CCB	0.45	0.02	4	3
			FG	0.43	0.07	17	3
			KA	0.41	0.10	24	3
			ICR	0.53	0.05	9	3
		Concrete	NaCl+GLT	0.48	0.04	8	3
			ICR	0.43	0.06	14	3
	Low	Asphalt	NaCl+GLT	0.51	0.07	14	3
			CCB	0.49	0.03	5	3
			FG	0.50	0.06	11	3
			KA	0.53	0.10	19	3
			ICR	0.50	0.04	8	3
			Control*	0.37	0.06	17	9
		Concrete	NaCl+GLT	0.42	0.13	32	3
			CCB	0.45	0.03	8	3
			FG	0.45	0.06	13	3
			KA	0.36	0.08	22	3
			ICR	0.47	0.03	7	3
			Control*	0.40	0.03	8	9
III (P32-SA30)	High	Asphalt	NaCl+GLT	0.44	0.03	6	3
			CCB	0.37	0.03	7	3
			FG	0.51	0.07	15	3
			KA	0.47	0.07	14	3
			ICR	0.50	0.03	5	3
		Concrete	NaCl+GLT	0.35	0.04	11	3
			CCB	0.45	0.06	13	3
			FG	0.51	0.04	9	3
			KA	0.44	0.04	10	3
			ICR	0.44	0.06	14	3
	Medium	Asphalt	NaCl+GLT	0.48	0.11	24	3
			CCB	0.37	0.04	12	3
			FG	0.45	0.06	14	3
			KA	0.45	0.07	15	3
			ICR	0.45	0.04	9	3
		Concrete	NaCl+GLT	0.50	0.07	14	3
			CCB	0.44	0.02	4	3
			FG	0.44	0.14	31	3
			KA	0.46	0.07	15	3
			ICR	0.44	0.06	14	3
	Low	Asphalt	NaCl+GLT	0.44	0.04	10	3
			CCB	0.42	0.06	15	3
			FG	0.36	0.07	18	3
			KA	0.40	0.10	25	3
			ICR	0.38	0.08	20	3
			Control*	0.34	0.03	10	9
		Concrete	NaCl+GLT	0.44	0.04	10	3
			CCB	0.47	0.06	14	3
			FG	0.45	0.06	13	3
			KA	0.44	0.07	16	3
			ICR	0.42	0.08	18	3
			Control*	0.39	0.05	13	12

* Average control value for the storm scenario

Table 15: P-values for Friction for All Possible Combinations of Experiment Variables

Storm Scenario		Application Rate					Concrete					
III	I	High	Medium	Low			NaCl	CaCl	MgCl	Kace	Agri	Control
					Asphalt	NaCl	0.82	0.00	0.00	0.25	0.01	0.03
						CaCl	0.17	0.00	0.00	0.00	0.27	0.00
						MgCl	0.93	0.00	0.00	0.00	0.00	0.01
						Kace	0.90	0.00	0.50	0.01	0.00	0.03
						Agri	0.63	0.00	0.00	0.00	0.00	0.01
						Control	0.00	0.00	0.00	0.00	0.00	0.03
					Asphalt	NaCl	0.73	0.61	0.69	0.52	0.87	0.07
						CaCl	0.88	0.78	0.94	0.76	0.45	0.09
						MgCl	0.74	0.81	0.69	0.73	0.54	0.14
						Kace	0.77	0.85	1.00	0.57	0.42	0.49
						Agri	0.36	0.33	0.45	0.54	0.60	0.02
						Control	0.07	0.04	0.03	0.05	0.01	0.21
					Asphalt	NaCl	0.45	0.42	0.32	0.55	0.90	0.20
						CaCl	0.02	0.01	0.66	0.82	0.40	0.01
						MgCl	0.65	0.12	0.47	0.56	0.31	0.02
						Kace	0.58	0.10	0.95	0.70	0.56	0.02
						Agri	0.69	0.05	0.91	0.85	0.74	0.00
						Control	0.05	0.06	0.01	0.01	0.00	0.03
					Asphalt	NaCl	0.92	0.31	0.11	0.09	0.21	na
						CaCl	0.41	0.07	0.42	0.42	0.66	na
						MgCl	0.16	0.03	0.92	0.85	0.76	na
						Kace	0.37	0.07	0.47	0.40	0.86	na
						Agri	0.30	0.06	0.62	0.83	0.79	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.49	0.07	0.62	0.61	0.07	na
						CaCl	0.35	0.35	0.96	0.61	0.65	na
						MgCl	0.69	0.47	0.96	0.82	0.85	na
						Kace	0.60	0.67	0.84	0.54	0.48	na
						Agri	0.51	0.04	0.17	0.17	0.09	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.33	0.53	0.66	0.56	0.71	na
						CaCl	0.50	0.84	0.77	0.17	0.73	na
						MgCl	0.35	0.65	0.68	0.25	0.94	na
						Kace	0.79	0.85	0.61	0.32	0.28	na
						Agri	0.43	0.81	0.84	0.73	0.89	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.23	0.52	0.60	0.35	0.75	na
						CaCl	0.80	0.55	0.94	0.26	0.49	na
						MgCl	0.37	0.51	0.93	0.31	0.53	na
						Kace	0.49	0.68	0.48	0.04	0.89	na
						Agri	0.65	0.88	0.35	0.60	0.30	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.45	-	-	-	-	na
						CaCl	0.67	-	-	-	-	na
						MgCl	0.95	0.55	-	-	-	na
						Kace	0.84	0.54	0.87	-	-	na
						Agri	0.19	0.14	0.13	0.21	0.10	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.36	0.78	0.79	0.56	0.59	na
						CaCl	0.62	0.18	1.00	0.24	0.41	na
						MgCl	0.82	0.76	0.33	0.24	0.56	na
						Kace	0.82	0.55	0.68	0.10	0.16	na
						Agri	0.80	0.67	1.00	0.68	0.39	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.04	0.08	0.02	0.07	0.12	na
						CaCl	0.02	0.13	0.28	0.78	0.75	na
						MgCl	0.30	0.09	0.94	0.16	0.19	na
						Kace	0.58	0.13	0.57	0.60	0.93	na
						Agri	0.08	0.01	0.87	0.57	0.26	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	0.88	0.28	0.59	0.59	0.35	na
						CaCl	0.25	0.13	0.96	0.61	1.00	na
						MgCl	0.68	0.17	0.93	0.82	0.97	na
						Kace	0.65	0.20	0.94	0.78	0.67	na
						Agri	0.68	0.10	1.00	0.93	0.79	na
						Control	na	na	na	na	na	na
					Asphalt	NaCl	1.00	0.56	0.78	1.00	0.75	na
						CaCl	0.61	0.36	0.75	0.62	0.47	na
						MgCl	0.18	0.37	0.16	0.82	0.62	na
						Kace	0.54	0.78	0.66	0.55	0.79	na
						Agri	0.33	0.60	0.74	0.87	0.55	na
						Control	na	na	na	na	na	na

APPENDIX E: WEATHER DATA DURING FIELD TESTING EVENTS

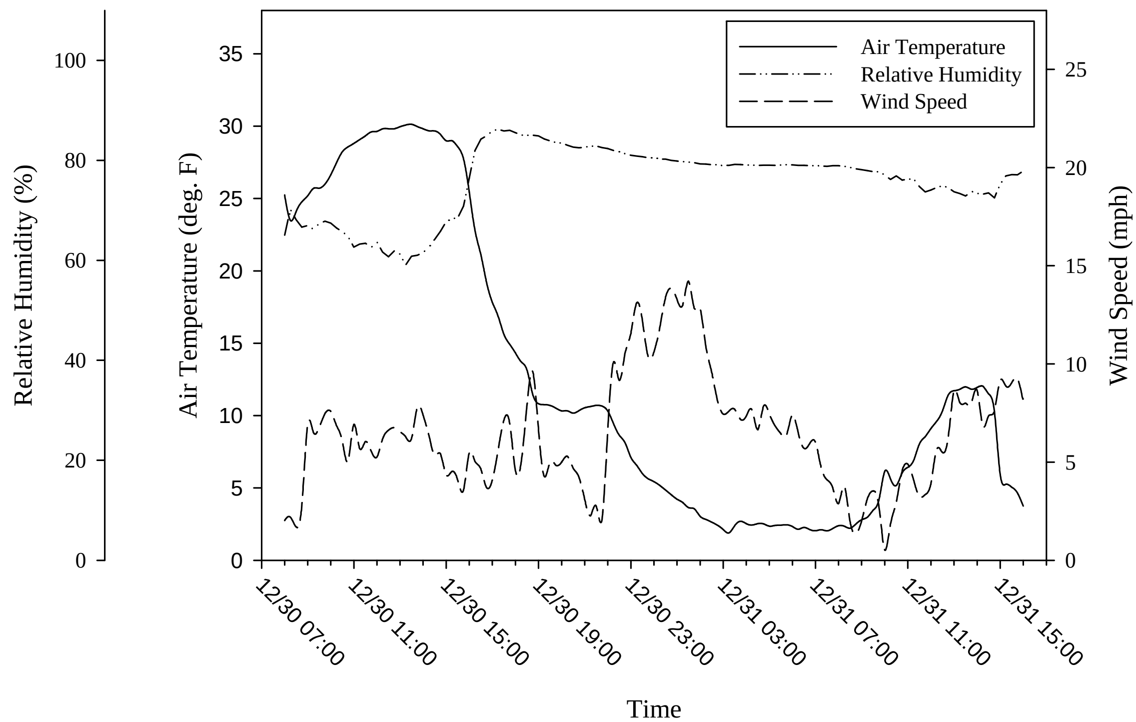


Figure 68: Weather data for Field Test Trial, December 30–31, 2009

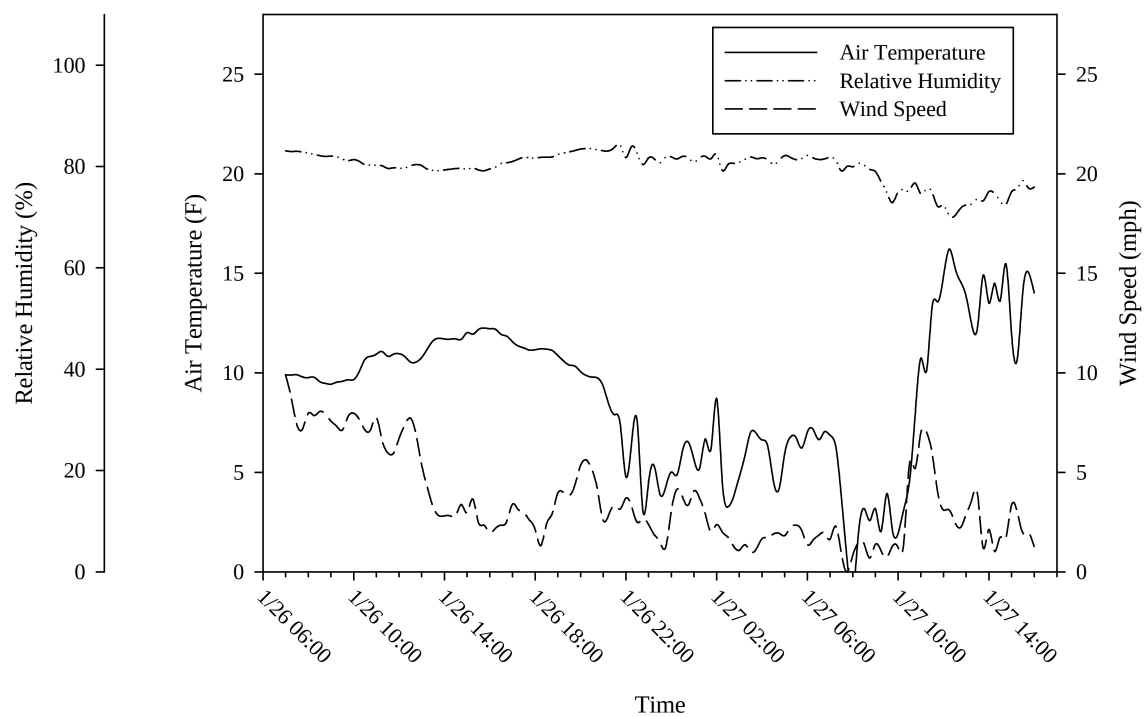


Figure 69: Weather data during Field Test 1, January 26–27, 2010

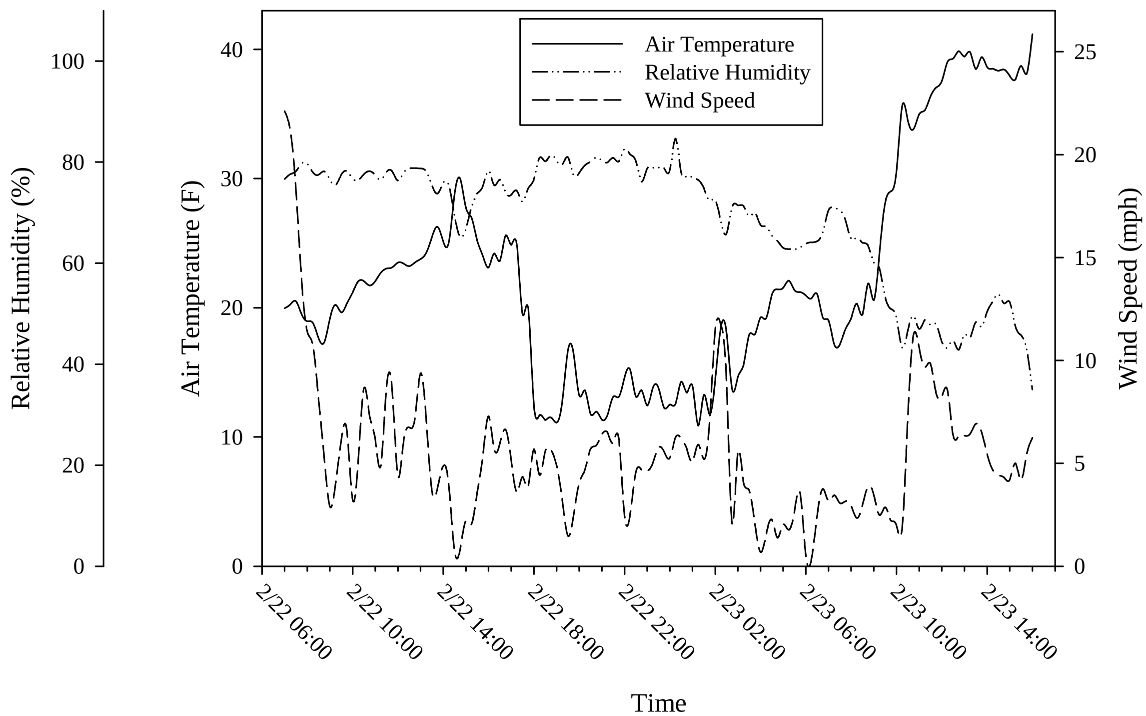


Figure 70: Weather data during Field Test 2, February 22–23, 2010

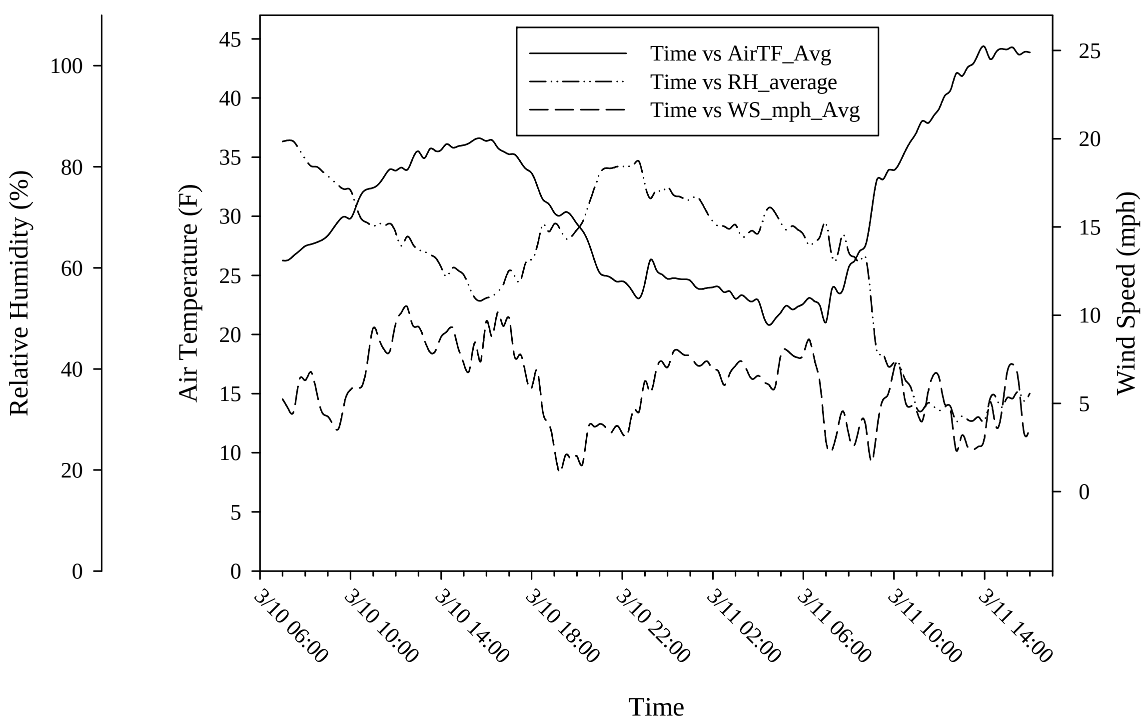


Figure 71: Weather data during Field Test 3, March 10–11, 2010