e

SPR 617 SEPTEMBER 2014

Effects of Deicing/Anti-Icing Chemicals (DIAICs) on Rubberized Asphalt Pavements

Arizona Department of Transportation Research Center

Effects of Deicing/Anti-Icing Chemicals (DIAICs) on Rubberized Asphalt Pavements

SPR-617
September 2014

Rita Leahy
Shih-Shien Sam Yang
Adriana Vargas
Peter Schmalzer
Nichols Consulting Engineers, Chtd.
1885 S. Arlington Ave.
Reno, NV 89509

Arizona Department of Transportation
206 S. 17th Avenue
Phoenix, AZ 85007

in cooperation with

US Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No. FHWA-AZ-14-617	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Effects of Deicing/Anti-Icing Chemicals (DIAICs) on Rubberized Asphalt Pavements	5. Report Date September 2014
	6. Performing Organization Code
7. Author(s) Rita Leahy, Shih-Shien Sam Yang, Adriana Vargas, and Peter Schmalzer	8. Performing Organization Report No.
9. Performing Organization Name and Address Nichols Consulting Engineers, Chtd. 1885 S. Arlington Avenue, Suite 111 Reno, Nevada 89509	10. Work Unit No.
	11. Contract or Grant No. SPR-000 1(169) 617
12. Sponsoring Agency Name and Address Arizona Department of Transportation 206 S. 17th Avenue Phoenix, Arizona 85007	13.Type of Report & Period Covered FINAL REPORT
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract

The objective of this study was to evaluate the effect of typical chemical winter maintenance practices on Arizona Department of Transportation (ADOT) pavements. A review of previous studies on the effect of deicing/anti-icing chemicals (DIAICs) did not yield definitive recommendations, especially for DIAICs typically used by ADOT. Researchers conducted a laboratory study evaluating the effects of magnesium chloride, potassium chloride, sodium chloride, and distilled water on eight different open-graded rubber-modified asphalt concrete mixes using the boiling test (ASTM D3625). All experimental factors were found to be statistically significant, and the researchers provide recommendations on which DIAICs should be used for different binder and aggregate types.

17. Key Words Deicing, anti-icing, rubberized asphalt, salt, magnesium chloride, potassium chloride, sodium chloride, DIAIC, binder, aggregate		18. Distribution Statement Document available to the US public through the National Technical Information Service, Springfield, Virginia, 22161		23. Registrant's Seal
19. Security Classification Unclassified	20. Security Classification Unclassified	21. No. of Pages 54	22. Price	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Contents

List of Figures

List of Tables

List of Abbreviations, Acronyms, and Symbols

AAPTP	Airfield Asphalt Pavement Technology Program
AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
ASTM	American Society for Testing and Materials
$CaCl_2$	calcium chloride
DIAIC	deicing/anti-icing chemical
DOT	department of transportation
FTIR	Fourier transform infrared
HMA	hot-mix asphalt
IDT	indirect tension
IT	immersion tension
ITS	indirect tensile strength
KCl	potassium chloride
$MgCl_2$	magnesium chloride
NaCl	sodium chloride
NMR	nuclear magnetic resonance
NMRI	nuclear magnetic resonance imaging
OGFC	open-graded friction course
PAH	polycyclic aromatic hydrocarbon
PG	performance-graded
TSR	tensile strength ratio

EXECUTIVE SUMMARY

The Arizona Department of Transportation (ADOT) makes significant use of open-graded rubber-modified asphalt concrete for roadway surfacing. There is concern that this type of surface may be more vulnerable than conventional dense-graded asphalt concrete to damage caused by the chemical deicing techniques ADOT uses to fight winter storms.

Previous studies on the effects of deicing/anti-icing chemicals (DIAICs) on pavements have yielded varying conclusions. Most studies have focused on airfields, where urea, formates, or acetates are primarily used, as opposed to the chloride DIAICs predominantly used on highways. There is general agreement that these airfield DIAICs accelerate stripping (loss of adhesion between asphalt binder and aggregate) to some degree. However, the damage mechanism is unclear, as is the degree to which the effect is significant under real-world conditions.

For this project, researchers conducted a laboratory study to investigate the effect of DIAICs commonly used by ADOT on typical open-graded rubber-modified asphalt concrete mixes. Asphalt binder and crumb rubber were obtained from two ADOT suppliers, and aggregate was obtained from four ADOT-approved sources. These components were used to produce eight asphalt concrete mixes in accordance with Section 414 of the ADOT Standard Specifications, “Asphaltic Concrete Friction Course (Asphalt-Rubber).” The mixes were evaluated for stripping potential using the boiling test (ASTM D3625) after soaking in solutions of magnesium chloride, sodium chloride, potassium chloride, and distilled water. None of the mixes performed significantly worse after soaking in magnesium chloride than after soaking in distilled water. The effects of potassium chloride and sodium chloride varied with aggregate and binder source.

Based on the results of the laboratory study, the researchers recommend magnesium chloride as the DIAIC with the least potential to damage open-graded rubber-modified asphalt concrete pavements. If DIAIC-induced damage is a concern, they recommend using stiffer binders, which appear to help mitigate the damage. Of the four aggregate sources tested, CM-2176 aggregate is recommended for rubberized pavements where DIAICs will be used.

CHAPTER 1. INTRODUCTION

PROBLEM

Recent observations show that the winter maintenance techniques that the Arizona Department of Transportation (ADOT) currently uses may adversely affect pavement performance. ADOT's standard approaches to clearing winter precipitation are to apply deicing/anti-icing chemicals (DIAICs) and to mechanically remove accumulated snow and ice. In Arizona, significant portions of the roadways are surfaced with open-graded rubber-modified asphalt concrete. This type of pavement may be more vulnerable than conventional dense-graded pavement to damage caused by chemical deicing techniques.

ADOT currently selects winter maintenance treatment strategies based on pavement temperature and pavement surface conditions, following these guidelines:

- If the pavement temperature is steadily below 15° F and falling, accumulated snow and ice should be plowed and/or abrasives should be applied to the road.
- If the pavement temperature is above 15° F and the pavement surface is icy, accumulated snow and ice should be plowed and/or deicing should be initiated.
- If the pavement temperature is above 15° F and the pavement surface is not yet icy but precipitation is anticipated, anti-icing should be initiated.

Chemical treatment strategies involve applying deicing or anti-icing chemicals to the pavement surface. Anti-icing agents are used to prevent snow and ice from bonding with the pavement surface through the timely application of a chemical freezing point depressant, while deicing agents are used to destroy an existing bond between snow and ice and the pavement surface. The DIAICs that ADOT most commonly uses are magnesium chloride ($MgCl_2$), sodium chloride (NaCl), calcium chloride ($CaCl_2$), and calcium magnesium acetate. It has been hypothesized that the use of these chemicals exacerbates the effects of freeze-thaw cycles on pavements. There is also concern that the chemicals may adversely affect the component materials of asphalt concrete (asphalt, rubber, and aggregate). Additionally, the chemicals may accelerate the oxidation process or cause other chemical or physical changes that may reduce the overall serviceability of the pavement.

OBJECTIVES

The effect of deicing/anti-icing chemicals on open-graded rubberized asphalt pavements needs to be fully understood so that pavement damage related to these chemicals can be minimized. Accordingly, the objectives of this study were to (1) use laboratory experiments to evaluate the effect of DIAICs on open-graded rubberized pavements, and (2) select the best combinations of DIAICs, aggregates, and binders for open-graded rubberized pavements.

CHAPTER 2. LITERATURE REVIEW

This chapter summarizes existing research on the effect of deicing and anti-icing chemicals on hot-mix asphalt (HMA) pavements. It includes recent studies on DIAIC-induced damage in HMA pavements; possible mechanisms for this damage and factors affecting its extent; test methods for evaluating pavement susceptibility to DIAIC-induced damage; and methods for identifying when pavement damage has been caused by DIAICs. This chapter concludes with a short summary of the chemical composition of asphalt.

DEICING AND ANTI-ICING CHEMICALS

Applying DIAIC compounds to roadways is an essential winter maintenance strategy in areas where ice and snow are common. These chemicals help vehicles maintain traction by melting ice on the pavement surface. Unfortunately, common deicing salts such as sodium chloride and calcium chloride can cause corrosion to vehicles and infrastructure. Other deicing chemicals have been developed that perform effectively without significantly accelerating the corrosion of metals and alloys. These noncorrosive DIAIC compounds include ethylene glycol, propylene glycol, urea, potassium acetate, sodium acetate, sodium formate, and calcium magnesium acetate.

Noncorrosive DIAICs may be applied to the pavement in solid form (pellets or granules), or in liquid form as solutions. For many years, it has been assumed that these DIAICs do little or no damage to either portland cement pavements or HMA pavements. However, recent evidence suggests that these DIAICs can damage both materials.

RECENT STUDIES OF DEICER DAMAGE TO HMA PAVEMENTS

Studies on DIAIC-induced damage to HMA can be grouped into two categories: laboratory investigations and field testing. In the laboratory investigations described below, the mechanical and physical properties of asphalt mixture samples conditioned with DIAIC solutions were compared with the properties of mixtures conditioned with dry or distilled water. The field studies were conducted by comparing the friction resistance of DIAIC-treated pavement sections and sections not treated with DIAICs.

Laboratory Investigations

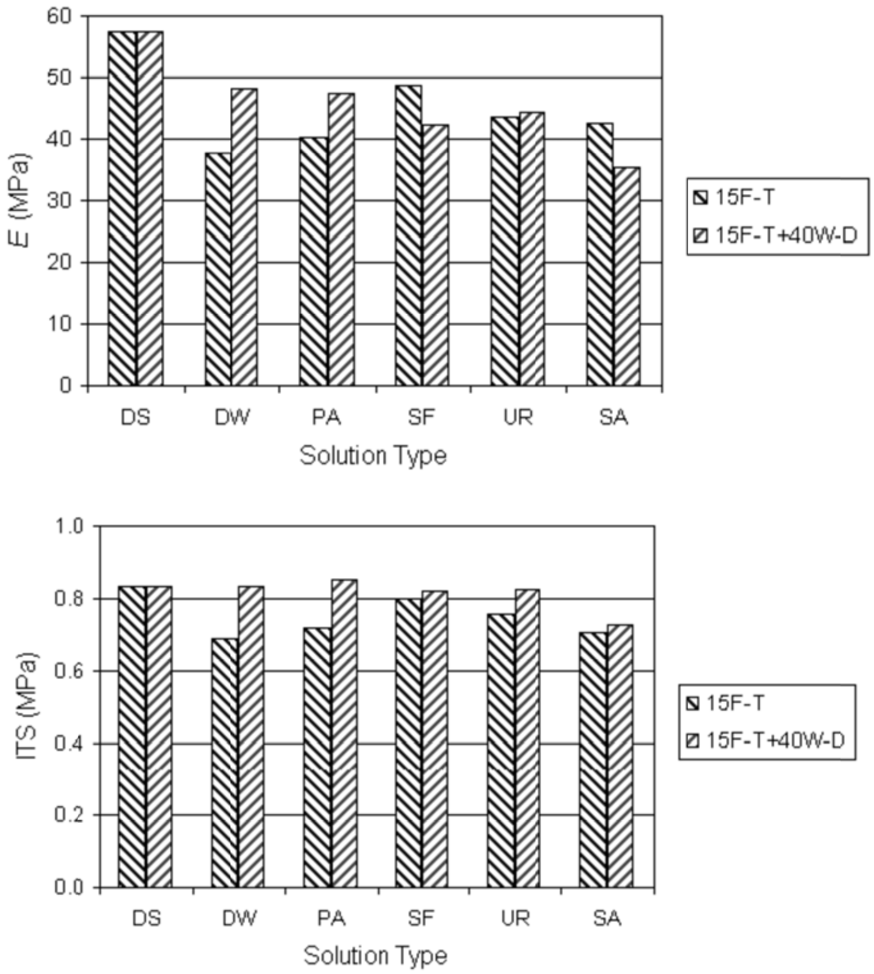
Canadian Airfields Study

Researchers from Transport Canada and Carleton University (Ottawa, Ontario) conducted a study on the effects of various DIAICs on asphalt concrete pavements at Canadian airfields (Hassan et al. 2001). This study was initiated not because DIAIC-induced damage was believed to be a problem at Canadian airfields, but because airports in Canada had recently switched from urea-based pavement deicers to newer compounds such as sodium formate, potassium acetate, and sodium acetate, and there was concern that these new DIAICs might damage HMA pavements.

This research was conducted in three phases. In the first phase, two types of aggregate representative of those commonly used in HMA mixes for Canadian airfield pavements were subjected to freeze-thaw cycles after being immersed in urea, potassium acetate, and sodium formate at various concentrations, as well as distilled water as a control. All of the samples that had been soaked in the DIAICs showed significantly greater weight loss after freeze-thaw cycling than the samples that had been soaked in distilled water, with those soaked in urea exhibiting the greatest weight loss. The quartzite aggregate had greater weight loss than the limestone aggregate. Weight loss was greatest at a 1 to 2 percent concentration of the DIAICs.

In the second phase of the research, HMA cores were soaked in solutions of urea, potassium acetate, sodium acetate, and sodium formate at the most damaging concentrations identified in Phase 1, and then subjected to freeze-thaw cycles. A control group of cores was soaked in distilled water prior to freeze-thaw cycling, and a second control group was not conditioned at all. The cores were tested to determine change in weight, indirect tensile strength (ITS), elastic modulus, penetration of extracted binder, and gradation of extracted aggregate. All of the specimens gained weight during freeze-thaw testing, and the rate of weight gain decreased as the number of freeze-thaw cycles increased. The first indications of damage to the specimens occurred after 15 cycles. ITS was significantly lower for all of the conditioned samples relative to the unconditioned samples. After 25 freeze-thaw cycles, the samples soaked in distilled water had the lowest ITS values, while the samples soaked in DIAICs had similar and slightly higher ITS values. After 50 freeze-thaw cycles, the ITS of the samples soaked in distilled water had not decreased further, whereas the ITS of the samples soaked in DIAICs had decreased substantially. The samples soaked in urea had the lowest ITS values after 50 cycles by a significant amount, whereas the ITS values of the samples soaked in potassium acetate and sodium formate were slightly lower than those soaked in distilled water. The ITS values of the samples soaked in sodium acetate were slightly higher than those soaked in distilled water.

Phase 3 was similar to Phase 2, except that only 15 freeze-thaw cycles were conducted, followed by 40 wet-dry cycles at 104° F. As shown in Figure 1, ITS decreased after the 15 freeze-thaw cycles, but recovered after the wet-dry cycles. The trend is less clear for elastic modulus. While the modulus of all the specimens decreased following freeze-thaw cycling, it recovered substantially in some cases. Penetration of extracted binder increased for some specimens following freeze-thaw cycling. In the cases where penetration increased, it recovered fully after the wet-dry cycles. No significant change in the gradation of extracted aggregate was observed.



DS = dry specimen; DW = distilled water; PA = potassium acetate;
SF = sodium formate; UR = urea; SA = sodium acetate.

Figure 1. Effect of Different DIAIC Solutions on Indirect Tensile Strength (Farha et al. 2002, Figure 6)

Several factors limit this study's applicability to Arizona roadways. First, the study did not include the DIAICs commonly used in Arizona, especially chlorides. In addition, the mechanical test results showed that the damage induced by the DIAIC solutions was similar to moisture-induced damage, and it is well known that moisture damage in HMA is strongly related to both binder source and aggregate type (Thelen 1958, Majidzadeh and Brovold 1968, Kim et al. 1985, Curtis et al. 1991, Tunnicliff and Root 1982). However, this study included a very limited range of aggregate and binder types. The material selections are poorly documented in the report, but they are presumably most applicable to airfield pavements in cold climates. Therefore, it is possible that the results of this study would be different if a broader range of materials had been used. As discussed below, it is also possible that the temperatures used in the study's high-temperature cycling were not high enough to produce the reactions needed to cause DIAIC-induced damage.

Helsinki University of Technology Study

Researchers at the Helsinki University of Technology in Finland conducted a study (Alatyppö and Valtonen 2007) similar in concept to the Canadian airfields study. However, the study was conducted reactively, to investigate the potential role of new DIAICs in observed airfield pavement failures, rather than proactively. The failures occurred on recently overlaid pavements where the original surface layer had been subjected to acetates and formates as part of routine deicing procedures. Observed surface distresses included blistering, raveling, and staining. Coring of failure areas revealed that the lower layers of HMA had become very soft and odoriferous.

The study included laboratory testing of mixture components (binder and aggregate), laboratory-mixed HMA specimens, and cores taken from in-service pavements and specially constructed test sections. Key findings included:

- Samples of binder boiled in DIAIC solutions did not appear to undergo chemical changes (as determined by gas chromatography and pH measurements). Specimen weight did increase, but the investigators could not determine the reason.
- Surface tension was significantly higher between distilled water and binder than between DIAIC solutions and binder. An emulsion consisting of finely dispersed formate–water solution in binder could be created easily in the lab. Distilled water could not be as easily or as finely mixed into the same binder. The investigators concluded that DIAIC solutions facilitate the penetration of water into binder.
- Neutralization was observed between DIAIC solutions and felsic aggregates. Limited aggregate soundness testing indicated that acetic aggregates degrade more when soaked in DIAIC solutions than basic aggregates do.
- Samples of binder-coated aggregates boiled in DIAIC solutions showed significant stripping. Formate solutions showed greater stripping than acetate solutions. The softer binder performed worse than the harder binder. The rubber-modified binder exhibited little stripping. Gas chromatography detected the presence of polycyclic aromatic hydrocarbons (PAHs), which were interpreted as potential binder decomposition products. PAHs were not detected when the binder alone was boiled in DIAICs, suggesting that a complex chemical interaction involving the binder, aggregate, and DIAIC was occurring at high temperatures.
- Testing of laboratory-compacted mixes and field cores subjected to freeze-thaw cycling showed little difference among ITS values for specimens soaked in water and DIAICs.
- Core samples from a failed runway showed that the bottom of the HMA pavement was extremely soft and odoriferous. Samples had low concentrations of DIAICs and high pH values. One sample had high PAH content.

In one experiment, 10 test sections were constructed consisting of an HMA overlay over existing pavement treated with potassium formate. Experimental variables included binder, aggregate type, and mineral filler. Minor damage ascribed to the potassium formate was observed after 1 year.

A second experiment consisting of 12 test sections was constructed at a different location. Little damage was observed after 3 years. Some damage was observed after 4 years, and the only section without damage had an alkaline aggregate and a stiff binder with a gilsonite modifier. Cores from damaged areas bled a very soft, sticky, bitumen-like fluid.

To manage the effect of DIAICs on HMA pavement, the investigators suggested: (1) using low air void contents; (2) using high-viscosity or polymer-modified binders; (3) using alkaline aggregates or high-quality aggregates (avoiding limestone filler or heavily contaminated reclaimed asphalt pavement if acetates or formates will be used as DIAICs); and (4) testing the compatibility of the materials using the boiling test.

Colorado DOT Study

The Western Transportation Institute at Montana State University conducted a study of the effects of acetate-based DIAICs on airfield pavements for the Colorado Department of Transportation (CDOT) using sodium chloride and magnesium chloride as the baseline DIAICs (Pan et al. 2008). The study evaluated potassium acetate, potassium formate, and sodium acetate/formate–blend DIAICs as alternatives to the sodium chloride, salt-sand mixtures, and magnesium chloride that were CDOT's standard treatments for both portland cement concrete and HMA pavements. The findings related to HMA pavement are summarized below.

A boiling water test of a single PG 67-22 binder mixed with limestone and crushed gravel aggregate was performed at various concentrations of sodium acetate. Significant stripping was observed with both aggregate types, indicating that aggregate type is a secondary factor. Stripping was 4 percent at a 0 percent concentration of sodium acetate and increased to 42 percent at a 40 percent concentration of sodium acetate.

Emulsification of binder samples in solutions of varying concentrations of sodium acetate at varying temperatures was examined using low-speed magnetic stirring. No emulsification was observed at the 0 percent sodium acetate concentration or at temperatures below 104° F. Emulsification increased with both sodium acetate concentration and temperature. No emulsification was seen with the sodium chloride or sodium hydroxide solutions, indicating that the emulsification phenomenon was due to the acetate anion, not the sodium cation or the pH value. Solutions of calcium magnesium acetate behaved similarly to the sodium acetate solutions. Of the three binders tested, the PG 58-22 exhibited the highest degree of emulsification, whereas the PG 64-22 and PG 67-22 binders behaved similarly.

Fourier transform infrared (FTIR) spectroscopy of the asphalt-acetate emulsions showed that the alkane component of the binder was present, and the test did not show the presence of any new chemicals, indicating that no chemical reaction had taken place. The authors proposed a mechanism by which asphalt binder at high temperatures swells and “sucks in” acetate solution from pore spaces, which greatly increases the contact area between binder and acetate ions. Acetate ions are attracted to nonpolar molecules in the binder by van der Waals’ forces and form hydrogen bonds with water.

Airfield Asphalt Pavement Technology Program (AAPTP) Study

A recently completed Airfield Asphalt Pavement Technology Program study conducted by Advanced Asphalt Technologies investigated the performance of HMA airfield pavement subjected to DIAICs (Advanced Asphalt Technologies 2009). The study used five common DIAICs (potassium acetate, sodium acetate, urea, and ethylene and propylene glycol), five types of aggregates, four different binders, two air void content levels, and one mixture additive to investigate the effects of various factors on DIAIC-related pavement damage. The immersion tension (IT) test, a modified version of the AASHTO T283 test, was developed in the study and used to evaluate the mechanical properties of various combinations of these factors. The FTIR test was used to investigate the potential chemical reactions between DIAICs and asphalt binders and aggregates. The surface tension between the binders and DIAIC solutions was measured using the nuclear magnetic resonance (NMR) imaging method. The study's key findings included:

- For some tested mixtures, the HMA pavement damage attributed to DIAICs is most likely a form of moisture-induced damage. Therefore, it should not be considered a unique form of distress, but rather an accelerated type of moisture damage, and should be referred to as "DIAIC-related damage" rather than "DIAIC-induced damage."
- DIAIC-related damage on HMA pavement was mainly limited to mixtures containing highly siliceous aggregates; however, many siliceous aggregates may not exhibit significant damage. In this study, DIAIC-related damage was associated with relatively high testing temperatures when acetate- and formate-based DIAICs were used. In addition, the softer the binder, the more severe the damage.
- To minimize the effect of DIAIC-related damage on HMA pavement, researchers recommended adding hydrated lime to the mixture, decreasing the mixture's air void content, and using a stiffer binder.
- The FTIR test showed that significant amounts of carboxylate salts were generated during conditioning of the HMA specimen in DIAIC solutions. However, this compound was observed both in mixes exhibiting DIAIC-related damage and in those not exhibiting DIAIC-related damage. Thus, this technique does not produce a reliable indicator of DIAIC-related damage.
- There was no conclusive evidence that PAHs are generated in HMA pavements subjected to DIAICs as was suggested by the Helsinki University of Technology study (Alatyppö and Valtonen 2007).

Laboratory Study Implications

These four research projects paint a potentially contradictory picture regarding DIAIC-induced damage in HMA pavements. In general, laboratory testing has not indicated that DIAIC solutions significantly accelerate moisture damage from a mechanical testing standpoint. However, these tests have been limited in scope, and it is possible that if a wider range of asphalt binders, aggregates, and environments were tested using the full range of commercial DIAIC solutions, some contribution to pavement damage would be observed. Also, the Helsinki University of Technology study (Alatyppö and Valtonen 2007) suggests that elevated temperatures may be necessary for DIAICs to contribute significantly to HMA pavement damage. Although that study did observe significant moisture damage in pavements exposed to DIAICs, it is not certain that this is a cause-and-effect relationship—the damage might have occurred even without DIAIC use. In other words, in this and other cases of apparent DIAIC-induced damage in HMA pavements, the DIAIC use may be merely coincidental in a pavement prone to moisture-induced damage.

Field Study

The Oregon Department of Transportation (ODOT) conducted a research project to evaluate the effects of DIAICs on open-graded pavements (Martinez and Poecker 2006). The motivation for this study was the increased number of accidents on ODOT highways constructed with these pavements after winter maintenance chemicals had been applied. The accidents were believed to be related to loss of surface friction caused by the application of DIAICs to the road surface. The study consisted of skid tests on four test sections under three conditions: (1) no DIAIC application; (2) after DIAICs were applied at a rate of 15 gallons per lane mile; and (3) after DIAICs were applied at 30 gallons per lane mile. Researchers found that the application of DIAICs to either type of pavement at either application rate appeared to have little if any effect on the friction number of the pavement surface. The friction numbers obtained in the skid tests were also compared with those recommended in a Federal Highway Administration study, and they were found to be well above the recommended values.

POSSIBLE MECHANISMS FOR DIAIC-INDUCED DAMAGE

The literature reviewed above suggests three potential mechanisms by which DIAICs can damage HMA:

1. DIAICs may promote emulsification of the asphalt binder, causing the binder to become soft and lose adhesion to aggregate surfaces. The CDOT study provides direct evidence of binder emulsification in acetate solutions under laboratory conditions, and the Helsinki University of Technology study provides indirect evidence of binder emulsification in acetate- and formate-contaminated pavements under field conditions. Both studies indicate that high temperatures, such as those experienced in hot summer weather or during repaving operations, are required for this phenomenon. The Helsinki University of Technology study did not address chloride-based DIAICs, while the CDOT study found that sodium chloride does not promote binder emulsification.

2. DIAICs may promote stripping by causing chemical deterioration of the aggregate surface; by binding to aggregate surfaces in preference to asphalt, thereby weakening the bond between aggregate and binder; or by accelerating normal moisture damage processes by decreasing surface tension, thereby facilitating the penetration of water into the pavement. The Canadian airfields study, the Helsinki University of Technology study, and the AAPTP study all found that mixes with siliceous aggregates were more susceptible to DIAIC-induced damage than mixes with limestone aggregates. The Helsinki University of Technology study and the AAPTP study also found that acetate and formate greatly reduced the surface tension between the DIAIC solution and the asphalt, promoting dispersion of the solution through the binder.

3. DIAICs may directly attack the asphalt binder. The Helsinki University of Technology study detected the presence of PAHs, which are presumed to be a product of binder decomposition, in

asphalt mixes exposed to DIAICs in both the laboratory and the field. The CDOT and AAPTP studies did not detect PAHs or other chemicals indicating decomposition of the asphalt binder. The Canadian airfields study found that the penetration of extracted binder increased following freeze-thaw cycling and decreased following wet-dry cycling in DIAIC solutions, which may indicate accelerated aging of the binder.

DIAIC-induced damage may involve a combination of the three mechanisms described above. The Helsinki University of Technology study noted no change in binder samples boiled in DIAIC solutions, but researchers found significant changes, including apparent organic decomposition products, in samples of asphalt-coated aggregate that had been boiled in DIAIC solutions. This may indicate a complex chemical interaction among the asphalt, aggregate, and DIAIC. It is also possible that DIAICs do not significantly damage asphalt pavements under real-world conditions, and that the relatively few field observations of damage in the literature are coincidental. It should also be noted that the DIAICs commonly used on airfields are the most heavily represented in the literature. Relatively little research has been done on the effects of chloride-based DIAICs commonly used on highways.

FACTORS AFFECTING DEICER-INDUCED DAMAGE IN HMA PAVEMENTS

Research on DIAIC-induced damage in HMA pavements has been limited. Anecdotal evidence from airfields in the northern United States, Canada, and northern Europe seems to suggest that DIAIC solutions can cause damage to HMA pavements, while laboratory evidence is somewhat ambiguous. It appears that the most likely mechanism by which DIAICs cause or accelerate damage is by increasing the potential for moisture damage, which is related to a decrease in the surface tension of water in DIAIC solutions. Based on this proposed mechanism and the research summarized above, a number of factors may affect the extent to which DIAICs cause damage to HMA pavements:

- **Aggregate type:** The Canadian airfields study, the Helsinki University of Technology study, and the AAPTP study all indicate that siliceous aggregates are more susceptible to DIAIC-related damage than calcareous aggregates. Most DIAICs promote alkaline pore water environments, which may cause a reaction with siliceous aggregates similar to alkali-silica reactivity.
- **Binder type:** The Helsinki University of Technology study and the AAPTP study indicate that softer binders are more susceptible to DIAIC-related damage than harder binders. However, in the CDOT study, all three binders had the same low temperature grade, but the binder with the lowest high temperature grade exhibited the most emulsification. The Helsinki University of Technology study also found that rubber- and gilsonite-modified asphalts were the least susceptible to DIAIC-related damage. The mechanisms behind these effects are uncertain.
- **Air void content:** The AAPTP study is the only one reviewed that investigated the effect of air void content. The study found that mixes with higher air void contents experienced more DIAIC-related damage. Air voids increase the permeability of asphalt, which enhances the dispersion of the DIAIC solution through the pavement layers. Air voids also provide spaces where DIAICs can accumulate within the pavement.

- **DIAIC type:** The studies reviewed were primarily focused on DIAICs used on airfield pavements, and investigation of the chlorides commonly used on highway pavements has been limited. Still, most studies found that DIAIC-related damage varied with DIAIC type.
- **DIAIC concentration:** The Canadian airfields study found that aggregate degradation was highest at DIAIC concentrations of about 1 to 2 percent. The Helsinki University of Technology study found that damage to asphalt mixes was similar at concentrations of 5 percent and 50 percent, which is not inconsistent with the Canadian airfields study. The CDOT study found that emulsification of asphalt binder increased with increasing DIAIC concentration. It is possible that DIAIC concentration has different (and possibly offsetting) effects on different damage mechanisms.
- **Temperature:** The CDOT study found that emulsification of asphalt binder increased with increasing temperature, and was negligible below 104° F. The Helsinki University of Technology study found that PAH compounds were detectable at 104° F, but were significantly more concentrated at 212° F.

TEST METHODS FOR EVALUATING RESISTANCE TO DEICER-INDUCED DAMAGE

As discussed above, it appears that the most likely mechanism for DIAIC-induced damage to HMA pavements is an acceleration of moisture damage in mixes prone to this type of distress. The test for moisture damage susceptibility that is most widely used in the United States is AASHTO T283, also known as the modified Lottman procedure. Unfortunately, this test is not highly effective since it does not consistently and accurately identify HMA systems' level of resistance (or lack thereof) to moisture damage. Additionally, the test results sometimes vary across different laboratories. Furthermore, AASHTO T283 is an expensive and time-consuming procedure. It involves vacuum saturation of three HMA specimens followed by freezing and thawing. The specimens are then tested using the indirect tension (IDT) strength test. The IDT strength of these conditioned specimens is then compared to the strength of unconditioned specimens. The ratio of conditioned strength to unconditioned strength is called the tensile strength ratio (TSR), often expressed as a percentage. Values below 0.70 to 0.80 are generally considered to indicate susceptibility to moisture damage.

In the AAPTP study, the research team developed a modified and simplified version of the AASHTO T283 procedure called the immersion tension (IT) test. This procedure allowed a relatively large number of HMA systems to be quickly evaluated. The IT test does not apply a vacuum saturation process prior to conditioning the specimen. Instead of conditioning the specimen in a freezing cycle, the test conditions the specimens in distilled water or DIAIC solutions at 60° C (140° F) for 4 days, since previous studies showed the combination of DIAICs and high temperatures can lead to HMA damage. The IT test procedure also omits the step of testing the dry specimen, instead focusing on comparing the tensile strengths of specimens conditioned in water with the strengths of those conditioned in DIAIC solution. The IDT strength test is performed on three replicate specimens for each conditioning level using the same procedure as in AASHTO T283. Retained tensile strength/DIAIC treatment (TSR/D) is calculated as the IDT strength after DIAIC conditioning divided by the IDT strength after conditioning in distilled water, expressed as a percentage. The authors recommended that TSR/D values below 80 percent be considered evidence of DIAIC-related damage.

The AAPTP study focused on dense-graded HMA mixes. Testing open-graded friction course (OGFC) mixes using the AASHTO T283 method can be problematic since the material could be damaged during specimen conditioning. Therefore, a modified specimen conditioning procedure proposed by Birgisson et al. (2006) could be adopted. The major modification in this test method is to skip the step of vacuum saturation for the specimens prior to the hot water bath. Since OGFC mixes have air void levels of at least 16 percent, it is possible that the specimens would experience creep or failure during moisture conditioning. In order to eliminate the likelihood of premature specimen failure or damage during conditioning, the specimens were wrapped in 1/8-inch wire mesh. Two clamps held the mesh in place without exerting pressure onto the specimens.

A much simpler and quicker procedure for identifying susceptibility to moisture damage is the boiling test (ASTM D3625). In this test, a small sample of asphalt-coated aggregate is boiled in distilled water for a set period of time. The water is then decanted, and the aggregate is poured out onto filter paper and examined to determine how much of the coating has been stripped from the aggregate. An analysis of data published by Kennedy and Ping indicates that the results of this test relate reasonably well to the results of the modified Lottman test (also known as AASHTO T283) (Kennedy and Ping 1991). A boiling test was used in the Helsinki University of Technology research on DIAIC damage, and it appeared to be more effective than the modified Lottman test at identifying DIAIC-induced damage in HMA samples. The test is well suited to the study of DIAIC damage for several reasons:

- The test can be run in distilled water and any number of DIAIC solutions.
- The test is simple and quick, so it can be run on a large number of specimens. This facilitates a thorough study addressing a large number of factors.
- The test is run at an elevated temperature, which might be necessary to promote DIAIC damage in HMA mixes.
- After the test, the solution can be used for chemical analyses to determine whether PAHs or similar chemicals are present. These presence of these chemicals indicates that deicing compounds have reacted with the asphalt binder to cause HMA damage.

Another test procedure that may be used to evaluate the effect of DIAICs on moisture damage in HMA is nuclear magnetic resonance (NMR) spectroscopy. NMR spectroscopy has been a powerful tool in the structural characterization of chemical compounds for a number of years. It has only recently been used in the characterization of asphalts. Work at the Western Research Institute has demonstrated that solid-state NMR imaging (NMRI) can be used for noninvasive chemical, physical, and morphological characterization of local regions in the interior of intact asphalt samples (Miknis and Netzel 1996). In addition, NMRI can be used to characterize chemical and physical processes noninvasively over time. With respect to DIAICs' effect on moisture damage in HMA, the results from NMRI analysis could be used to measure the effect that the addition of DIAICs has on the penetration of water in asphalt concrete. Moisture damage is one of the major sources of failure in HMA pavements. As reported in the Helsinki University of Technology study, it is expected that mixing DIAICs with water will lower the surface tension of the solution. This should result in greater penetration of the asphalt concrete by the solution and could produce a marked increase in water-induced damage.

Besides contributing to moisture damage in HMA pavements, it is also possible that DIAICs might in some cases accelerate age hardening or interact with compounds produced in asphalt binders during long-term oxidative aging. To evaluate this hypothesis, asphalt binder/sand briquettes could be conditioned using a modified version of the pressure-aging vessel test (AASHTO PP1). The briquettes would be made in accordance with the ADOT job mix formulas for conventional and rubberized asphalt concrete. The briquettes would be completely saturated by immersion in various DIAIC solutions while being held in a vacuum desiccator. Next, the briquettes would be artificially aged in the pressure-aging vessel at 60° C (140° F) in the presence of water for 20 hours. Once the artificial aging of the briquettes is completed, they would be chemically analyzed using Fourier transform infrared (FTIR) analysis to determine whether the conditioning produced any unusual chemical compounds or changed the chemistry of the asphalt in a characteristic way. FTIR analysis and related chemical procedures are discussed in more detail below.

IDENTIFYING DEICER-INDUCED DAMAGE IN HMA

It would be extremely useful if one or more chemical “flags” could be identified that indicate DIAIC-induced damage has occurred in HMA pavements. For example, the results of the Helsinki University of Technology study suggest that PAHs are the result of reactions occurring between DIAICs and asphalt binder, and indicate DIAIC-related damage in HMA pavements. Confirmation of this finding would mean that gas chromatography tests could be used on field samples of airfield pavements to confirm that damage was caused (or accelerated) by DIAIC use. Although the AAPTP study was not able to confirm the presence of PAH molecules, it is possible that the conditioning temperature used in the AAPTP study was not high enough to trigger the chemical interaction. It is possible that other, or perhaps more specific, flags exist. In the asphalt chemistry field, there is significant interest in further basic research geared toward identifying and verifying chemical flags that indicate DIAIC-induced damage in HMA pavements. The primary method for identifying these chemical flags would be FTIR analyses.

Asphalts are composed of a variety of different types of compounds. These include relatively nonpolar compounds like aliphatics and aromatics as well as more polar compounds like carboxylic acids, sulfoxides, ketones, and nitrogen-containing compounds. FTIR analysis can be used to identify and quantify the latter types of compounds (Petersen 1986). To obtain quantitative information on the specific carbonyl compounds (such as carboxylic acids and ketones) in asphalt, a series of infrared spectra that are the result of selective chemical reactions and the evaluation of differential spectra must be recorded. From this series of spectra, sulfoxides, ketones, carboxylic acids, carboxylic acid salts, 2-quinolones, anhydrides, pyrroles, and phenols can be identified and quantified. In addition, the extent of hydrogen bonding can be quantitatively estimated. Note that asphalt is composed of a mixture of mono-, di-, and polyfunctional compounds (Petersen 1986).

SUMMARY

Anecdotal field evidence in Europe, Canada, and the United States suggests that some DIAIC compounds might cause or contribute to the damage of HMA pavements. However, there is a lack of laboratory evidence that DIAIC compounds can cause such damage. This might be because of the limited scope of laboratory testing conducted to date, or it could be because factors critical to DIAIC-related damage have not been included in previous studies. It is also possible that HMA pavements subject to DIAIC use are experiencing other types of damage, such as moisture damage or snowplow damage. This pavement damage may in fact be coincidental to the use of DIAIC compounds, not the result of a cause-and-effect relationship. In moving forward with this project, the technical advisory committee recommended a focus on DIAICs' impacts on Arizona's pavements, since DIAIC-related damage is less well understood and harder to remedy than snowplow damage.

There are several possible mechanisms by which DIAIC compounds might damage HMA pavements. DIAICs may:

- Act to accelerate moisture damage in HMA.
- Interact with the asphalt binder to cause emulsification of the binder.
- Damage aggregates as a result of wet-dry cycling.
- Accelerate age-hardening damage to the binder.

Of these, the most likely cause of damage, and the mechanism focused on by most researchers, is moisture damage. Researchers have suggested that high temperatures—those in the range of 158° F to 212° F—might be necessary in order for DIAICs to damage HMA pavements (Alatyppö and Valtonen 2007, Pan et al. 2008). One study (Alatyppö and Valtonen 2007) suggested that resurfacing HMA pavements that have been exposed to DIAICs is especially damaging to the underlying pavement because of the extremely high temperatures that are produced during paving. Given the proposed mechanisms, factors that might affect DIAIC damage to HMA pavements include DIAIC type, DIAIC concentration, asphalt binder chemistry and grade, use of crumb rubber modified binder, aggregate type, HMA permeability, and temperature.

ADOT most commonly uses potassium chloride and sodium chloride for deicing and anti-icing. The majority of pavement surfaces in Arizona are rubberized open-graded friction courses (OGFC), and the potential for DIAIC-induced damage is higher for this type of mix compared to conventional dense mixes. Since OGFC mixes have a high air void content, it is easier for the DIAIC solution to penetrate into the pavement structure. Therefore, a larger portion of the pavement would be exposed to DIAIC solution as compared to a conventional dense mix. If the surface tension between the DIAIC solution and the asphalt is high, the DIAIC solution could penetrate the thin film of asphalt binder on the aggregate and gradually strip it away. In addition, if a pavement that has been exposed to DIAICs is subjected to overlay, it is possible that the elevated temperature could trigger chemical reactions or between the DIAIC solution and the asphalt binder or emulsification of the binder. However, studies have also indicated that stiffer binders or polymer-modified binders may be better able to resist DIAIC-related damage. As with any pavement, the performance of rubberized OGFC may also be impacted by the aggregate type used. In general, studies have shown that mixes containing siliceous aggregates are more susceptible to moisture damage than those made with caustic aggregates.

In the studies identified in this literature review, a variety of test procedures were used to evaluate DIAIC-induced damage in HMA pavements. Because the primary mechanism of DIAIC-induced damage appears to be moisture damage, many of the test methods used are those normally used to evaluate moisture resistance in asphalt concrete pavements. These include boiling tests and modifications of the AASHTO T283 procedure. Gas chromatography has been used to identify PAHs in HMA pavements that appear to have been damaged by DIAICs; FTIR could be used for the same purpose. It is recommended that ADOT consider using the boiling test as an initial screening tool to evaluate combinations of aggregates, binder types, and mixture structures for moisture damage susceptibility. If the boiling test results show a significant difference before and after the test, the modified AASHTO T283 procedure could be used as a supplementary test to verify the changes in mix mechanical properties.

CHAPTER 3. LABORATORY TESTING

Based on the literature review, the researchers determined that DIAIC-induced damage to HMA mixtures is influenced by aggregate and binder properties, as well as by interactions among these properties. To investigate the extent of the phenomenon in typical ADOT materials and under typical ADOT practices, a laboratory study was undertaken with a full-factorial experimental design.

EXPERIMENTAL DESIGN

Asphalt mixes were prepared using four aggregate sources and two asphalt binder sources selected from those ADOT typically uses in areas that require winter storm maintenance. Throughout this report, the aggregate sources are referred to as CM-0323, CM-0343, CM-2176, and CM-2058, and the binder sources are labeled A and B. Susceptibility to moisture damage was calculated using the boiling test by comparing samples tested in distilled water with samples tested in three chemical solutions. Table 1 shows the experimental matrix. Three DIAICs, magnesium chloride ($MgCl_2$), potassium chloride (KCl), and sodium chloride (NaCl), were used in the study to investigate the effect of DIAICs on the various mixture types. Distilled water was used as the control to simulate the effect of moisture damage alone, without the presence of DIAIC compounds.

MATERIALS

Aggregate Sources

Aggregates from four sources were used to construct the mixes. The aggregates were from ADOT-approved sources that are commonly used in the production of rubberized mixes. Their properties are shown in Table 2. As shown, the general aggregate type in CM-0343 is basalt. The remaining aggregates are alluvial, with chemical compositions that are difficult to predict.

Table 1. Experimental Matrix

Aggregate Source	Binder Source	DIAIC
CM-0323	A	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
	B	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
CM-0343	A	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
	B	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
CM-2176	A	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
	B	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
CM-2058	A	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride
	B	Distilled water
		Magnesium chloride
		Potassium chloride
		Sodium chloride

Table 2. Aggregate Properties

Property	Aggregate Source				ADOT Specification Requirement
	CM-0323	CM-0343	CM-2176	CM-2058	
Mass loss at 100 revolutions (%)	4	4	3	4	9 max.
Mass loss at 500 revolutions (%)	20	15	17	20	40 max.
Sand equivalent value (%)	77	77	82	87	45 min.
Percentage of aggregates with at least two fractured faces (%)	100	100	96	100	85 min.
Flakiness index (%)	17	15	12	16	25 max.
Percentage of carbonates (%)	0.7	1.1	0.8	0.5	30 max.
Combined specific gravity	2.586	2.768	2.637	2.550	2.35–2.85
Corrected combined specific gravity	2.582	2.761	2.632	2.555	--
Combined water absorption (%)	1.04	1.70	1.02	1.65	2.50 max.
Aggregate classification	Alluvial	Basalt	Alluvial	Alluvial	--

Asphalt Binder and Crumb Rubber

Two asphalt-rubber blends were used in this experiment. The blends were prepared by heating a known quantity of asphalt binder PG 58-22 to 400° F and slowly stirring the crumb rubber into the hot asphalt cement. Table 3 shows the percentages of crumb rubber in each blend by weight, and Table 4 shows the rubber gradations in each blend.

Table 3. Asphalt-Rubber Binder Properties

	Blend 1	Blend 2
PG 58-22 binder source	A	B
Percentage crumb rubber by weight (%)	20.0	22.7

Table 4. Crumb Rubber Gradation

Sieve Size	Percentage Passing		ADOT Specification Requirement
	Blend 1	Blend 2	
No. 10	100	100	100%
No. 16	83	77	65–100%
No. 30	44	27	20–100%
No. 50	5	6	0–45%
No. 200	0	0.4	0–5%

Several tests were conducted to evaluate asphalt-rubber binder stability and retention properties. The tests were timed to identify binder properties after four reaction periods, covering a time range designed to represent changes that could occur following completion of field mixing (60 minutes), after a possible job delay (4 hours), and one day after mixing. The test results are presented in Tables 5 and 6.

Table 5. Physical Properties of Asphalt-Rubber Binder (Blend 1)

Test Performed	Minutes of Reaction				ADOT Specification Requirement
	60	120	240	1440	
Rotational viscosity at 350° F (poise)	1700	2000	2300	2200	1500–4000
Penetration at 39.2° F, 200 g, 60 sec (0.1 mm)	29	29	25	30	15 min.
Resilience at 77° F (rebound percentage)	50	49	51	48	20 min.
Softening point (° F)	148.2	150.0	148.5	152.1	130 min.

Table 6. Physical Properties of Asphalt-Rubber Binder (Blend 2)

Test Performed	Minutes of Reaction				ADOT Specification Requirement
	60	135	240	1440	
Rotational viscosity at 350° F (poise)	1600	2500	2800	3100	1500–4000
Penetration at 39.2° F, 200 g, 60 sec (0.1 mm)	19	19	--	24	15 min.
Resilience at 77° F (rebound percentage)	46	51	--	52	20 min.
Softening point (° F)	146.0	146.5	146.5	155.5	130 min.

Mix Design

The asphalt mixtures were designed according to Section 414 of the ADOT Standard Specifications, “Asphaltic Concrete Friction Course (Asphalt-Rubber).” Table 7 shows the mix properties for each aggregate type.

Table 7. Mix Properties

Property	Aggregate Source			
	CM-0323	CM-0343	CM-2176	CM-2058
Design binder content (%)	9.8	9.9	9.5	9.5
Bulk density (pcf)	115.6	130.6	116.1	113.2
Asphalt absorption (%)	0.26	0.61	0.28	0.69

DIAIC Solutions

Three deicer chemical solutions were used to evaluate the moisture susceptibility of the rubberized asphalt mixes: magnesium chloride ($MgCl_2$), potassium chloride (KCl), and sodium chloride (NaCl). All solutions were 20 percent salt solutions by weight and were made with technical-grade salts. Distilled water was used as the control solution.

Test Procedure

Moisture susceptibility was evaluated using the boiling test (ASTM D3625). This test is a rapid procedure for visually observing the loss of adhesion in uncompacted bituminous-coated aggregate mixtures due to the action of boiling water. The procedure involves adding loose HMA to boiling water (or in this case, boiling DIAIC solutions) and bringing the liquid back to boiling after this addition. After 10 minutes, the mixture is allowed to cool while the stripped asphalt is skimmed away. The water is drained, and the wet mixture is placed on a paper towel and allowed to dry. The percentage of the total visible area of aggregate surface that retains its asphalt binder coating is measured.

RESULTS

The results of the boiling test are shown in the Appendix to this report, which includes photographs of the portions of the mixture that were stripped and those that were not stripped. An analysis of variance (shown in Table 8) indicated that at a 95 percent confidence level, the amount of stripping was significantly influenced by all factors and factor interactions (p-values < 0.001).

Table 8. Analysis of Variance of Boiling Test Results

Factor	F-Statistic	p-Value
Aggregate source	1567.31	< 0.001
Binder source	268.66	< 0.001
DIAIC solution	970.15	< 0.001
Aggregate x binder	224.59	< 0.001
Aggregate x solution	144.61	< 0.001
Binder x solution	24.33	< 0.001
Aggregate x binder x solution	79.67	< 0.001

The percentage of stripped material differed significantly across the different aggregate types (see Figure 2). Source CM-0323 was significantly more susceptible to moisture damage than the other three sources, with an average of 65.6 percent of the aggregate stripped. Source CM-2176 had the best results, with an average of 10.3 percent stripped.

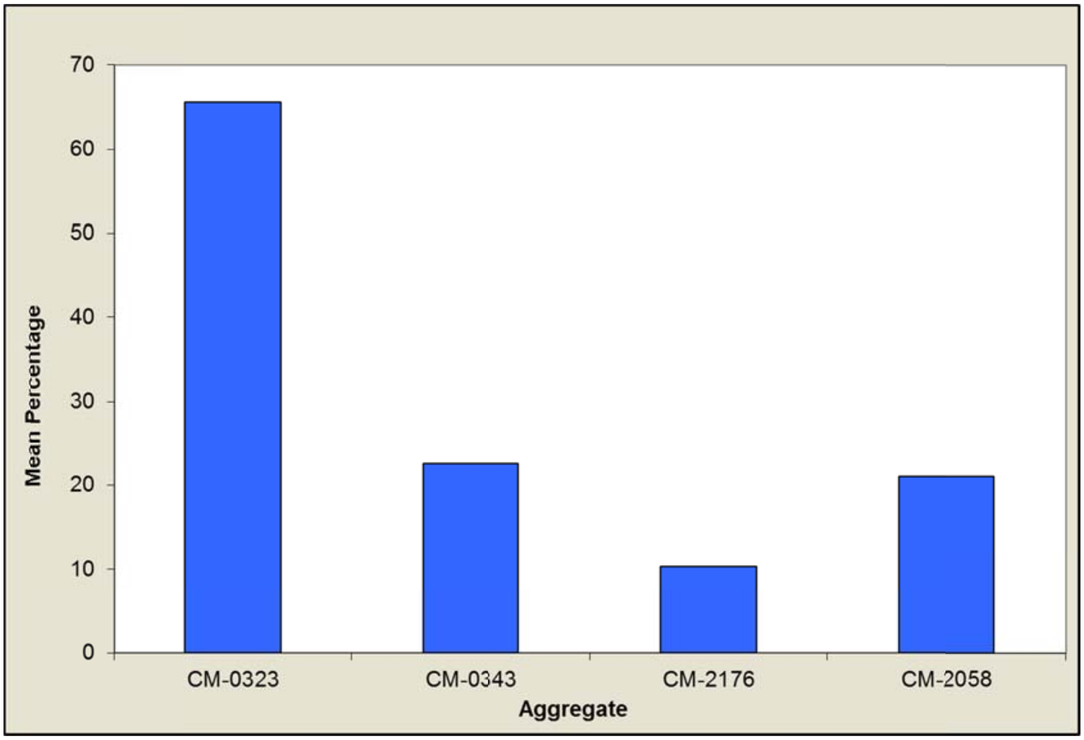
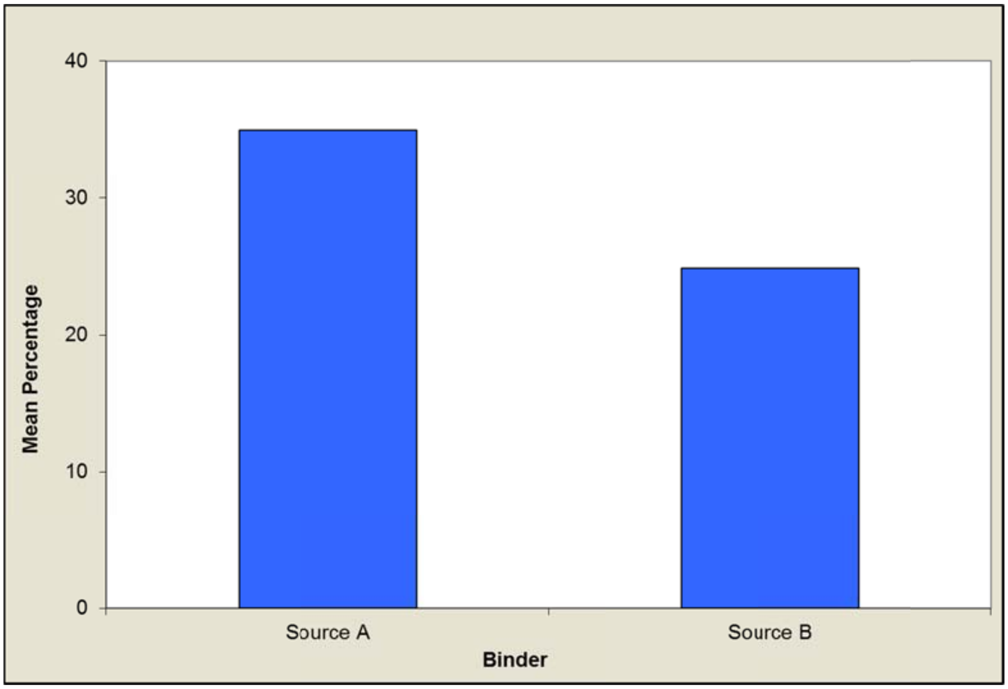


Figure 2. Percentage of Material Stripped by Aggregate Source

The analysis also showed that mixtures containing the binder blend from Source A had significantly higher moisture susceptibility (on average 10.1 percent higher than mixtures containing the binder blend from Source B, as shown in Figure 3). This was expected, because in general the Source A blend had lower viscosity than the Source B blend. The lower viscosity can be attributed to the lower crumb rubber content; the PG 58-22 binder made with the Source A blend contained 20 percent crumb rubber, while the PG 58-22 binder made with the Source B blend contained 22.7 percent crumb rubber. As reported in the literature, stiffer binders and polymer-modified binders are more resistant to DIAIC-related damage.



Note: The Source A binder contained 20 percent crumb rubber; the Source B binder contained 22.7 percent crumb rubber.

Figure 3. Percentage of Material Stripped by Binder Source

The potassium chloride and sodium chloride solutions caused significantly more moisture damage to the rubberized asphalt mixtures than the other two solutions (see Figure 4). The least amount of stripping was obtained with the magnesium chloride solution, which (unexpectedly) caused less damage than the control solution of distilled water.

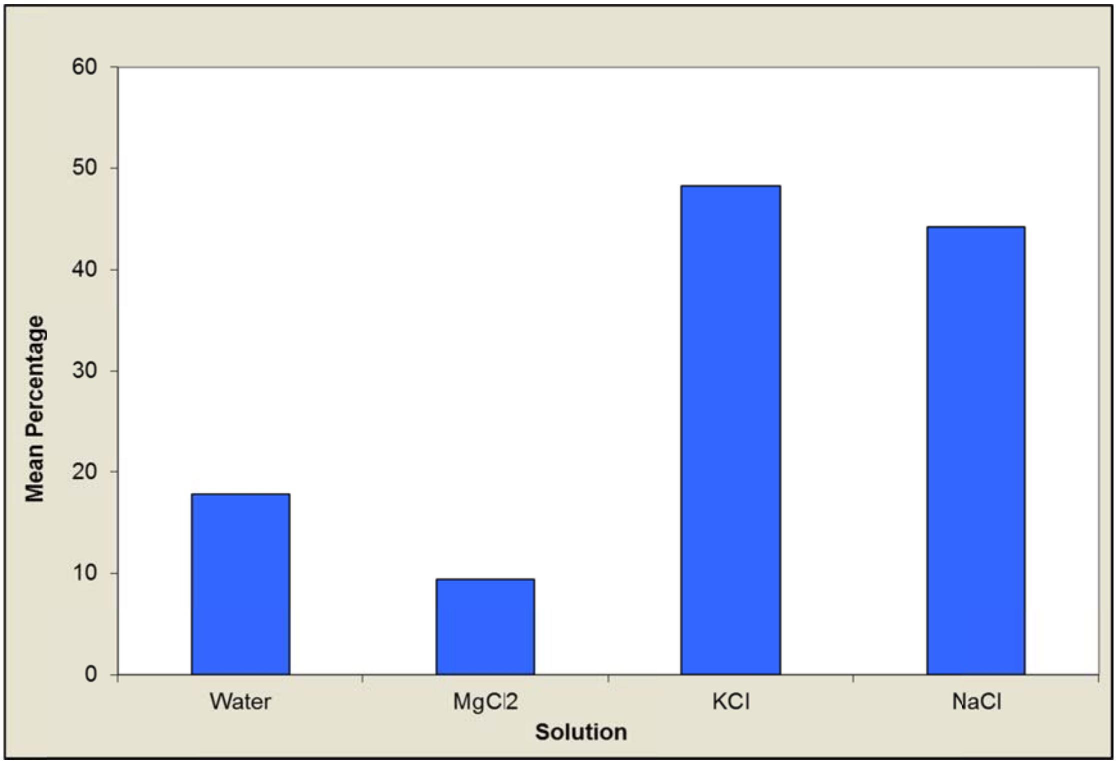


Figure 4. Percentage of Material Stripped by Type of DIAIC

Figures 5 through 7 illustrate the interactions among the different factors. As indicated by the analysis of variance discussed earlier, the interaction terms are highly significant. This means that the differences in the levels of one factor depend on the levels of the other factors.

For example, the percentage of stripped material varied for a particular binder blend depending on the aggregate source used (see Figure 5). Only the CM-2058 aggregate did not show a significant difference in results across binder blends. The CM-0323 aggregate showed a particularly high percentage of stripped material regardless of the binder blend used. Regarding the interaction of aggregate type and DIAIC solution, the CM-2176 aggregate was the least influenced by the type of DIAIC solution (see Figure 6). On the other hand, the percentage of stripped material varied greatly with the solution type when the CM-0323 aggregate was tested.

The interaction between binder blend and DIAIC solution type was also analyzed (see Figure 7). Both binder blends showed a large variation in the percentage of stripped material when different DIAIC solutions were used. However, two trends clearly stand out. Regardless of the binder blend, a lower percentage of stripped material was observed when water and magnesium chloride solutions were used than when potassium chloride and sodium chloride solutions were used.

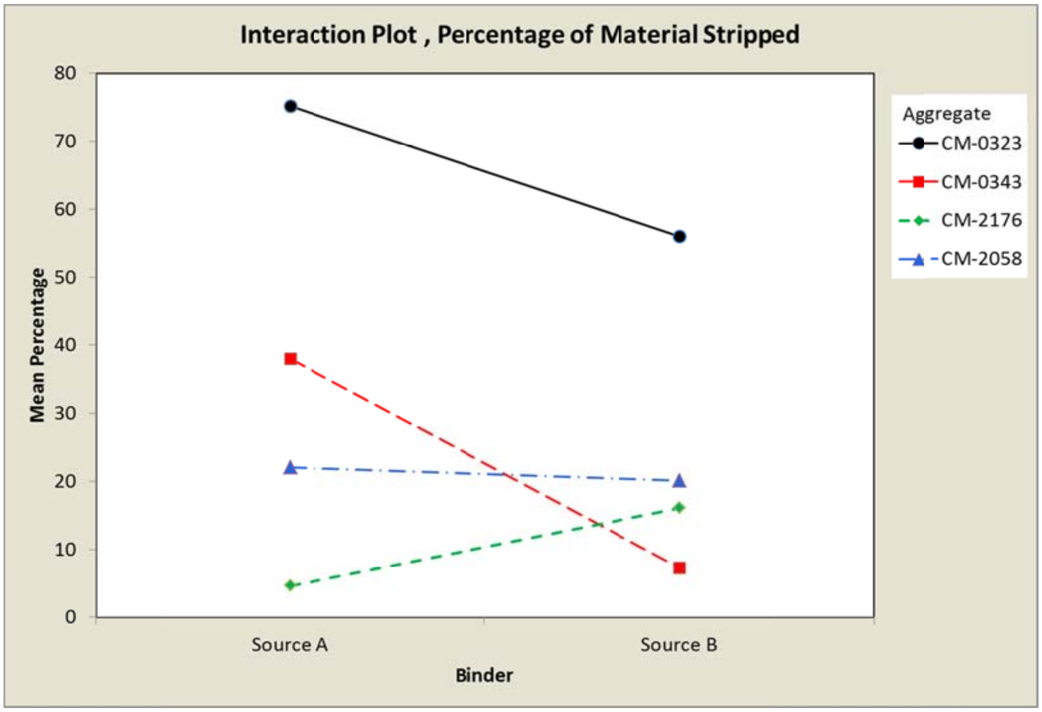


Figure 5. Interaction Between Aggregate Source and Binder Blend

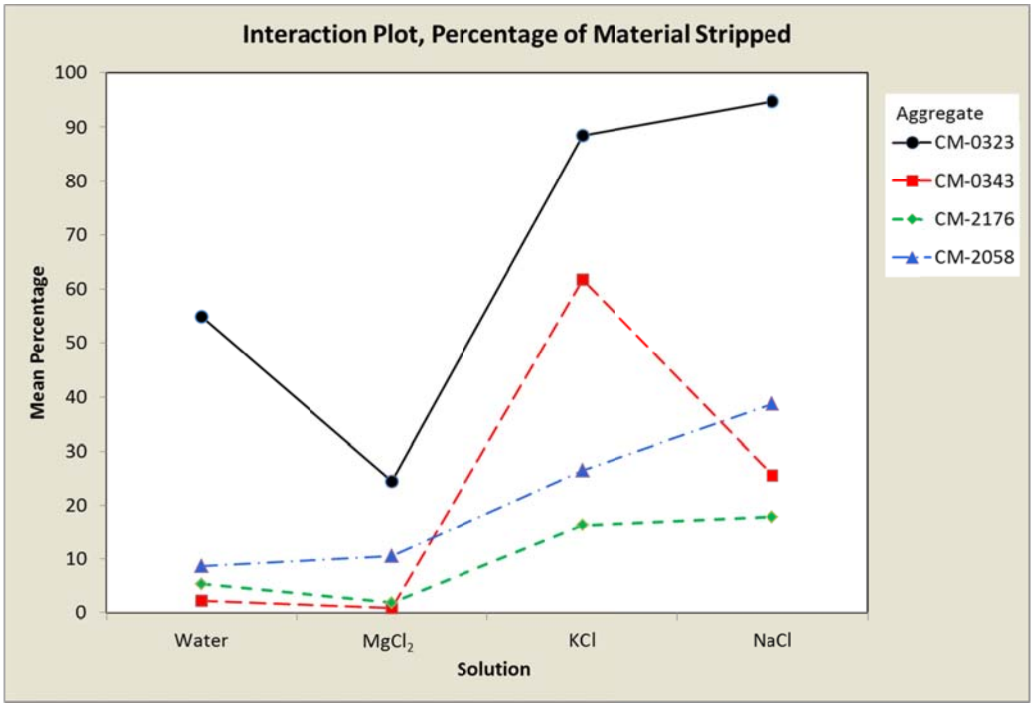


Figure 6. Interaction Between Aggregate Source and Type of DIAIC Solution

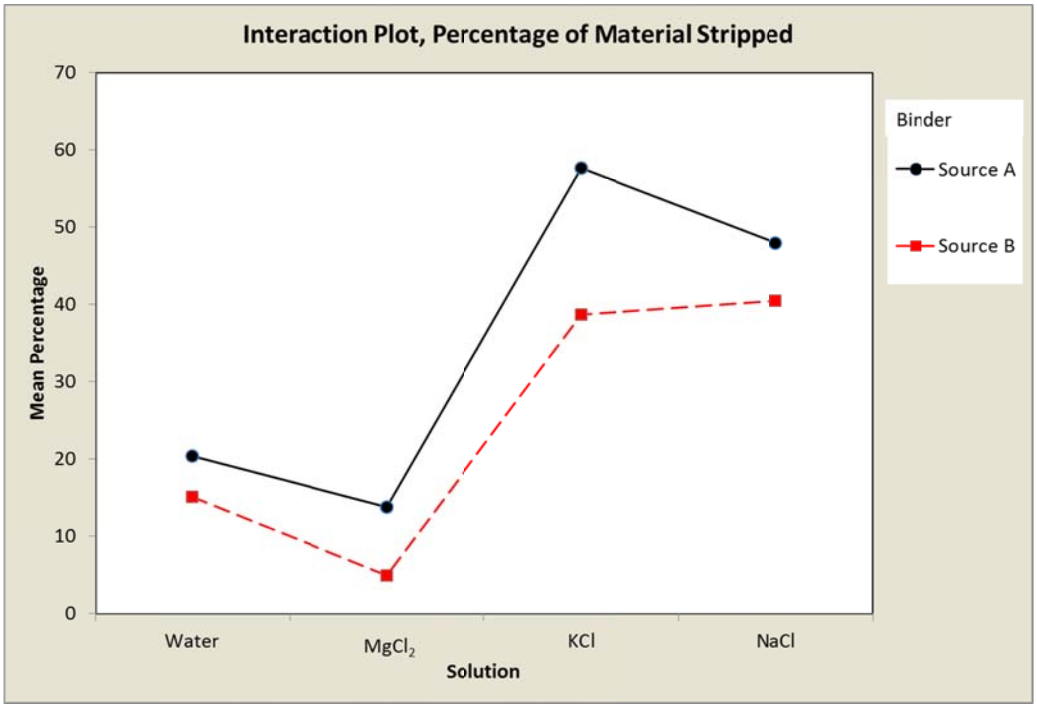


Figure 7. Interaction Between Binder Blend and Type of DIAIC Solution

To examine this effect more closely, Figures 8 and 9 present the data on percentage of stripped material as three-dimensional diagrams.

Figure 8 shows the percentages of stripped material for four mix combinations (aggregates CM-0343 and CM-0323 blended with Source A and B binders) and the four DIAIC solutions. The mixes made with aggregate CM-0323 demonstrated the highest moisture damage potential. Stripping levels were especially high when the mixes were conditioned in the potassium chloride and sodium chloride solutions (an average of 91.7 percent stripped material). Stripping decreased when CM-0323 mixes were conditioned in the magnesium chloride solution or in water. In addition, the mixes containing CM-0323 aggregate exhibited a high level of stripping not only when they were conditioned with potassium and sodium chloride solutions, but also when they were conditioned with water. This reveals that these mixes also had high moisture susceptibility. As mentioned earlier, mixes blended with the Source B binder exhibited less stripping. For CM-0343 mixes, stripping levels were very high regardless of which binder was used, which might imply that the CM-0343 aggregate is more hydrophilic than the other aggregates used in this study. On the other hand, mixes composed of CM-0343 aggregate showed lower percentages of stripping than CM-0323 mixes in general. The exceptions were when the Source A binder was mixed with CM-0343 and conditioned in the potassium chloride and sodium chloride solutions (percentages of stripped material were 98.1 percent and 50.3 percent, respectively). This also shows that using a stiffer binder (the Source B binder in this experiment) can help decrease stripping levels.

Finally, surprisingly, stripping levels were higher when the mixes were conditioned in water than when they were conditioned in the magnesium chloride solution.

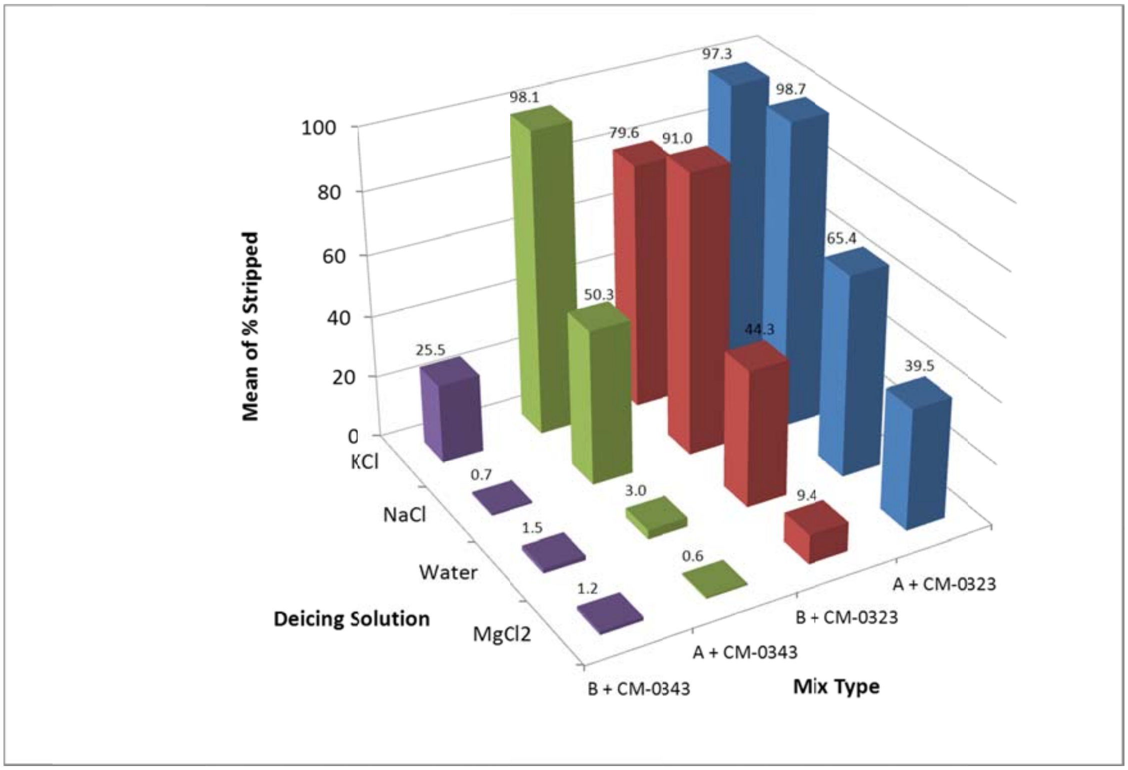


Figure 8. Percentage of Material Stripped by DIAIC Type (CM-0343 and CM-0323 Mixes)

Figure 9 shows the percentages of stripped material for the remaining four mix combinations (aggregates CM-2176 and CM-2058 blended with Source A and B binders) and the four DIAIC solutions. Stripping levels were much lower for these mixes than for the four mixes shown in Figure 8. For these four mixes, the highest stripping level was 39.3 percent; this occurred when the mix made with the CM-2058 aggregate and the Source B binder blend was conditioned in the sodium chloride solution. The lowest stripping level was 1.7 percent, yielded by the combination of CM-2176 aggregate and Source A binder conditioned in the magnesium chloride solution. As in Figure 8, two groups were still distinct from each other: Mixes conditioned in the potassium and sodium chloride solutions had higher stripping levels (an average of 25 percent stripped material) than mixes conditioned in the water and magnesium chloride solutions (an average of 6.6 percent stripped material). The benefit of using a stiffer binder was not significant for these four mixes.

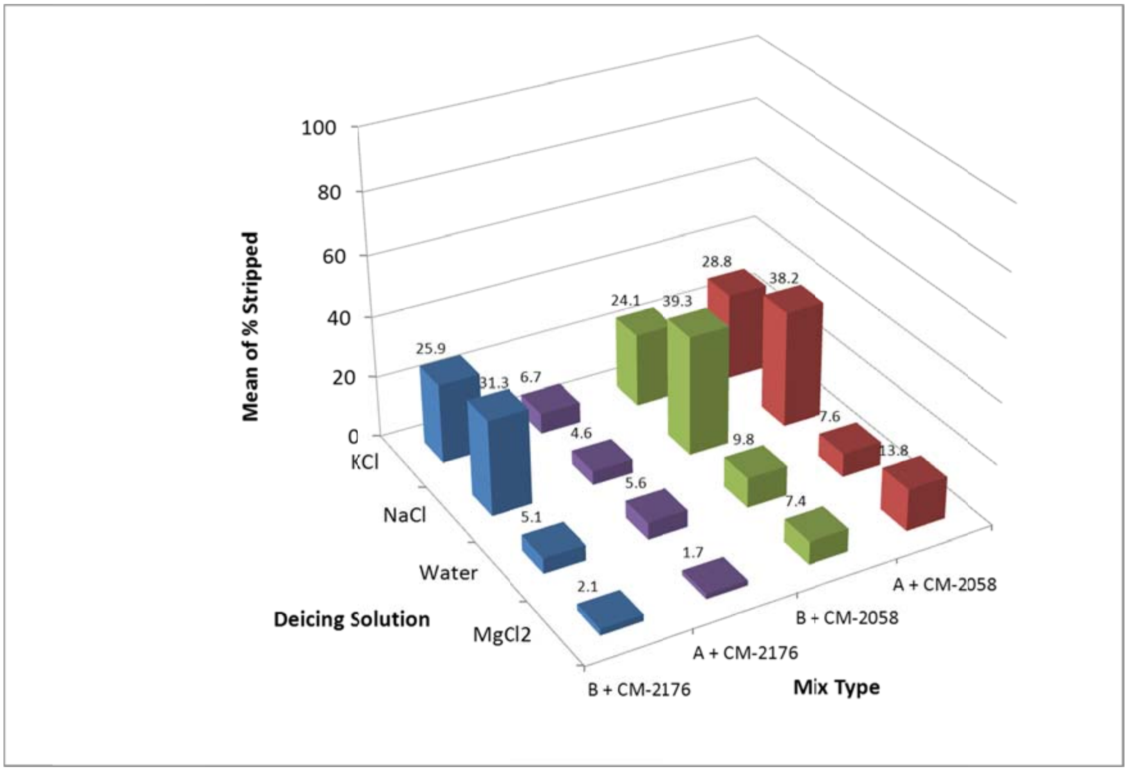


Figure 9. Percentage of Material Stripped by DIAIC Type (CM-2176 and CM-2058 Mixes)

Stripping levels across all mix types and DIAIC solutions are shown in Table 9. For the purpose of comparison, the percentage of stripped material observed in the DIAIC solutions was normalized with respect to the percentage of stripped material observed in water. A value greater than 1 indicates that the combination of that mix type and DIAIC solution yielded an increased level of moisture damage compared with conditioning that mix in water. Conversely, a value less than 1 indicates that the combination of mix type and DIAIC solution yielded less moisture damage than conditioning that mix in water did. Although the overall analysis of variance showed that stripping levels were highly affected by all factors (binder type, aggregate type, and DIAIC type), the most severe stripping was observed when the sodium chloride and potassium chloride solutions were combined with the CM-0343 and CM-0323 mixes and the Source A binder. Using magnesium chloride as a DIAIC solution appeared to yield the least moisture damage, except when it was used with the Source B binder blended with the CM-2176 aggregate. Note that even in this case, stripping levels were still much lower than when sodium and potassium chloride solutions were used.

Table 9. Level of Stripping Caused by DIAIC Solutions vs. Water

Mix Type (Binder + Aggregate Source)	Solution			
	Water	$MgCl_2$	NaCl	KCl
Source A + CM-0323	1	0.60	1.51	1.49
Source B + CM-0323	1	0.29	0.81	1.20
Source A + CM-0343	1	0.21	2.05	1.80
Source B + CM-0343	1	0.41	6.19	5.13
Source A + CM-2058	1	0.18	16.75	32.70
Source B + CM-2058	1	0.75	4.01	2.45
Source A + CM-2176	1	0.77	0.47	17.00
Source B + CM-2176	1	1.81	5.02	3.78

CHAPTER 4. SUMMARY AND RECOMMENDATIONS

SUMMARY

The literature review and the results of the laboratory experiment conducted for this project reflect both the complexity and the challenges of evaluating the effects of various DIAICs on HMA pavements. While the literature is inconclusive regarding DIAICs' impact on skid resistance, DIAICs have been shown to affect pavement structure and to cause a loss of strength in HMA pavements. Most studies on DIAICs' effects on HMA pavement have focused on formate- and acetate-based deicers used at airports, finding that these chemicals have significantly damaged the pavements by causing emulsification of the asphalt or accelerating moisture damage. The hypothesized damage mechanism of these deicers is a combination of chemical reactions, emulsifications, and distillations as well as the generation of additional stress inside the HMA pavements.

However, little is known about the effects of chloride-based deicers, which are widely used in ADOT's winter maintenance efforts on HMA pavements. Based on the results of the laboratory experiments conducted for this project on the interactions between DIAIC solutions and HMA pavement, all tested factors (binder type, aggregate type, and DIAIC solution type) and the interactions of these factors significantly affect the extent of DIAIC-related moisture damage. The most significant factor in these experiments was aggregate type, which presented differences of up to 55 percent in stripping levels as measured with the boiling test. However, the most severe stripping was observed when sodium chloride and potassium chloride solutions were used to condition mixes made with CM-0323 and CM-0343 aggregates and Source A binder. The Source A binder has lower viscosity than the Source B binder, and this result is consistent with the literature. The CM-0323 and CM-0343 aggregates are alluvial and basalt sources, respectively. For the CM-0323 mix, because of its high moisture susceptibility, even when a stiffer binder with a higher percentage of crumb rubber was used, the tests still showed very high stripping levels.

Based on these test results, the following mix types and DIAIC solutions are recommended for areas where deicing chemicals will be used on rubberized asphalt pavements:

- **DIAIC solution**: Magnesium chloride is recommended as the best DIAIC solution for use on rubberized asphalt pavement. Potassium chloride and sodium chloride are not recommended, as both increase the potential for moisture damage.

- **Aggregate source:** Source CM-2176 aggregate is recommended for use in the rubberized asphalt mix. CM-0323 aggregate is not recommended unless it is blended with high-viscosity binder; in addition, magnesium chloride should be the only DIAIC used with CM-0323.

- **Binder type:** Stiffer binder is recommended, as it apparently helps mitigate moisture damage.

Table 10 summarizes the best and the worst combinations of mix types and DIAICs.

Table 10. Best and Worst Combinations of Mix Types and DIAICs

Mix Type (Binder + Aggregate Source)	DIAIC Solution		
	$MgCl_2$	NaCl	KCl
Source A + CM-0323	✗	✗✗	✗✗
Source B + CM-0323	✓✓	✗✗	✗✗
Source A + CM-0343	✓✓	✗	✗✗
Source B + CM-0343	✓✓	✓✓	✓
Source A + CM-2058	✓✓	✗	✓
Source B + CM-2058	✓✓	✗	✓
Source A + CM-2176	✓✓	✓✓	✓✓
Source B + CM-2176	✓✓	✗	✓

✓✓ Highly recommended (0–15% stripping)
✓ Recommended (15–30% stripping)
✗ Avoid (31–60% stripping)
✗✗ Definitely avoid (61–100% stripping)

RECOMMENDATIONS

Because of the complexity of the interactions among DIAICs, asphalt binder, and aggregate and the lack of literature on the effect of chloride-based deicers on rubberized HMA pavements, the research team suggests conducting the following experiments to obtain more detail on the interactions among the factors.

Experiment 1: Evaluate the interactions between DIAIC solutions and ADOT-approved crumb rubber modified binders using the boiling test (ASTM D3625). This experiment should test several DIAIC solution concentrations, ranging from 1 percent to 10 percent. The proposed experiment design is presented in Table 11. These tests would verify the existence of chemical interactions between DIAIC solutions and ADOT crumb rubber modified binders. The tests would also clarify the results of the experiments conducted during this project, which showed that all factors examined were significant.

Experiment 2: From the results of Experiment 1, combinations of binders and DIAICs that create a high potential for moisture damage should be identified. For Experiment 2, selected aggregates should be incorporated as a third factor for testing with these identified combinations. The selected aggregates should be tested prior to mixing with the binders to determine their chemical compositions. The aggregate–binder mixes should be tested as loose mixes using the boiling test, or through modified immersion tension testing as proposed in the AAPTP study (Advanced Asphalt Technologies 2009), using the modified specimen conditioning procedure for OGFC mixes proposed by Birgisson et al. (2006).

Table 11. Proposed Experiment Design for Testing Binder–DIAIC Interaction

Binder Type	DIAIC Solution	Concentration	Binder Type	DIAIC Solution	Concentration
Source A	Water	N/A	Source B	Water	N/A
	NaCl	1%		NaCl	1%
		2%			2%
		5%			5%
		10%			10%
	KCl	1%		KCl	1%
		2%			2%
		5%			5%
		10%			10%
	$MgCl_2$	1%		$MgCl_2$	1%
		2%			2%
		5%			5%
		10%			10%

The results of these follow-up experiments could be used to make more detailed recommendations to ADOT as to the best combination of binder type, aggregate classification, and DIAIC solution for ADOT's winter maintenance program.

REFERENCES

Advanced Asphalt Technologies. 2009. *Effect of Deicing Chemicals on HMA Airfield Pavements*. Project 05-03, Final Report. Auburn, Alabama: Airfield Asphalt Pavement Technology Program, Auburn University.

Alatyppö, V., and J. Valtonen. 2007. "Experiences on the Effects of De-Icing Chemicals on Bituminous Airfield Runways in Finland." Presented at the Federal Aviation Administration Worldwide Airport Technology Transfer Conference, Atlantic City, NJ, April 2007.

Birgisson, B., R. Roque, A. Varadhan, T. Thai, and L. Jaiswal. 2006. *Evaluation of Thick Open Graded and Bonded Friction Courses for Florida.* Gainesville: University of Florida.

Curtis, C. W., R. L. Terrel, L. M. Perry, S. Al-Swailm, and C. J. Braanan. 1991. "Importance of Asphalt-Aggregate Interactions in Adhesion." *Journal of the Association of Asphalt Paving Technologists* 60: 476–532.

Farha, M. H., Y. Hassan, A. O. Abd El Halim, A. G. Razaqpur, A. El-Desouky, and A. Mostafa. 2002. "Effects of New Deicing Alternatives on Airfield Asphalt Concrete Pavements." Presented at the Federal Aviation Administration Technology Transfer Conference, Atlantic City, NJ, 2002.

Hassan, Y., A. O. Abd El Halim, A. G. Razaqpur, and M. Farha. 2001. "Laboratory Investigation of Effect of Deicing Chemicals on Airfield Asphalt Concrete Pavement Materials." *Proceedings of 2nd International Conference on Engineering Materials*, Vol. 1: 299–308.

Kennedy, T. W., and W. V. Ping. 1991. "An Evaluation of Effectiveness of Antistripping Additives in Protecting Asphalt Mixtures from Moisture Damage." *Journal of the Association of Asphalt Paving Technologists* 60: 230–263.

Kim, O., C. A. Bell, and R. G. Hicks. 1985. "The Effect of Moisture on the Performance of Asphalt Mixtures." *Special Technical Publication 899: Evaluation and Prevention of Water Damage to Asphalt Pavement Materials:* 51–72. West Conshohocken, PA: American Society for Testing and Materials.

Majidzadeh, K., and F. N. Brovold. 1968. *State of the Art: Effect of Water on Bitumen-Aggregate Mixtures*. Highway Research Board Special Report 98. Washington, D.C.: Highway Research Board.

Martinez, F. C., and R. A. Poecker. 2006. *Evaluation of Deicer Applications on Open Graded Pavements.* Salem: Oregon Department of Transportation.

Miknis, F. P., and D. A. Netzel. 1996. "Use of Nuclear Magnetic Resonance Imaging to Study Asphalt." *Preprints of Papers, American Chemical Society, Division of Fuel Chemistry* 41(4): 1327–1331.

Pan, T. S., X. He, and X. Shi. 2008. “Laboratory Investigation of Acetate-Based Deicing/Anti-Icing Agents Deteriorating Airfield Asphalt Concrete.” *Journal of the Association of Asphalt Paving Technologists* 77: 773–794.

Thelen, E. 1958. “Surface Energy and Adhesion Properties in Asphalt-Aggregate Systems.” *Highway Research Board Bulletin* 192: 63–74.

Tunnicliff, D. G., and R. E. Root. 1982. “Antistripping Additives in Asphalt Concrete—State-of-the-Art 1981.” *Proceedings of the Association of Asphalt Paving Technologists Technical Sessions* 53: 265–293.

APPENDIX: BOILING TEST RESULTS

This appendix presents the results of the boiling test (ASTM 3625) laboratory experiments. Researchers conducted the test on 32 combinations of aggregates, binders, and DIAICs (see Table 1 for the experimental matrix). For each combination, the test was replicated twice with different samples.

CM-0323 Aggregate Source A Binder Distilled Water

Replicate 1—63.7% Stripped **Replicate 2—67.1% Stripped**

CM-0323 Aggregate Source A Binder Magnesium Chloride

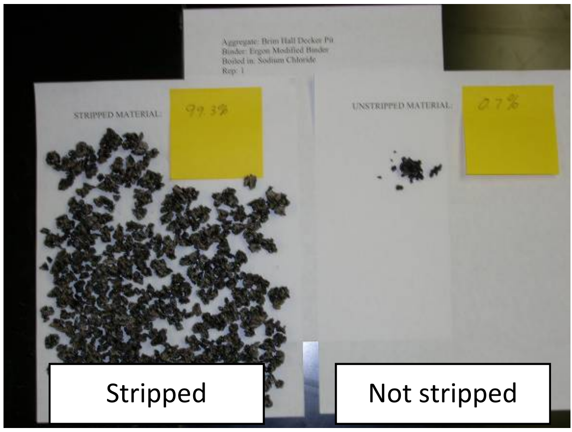
Replicate 1—39.4% Stripped **Replicate 2—39.5% Stripped**

CM-0323 Aggregate Source A Binder Potassium Chloride

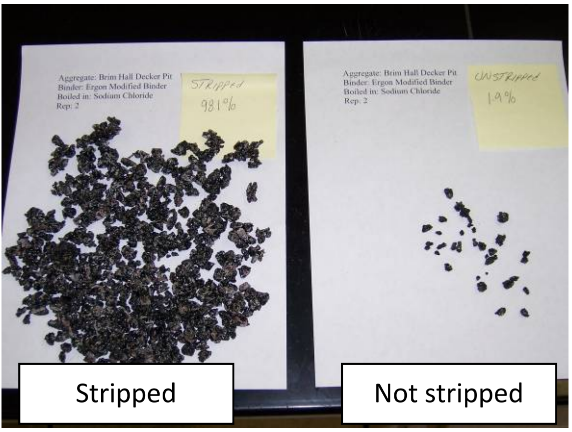
Replicate 1—96.9% Stripped

Replicate 2—97.7% Stripped

CM-0323 Aggregate Source A Binder Sodium Chloride



Replicate 1—99.3% Stripped



Replicate 2—98.1% Stripped

CM-0323 Aggregate Source B Binder Distilled Water

Replicate 1—45.2% Stripped

Replicate 2—43.4% Stripped

CM-0323 Aggregate Source B Binder Magnesium Chloride

Replicate 1—4.6% Stripped

Replicate 2—14.1% Stripped

CM-0323 Aggregate Source B Binder Potassium Chloride

Replicate 1—80.2% Stripped

Replicate 2—78.9% Stripped

CM-0323 Aggregate Source B Binder Sodium Chloride

Replicate 1—96.1% Stripped

Replicate 2—85.8% Stripped

CM-0343 Aggregate Source A Binder Distilled Water

Replicate 1—3.6% Stripped

Replicate 2—2.4% Stripped

CM-0343 Aggregate Source A Binder Magnesium Chloride

Replicate 1—0.2% Stripped

Replicate 2—0.9% Stripped

CM-0343 Aggregate Source A Binder Potassium Chloride

Replicate 1—98.7% Stripped

Replicate 2—97.5% Stripped

CM-0343 Aggregate Source A Binder Sodium Chloride

Replicate 1—49.1% Stripped

Replicate 2—51.4% Stripped

CM-0343 Aggregate Source B Binder Distilled Water

Replicate 1—2.1% Stripped

Replicate 2—0.9% Stripped

CM-0343 Aggregate Source B Binder Magnesium Chloride

Replicate 1—1.2% Stripped

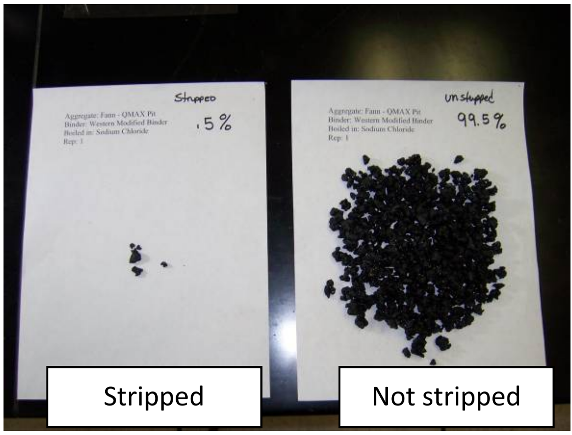
Replicate 2—1.1% Stripped

CM-0343 Aggregate Source B Binder Potassium Chloride

Replicate 1—25.5% Stripped

Replicate 2—25.5% Stripped

CM-0343 Aggregate Source B Binder Sodium Chloride



Replicate 1—0.5% Stripped

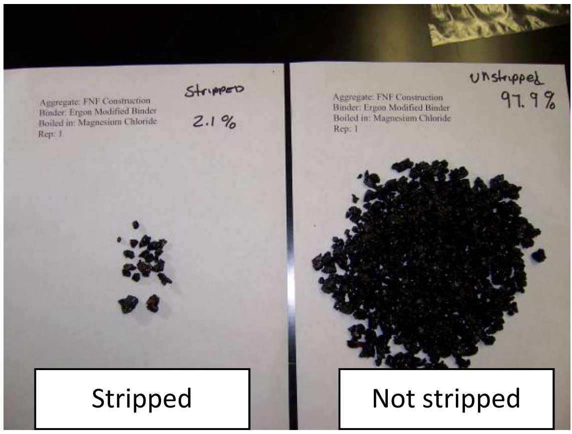
Replicate 2—0.9% Stripped

CM-2176 Aggregate Source A Binder Distilled Water

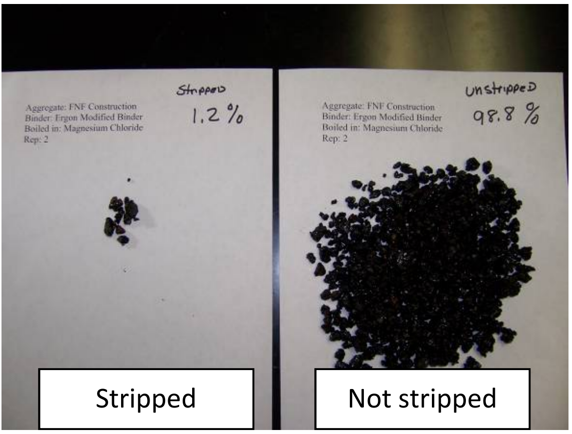
Replicate 1—8.8% Stripped

Replicate 2—2.4% Stripped

CM-2176 Aggregate Source A Binder Magnesium Chloride



Replicate 1—2.1% Stripped



Replicate 2—1.2% Stripped

CM-2176 Aggregate Source A Binder Potassium Chloride

Replicate 1—6.8% Stripped

Replicate 2—6.6% Stripped

CM-2176 Aggregate Source A Binder Sodium Chloride

Replicate 1—6.3% Stripped

Replicate 2—2.8% Stripped

CM-2176 Aggregate Source B Binder Distilled Water

Replicate 1—5.7% Stripped

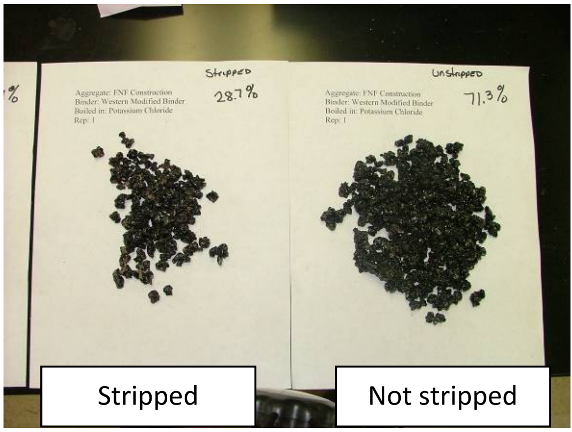
Replicate 2—4.4% Stripped

CM-2176 Aggregate Source B Binder Magnesium Chloride

Replicate 1—2.4% Stripped

Replicate 2—1.7% Stripped

CM-2176 Aggregate Source B Binder Potassium Chloride



Replicate 1—28.7% Stripped

Replicate 2—23.1% Stripped

CM-2176 Aggregate Source B Binder Sodium Chloride

Replicate 1—30.0% Stripped

Replicate 2—32.5% Stripped

CM-2058 Aggregate Source A Binder Distilled Water

Replicate 1—6.5% Stripped

Replicate 2—8.7% Stripped

CM-2058 Aggregate Source A Binder Magnesium Chloride

Replicate 1—13.1% Stripped

Replicate 2—14.4% Stripped

CM-2058 Aggregate Source A Binder Potassium Chloride

Replicate 1—27.4% Stripped

Replicate 2—30.1% Stripped

CM-2058 Aggregate Source A Binder Sodium Chloride

Replicate 1—36.6% Stripped

Replicate 2—39.7% Stripped

CM-2058 Aggregate Source B Binder Distilled Water

Replicate 1—7.2% Stripped

Replicate 2—12.4% Stripped

CM-2058 Aggregate Source B Binder Magnesium Chloride

Replicate 1—6.8% Stripped

Replicate 2—7.9% Stripped

CM-2058 Aggregate Source B Binder Potassium Chloride

Replicate 1—22.0% Stripped

Replicate 2—26.1% Stripped

CM-2058 Aggregate Source B Binder Sodium Chloride

Replicate 1—40.0% Stripped

Replicate 2—38.5% Stripped