

Pavement Winter Operations in Cold Regions

FINAL PROJECT REPORT

by

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University of Idaho**

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16. Abstract Deicing and anti-icing chemicals are both used to improve the mobility of motorists in cold climates. Deicers are applied to melt and break bonded snow and ice. Anti-icers are proactively applied before ice formation to prevent and weaken the bond between the pavement surface and ice. This study evaluated a laboratory testing protocol to examine the performance of different deicing and anti-icing materials under different conditions for efficient winter maintenance operations. For this purpose, this study used three deicers—liquid calcium chloride (CaCl ₂), liquid potassium (K), and granular sodium acetate (NaCl) (i.e., D1, D2, and D3)—and two anti-icers—magnesium chloride (MgCl ₂) with two different inhibitors (i.e., A1 and A2). The proposed laboratory evaluation protocol included three tests: a friction test, an accelerated loading test, and a debonding test. The results demonstrated that the following: 1) All test products were effective at melting the ice and weakening the bond between the pavement surface and ice. 2) Better performance of various products was obtained at a higher application rates. 3) Various chemicals had comparable friction performance. 4) The accelerated loading test with a three-wheel polishing device indicated that all test products were effective on both asphalt and concrete surfaces; however, deicers D2 and D3 had better performances than the other products. 5) A new debonding test was used to evaluate the effectiveness of deicers/anti-icers at weakening the bond between the ice and test surfaces, and the test chemicals were found to reduce the shear force required to break the bond between the ice and test surfaces. On the basis of the results of this study, the proposed three testing protocols combined can provide a comprehensive assessment of the performance of various products under different environmental and operational conditions for efficient winter maintenance operations.			
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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
<small>*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)</small>				

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LIST OF ABBREVIATIONS

BPT	British Pendulum Tester
CaCl ₂	Calcium chloride
CMA	Magnesium acetate
DFT	Dynamic friction tester
FHWA	Federal Highway Administration
GLM	Gallons per lane-mile
KAc	Potassium acetate
MgCl ₂	Magnesium chloride
NaCl	Sodium chloride
PCC	Portland cement concrete
SHRP	Strategic Roads Research Program
TWPD	Three-wheel polisher device

EXECUTIVE SUMMARY

An executive summary is needed here.

CHAPTER 1. INTRODUCTION

1.1. Research Goal

Transportation agencies use various winter maintenance operations and techniques to improve road safety. These techniques include the application of deicing and anti-icing chemicals combined with snow removal. Anti-icing is applied before ice formation to prevent and weaken the bond between the pavement surface and ice, while deicers are applied to melt and break ice that has formed. The application of anti-icing has several advantages over deicing operations, including less cost and less effort to remove the snow and fewer negative impacts on the environment. The selection of the proper types of both deicing and anti-icing materials, as well as their application rates, is necessary for optimal performance. A lack of test methods used to evaluate the effectiveness of the different materials and application rates limits viable options for effective winter maintenance operations.

This study aimed to evaluate a new laboratory testing protocol for examining the performance of various deicing and anti-icing materials under different conditions for efficient winter maintenance operations. There were two main objectives for this study:

- Develop and evaluate a new laboratory testing protocol that can be used to examine the effectiveness of various deicing and anti-icing chemicals under conditions similar to those in the field.
- Develop guidelines and recommendations for the selection of anti-icing and deicing materials and their proper application rates.

The outcome of this study will assist transportation agencies in making informed decisions that lead to efficient winter maintenance operations.

1.2. Research Background and Problem Statement

Deicing and anti-icing chemicals are both used to improve the mobility of motorists in cold climates. Deicers are applied to melt and break already bonded snow and ice (FHWA, 1996). Several deicers are used for this purpose, including sodium chloride, magnesium chloride, calcium chloride, and potassium acetate. On the other hand, anti-icing is proactively applied before ice formation to prevent and weaken the bond between the pavement surface and ice. The above-mentioned deicing chemicals can be used for both anti-icing and pre-treatments (FHWA, 1996).

The effectiveness of deicing applications and anti-icing treatments depends on several factors, including chemical product type, application rate, and pavement type. An inappropriate application rate for anti-icing chemicals may reduce tire-pavement friction in dry conditions. This study focused on chemicals used in deicing and anti-icing treatments in the Pacific Northwest. New test methods were utilized to study and evaluate the effectiveness of various deicing and anti-icing chemicals with the goal of developing guidelines and recommendations for determining the proper chemical type and application rate for effective applications.

1.3. Research Approach

The objectives of the proposed project were achieved by conducting the research tasks discussed below.

1.3.1. Task 1. Literature Review

Under this task, the researchers reviewed and collected pertinent information related to the research subject, including

- Conventional and new chemical products used in deicing and anti-icing applications
- Recommended application rates for various deicing and anti-icing treatments
- The effects of deicing and anti-icing treatments on pavement friction
- Test methods used to evaluate the effectiveness of deicing and anti-icing chemicals.

1.3.2. Task 2. Laboratory Investigation

Under this task, the research team conducted laboratory testing to evaluate the frictional characteristics of various chemical products at different applications rates. The two pavement surfaces examined were asphalt and concrete surfaces. The research team used a portable, three-wheel polisher device (TWPD) along with a dynamic friction tester (DFT) to measure the frictional characteristics of test pavement surfaces before and after the application of selected deicers and anti-icers. Friction was measured in both dry and wet conditions. The research team prepared test slabs (20 in, x 20 in, x 2 in, thick) for the application of anti-icers and snow/ice. Figure 1.1 shows the three-wheel polishing device that was used in laboratory testing. This device was used to simulate the effects of traffic on pavements covered with snow/ice. The three-wheel polishing device consisted of three pneumatic rubber wheels attached to a turntable that rotated over the test substrates. A steel scraper blade was attached to the assembly to simulate snow removal in the laboratory. This method was recently used at the University of Idaho to examine the deterioration of pavement markings caused by snow removal and showed great

success (Mohammed et al., 2019). In that study, the research team moved the portable three-wheel polisher outdoors to conduct the accelerated loading in typical winter conditions in Idaho.

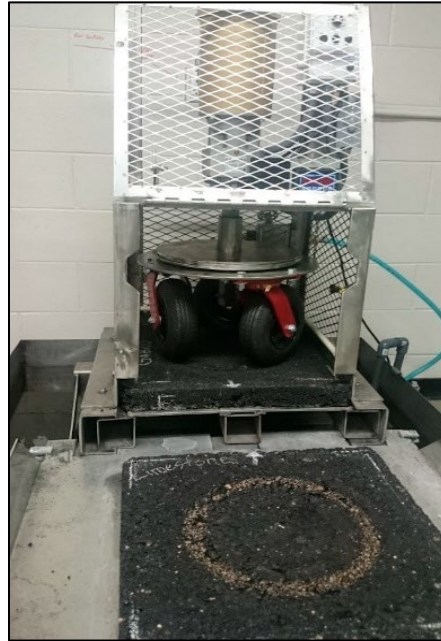


Figure 1.1 Three-wheel polisher device (TWPD)

The DFT was used to measure the coefficient of friction of the test substrates before and after the application of chemical products under both dry (no water applied during the test) and wet (water applied during the test) conditions. The DFT measured the coefficient of friction between rubber sliders and the surfaces of the test substrates. The DFT had three rubber sliders attached to a bottom rotating disk, as shown in figure 1.2. The rotating disk came in contact with the surface when the specified speed was reached. The coefficient of friction was continuously measured with speed until the rotating disk came to a complete stop.

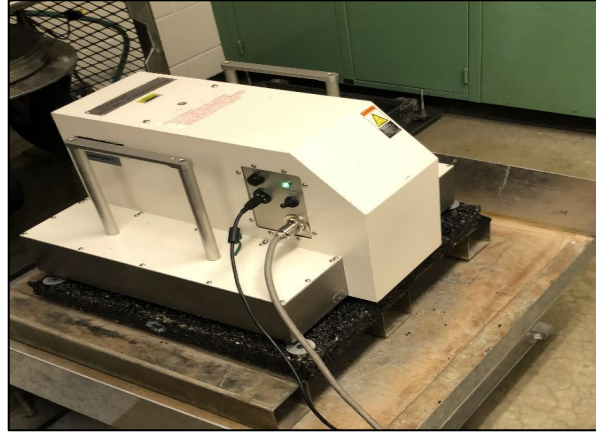


Figure 1.2 Dynamic friction tester (DFT)

1.3.3. Task 3. Analysis of the Results

Under this task, the research team analyzed the test results. The outcome assisted the researchers in identifying parameters that affect the performance of various chemical products, including application rate and pavement type. On the basis of the results, the researchers proposed recommendations regarding proper chemical product(s) and application rates. The proposed procedure and testing methods can be used by transportation agencies to evaluate new chemical products to determine proper conditions for optimal performance.

1.3.4. Task 4. Final Report

The research team prepared this final report to provide background on the subject, information on the selected chemical products, a testing matrix, results and discussion, and recommendations.

1.4. Organization of Report

This report documents the research methodology, presents the results and analysis, summarizes the findings, and provides recommendations for future studies and implementation. The report has five chapters. Chapter 2 presents the main findings of the literature review on conventional and new chemical products, the effects of deicing and anti-icing, recommended application rates, and the test methods used. Chapter 3 presents the experimental testing design, materials, and equipment used, as well as the testing protocols. Chapter 4 presents the results of the study and analysis of the findings. Finally, Chapter 5 summarizes the findings and conclusions of this study and provides guidelines and recommendations.

CHAPTER 2. BACKGROUND

2.1. Conventional and New Chemical Products Used in Deicing and Anti-Icing Applications

Since 1930, deicing products have been used as a method of controlling snow and ice on roads. Early products used for this purpose were sand and sodium chloride (NaCl). Other products are considered conventional because they are based on chloride, such as sodium chloride (NaCl), calcium chloride (CaCl₂), and magnesium chloride (MgCl₂) (Hashemloo, 2008). These products have currently been used to make new products. Chemicals such as potassium acetate (KAc) and calcium and magnesium acetate (CMA) are also used. These two latter chemicals (CMA and KAc) cause less pollution but are more expensive.

These conventional products can be used as deicers or anti-icers, depending on their composition and application. Some of the conventional products do not fulfill the function of anti-icers because the chemicals act in reaction to the presence of ice or snow. The most conventional chemicals for anti-icing treatments or deicing include calcium chloride (CaCl₂), sodium chloride (NaCl), magnesium chloride (MgCl₂), calcium magnesium acetate (CMA), and potassium acetate (KAc) (Ketcham et al. 1996). Table 2.1 provides the eutectic temperatures and concentrations for these products (Ketcham et al. 1996).

Table 2.1 Conventional deicing materials (Ketcham et al., 1996)

Chemical	Eutectic temperature °C (°F)	Eutectic concentration %
calcium chloride (CaCl ₂)	-51 (-60)	29.8
sodium chloride (NaCl)	-21 (-5.8)	23.3
magnesium chloride (MgCl ₂)	-33 (-28)	21.6
calcium magnesium acetate (CMA)	-27.5 (-17.5)	32.5
potassium acetate (KAc)	-60 (-76)	49

According to Blackburn et al. (2014), the conventional products most used by different agencies are divided into common brine chemicals for snow and ice control without inhibitors and commercially produced chemicals for ice and liquid snow control with inhibitors. Table 2.2 summarizes the different chemical products used by various transportation agencies. The selection of these products is based on the experience of each agency and previous studies (Blackburn et al., 2014).

Table 2.2 Control chemicals used by surveyed highway agencies (Blackburn et al., 2014)

Highway Agency	Common Snow and Ice Control Brine Chemicals w/o Inhibitor				Liquid Snow and Ice Control Chemicals w/o Inhibitor Commercially Produced		
	NaCl	CaCl ₂	MgCl ₂	KAc	Apogee	Alpine Ice Melt	CF-7
Brine Chemical(s)	Na	Ca	Mg	KAc	Ac	KAc	KAc
Phase Diagram Available	X	X	X	X	X	X	X
Agencies							
Colorado DOT	1		1		1		
Idaho DOT	1			1			1
Illinois DOT	1	1					
Iowa DOT	1	1					
Kansas DOT	1		1				
Maine DOT	1						
Massachusetts DOT							
Michigan DOT	1		1	1			1
Minnesota DOT	1	1	1	1		1	1
Missouri DOT	1	1					
Montana DOT	1		1				
Nebraska DOT	1			1			1
New York DOT	1						
North Dakota DOT	1						
Ohio DOT	1	1					
Rhode Island DOT	1	1	1				
Utah DOT	1			1			1
Vermont DOT							
Virginia DOT							
Washington State DOT				1			1
West Virginia DOT	1	1					
Wisconsin DOT	1	1					
Wyoming DOT	1						
Subtotal	19	8	6	6	1	1	6

Some agencies use conventional products, such as granular sodium chloride (NaCl), with coarse sand. This combination allows the accumulated ice to melt and provides friction with the pavement (Muthumani et al., 2013). Other studies don't recommend the use of such combinations because of their negative environmental impact. When water evaporates, the remaining sand particles are transported by air, causing pollution and driving problems (Cottier et al., 2005). A study found that many transportation agencies carry out their winter operations with magnesium chloride (MgCl₂) (Fischel, 2001). Table 2.3 summarizes some of the primary and secondary deicer chemicals used by different state agencies.

Table 2.3 Primary and secondary deicers used in different states (Fischel, 2001)

State	Deicing Chemicals
Alaska	Sodium chloride (p); Magnesium chloride (s).
Colorado	Magnesium chloride (p); sand/salt (s); some Caliber M1000 and Ice Slicer.
Connecticut	Sodium chloride (p); Calcium chloride (s).
Delaware	Sodium chloride (p); Ice Ban+sodium chloride for anti-icing; occasionally salt brine; CMA on some bridges.
Idaho	Magnesium chloride for anti-icing and prewetting of sand; sodium chloride and corrosion-inhibited sodium chloride with sand for deicing.
Illinois	Solid and liquid sodium chloride (p); solid and liquid calcium chloride (s).
Indiana	Calcium chloride and magnesium chloride; some salt brine.
Iowa	Sodium chloride (p); calcium chloride (s).
Maine	Sodium Chloride.
Maryland	Sodium chloride (p); salt brine (s); magnesium chloride in colder regions.
Massachusetts	Calcium chloride (p); occasionally sand/salt.
Michigan	Salt and sand (p); magnesium chloride (s)
Minnesota	Potassium acetate; CMA, calcium chloride; FreezGard Zero, Magnesium chloride; Ice Ban M50 and M80, Nu-salt.
Missouri	Sodium chloride (p); use salt brine or liquid calcium chloride for prewetting.
Montana	Magnesium chloride (FreezGardZero w/Shield LS and Ice-Stop CI 2000); prewet salt/sand with magnesium chloride.
New Jersey	Rock salt treated with liquid calcium chloride (p); magnesium chloride (s); also use sand/salt in some areas.
New York	Sodium chloride; Enhance the salt with MAGic (Ice Ban+MgCl ₂); magnesium chloride; calcium chloride; sodium chloride brine (in descending order).
Ohio	Rock salt (p); liquid calcium chloride (s).
Oregon	Magnesium chloride (p); CMA (s); Potassium Acetate when too cold for CMA.
Rhode Island	Sodium chloride (p); magnesium chloride on bridges.
South Dakota	Calcium chloride (p), magnesium chloride (s).
Utah	Deicing – Salt and salt/sand (p); Anti-icing – magnesium chloride and liquid brine.
Vermont	Calcium chloride (p); sand (s).
Washington	Magnesium chloride; Cal-Ban 70 (Calcium chloride/Ice Ban); CMA.
Wyoming	Sand/salt (p); sodium chloride; liquid magnesium chloride.

2.2. Recommended Application Rates of Various Deicing and Anti-Icing Treatments

Many chemicals and products used in winter treatments have a recommended application rate or dosage. These recommended rates are usually based on performance tests conducted by the manufacturers. Studies have shown that the application rate directly affects the friction between the surface of the pavement and vehicle tires. Snow and ice reduce the friction between vehicle tires and pavement surfaces. Ketcham et al. (1996) demonstrated that application rates vary depending on the composition of the products used and other chemicals and solvents that are usually added (Hashemloo, 2008). They emphasized the importance of the preparation of solid products such as granular salt because the combination must be balanced and optimized to achieve optimal results. The most common solvents are water, wet agents, and sometimes direct chemical application. Likewise, the placement of these chemicals in the field is carried out with special vehicles that allow the spreading of chemicals along the road (figure 2.1a). To spread

these products in small areas such as in the laboratory, it is necessary to use a device for proper and uniform application such as a manual spreader pump (figure 2.1b). Some studies developed an automatic sprayer to obtain more precise applications and to control the application rates. For instance, they used a paint sprayer to achieve a finer and more precise application (Shi et al., 2014).

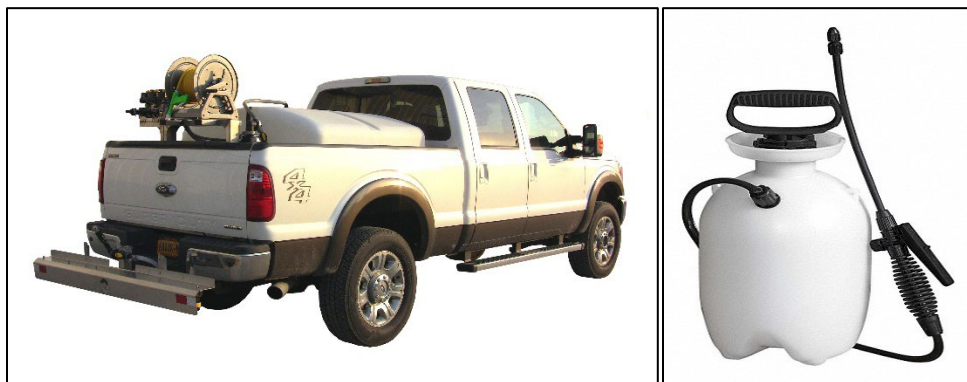


Figure 2.1 (a) Truck-mount skid sprayer (Rhett M Clark Inc., 2022), **(b)** Manual sprayer pump (W.W. Grainger, Inc., 2022)

The most common products used by agencies are magnesium chloride, sodium chloride, calcium chloride, and calcium and magnesium acetate. The application of these chemicals at the correct time and under the correct temperature increases their performance and effectiveness. Table 2.4 shows the temperature ranges and application rates of the deicers and their different combinations (Leahy et al., 2014).

Most products usually come with a recommended application rate from the manufacturer. Conventional products such as sodium chloride have an application rate of 100 to 300 pounds per linear mile (lb./lm) as a granular product. The recommendation for the same product in a liquid form is from 45 to 165 gallons per linear mile (gal/lm) (O'Keefe and Shi, 2005).

Recently, more deicing and anti-icing products based on conventional chemicals have become available, such as NaCl. Table 2.5 shows chemical application rates in gallons per lane-mile (GLM) (Schneider IV et al., 2021).

To find the correct application rates for deicers and anti-icers, it is important to consider factors that help determine the correct application rate. Muthumani et al. (2013) demonstrated

that traffic level, pavement condition, and temperature are the most important factors to be considered (Muthumani et al., 2013).

Table 2.4 Application rates according to temperature and different combinations of products (Clear Roads, 2015)

Pavement Temp. (°F) and Trend (↑↓)	Weather Condition	Maintenance Actions	lbs/ two-lane mile			
			Salt Prewetted/ Pretreated with Salt Brine	Salt Prewetted/ Pretreated w/ Other Blends	Dry Salt*	Winter Sand (abrasives)
>30° ↑	Snow	Plow, treat intersections only	80	70	100	Not recommended
	Frz. rain	Apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
30° ↓	Snow	Plow & apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 – 30° ↑	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 – 30° ↓	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	160 – 240	140 – 210	200 – 300*	400
20 – 25° ↑	Snow or frz. rain	Plow & apply chemical	160 – 240	140 – 210	200 – 300*	400
20 – 25° ↓	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 – 20° ↑	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 – 20° ↓	Snow or Frz. rain	Plow & apply chemical	240 – 320	210 – 280	300 – 400*	500 for Frz. rain
0 – 15° ↑	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	300 – 400	Not recommended	500 – 750 spot treat as needed
< 0°	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	400 – 600**	Not recommended	500 – 750 spot treat as needed

*Dry salt is not recommended. It is likely to blow off the road before it melts ice.
 **A blend of 6 – 8 gal/ton MgCl₂ or CaCl₂ added to NaCl may melt ice as low as -10°F.
 Note: Below 15°F salt and brine need assistance or they are not recommended for use. These rates are not fixed values, but rather, the middle of a range to be selected and adjusted by an agency according to its local conditions and experience.

Table 2.5 Different application rates for deicing and anti-icing products (Schneider IV et al., 2021)

Beet Heet Severe	15-25 depending on incoming weather
IceBan	25
ThermaPoint	25-30
XO-Melt2	15-25
Cryotech CF7	21

The application rate of granular products such as sand is usually higher than the application rates of these chemicals. Chang et al, (1994) found that in the Denver metro area, the application rate of sand varied between 800 and 1,200 pounds per lane mile. This variation can

be due to traffic levels and geolocation. Similarly, sand can be combined with granular products such as salt (NaCl) at a ratio of 3 percent to 20 percent sodium chloride content.

The State of Minnesota established a guide for winter operations. Table 2.6 shows the application rates for conventional deicers such as calcium chloride (CaCl₂), magnesium chloride (MgCl₂), and sodium chloride (NaCl) based on the time of application (Minnesota Local Road Research Board, 2012).

Table 2.6 Application rates of conventional products based on the time of application (Minnesota Local Road Research Board, 2012)

Condition	Gallons/Lane Mile			Other Products
	CaCl ₂	MgCl ₂	Salt Brine	
1. Regularly scheduled applications	15 – 25	15 – 25	20 – 40	Follow manufacturers' recommendations.
2. Prior to frost or black ice event	15 – 25	15 – 25	20 – 40	
3. Prior to light or moderate snow	15 – 25	15 – 25	20 – 50	

The application rates of products mixed with liquid salt or prewet salt are provided in table 2.7. These application rates are classified on the basis of the application temperature, weather conditions, and type of maintenance activity (Minnesota Local Road Research Board, 2012).

Table 2.7 Application rates recommended by the Minnesota Local Road Research Board (2012)

Pavement Temp. (°F) and Trend (↑↓)	Weather Condition	Maintenance Actions	Lbs/ two-lane mile			
			Salt Prewetted/ Pretreated With Salt Brine	Salt Prewetted/ Pretreated With Other Blends	Dry Salt*	Winter Sand (abrasives)
>30° ↑	Snow	Plow, treat intersections only	80 (40/lane mile)	70	100*	Not recommended
	Frz. rain	Apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
30° ↓	Snow	Plow & apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 - 30° ↑	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 - 30° ↓	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	160 – 240	140 – 210	200 – 300*	400
20 - 25° ↑	Snow or frz. rain	Plow & apply chemical	160 – 240	140 – 210	200 – 300*	400
20 - 25° ↓	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 - 20° ↑	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 - 20° ↓	Snow or Frz. rain	Plow & apply chemical	240 – 320	210 – 280	300 – 400*	500 for frz. rain
0 to 15° ↑↓	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	300 – 400	Not recommended	500 – 750 spot treat as needed
< 0°	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	400 – 600**	Not recommended	500 – 750 spot treat as needed

*Dry salt is not recommended. It is likely to blow off the road before it melts ice.

**A blend of 6 – 8 gal/ton MgCl₂ or CaCl₂ added to NaCl can melt ice as low as -10°.

Chang et al. (1994) established application rates for calcium magnesium-based products based on recommendations from different agencies (table 2.8). Also, they presented application rates for liquid magnesium chloride (table 2.9), with rates based on the temperature and thickness of the snow accumulated on the roadway (Chang et al., 1994).

Table 2.8 CMA usage rates (Chang et al., 1994)

CMA Usage Rates				
Transportation Agency	Mix	Average Daily Traffic	Application Rate lbs/Ln Mile	Usage Comparison CMA/Salt
Denver	CMA/Sand	24,000 – 30,000	167–333	1/1
Massachusetts DPW District 7	CMA	12,000	280	0.87/1
Massachusetts DPW District 6	CMA	2,000	300	0.44/1
Michigan DOT	CMA	31,000	300	1/1
Nebraska DOH	CMA/Sand	29,000	400–500	1/1
West Virginia DOH	CMA	13,000	325	1.3/1
Caltrans	CMA	1,350 – 12,000	350–400	NA
Ontario MOT	CMA	32,000	266	NA

Table 2.9 Application rates for liquid magnesium chloride (Chang et al., 1994)

A. DEICING Packed Snow and Ice Gallons per lane mile			
DEPTH	TEMPERATURE		
	20 to 32 F	10 to 20 F	10 F and below
2 to 3 inches	234 gal / ln mi	291 gal / ln mi	577 gal / ln mi
1 to 2 inches	144 gal / ln mi	171 gal / ln mi	380 gal / ln mi
1/2 to 1 inch	76 gal / ln mi	114 gal / ln mi	191 gal / ln mi
Less than 1/2 inch	57 gal / ln mi	76 gal / ln mi	114 gal / ln mi
Glare ice	57 gal / ln mi	76 gal / ln mi	114 gal / ln mi

Note: It is not recommended that liquid deicers be used, without abrasives, at higher snow and ice depths.

B. ANTI-ICING	
Expected freezing conditions :	21 to 32 gallon per lane mile

Chang et al. (1994), found that liquid magnesium chloride performs differently depending on the temperature and thickness of the snow. For 1- to 2-in thick packed snow and ice, 144 gal/lane mile is needed with a temperature of between 20°F and 32°F. However, as the temperature decreases, the rate increases to 380 gal/lane mile. Meanwhile, the liquid magnesium chloride generally does not work at lower temperatures because of over-application.

2.3. Effects of Deicing and Anti-Icing Treatments on Pavement Friction

Friction is one of the important characteristics of pavements to ensure road safety and prevent vehicle crashes (Flintsch et al., 2012). To study the effects of deicing and anti-icing chemicals on pavement surface friction, it is necessary to understand how interaction between the pavement surface and tires occurs. Two mechanisms affect friction between the pavement surface and vehicle tires, as illustrated in figure 2.2 (Kumar and Gupta, 2021). Adhesion friction depends mostly on micro-level surface roughness, while hysteresis mostly depends on macro-

level surface roughness and is caused by the deformation of rubber materials (Kumar and Gupta, 2021).

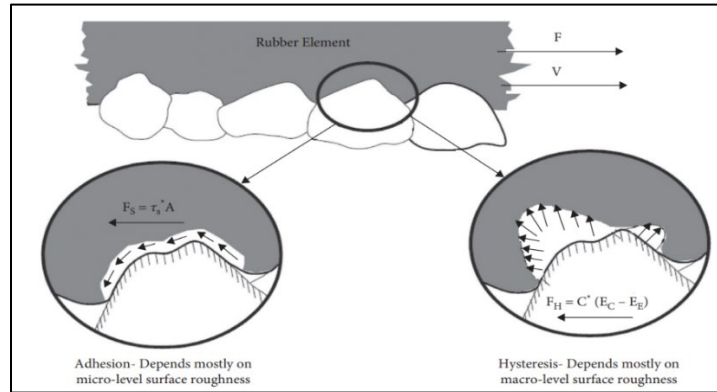


Figure 2.2 Schematics of the interaction between the tire rubber and pavement surface (Kumar and Gupta, 2021)

The friction generated as a result of the interaction between the tires and pavement surface is highly influenced by road surface conditions. Table 2.10 shows the different coefficients of friction, depending on the condition of the pavement (Wallman and Åström, 2001, Schneider IV et al., 2021).

Table 2.10 Friction coefficients under different pavement conditions (Wallman and Åström, 2001, Schneider IV et al., 2021)

Road Surface Condition	Friction Coefficient
Dry bare surface	0.8–1.0
Wet, bare surface	0.7–0.8
Packed snow	0.20–0.30
Loose snow/slush	0.20–0.50 (the higher value when the tires are in contact with the pavement)
Black ice	0.15–0.30
Loose snow on black ice	0.15–0.25
Wet black ice	0.05–0.10

Note: The friction numbers were obtained by skiddometer measurements with 17% slip (Saab Friction Tester).

Different factors influence the level of friction. Table 2.11 summarizes the parameters that affect friction, including pavement surface characteristics, vehicle operating parameters, tire properties, and environmental conditions (Muthumani et al., 2013, Hall et al, 2009). Some

research studies have evaluated the effects of winter treatments on road safety, the cost of various treatments, and their benefits. Additionally, other studies have focused on the effects of various products and chemicals (deicers and anti-icers) on pavement friction. These products are applied to improve motorist mobility; however, not much research has been conducted on the effects on pavement friction for different pavement types (i.e., concrete and asphalt) (Hall et al, 2009).

Table 2.11 Factors affecting pavement friction (Muthumani et al., 2013, Hall et al, 2009)

Pavement Surface Characteristics	Vehicle Operating Parameters	Tire Properties	Environment
<ul style="list-style-type: none"> •Macrotexture •Microtexture •Material properties •Unevenness •Temperature 	<ul style="list-style-type: none"> •Slip speed •vehicle speed •braking action •Driving maneuver •turning •overtaking 	<ul style="list-style-type: none"> •Tread pattern design and condition •Inflation pressure •Rubber composition and hardness •Footprint •Load •Temperature 	<ul style="list-style-type: none"> •Climate •Wind •Temperature •Water (rainfall, condensation) •Snow and Ice •Contaminants •Anti-skid material (salt, sand) •Dirt, mud, debris

Note: Critical factors are shown in bold

Kumar et al. (2021), summarized different methods for measuring friction. Table 2.12 shows available methods and devices, as well as their advantages and disadvantages (Kumar and Gupta, 2021).

Table 2.12 Different methods of friction measurement, advantages, and disadvantages (Kumar and Gupta, 2021)

Method	Measuring principle	Advantage	Disadvantage
Computed tomography	Based on attenuation of X-rays. A 3D voxel is reconstructed and a grey value is attributed to each voxel depending on X-ray absorption of surface and path followed by X-ray.	Nondestructive testing. Determination of inner and outer geometry, volume data of high density, short scanning time. Higher accuracy if reconstructed correctly.	Complex and numerous parameters influencing measurement, with results being not traceable. No accepted test procedure. Highly sophisticated, requiring a skilled operator.
Microscopy	Based on an image captured by camera or microscope and analysed using proprietary software for 3D modelling of capture surface.	Inexpensive. Ability to visualize surface texture in 3D. Covering micro-, macro- & megatexture scale. Correlating well with MTD from sand patch test.	Accuracy depends on user-adopted imaging setup, lens optics & eliminating the effect of camera shake. Requiring skill & software for analysis of 3D models.
Laser scanning	Recording intensity of reflected laser light from the target surface & lens height for each point under observation.	No surface damage. A simultaneous and quick observation of surface image and the height profile. Continuous data collection at high speed. Ability to calculate MPD & RMS of profile height.	Limited measurement target size. Expensive, requiring skilled operators for data collection & processing. Inability to determine the internal structure of the surface mix.
Sand patch method	Patch area is calculated by pouring fixed volume of sand or glass spheres over the surface. Mean texture depth (MTD) is obtained by dividing the volume of sand or glass sphere by calculated patch area.	It is simple to use and is the least expensive among all. It is useful in every type of pavement surface measurement. It directly measures mean texture depth. Surface profiling can be constructed in 3D.	It cannot accurately predict the texture of a very rough or porous surface. It is vulnerable to operator inconsistencies. Repeated measurements at regular intervals are required. It is a slow method; traffic management is required to protect the operator.
Outflow meter	It is based on a known volume of water, under a standard pressure head, which is then allowed to disperse through the gaps between a circular rubber ring and the road surface. It relates to the drainage capability of the pavement through its surface and subsurface voids.	It is useful for an open-graded porous asphalt surface. It indicates hydroplaning potential under wet conditions. It is simple to execute and needs inexpensive equipment. It measures the relative drainage ability of the pavement surface and detects surface wear.	It is appropriate only for surfaces with low texture depth. Reproducibility is poor. It cannot measure outflow time less than 1 sec. It does not measure the texture depth directly. It is a slow method and requires lane closure to perform the test.
Circular texture meter	It uses a laser to measure the profile of a circle and is divided into eight segments. The average MPD is determined for each segment of the circle.	It is a small (approx. 13 kg) and portable instrument, with short measurement time (approx. 45 sec). Four directions of data can be obtained during only one measurement.	It does not record the 3D surface profile. It is not practical in measuring the macrotexture of large pavement segments. It underestimates the actual texture.
Light detection and ranging (LiDAR)	Parameters related to texture and material information are detected and calculated by LiDAR system.	It can be equipped on vehicles for rapid and economical estimation of pavement friction level.	The test accuracy is affected by road markings, natural light & weather conditions. More data is needed to improve the accuracy of the estimation of the friction.

Different pieces of equipment have been designed to evaluate the friction coefficient of pavements under different conditions (wet and dry). Table 2.13 shows different kinds of equipment and their basic measurement principles (Kumar and Gupta, 2021).

Table 2.13 Devices and principles of friction measurement (Kumar and Gupta, 2021)

Device	Measurement principle and measuring condition
British pendulum test (BPT)	Impact manner: As the rubber pad swipes on the pavement surface, the tire-pavement friction will resist the swinging tendency of the pendulum, and the reduced kinetic energy of the pendulum will be converted to potential energy when the pendulum gets the maximum height, which is represented by BPN. Contact area (mm ²): 9601.2, measured speed (km/h): 10.
Dynamic friction tester (DFT)	Impact manner: Rubber pads on the rotating plate are brought into contact with the testing surface, as the plate is set to reach the target speed. Afterwards, the speed of pads will be slowed down to zero owing to the friction in the contacting interface, with the friction coefficient measured at a given speed. This device can be used both in the laboratory and in the field. Contact area (mm ²): 64242.4, measured speed (km/h): 10–80, contact pressure (MPa): 0.15.
Wehner/Schulze (W/S)	Impact manner: In the phase of friction testing, rotation beads are accelerated to 100 km/h initially, and then water is sprayed on the specimen surface. Then, the beads are lowered onto the test surface, and the friction coefficient is recorded. Contact area (mm ²): 39760.8, measured speed (km/h): 60, contact pressure (MPa): 0.2.
Tire-pavement dynamic friction analyser (TDFA)	Impact manner: Driven by the engine, a pavement specimen is rotated, driving the rotation of upper tires. The friction force and upper loading can be measured in real time in this period for the calculation of the friction coefficient. Contact area (mm ²): 49087.4, measured speed (km/h): 10–100, contact pressure (MPa): 0.2–1.1, slip ratio (%): 0–100.

Some laboratory studies have been conducted to evaluate the effects of deicers and anti-icers on friction; however, the results may not necessarily resemble performance in the field. Meanwhile, such methodologies and equipment can be used for performance evaluation and to establish performance parameters (Muthumani et al., 2013). Some studies have demonstrated the need to measure friction before and after treatment application to study the performance of examined products (Ye et al., 2013).

Many agencies use granular products that minimize friction loss as a result of their shape. They also use snow control activities, such as the operation of snowplows. A study was carried out to evaluate friction at two levels of deicing liquid application on an open-grade pavement surface. Reference values established by the FHWA were used, and the results were found to be above those established values (Martinez and Poecker, 2006). Al-Qadi et al. (2002) examined the use of friction measurements for improving winter maintenance operations and mobility. The testing program included compacted snow and loose snow on the pavement surface (Al-Qadi et al., 2002). The results showed such an approach to be promising and practical in supporting winter operations decision making.

Some test procedures are used to evaluate pavement friction characteristics during snowfall in the field, while other methods have been developed for laboratory evaluation. A skid trailer is used to measure the skid number in the field, and the test can be conducted at speeds. Friction is measured between a locked wheel and the pavement surface. Friction can also be

measured while the wheel is slowing down. In some cases, a combination of locked wheel and freewheel allows the evaluation of friction in both circumstances (Muthumani et al., 2013).

Another test is used to evaluate shear stress between the snow or ice and the pavement surface. This test evaluates the bond between the snow/ice and pavement (Muthumani et al., 2013). Fay et al. (2010), carried out tests to evaluate the efficiency of deicers and anti-icers on the detachment force and the shear force between the pavement and snow or ice.

Others found that the coefficient of friction of asphalt pavement sprayed with pure water was 60 percent of the dry coefficient. Similarly, with the application of de-icing or antifreeze liquids, the coefficient of friction is expected to be affected at the same level under the same conditions, whether the pavement is wet or with snow and ice (Nixon et al., 2007). Another study conducted in Colorado found that magnesium chloride ($MgCl_2$), used as antifreeze, produced high friction values during stormy weather (Nixon et al., 2007). In another study using the same product in Wisconsin, the loss of friction could be delayed, improving the safety of users (Ketchum et al., 1998). Nixon et al. (2007) also demonstrated the importance of the proper application process because it affects friction level. Accumulation or excess application of deicers or antifreeze can significantly reduce friction.

Chappelow et al. (1992) documented multiple test methods for complete evaluation of deicing chemicals, including their friction properties. Fawzy et al. (2021) examined friction or slip resistance on different pavement surfaces in snow conditions. They evaluated the performance of pavements with surface treatments such as chip seal and fog seal with and without the application of deicing products. They used the British Pendulum Tester (BPT) (figure 2.3) to evaluate surface friction in their study.

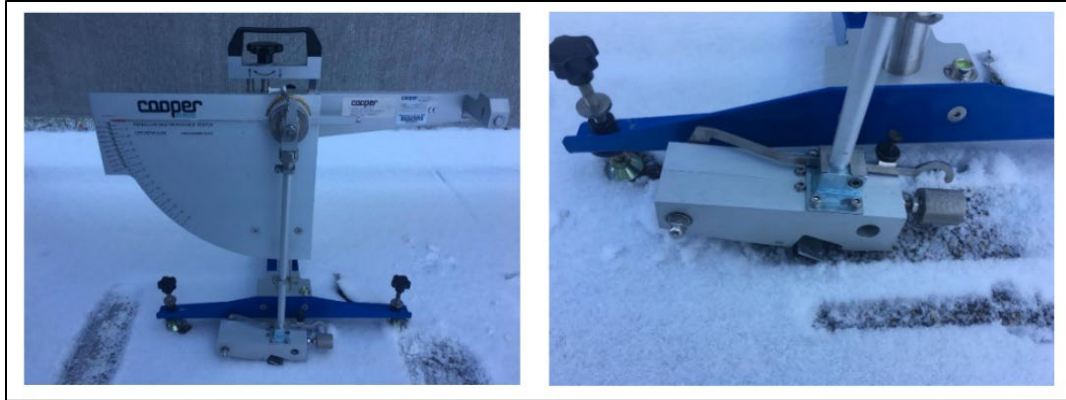


Figure 2.3 Measuring friction using BPT in snow conditions (Fawzy et al., 2021)

2.4. Test Methods Used to Evaluate the Effectiveness of Deicing and Anti-Icing Chemicals

Different test methods are used to evaluate the effectiveness of deicing and anti-icing chemicals. However, these tests are limited in simulating field conditions. Many tests used to evaluate the efficiency of these chemicals were developed during the Strategic Roads Research Program (SHRP). According to Chappelow et al. (1992), these tests focus on deicing performance in melting ice (snow/ice), penetration, and the ability to reduce the bond between the pavement and snow. Most of these tests are conducted in the laboratory. In an uncontrolled environment such as in the field, the effects of environmental conditions (e.g., air temperature, solar radiation, pavement temperature, wind speed, humidity) and vehicular traffic may make it difficult to carry out these tests. On the other hand, in the laboratory, these tests are limited because it is difficult to achieve the same environmental conditions as those in the field and to simulate vehicular traffic. Meanwhile, these tests can be used to quantify the application rates of anti-icers and thus measure their melting capacity. The literature review indicated that laboratory testing may not be necessary to simulate the results that would be expected in the field.

CHAPTER 3. EXPERIMENT TEST DESIGN

3.1. Experimental Laboratory Testing

The laboratory testing involved developing and conducting an experimental program to evaluate and analyze the effectiveness of the selected chemical products. The testing was conducted in a controlled environment inside the laboratory using a dynamic friction tester (DFT). In addition, a three-wheel polisher device (TWPD) was placed outside of the laboratory to conduct testing in a typical winter environment. The team evaluated the effects of the tested chemical products on pavement surface friction under different conditions (i.e., dry and wet). The dry condition simulated the application of the test products as pre-treatments to evaluate how these chemicals could affect friction if snow did not fall or in combination with sleet or hail. The wet condition evaluated the test chemicals as post-treatments to evaluate surface friction after snowfall. The laboratory experiments conducted in this study were intended to develop a new method for evaluating the performance of various products as winter treatments.

3.2. Test Products

The research team selected five products to test in this study, as shown in table 3.1, based on the main findings of the literature review and the availability of these products in the region. The selected products were divided into two categories: deicing chemicals and anti-icing chemicals. In the deicer category, three chemicals were included: liquid calcium chloride (CaCl_2), liquid potassium (K), and granular sodium chloride (NaCl). Under the anti-icer category, two chemicals were evaluated: magnesium chlorides (MgCl_2) with two different inhibitors.

Table 3.1 Deicers and anti-icers selected in the study

#	Code	Chemical Composition
1	D-1	CaCl ₂
2	D-2	K
3	D-3	NAAC
4	A-1	MgCl ₂ *
5	A-2	MgCl ₂ **
* Product combined with corn-based corrosion inhibitor		
** Product combined with Shield AP Corrosion Inhibitor		

The research team collected loose asphalt mix from an asphalt plant located in Pullman, Washington. The dense graded asphalt mix had a nominal maximum aggregate size of 12.5 mm. The loose mix was placed in boxes of 40 lb each. The mix was reheated and then compacted to prepare asphalt mix slabs (20 in. × 20 in. × 2 in.). The slabs were compacted with a portable compactor plate and a metal mold, as shown in figure 3.1. The compacted slab was left in the mold to cool overnight before it was removed from the mold to avoid any damage or deformation.



Figure 3.1 Plate compactor and asphalt test slab prepared in the study

In addition, the team prepared concrete slabs. The Portland cement concrete (PCC) was prepared in the laboratory using coarse and fine aggregates that were collected from local

stockpiles located in Lewiston, Idaho. The PCC had a water/cement ratio of 0.5. The mix was prepared and cast in a mold of 20 in. × 20 in. × 2 in., as shown in figure 3.2.



Figure 3.2 Concrete test slab prepared in the study

More information about the asphalt and concrete slab preparation process is provided in Appendix A. Once the slabs had been prepared and removed from the mold, the initial friction measurements were taken with the DFT. A total of 12 asphalt and concrete slabs were prepared and tested in this study.

3.3. Application Rate

Four of the chemical products selected in this study were in liquid form (two deicers and two anti-icers), and one deicer was in granular form. These winter treatment chemicals are typically measured in pounds per 1,000 sq ft, gallons per linear mile (gal/linear mile), and pounds per linear mile (lbs./linear mile).

The application rates of the selected products were determined on the basis of a small surface area of 20 in. x 20 in. In the group of chemicals in liquid form, the D-1 deicer and the two anti-icers (A-1 and A-2) had an application rate of 6.6 ml per slab, which corresponded to a typical application rate ranging from 35 to 40 gallons per linear mile. The deicers D-2 and D-3 had an application rate of 9.1 ml per slab and 9 gr per slab, respectively. The granular deicer (D-3) came in a solid form, so it was necessary to dilute it in water to maintain the same testing conditions as those of all the other liquid products. Deicer D-3 was diluted in water at a ratio of 1:1, so the application rates of this chemical were 9 gr (D-3) + 9 ml (H₂O). The application rate of various products recommended by the manufacturers are summarized in table 3.2.

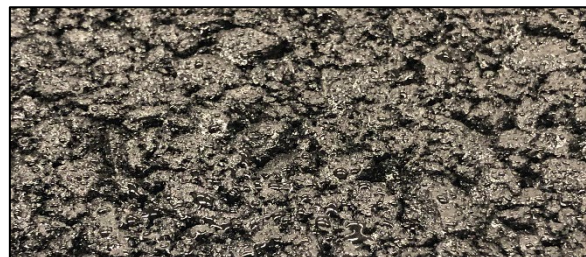
Table 3.2 Application rates based on the producer recommendations

Product	Calcium Chloride Liquid D1 (CaCl ₂)		Potassium Format Liquid D2 (K)		Sodium Chloride D3 (NaCl)		Magnesium Chloride A1 (MgCl ₂) *		Magnesium Chloride A2 (MgCl ₂) **	
	Code		Code		Code		Code		Code	
Code	D-1		D-2		D-3		A-1		A-2	
Application rate	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Gallons/Lane-Mile	35	40	25	55	-	-	30	40	35	40
lbs./1000 sq ft	-	-	-	-	10	25	-	-	-	-
* Product combined with corn-based corrosion inhibitor										
** Product combined with Shield AP Corrosion Inhibitor										

The research team carried out the DFT testing under the two conditions mentioned earlier (pre-treatment and post-treatment) and considered three different application rates. The team selected three application levels that ranged from the minimum application rate recommended by the manufacturer (Application Rate No. 1), twice the minimum rate (Application Rate No. 2), and triple the minimum application rate (Application Rate No. 3). Table 3.3 shows the exact amounts of chemicals used for the three application levels. The evaluation procedures with these three different application rates are presented in Appendix B. Figure 3.3 shows a surface before and after the application of chemicals.

Table 3.3 Level of application rates used in the study

	Deicers			Anti-icers	
	Calcium Chloride Liquid (CaCl ₂)	Potassium Format Liquid deicer (K)	Sodium Chloride Solid (NAAC)	Magnesium Chloride (MgCl ₂)*	Magnesium Chloride (MgCl ₂)**
Code	D-1	D-2	D-3	A-1	A-2
Application 1 (ml)	6.6	9.1	9.0	6.6	6.6
Application 2 (ml)	13.2	18.3	19.0	13.3	13.3
Application 3 (ml)	19.8	27.4	27.0	19.9	19.9
* Product combined with corn-based corrosion inhibitor					
** Product combined with Shield AP Corrosion Inhibitor					



3.4. Measuring the Coefficient of Friction

The coefficient of friction was measured by using a DFT, as shown in figure 3.4. The test was conducted at different speeds and under two conditions (dry and wet). This device consisted of a circular disk with three rubber pads attached to the disk. This device could provide a maximum tangential speed of 90 km/h (55 mph) when the test disk was turning. Once the disk had reached the specified speed, it was lowered to the pavement surface, and the coefficient of friction was measured as the speed of the rotating disk gradually decreased. In dry conditions, no water was sprayed before friction measurements were taken, whereas water was sprayed on the surface for wet conditions. The coefficient of friction was measured when the speed reached 50 km/hr in the dry condition, while it was measured when the speed reached 90 km/hr in wet conditions, since friction is critical in wet conditions. In addition, the friction was much higher in dry conditions than under wet conditions. Also, if friction was measured under dry condition at higher speeds (e.g., 90 km/hr), it would wear out the rubber sliders much faster and could damage the DFT device. The software of the DFT device reported the coefficient of friction at 20 km/hr and 40 km/hr in dry conditions and at 20 km/hr, 40 km/hr, 60 km/hr, and 80 km/hr in wet conditions.

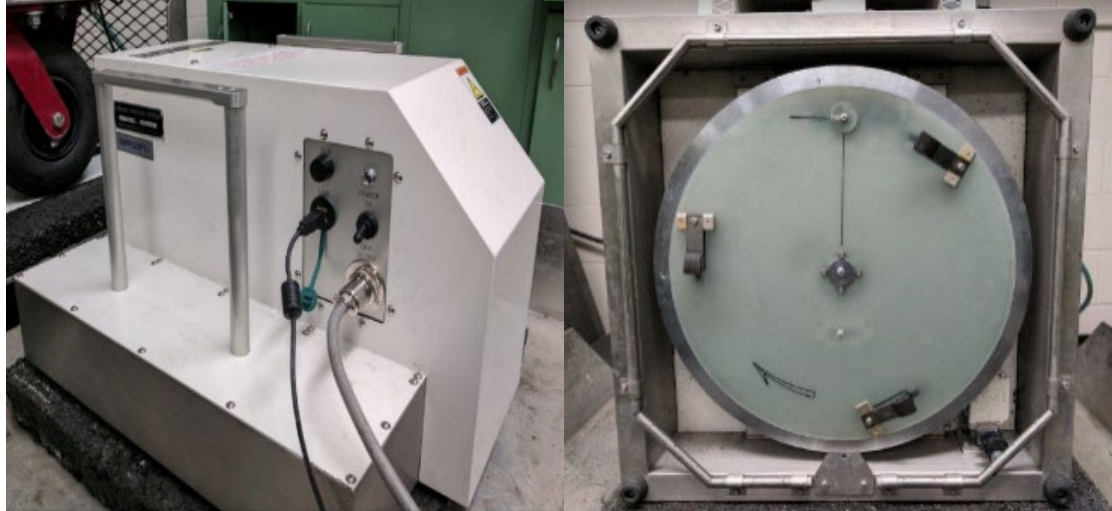


Figure 3.4 Dynamic friction tester (DFT) with three rubber sliders

Three rubber sliders were attached to the rotating circular disk of the DFT (figure 3.5). The research team replaced the rubber sliders when they exhibited signs of wear. Three measurements were taken on each surface, and an average coefficient of friction value was calculated. The results obtained were reported in bar graphs for better understanding and comparison. Figure 3.5 shows the conditions of the rubber sliders before testing and after testing, when rubber slider replacement was required.

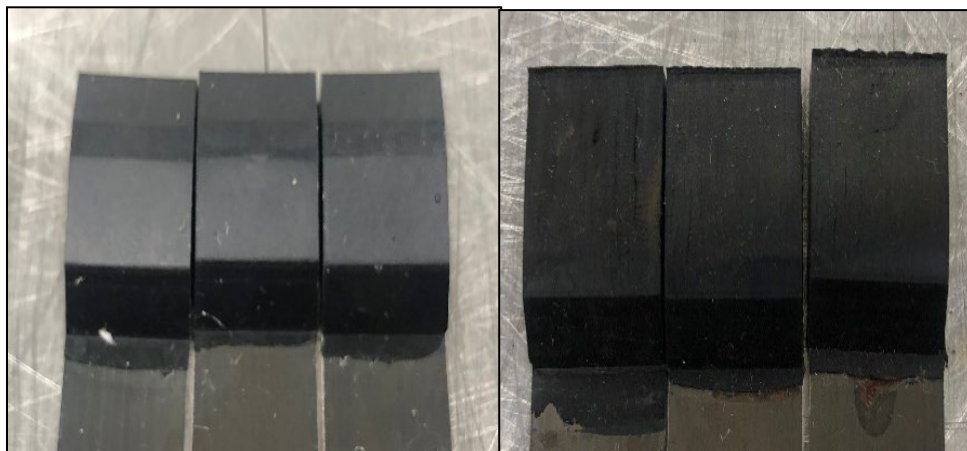


Figure 3.5 Rubber sliders: (a) before testing, (b) worn sliders

Deicing products require the presence of snow on the pavement surface (no greater than 2 inches) whereas anti-icers need to be applied before snowfall to prevent the accumulation of

snow or the creation of thin ice layers. In comparing both types of products (freezing and defrosting), the maintenance activities for each one should be established for each agency, since it is necessary to have a good response plan for their use.

3.5. Accelerated Traffic Simulation in Icy Climatic Conditions

A three-wheel polishing device (TWPD), as shown in figure 3.6a, was used to simulate the effects of traffic on pavements covered with snow/ice. The TWPD consisted of three pneumatic rubber wheels attached to a turntable that rotated over the test substrates. A scraper blade could be attached to the assembly to simulate snow removal in the laboratory (figure 3.6b). This method was recently used at the University of Idaho successfully to examine the deterioration of pavement markings due to snow removal (Mohammed et.al, 2019). The TWPD was used in this study to simulate ice melting caused by traffic loading in the field. The test was conducted on icy asphalt and concrete slabs. Each slab had an ice thickness of 0.8 inch on the top. After a set of loading cycles (3,500 cycles), the depth of ice melting at the top of the slab along the wheel path was measured to determine the melting rate under traffic loading, as shown in figures 3.7 and 3.8. Four depth measurements were taken at the surface, and an average value was calculated. The testing was conducted with and without the scraper blade.

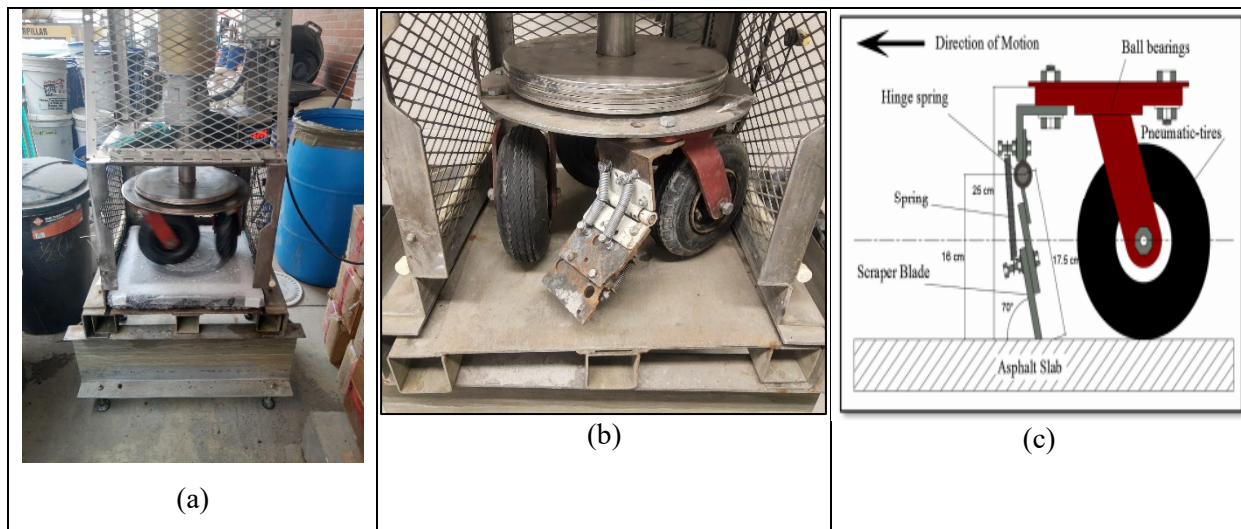


Figure 3.6 (a) Three-wheel polisher (b,c) Scraper blade attached to simulate snow removal

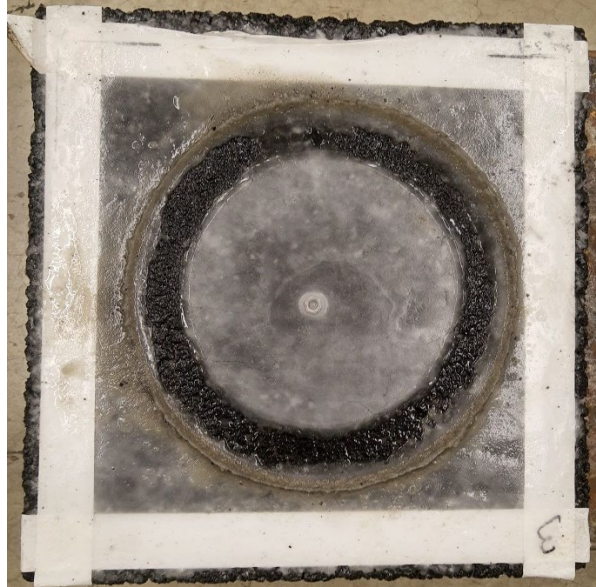


Figure 3.7 Asphalt slabs tested with the TWPD



Figure 3.8 Concrete slabs tested with the TWPD

3.6. Measuring Debonding Shear Force

In this study, the research team used the following procedure to measure the debonding shear force to quantify the adhesion between the pavement surface and ice covering the surface.

1. Divide the test surface into sections, where each section or area is covered with one type of deicer. In this study, the surface was divided into four different areas or segments, as shown in figure 3.9a. Each area was marked with the deicer type that was applied.
2. Apply the specified deicer application rate on the surface of the slab.
3. Place the slab in a freezer for at least four hours at 14 °F.
4. Prepare 1-in. ice cubes to be placed on the surface. This size was found to provide less variability and had a reasonable surface area and thus produced less force during testing.
5. Remove the test slab from the freezer and apply a thin film of water on the top of the slab, then immediately place the ice cube on the surface, as shown in figure 3.9b. The thin film of water started freezing within seconds, allowing the ice cube to fully bond with the slab surface. Once all cubes are placed, place the slab back into the freezer for conditioning for another two hours at 14 °F.
6. Take the slab out of the freezer for testing.
7. Place a spring scale on one side of the cube, as shown in figures 3.9c and 3.9d.
8. Pull the spring scale gradually and record the maximum load needed to separate the ice cube from the surface.
9. Repeat the procedure for the rest of the cubes. Take the average of at least three readings for each area.

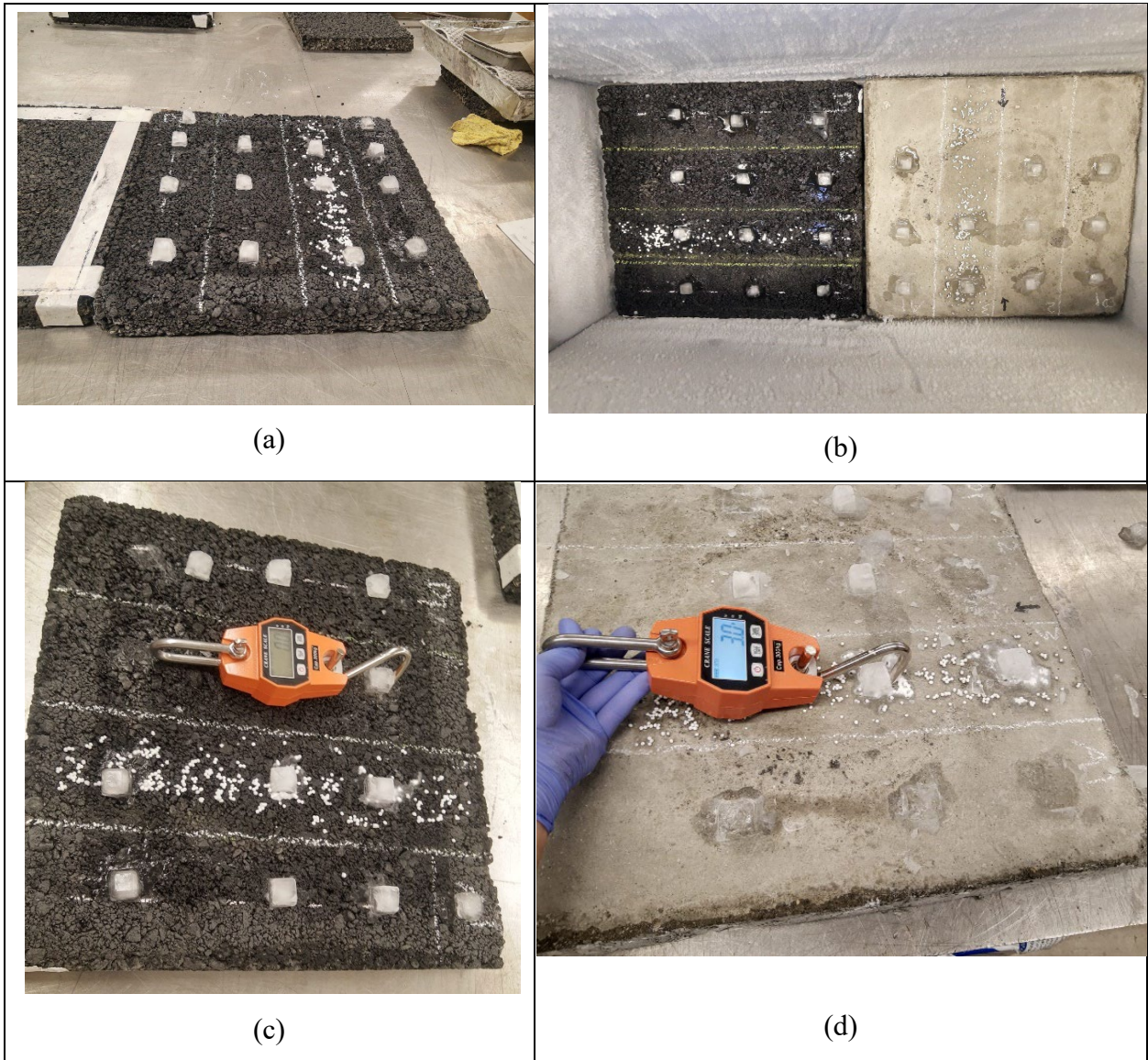


Figure 3.9 Debonding shear force testing procedure

CHAPTER 4. RESULTS AND ANALYSIS

4.1. Dynamic Friction Tester (DFT)

As mentioned in Chapter 3, five chemical products were recommended for winter treatments and selected for evaluation in this study. There were four liquid products and one granulated product. During DFT testing, three DFT measurements were taken after each application. The application procedure for the test products is presented in Appendix B, and detailed results are presented in Appendix C. The testing results showed that dry friction decreased with the use of the test products, as they acted as a lubricant between the rubber sliders and pavement surface. Also, the friction loss increased with an increase in application rate for some products. Because the products were not combined with ice or snow in dry conditions, the chemicals were concentrated on the pavement surface and reduced friction.

Note that a single asphalt slab was used for each application rate. Figures 4.1 and 4.2 show a summary of the DFT results obtained under the four testing conditions (control, first application rate, second application rate, and third application rate), with a speed of 40 km/h (DFT-40) for all five tested products. The results demonstrated a trend in friction reduction after the application of chemical products. On average, at 40 km/h and the initial or control friction (for which no product was applied to the test surfaces), the friction coefficient was around 0.88, which was typical of asphalt mixtures in dry conditions. After the first application, product D-1 provided relatively higher friction in comparison to all the other products. There was a 38.37 percent loss in friction in comparison to that of dry conditions. Products D-2 and A-1 produced an approximately 50 percent reduction in friction, which was higher than that of other products, in comparison to dry friction for the first application rate. Similarly, deicer D-3 and anti-icers A-2 experienced a 46 percent reduction in friction. In comparing the changes in friction between the first and second applications, D-1 had an approximately additional 28 percent friction loss. On the other hand, the change in friction for all other products ranged between ± 4 percent.

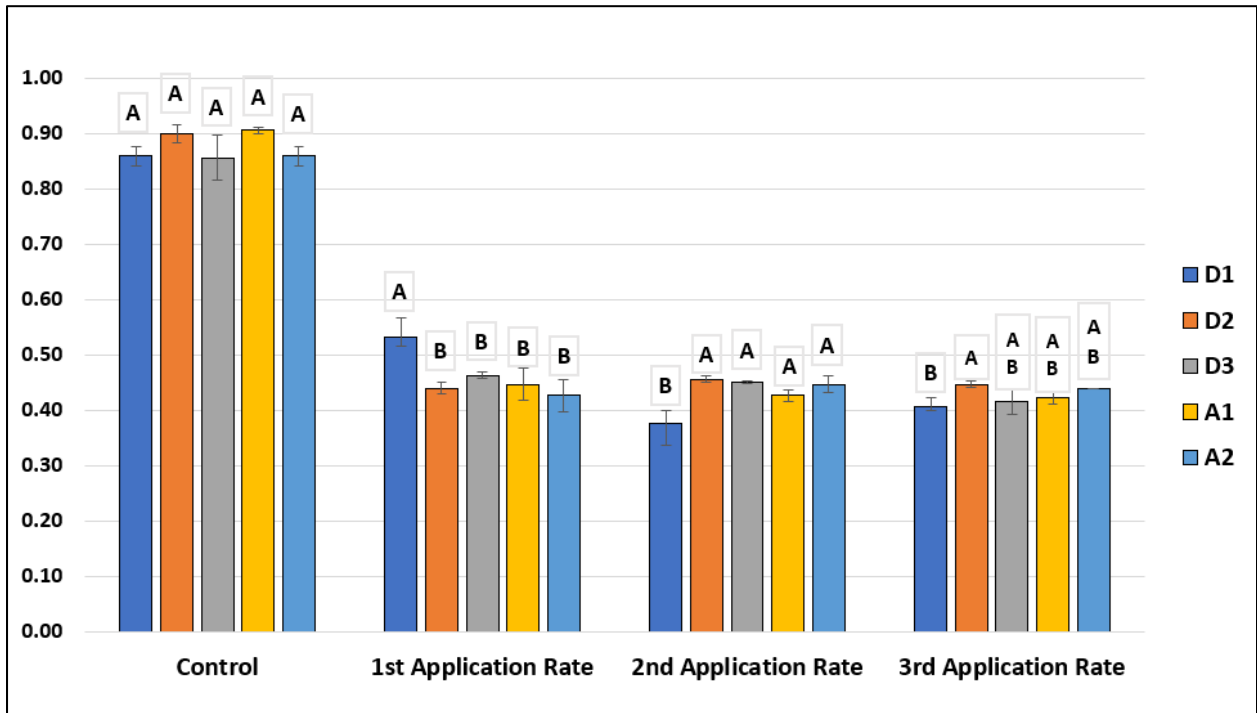


Figure 4.1 Summary of DFT-40 results under dry conditions (asphalt)

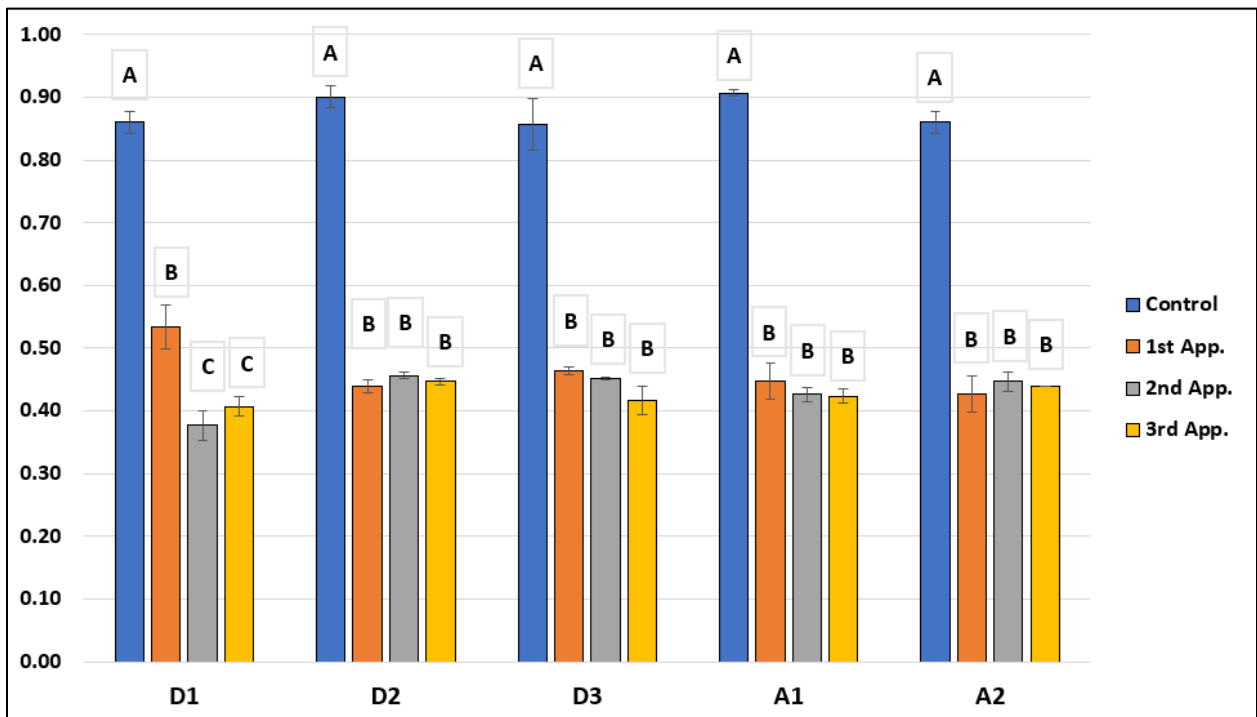


Figure 4.2 Summary of DFT-40 results under dry conditions (asphalt)

Tukey's Honestly Significant Difference (Tukey HSD) statistical analysis was conducted to compare the friction results at different application rates. The statistical test was performed at a 95 percent confidence interval (i.e., $\alpha = 0.05$). Testing values were assigned with different upper-case letters (e.g., A, B, C, etc.). If the testing groups shared the same letters, then there was no significant difference among the testing groups. The statistical analysis of the friction results after the first application showed that product D1 had higher friction than the other products, and the difference was statistically significant. However, after the second application, the friction of D1 was significantly lower than that of the others. After the third application rate, D1 had the lowest friction, and it was significantly lower than D2, but the performance was comparable to that of the other products.

Figure 4.2 shows the same testing results, but each group is presented for one product to compare the effects of the application rate increase. The statistical analysis showed that increasing the application rate did not significantly reduce friction, and performance was comparable for all products except D1, for which friction after the second and third applications was statically lower than friction after the first application.

The results demonstrated less variation in friction under wet conditions than variations in dry conditions. Figure 4.3 illustrates the friction results obtained under wet conditions for the DFT at 60 km/hr. At DFT-60, the initial friction values, without any products applied, were between 0.54 and 0.56. The application of different products did not result in significant change in friction in wet conditions, and there was no consistent relationship between reduction in friction and application rate. Meanwhile, figure 4.4 shows that there was a significant reduction in friction after the third application in comparison to the control, for all products except A2.

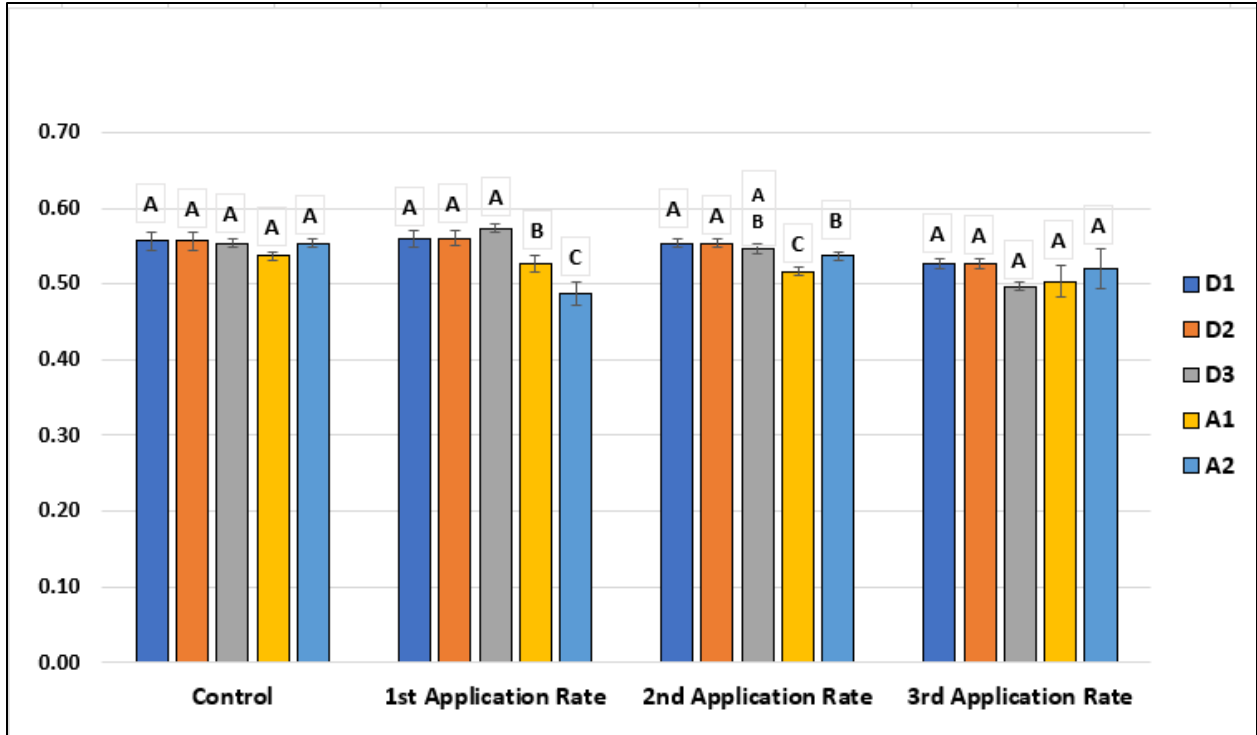


Figure 4.3 Summary of DFT-60 results under wet conditions (asphalt)

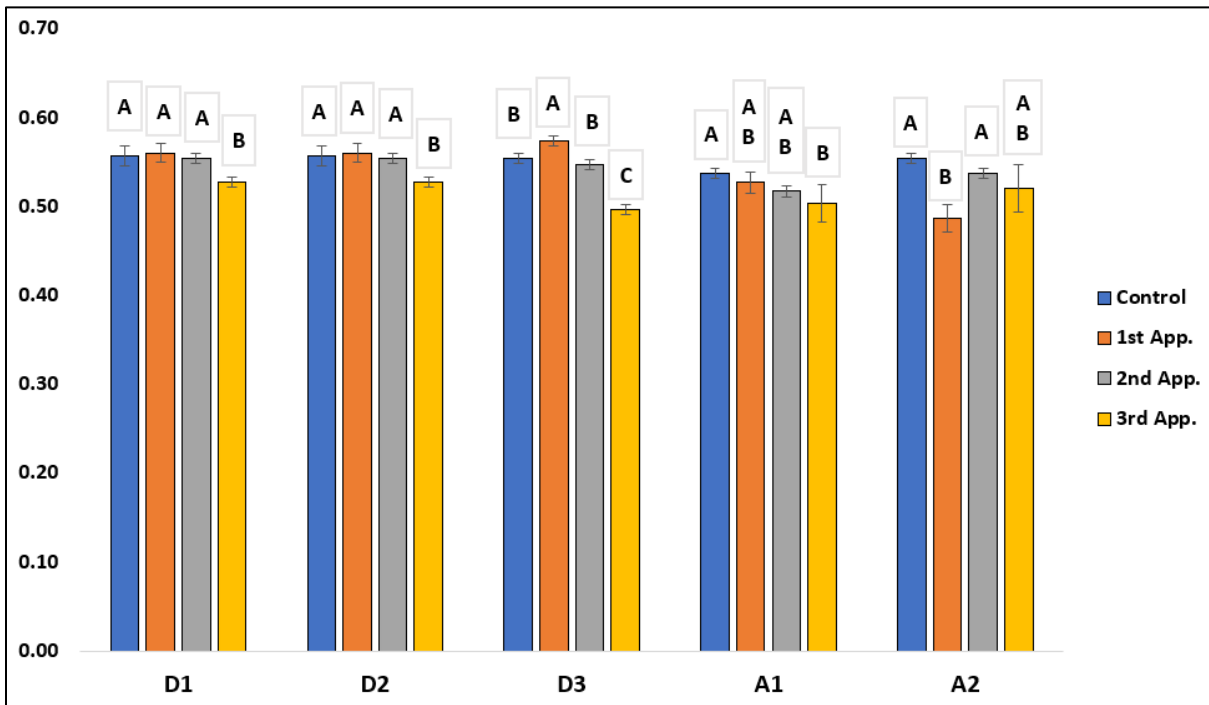


Figure 4.4 Summary of DFT-60 results under wet conditions (asphalt)

For the concrete slabs, the friction values obtained from the DFT at a speed of 40 km/hr. in dry conditions are summarized in figures 4.5 and 4.6. Overall, the initial friction decreased after the products had been applied on the surface, similar to the response of the asphalt slabs. The friction of anti-icer A1 decreased from 0.81 to 0.66 as the amount of product applied increased after the third application. Meanwhile, there was no consistent relationship between friction and application rates for other products. The statistical analysis for the second application rate showed that D1 had higher friction than all other products. After the third application, D1 still showed the highest friction among the others. Overall, all the products had friction coefficients ranging between 0.66 and 0.80.

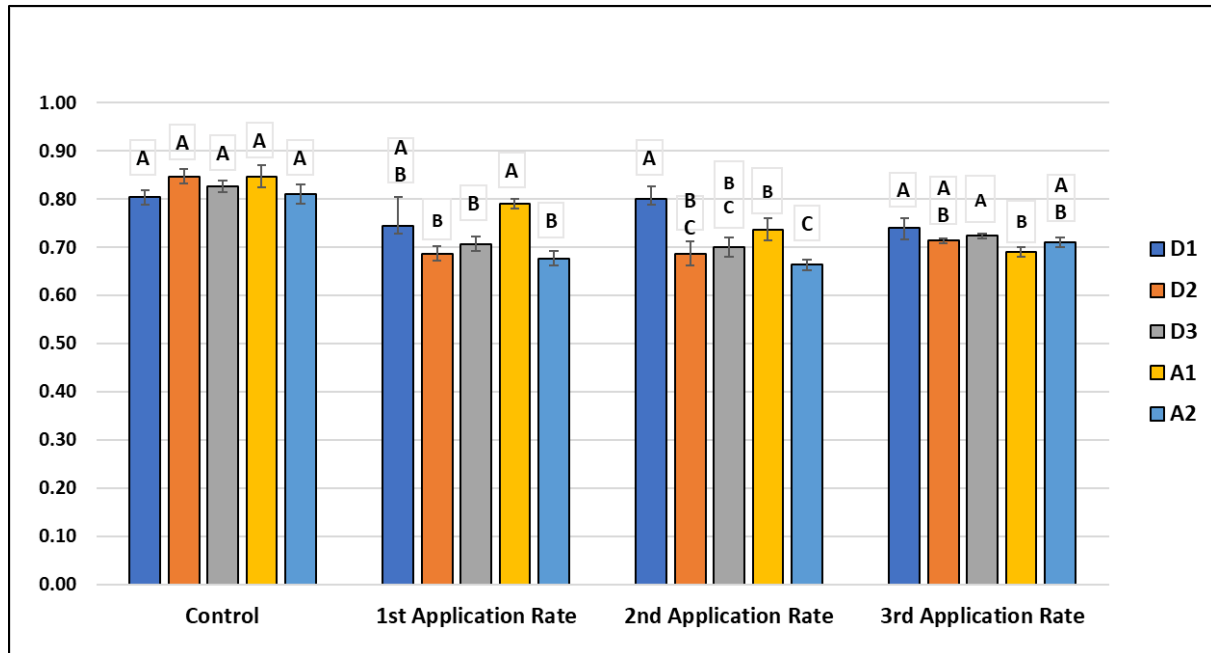


Figure 4.5 Summary of DFT-40 results under dry conditions (PCC)

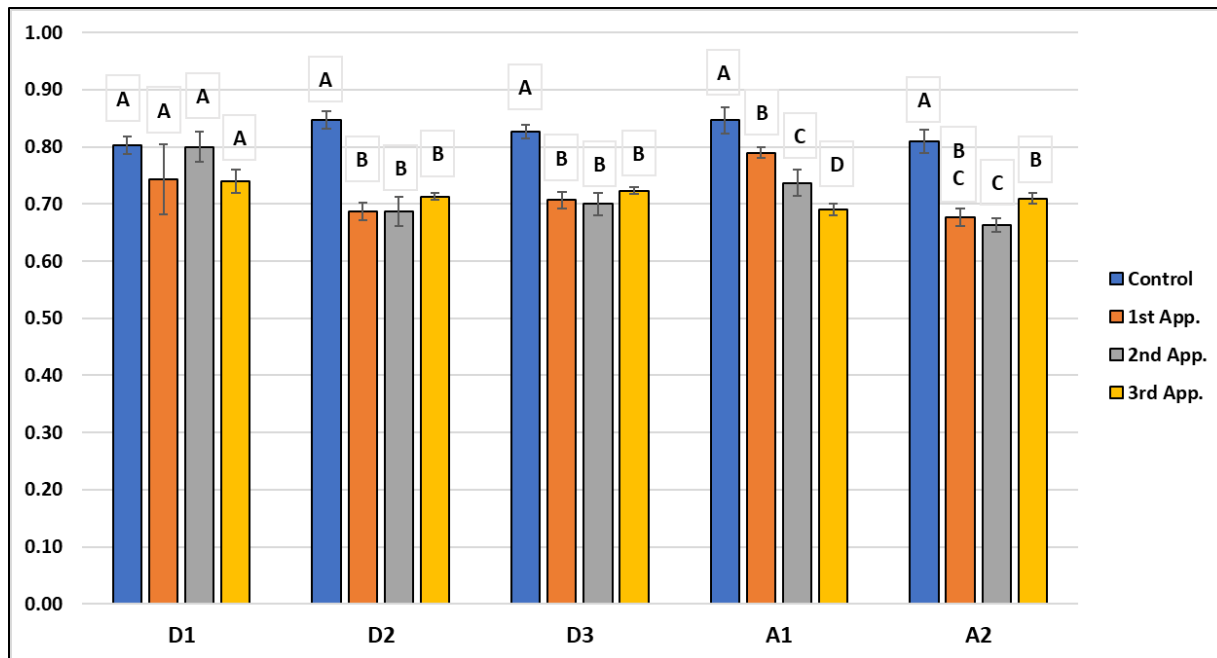


Figure 4.6 Summary of DFT-40 results under dry conditions (PCC)

Figure 4.7 summarizes the friction values obtained at 60 km/hr for PCC slabs in wet conditions. The friction measurements of D3 were the highest after the first application and were statistically different than those of the other products. After the second and third applications, A2 had the highest friction value, which was statistically higher than those of the other products. However, after the third application, the variation in the friction values for all the products ranged from 0.46 to 0.55. Figures 4.7 and 4.8 indicate that there is no clear trend in the results, similar to the results from the asphalt slabs in wet conditions.

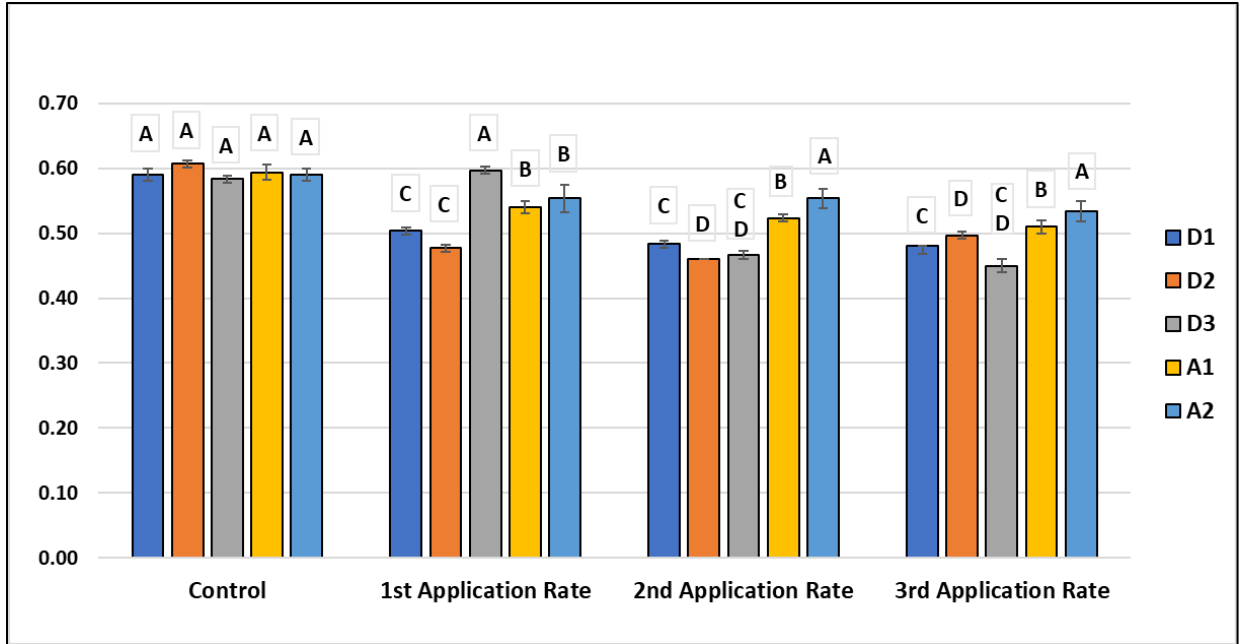


Figure 4.7 Summary of DFT-60 results under wet conditions (PCC)

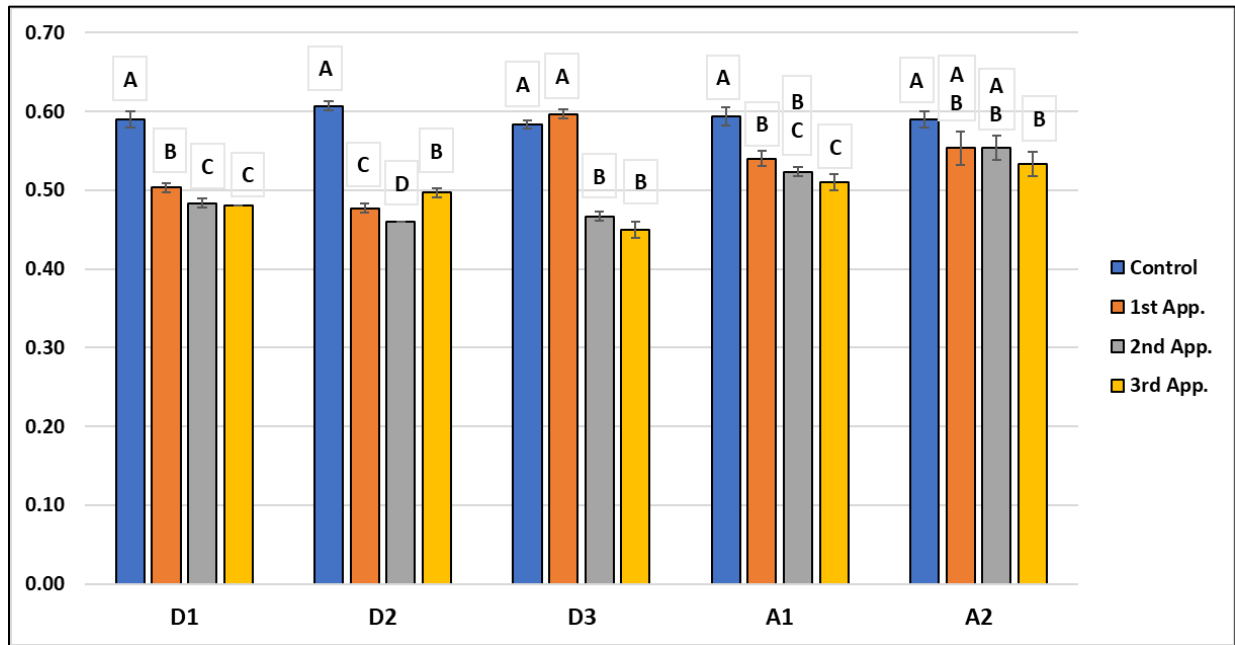


Figure 4.8 Summary of DFT-60 results under wet conditions (PCC)

4.2. Three-Wheel Polisher Device (TWPD)

The research team used the TWPD to simulate the effects of traffic on pavements under icy conditions. The TWPD came with six steel loading plates that could be placed on the top of a rotating turntable. There were three pneumatic tires attached to the turntable that rotated on the test specimen. The researchers used the device to test asphalt and concrete slabs using three different testing modes. The first testing mode used three steel plates (a total weight of 31.5 lb) on the top of the pneumatic tires to simulate a medium traffic load. The second testing mode utilized six plates (a total weight of 63.0 lb) to simulate a heavy traffic load. The last testing mode used a scraper blade attached to the turntable and pneumatic tires to simulate snow removal blades in the field.

The TWPD testing was conducted at an average temperature of 14 °F. Note that the researchers conducted trial tests at the minimum manufacturer recommended rate (first application rate) and 100 percent of the manufacturer's rate (the second application rate). The preliminary results showed these rates did not have a significant effect on breaking or melting the ice. Therefore, the team conduct the TWPD testing at a third application rate, which was 200 percent of the manufacturer's recommended rate.

4.2.1. First Testing Mode

Each test slab had a layer of ice (20 mm or 0.8 in. thick) at the top. After a set of loading cycles (3,500 cycles), the depth of melted ice along the wheel path was measured to determine the melting rate under the first mode of testing. The results indicated that D3 had the highest depth of 1.61 mm, and the statistical analysis showed that this was significantly different than those of the other deicers and anti-icers, as shown in figure 4.9. The performance of the other chemicals was better than that of the control surface, which demonstrated the effectiveness of the products in melting the ice, and the performances of the various products were close to each other except for D3, as mentioned earlier. Meanwhile, the depth of melted ice ranged from 1.07 mm (using A2) to 1.61 mm (using D3), which was smaller than the thickness of the ice layer (20 mm). This could be attributed to the weight applied to the turntable, which may not have been enough to break the ice and force the chemicals to infiltrate to the surface and accelerate the ice melting. Therefore, the team tested additional asphalt and concrete slabs after they increased the weight on the tires.

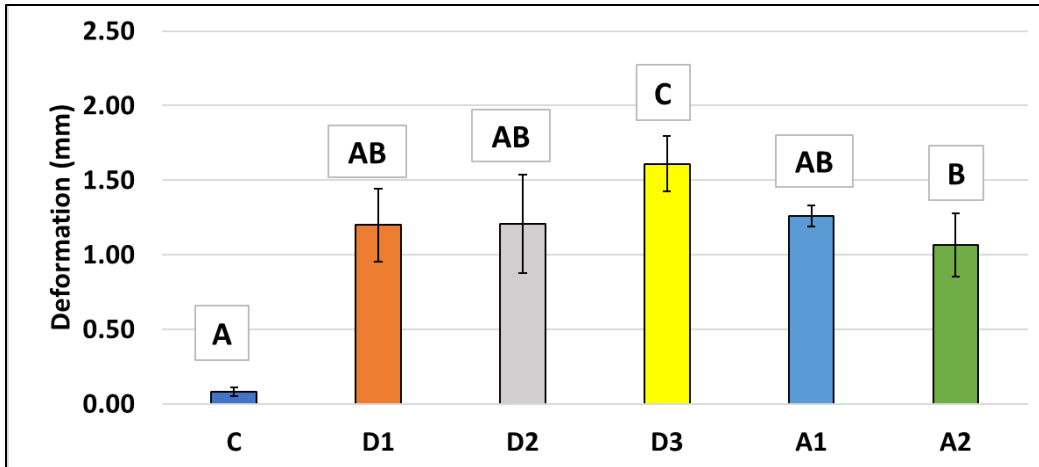


Figure 4.9 Ice melting results on asphalt slabs after TWPD testing (31.5 lb)

4.2.2. Second Testing Mode

The second set of tests utilized six steel plates that had a total weight of 63.0 lb on the turntable with the pneumatic tires. The results, shown in figure 4.10, indicated that D2 and D3 produced the greatest depth of melted ice at 6.17 mm and 5.81 mm, respectively. Also, the results of these two products (i.e., D2 and D3) were statistically significantly different than that of the control surface (0.56 mm). Results from products D1, A1, and A2 were also significantly greater than that of the control surface, with depth values of 4.18 mm, 3.42 mm, and 3.92 mm, respectively. The results showed that all chemicals were effective at melting the ice, while D2 and D3 showed the best results.

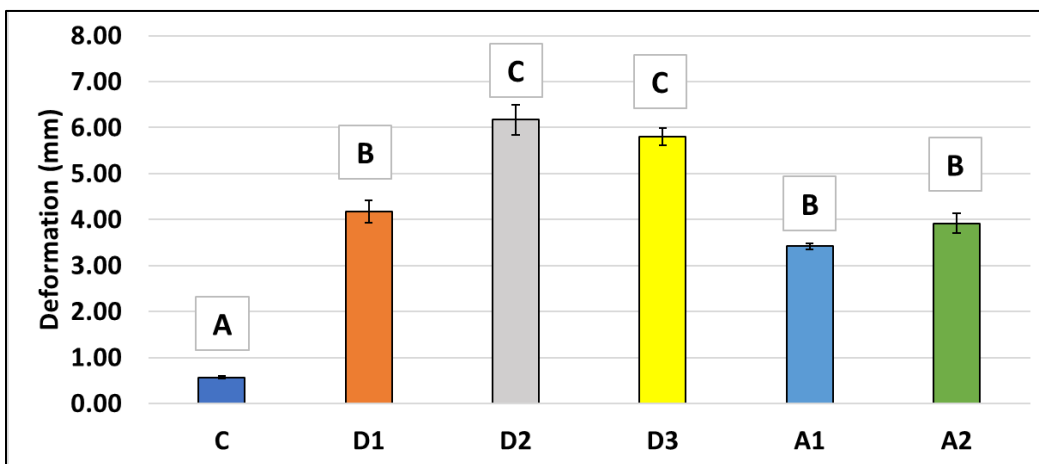


Figure 4.10 Ice melting results on asphalt slabs after TWPD testing (63 lb)

For the PCC concrete surfaces, the results also showed that all the chemicals were effective at melting the ice, as shown in figure 4.11. The testing results followed the same trend as that of the asphalt surfaces, where D2 and D3 had the greatest depth values of 6.01 mm and 6.57 mm, respectively, and those were significantly different than that of the control surface (0.73 mm). The other chemicals (i.e., D1, A1, and A2) also had greater values than that of the control surface. The statistical analysis showed that the results of all the products were significantly greater than that of the control surface. Meanwhile, products D2 and D3 provided the best results.

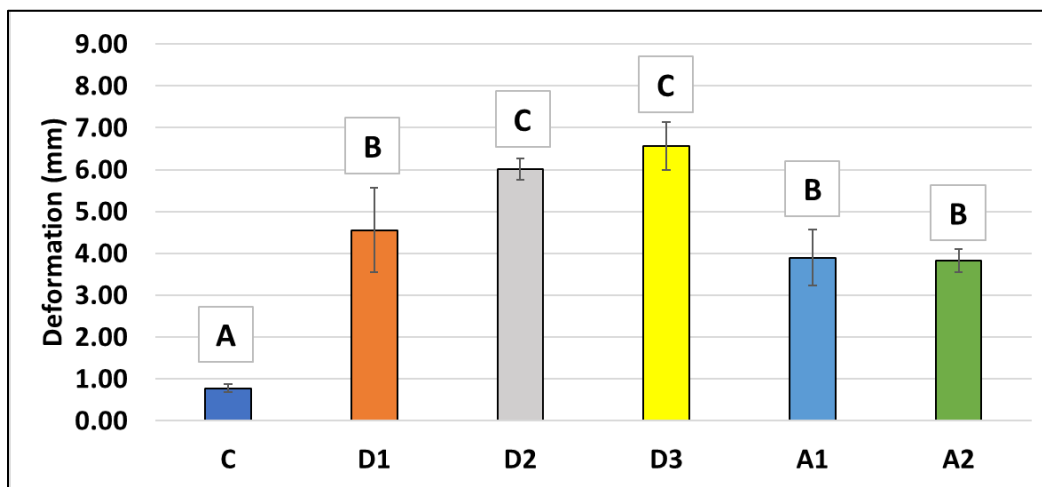


Figure 4.11 Ice melting results on PCC slabs after TWPD testing (63 lb)

4.2.3. *Third Testing Mode*

The third testing mode used six plates (total weight of 63.0 lb) in addition to a scraper blade that was attached to the turntable and pneumatic tires to simulate snow removal. Figure 4.12 demonstrates that all products had comparable performance, and the results were significantly higher than that of the control surface. Product D2 had the greatest depth value of 4.32 mm, whereas D3 had the lowest value of 3.21 mm. The statistical analysis indicated that the results of all the products were statistically significantly different from that of the control surface, and there was no significant difference in the performance among all products.

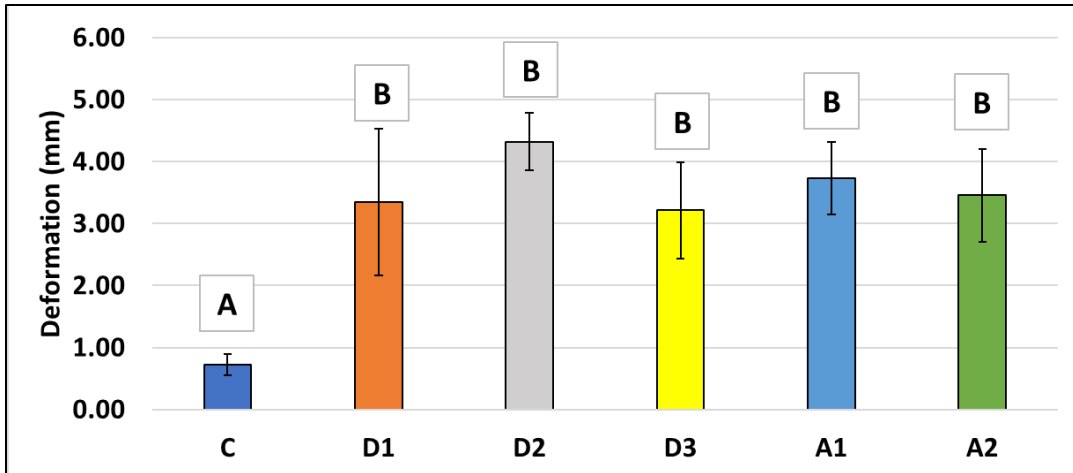


Figure 4.12 Ice melting results on asphalt slabs after TWPD testing (scraper blade)

The researcher team observed that the scraper blade pushed the chemicals, applied at the surface, away from the wheel path, which could have affected the ice melting rate. Also, the researchers observed that the greatest depth of melted ice occurred at the center of the wheel path; however, the use of the scraper blade resulted in a uniform depth of melted ice across the blade as expected, as illustrated in figure 4.13.

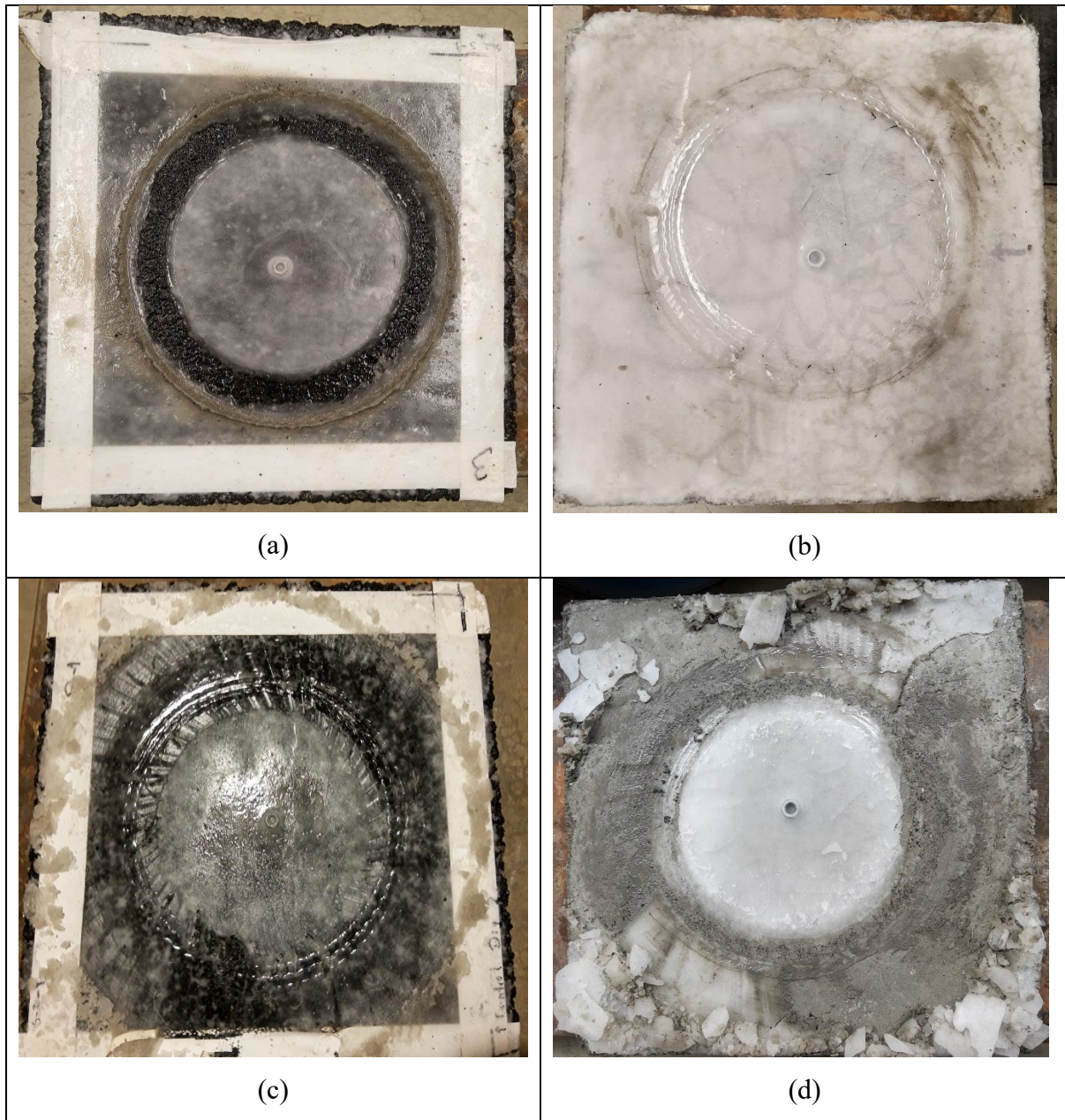


Figure 4.13 Ice melting shape **(a, b)** without scraper blade, **(c, d)** with scraper blade

For the PCC concrete surfaces, the results of testing with the scraper blade are shown in figure 4.14. The results indicated performances similar to those of the asphalt surface. All the test products improved the performance in comparison to that of the control surface. Product D3 exhibited the best performance with a depth of melted ice of 4.25 mm, whereas Product A1

provided the lowest depth value of 3.14 mm. The control surface experienced 0.77 mm of melted ice. The statistical analysis showed that all test products had comparable performance.

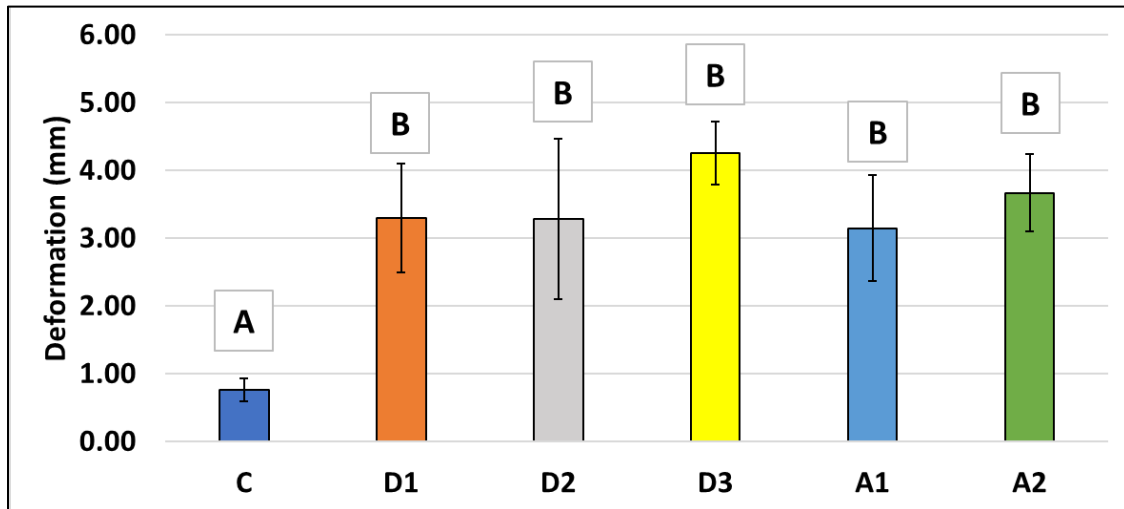


Figure 4.14 Ice melting results on PCC slabs after TWPD testing (scraper blade)

4.3. Ice Debonding Test

The researchers conducted a test to measure the shear force required to break the bond between the ice and the test pavement surfaces. The higher the shear force needed, the stronger the bond between the ice and the pavement surface. The testing demonstrated that all the deicer/anti-icer chemicals increased the debonding between the ice and the test surface, as expected. Regardless to the slab type (i.e., asphalt or concrete), all the deicers required less shear force than the control slab, as shown in figures 4.15 and 4.16. The results demonstrated that all five products were effective at weakening the bond between the ice and test surfaces. For the asphalt surface, the best performing product was D3 with a force of 18 lb. Product D2 required the highest force of 31.5 lb in comparison to 35.7 lb for the control slab. Anti-icers A1 and A2 had shear forces of 23.33 lb and 20.67 lb, respectively. However, the statistical analysis showed that there was no significant difference among all test products in comparison to the control surface. This could be attributed to the high variability of the measured force.

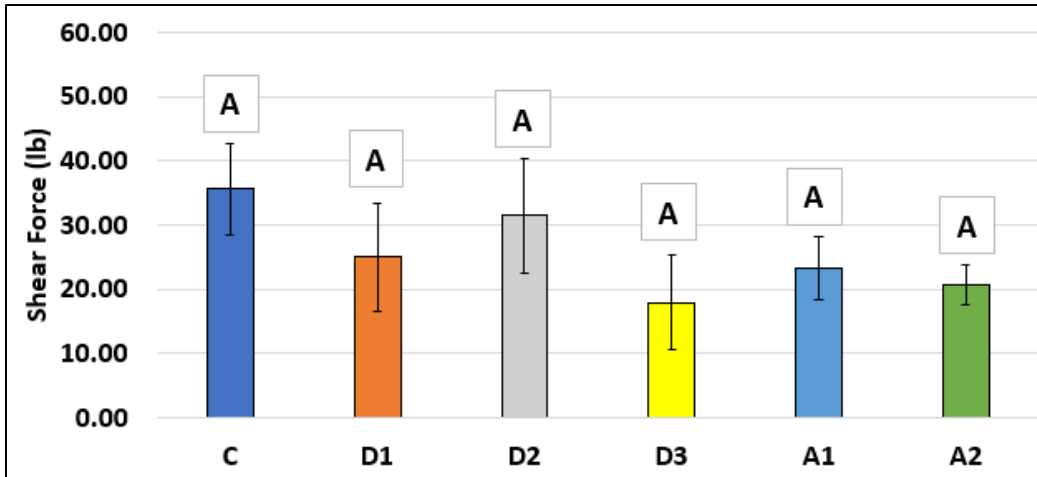


Figure 4.15 Debonding shear force of the asphalt slabs

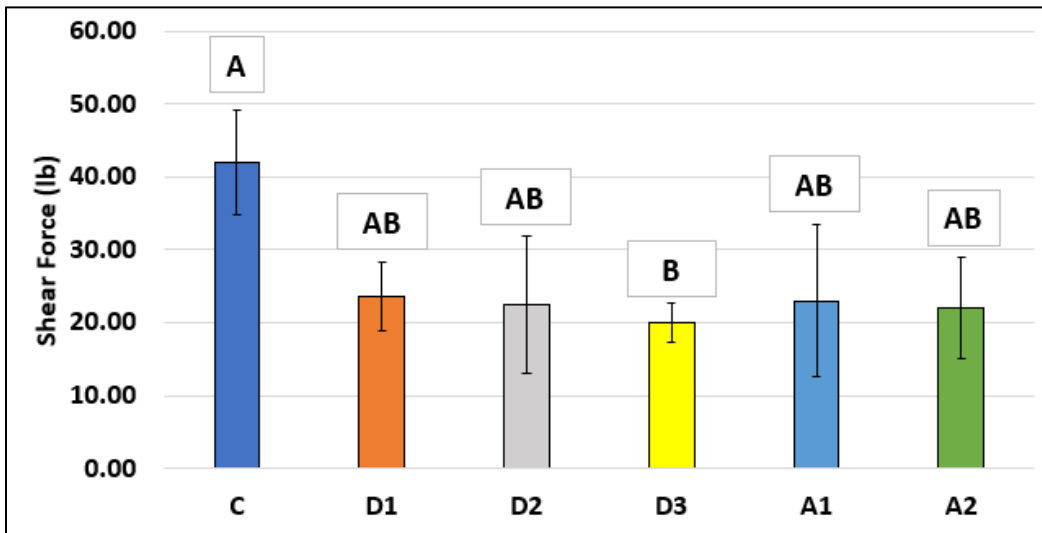


Figure 4.16 Debonding shear force of the concrete slabs

For the concrete surface, the best performing deicer was D3, similar to its performance on the asphalt surface, with a force of 20 lb, and its results were statistically significantly different than those of the control surface (42 lb). All other products required less force than on the control surface, but the difference was not significant. Product D1 and anti-icers A1 and A2 required 23.67 lb, 23 lb, and 22 lb, respectively, which was about half of the average force required for the control surface.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This study conducted a laboratory testing program to evaluate the performance of different deicing and anti-icing products under different conditions for efficient winter maintenance operations. On the basis of a literature review and market availability, three deicers (D1, D2, and D3) were identified: liquid calcium chloride (CaCl_2), liquid potassium (K), and granular sodium chloride (NaCl). In addition, two anti-icers (A1 and A2) were also obtained: magnesium chloride with two different inhibitors.

The research team used a portable, three-wheel polisher to simulate the effects of traffic loading during winter treatment operations. Pneumatic tires with two sets of loading plates were utilized. In addition, the pneumatic tires with a steel scraper blade were used to simulate snow removal operations. A dynamic friction tester (DFT) was used to measure the frictional characteristics of asphalt and concrete surfaces before and after the application of the test products. In addition, a new method was used to evaluate ice-pavement debonding by measuring the shear force required to break the bond between the ice and test surfaces.

The main findings of this research study can be summarized as follows:

- All test deicers and anti-icers were effective at melting ice accumulated on the asphalt and concrete pavement slabs, as expected. These results were consistent with other observations reported in the literature.
- The application of the test products resulted in a reduction in friction in comparison to the friction of the dry surface because these products act as a lubricant between the vehicle tires and pavement surface. Meanwhile, there was no significant change in friction for all the test products in wet conditions. In addition, there was no clear relationship between the application rate and a reduction in friction.
- The three-wheel polishing device testing results showed that deicers D2 and D3 outperformed the other products at melting the ice formed at the top of test surfaces. However, the application rates recommended by the manufacturers did not result in the best performance. Better performance was observed at higher rates (i.e., 100 percent and 200 percent higher than the recommended rate).
- The three-wheel polishing device testing results also demonstrated that all the test products were effective at melting and breaking the ice for both asphalt and concrete

- surfaces. The researchers noticed that the scraper blade pushed the products, applied at the surface, away from the wheel path, which affected the melting rate of the ice.
- A new protocol was used to evaluate the effectiveness of deicers/anti-icers in weakening the bond between the ice and test surfaces (i.e., asphalt and concrete). Overall, the use of the test products reduced the shear force required to break the bond between the ice and test surfaces. However, further research can be carried out to reduce the variability of the measured force. Such a procedure can be used to assess the performance of various anti-icing products and to select the proper application rate for different pavement types.
 - The researchers observed that after the application of the test deicers and anti-icers on the concrete surfaces a couple times, there was a clear change in the surface texture, which became eroded and exhibited signs of abrasion. Therefore, it is highly recommended to follow the manufacturer's recommendations when using deicers and anti-icers on concrete pavements in the field.
 - On the basis of the results of this study, the proposed laboratory evaluation protocol includes three tests. DFT testing assesses surface friction after the application of products. This test has direct safety implications, especially for the chemicals applied at the surface on dry conditions to prevent ice accumulation. The TWPD evaluates the performance of test products on icy roads under different traffic conditions. Finally, the proposed debonding test was found to be effective at evaluating the bond between the pavement surface and ice frozen at the top. The three testing protocols combined can provide a comprehensive assessment of the performance of various products under different environmental and operational conditions.

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APPENDIX A

Preparation of the Test Slabs

1. Assemble the metal compaction mold (figure A1a),
2. Use a thermal paper at the bottom of the mold (figure A1a),
3. Heat the loose asphalt mixtures and place the mix in the mold and level the materials evenly at the top (figure A1b),
4. Place another thermal paper at the top of the mold,
5. Place the compaction top plate and compact the loose mixtures for 10 minutes,
6. Remove the compaction top plate and let the slab to cool down.
7. Disassemble the compaction mold and remove the prepared slab.



Figure A1. Preparation and compaction of the test slabs

APPENDIX B

Preparation of Surface with Deicers or Anti-Icers

Needed Items

1. Spray with 20-ml capacity
2. Syringes of 10 ml
3. Scale in grams
4. Plastic gloves



Figure B 1. (a) Spray (20 ml), (b) Syringes, (c) Small scale



Figure B 2. Plastic gloves for protection

Procedure for Liquid and Solid Products

1. Record the weights of the spray (can and spreader), then wet the scale with the spray can at 0 gr.
2. Weigh 10 ml or more of the products (depending on the application rate) and with the syringe pour them into the bottle. For the granular product, weigh the amount of solid material (i.e., 10 gr).
3. Control the weight introduced into the pot (in grams) to reach the necessary measure of products to apply (i.e., 6 ml of D1 is equivalent to 6 grams), which is spread on the sample slab. For the solid product, mix it with water and stir for approximately 3 min.
4. Spray the product from side to side until the entire test surface is covered. For the solid product, spread the liquid part obtained from the combination of the solid product and the water onto the test surface. For the undissolved solid part, spread the beads on the test surface evenly.
5. Take friction measurements using the Dynamic Friction Tester (DFT) (three measurements)
6. Repeat this procedure for the three applications in dry conditions for the test products (i.e., five products).



Figure B 3 Example of controlling the amount of liquid deicer in the spray



Figure B 4 Solid deicer with water

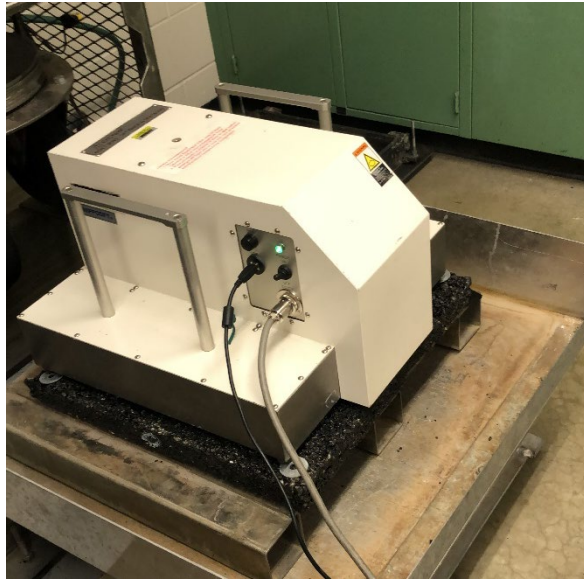


Figure B 5 DFT measuring the friction

APPENDIX C

Results at Dry Condition

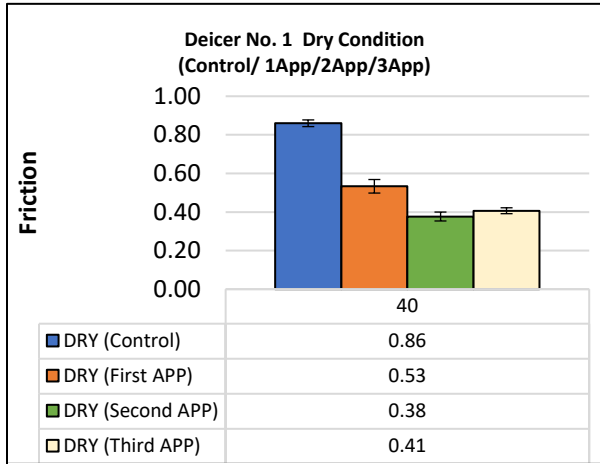


Figure C 1 Results at different application rates for D1 in dry conditions

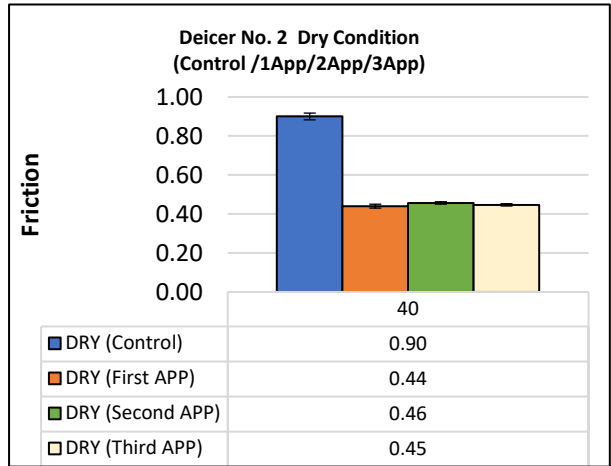


Figure C 2 Results at different application rates for D2 in dry conditions

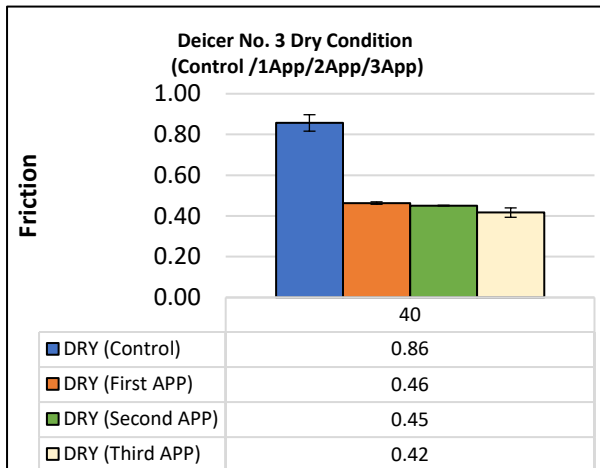


Figure C 3 Results at different application rates for D3 in dry conditions

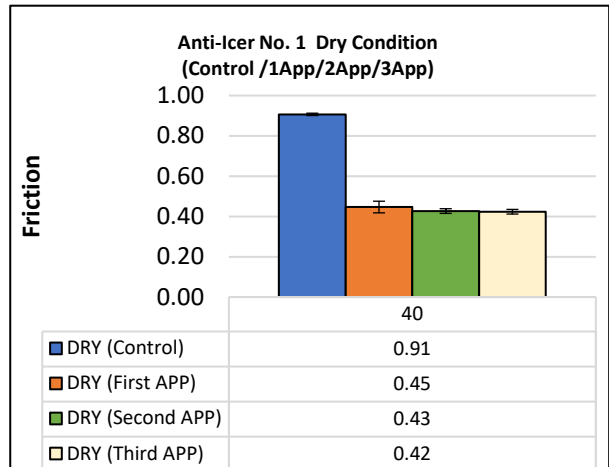


Figure C 4 Results at different application rates for A1 in dry conditions

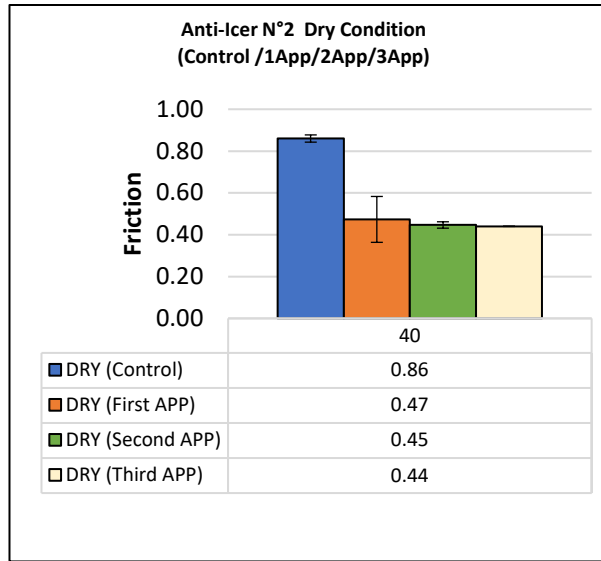


Figure C 1 Results at different application rates for A2 in dry conditions

Results at Wet Condition

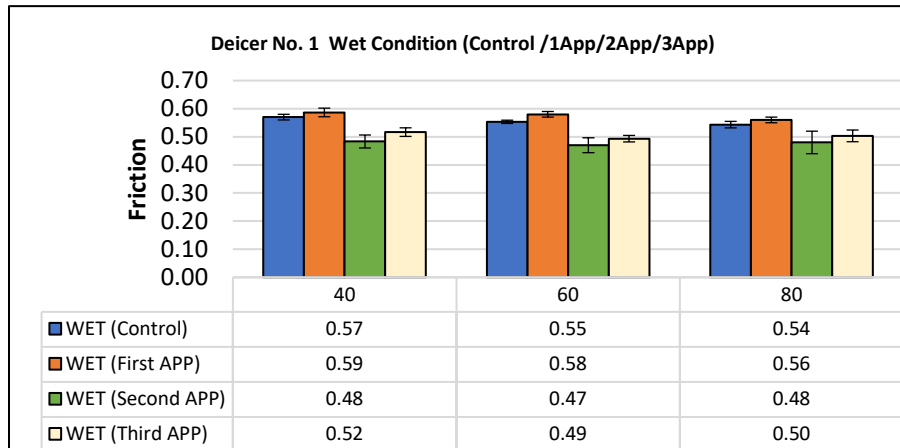


Figure C 2 Results at different application rates for D1 in wet conditions

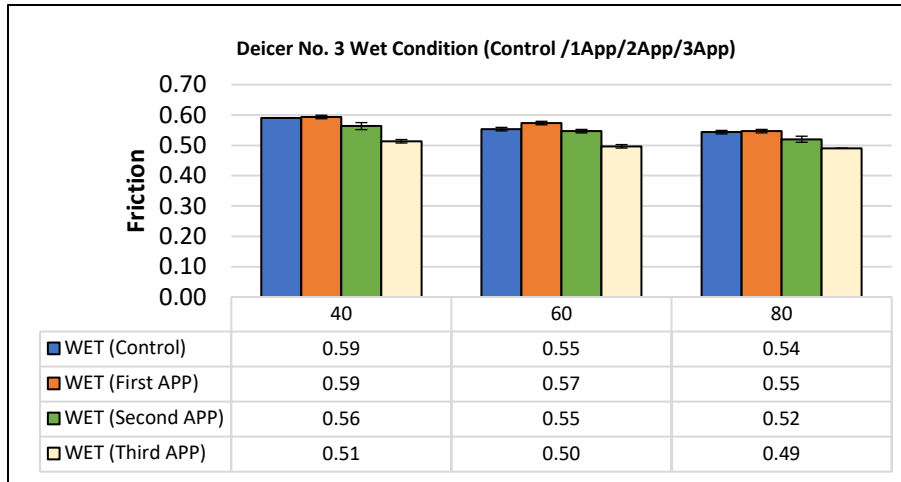


Figure C 3 Results at different application rates for D3 in wet conditions

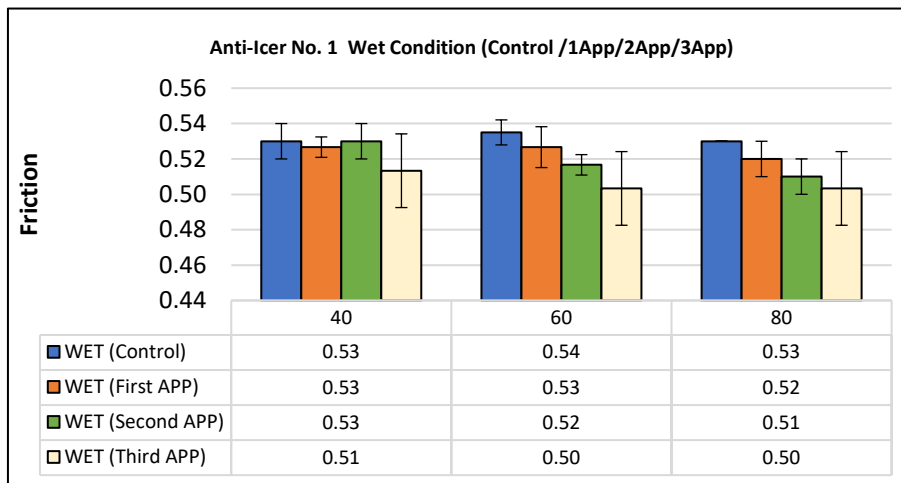


Figure C 4 Results at different application rates for A1 in wet conditions

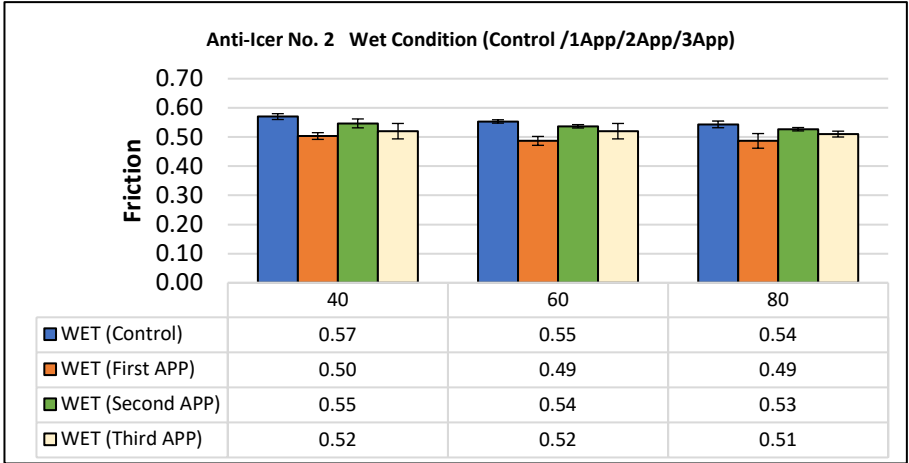


Figure C 6 Results at different application rates for A2 in wet conditions