Understanding the Chemical and Mechanical Performance of Snow and Ice Control Agents on Porous or Permeable Pavements

Submittal: Task 6: White Paper - Revised

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1. Introduction

Porous and permeable pavements (PPPs) often behave differently to winter conditions and snow and ice control treatment than dense graded pavements (DGPs). Key findings from the literature review and telephone interviews were used to design a laboratory test to compare the effectiveness of snow and ice control chemicals using a DGP made in Montana and several PPPs (from Missouri, New York and Massachusetts). The laboratory test methodology (equipment, steps) are described in the next section, followed by a statistical analysis of the data.

2. Laboratory Test Methods and Results

Laboratory tests were conducted at the Subzero Science and Engineering Research Facility (SSERF) at Montana State University, in the *Cold Structures Testing Chamber* at a temperature of 28°F. Information gathered in literature and from interviews indicated PPPs are more problematic at temperatures just below freezing (27–32°F).

Pavements

A series of laboratory tests were conducted on samples of DGPs and PPPs to simulate winter storms and determine the effectiveness of salt in reducing or preventing the snow–pavement bond and improving the friction of the road surface. The DGP (referred to as DGP-mt) was made at a field site in Montana. Two ultrathin friction course (UTFC) pavements were made in a laboratory from pavement mix supplied by New York and Missouri (referred to as UTFC-ny50i because it utilized ½” aggregate and UTFC-mo75i because it utilized ¾” aggregate). Two open-graded friction course (OGFC) pavements were made from cores of in-service pavements in Massachusetts (referred to as OGFC-ma5 and OGFC-ma2 because the pavements had service lives of 4-5 years and 1-2 years, respectively). All pavement samples were permanently mounted with epoxy onto a rigid aluminum plate to ensure stability during cleaning and storage at warmer temperatures. A summary of the pavement samples used for laboratory testing is in Table 1.

Table 1: Pavement Specimens

Pavement ID	Number of replicate samples	Source of Pavement Mix	Pavement type	Age	Size (in.)
DGP-mt	2	MT	Dense-graded pavement	Old* (>4 yrs)	9 x 19 x 1
UTFC-ny50i	2	NY	Ultrathin friction course	New	6 x 17 x 0.75
UTFC-mo75i	2	MO	Ultrathin friction course	New	6 x 17 x 0.75
OGFC-ma5y	1	MA	Open-graded friction course	Old (>4 yrs)	8.1 x 20 x 1.25
OGFC-ma2y	1	MA	Open-graded friction course	New (< 2 yrs)	8.1 x 20 x 1.25

* Pavement was newly made, but "aged" by lightly abrading the surface.

The DGP-mt pavement samples were made in Belgrade, Montana at a hot mix asphalt batch plant (Knife River Corporation – Belgrade Division). A large wood form with a depth of 1 inch was made by WTI staff and set up near the batch plant. Knife River produced, placed and compacted the hot mix asphalt (Figure 1, left). The asphalt mix had a nominal maximum aggregate size of ⅜ inch (some states refer to this as a 9.5 mm Superpave HMA), PG 58-28 asphalt binder, and air void content of 4.2%. A mix with ⅜ inch aggregate is common for 1-inch overlays (a very common pavement maintenance strategy), whereas 1½ and 2 inch overlays typically use asphalt mixes with aggregates up to ⅝ or ¾ inch. The pavement mix was compacted with a steel drum roller, without vibration. Samples measuring 9 inches by 19 inches were cut from the pad (Figure 1, right) and "aged" by lightly abrading the pavement surface with an angle grinder to expose the aggregate and make surface roughness and texture similar for all pavement samples (Figure 2).

Figure 1: DGP compacted in wood form (left) and cutting samples (right).

Figure 2: DGP pavement specimen after surface grinding.

The ultra-thin friction course pavements were made at the Highway Sustainability Research Center (HSRC) at the University of Massachusetts Dartmouth with a PReSBOX Asphalt Prism Shearbox Compactor using asphalt pavement mix collected from construction sites in Missouri and New York. Hot mix asphalt from these two sites was collected and shipped to HSRC for reheating and compaction. The PReSBOX compacts a pavement mixture that is 6 inches wide, 17.7 inches long, and 6 inches thick. From this, two samples were cut with “virgin” surfaces (the top and bottom of the beam) that were 6 x 17 x ¾ inches. The New York (UTFC-ny50i) hot mix was collected from a paving site on Rte 394 in Chautauqua County during September 2013. The NovaChip Type B mix has a maximum aggregate size of ½ inch. The Missouri hot mix (UTFC-mo75i) was collected from a paving site on US 61 near St. Charles, MO. The ultrathin bonded asphalt wearing surface (UBAWS) Type C mix has a maximum aggregate size of ¾ inch.

Figure 3: Ultrathin friction course pavements made with pavement mix from New York with ½ inch max aggregate (left) and Missouri with ¾ inch max aggregate (right).

The open-graded friction course pavements were made from cores of two in-service pavements in Massachusetts. Ten 6-in. diameter cores were collected from each site during April 2016. The pavement sample named OGFC-ma2y was from I-93 near Braintree, MA and had been in-service for 1.5 years (Figure 4). The pavement sample named OGFC-ma5y was harvested from I-95 near Woburn, MA and had been in-service for 4.5 years (Figure 5). The 4-in. thick cores were shipped to WTI where they were sliced to a uniform depth of 1¼ in. and the edges trimmed to form squares with 4 in. sides. Ten of these squares were epoxied onto an aluminum plate to provide a level 8 x 20 x 1¼ in. pavement specimen.

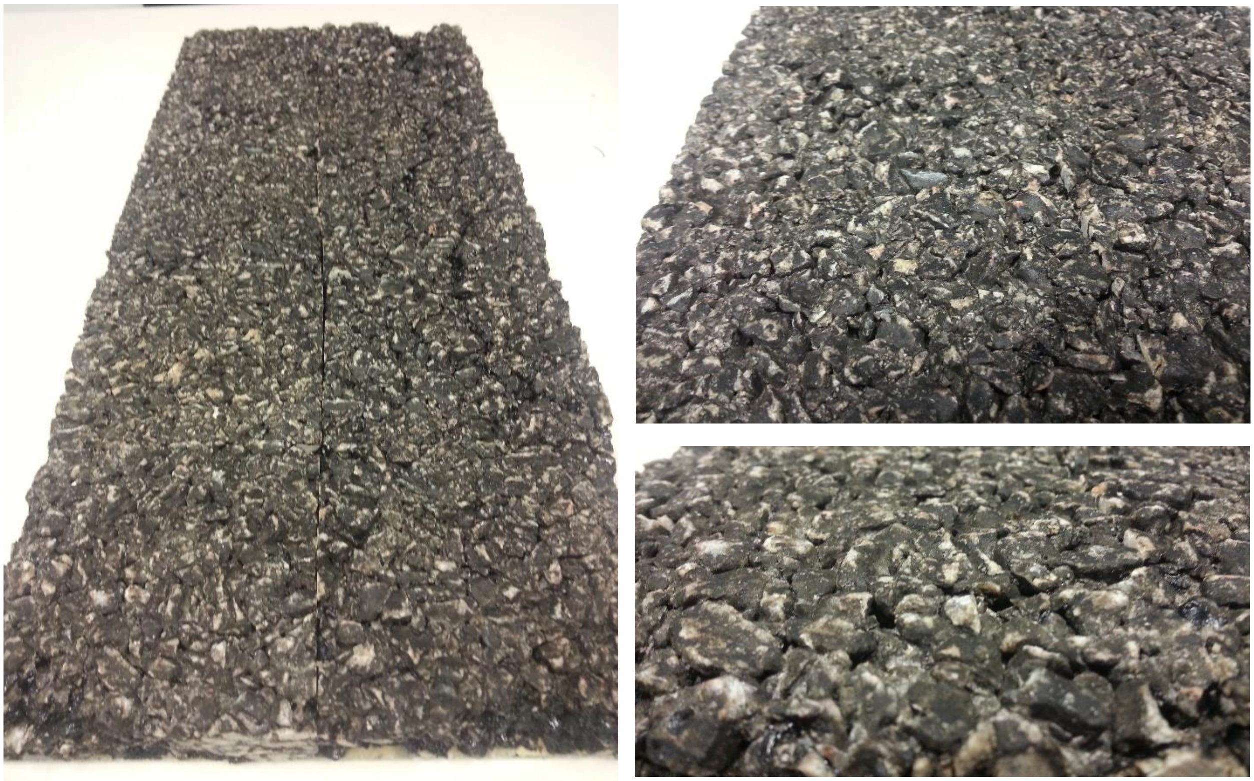


Figure 4: Open-graded friction course pavements from Massachusetts cores (OGFC-ma2y).

Figure 5: Open-graded friction course pavement from Massachusetts cores (OGFC-ma5y).

Sequence of Steps during a Lab Test

Four types of lab tests were conducted, distinguished by when and how salt (sodium chloride) was applied. The tests in which no salt was applied are referred to as the controls, and can be used to compare the effectiveness of deicing and anti-icing with salt. The sequence of steps during each of the four types of tests is shown in Table 2. Details of each activity (applying snow, applying salt, trafficking, and measuring snow–pavement bond and friction) are described next. All pavement samples were rinsed, scrubbed and dried before being placed back in the cold chamber.

Table 2: Sequence of Steps for Lab Tests

Control (No Salt)	Anti-icing (Salt Brine)	Deicing (Dry Salt)	Deicing (Pre-wet Salt)
1. Measure friction	1. Measure friction	1. Measure friction	1. Measure friction
	2. Apply salt brine		
2. Apply snow	3. Apply snow	2. Apply snow	2. Apply snow
		3. Apply dry salt	3. Apply pre-wet salt
3. Traffic	4. Traffic	4. Traffic	4. Traffic
4. Measure snow–pavement bond	5. Measure snow–pavement bond	5. Measure snow–pavement bond	5. Measure snow–pavement bond
5. Measure friction	6. Measure friction	6. Measure friction	6. Measure friction

Snow Application

Snow was made by SSERF staff in the *Cold Hydrodynamics Chamber* at MSU using a constructed system with a high humidity cold- temperature chute. Snow crystals form on strings and drop into a tray. Snow was collected from the tray and stored in insulated coolers in the *Experiment Preparation and Instructional Chamber* (Figure 6). The air temperature during snow-making was -13°F and in storage was 5°F, which produces “drier” snow. The decision to make snow rather than collecting natural deposits from the field was to ensure consistency, which is critical for comparing lab tests which were conducted over a long period of time. The snow used in laboratory tests was stored for at least 4 days and not more than 4 months to ensure consistency in morphology of grain structure.

Figure 6: Snow making process and snow storage.

At the beginning of each day of testing, manufactured snow was carried to the *Cold Structures Testing Chamber* in an insulated cooler for that day’s use (any extra snow was discarded and not returned to storage) and equilibrated to 28°F. The snow was sieved through a 1 mm mesh which breaks the bonds between the individual snow particles, and encourages sintering and bonding of the snow to the pavement surface. The loose, sieved snow had an average density of 19 lb/ft^3 (0.3 g/cm^3). The pavement sample was placed in a specially designed and constructed compaction box and 1.8 lb (800 g) of sieved snow was evenly distributed across the surface. The loose depth of snow was about ¾ in. thick. The lid of the box was fitted with a flexible and soft rubber bladder to apply a uniform compactive stress directly to the surface of the snow. The bladder assembly was filled with compressed air at 60 psi for 5 minutes to compact the snow onto the surface of the pavement. The compacted depth of snow was about ½ in. The process of snow application and compaction is illustrated in Figure 7.

Figure 7: Snow application and compaction sequence (top left: pavement sample in compaction box; top right: snow being re-sieved; bottom left: lid closed during compaction; bottom right: compacted snow).

Salt Application

Deicing and anti-icing tests were conducted where deicing tests used solid rock salt applied on top of compacted snow and anti-icing tests used salt brine applied to the pavement surface before snow application. Sodium chloride was used because it is the most widely used product, particularly at temperatures of 28°F. Anti-icing tests were conducted by applying salt brine (23.3% solution with specific gravity of 1.179, verified with a hydrometer) to clean, dry pavement samples at a rate of 50 gallons per lane mile. Salt brine was applied using a calibrated paint sprayer fitted with a nozzle that produced a very fine spray. A clear chamber was used to prevent the wind in the lab chamber from affecting the spray during application (Figure 8). Application rates were validated frequently by spraying onto parchment paper and weighing the mass of salt brine on the paper. The salt brine was allowed to dry onto the pavement surface before continuing with the next step of the experiment (Figure 9), which took approximately 15 minutes.

Figure 8: Enclosure and sprayer for anti-icing pavements.

Figure 9: Close-up of a pavement sample after applying salt brine (left) and after drying (right).

Two types of deicing tests were conducted, using either dry rock salt or pre-wet salt. The solid rock salt was sieved to ensure similar sized particles were applied across the samples. All salt particles passed the No. 8 sieve (opening size 0.093 in. (2.36 mm)) and were retained on the No. 10 sieve (0.079 in. (2.0 mm)). Individual salt particles were applied in a grid pattern with 1 inch spacing between particles across the entire pavement sample corresponding to a rate of 250 lb/LM (lb/lane-mile). The total mass and number of salt grains varied based on the size of the pavement samples. Experiments with pre-wet salt used the same number and mass of salt particles as the dry salt experiments; however, salt brine was mixed onto the salt at a rate of 10 gal/ton just prior to applying the salt to the pavement. Photographs after deicer application indicate the salt particles penetrated through the snow and spread out under the snow (Figure 10).

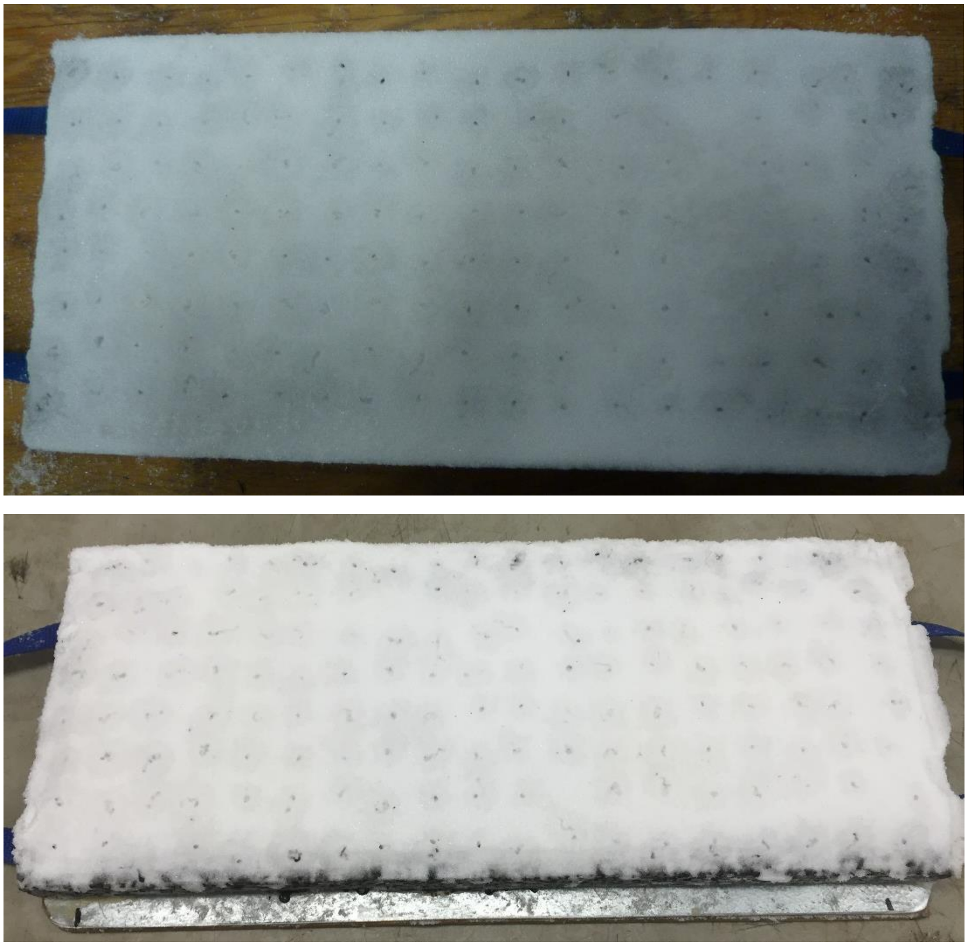


Figure 10: Five minutes after deicing (upper: DGP with dry salt; lower: OGFC with pre-wet salt).

Traffic Simulation

To simulate vehicle traffic in the laboratory, the pavement samples were trafficked using a custom built automated trafficking machine (Figure 11). Pneumatic cylinders apply load onto an axle fitted with a single tire, which presses down onto the pavement samples. The load applied to the pavement samples was 1,130 lb. The wheel assembly is stationary and a platform containing the sample translates back and forth under the tire, causing the tire to rotate. During testing the track moved at a speed of about 0.7 mph (1.0 feet per second). Traffic simulation occurred after snow compaction during control and anti-icing tests. During deicing tests, traffic simulation occurred 5 minutes after the last salt particle was applied to the snow. The samples were trafficked for 600 single tire passes (equivalent to 300 2-axle vehicles passes of a single tire on the pavement sample), which took 18 minutes. Photos of a pavement sample during a deicing test before and after trafficking are shown in Figure 12.

Figure 11: Simulated trafficking device.

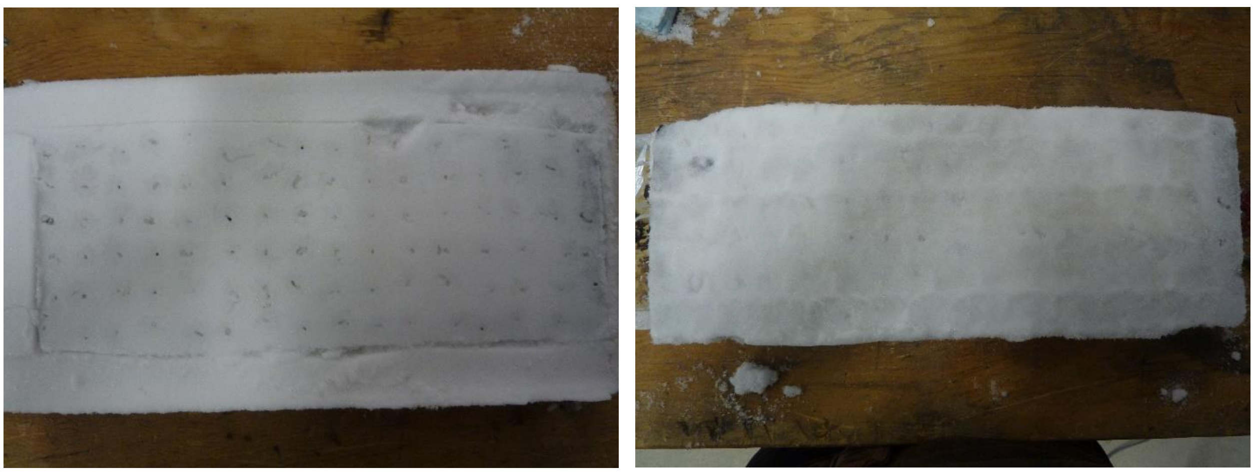


Figure 12: UTFC-ny sample during a deicing test with dry salt before and after trafficking.

Measurement of Snow–Pavement Bond

The shear force required to plow the snow from the pavement surface was measured to investigate the effect of deicing and anti-icing on the snow–pavement bond. After trafficking, individual sections of snow were isolated by cutting the snow with a serrated saw and carefully removing snow adjacent to intact 2-in. square specimens. A hollow metal box was placed around the specimen and pulled horizontally using a spring scale to measure the maximum force required to shear the snow from the pavement. The process of isolating the snow specimens for shearing and shearing the sample from the pavement is shown in Figure 13. The number of shear tests varied for each type of pavement based on the size of the pavement sample. The larger area of the DGP and OGFC pavements accommodated 10 snow specimens, while only five samples fit on the smaller UTFC pavements.

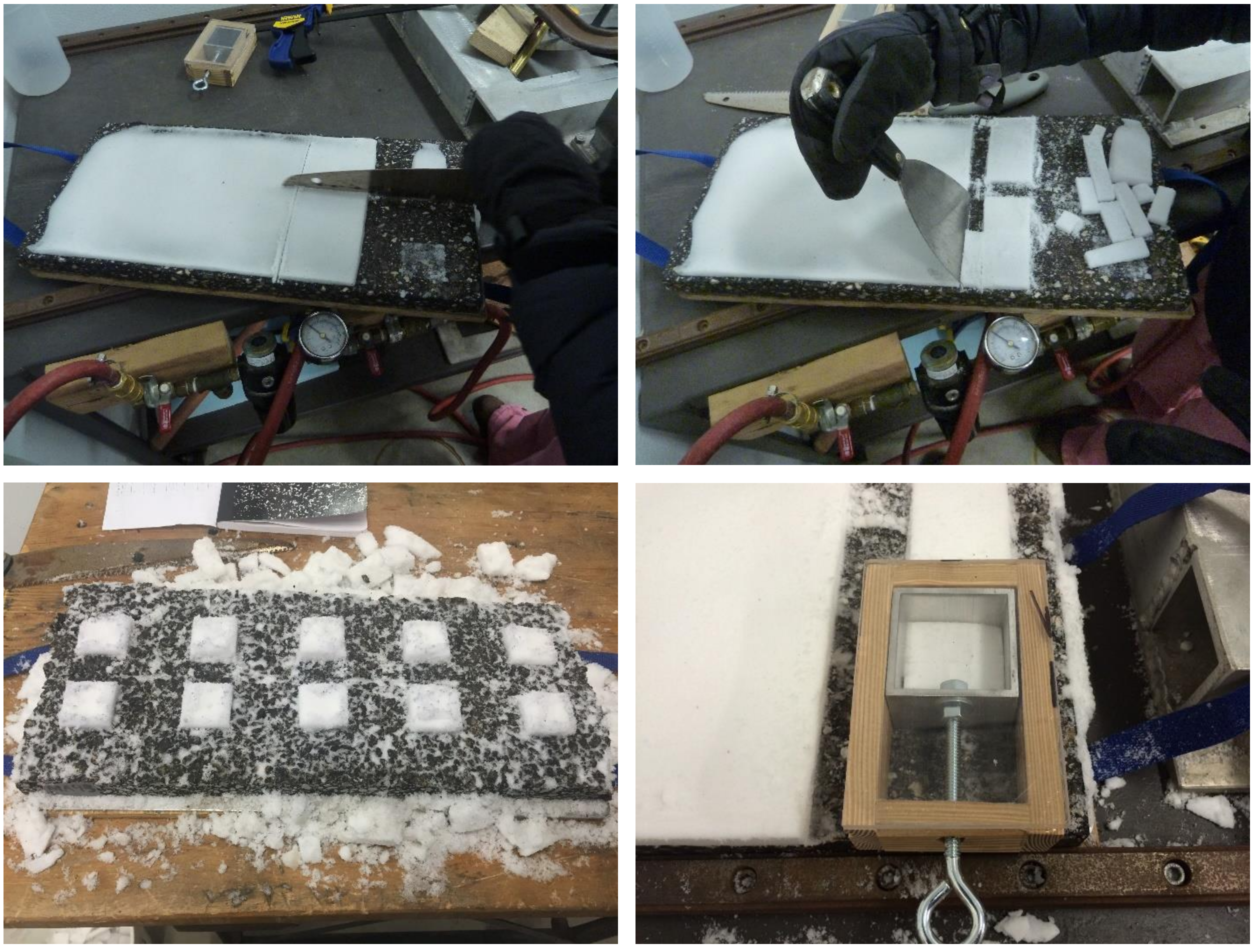


Figure 13: Measuring snow-pavement bond by sawing and isolating snow samples for shearing and using a hollow metal box for plowing.

Theoretically, weaker snow-pavement bonds should be more easily plowed, while stronger bonds should be more difficult to plow; however, specific limits of snow bond are not established, and direct correlations between the snow-bond measured in the laboratory and actual plowing stresses on roadways were not made. Thus, all snow bond measurement results should be viewed as relative comparisons to one another used to help understand how the various treatments affect the bonding of snow to the pavement. The results of snow-bond measurements for all tests are shown in Figure 14. Average snow bond ranged from about 0.5 to 10 psi. For a single pavement type, control tests with no salt generally had higher snow bond values than tests with salt. A statistical analysis was used to determine whether differences in snow-bond between pavement types and treatment types were statistically significant. The results of this analysis are presented and discussed in the next section.

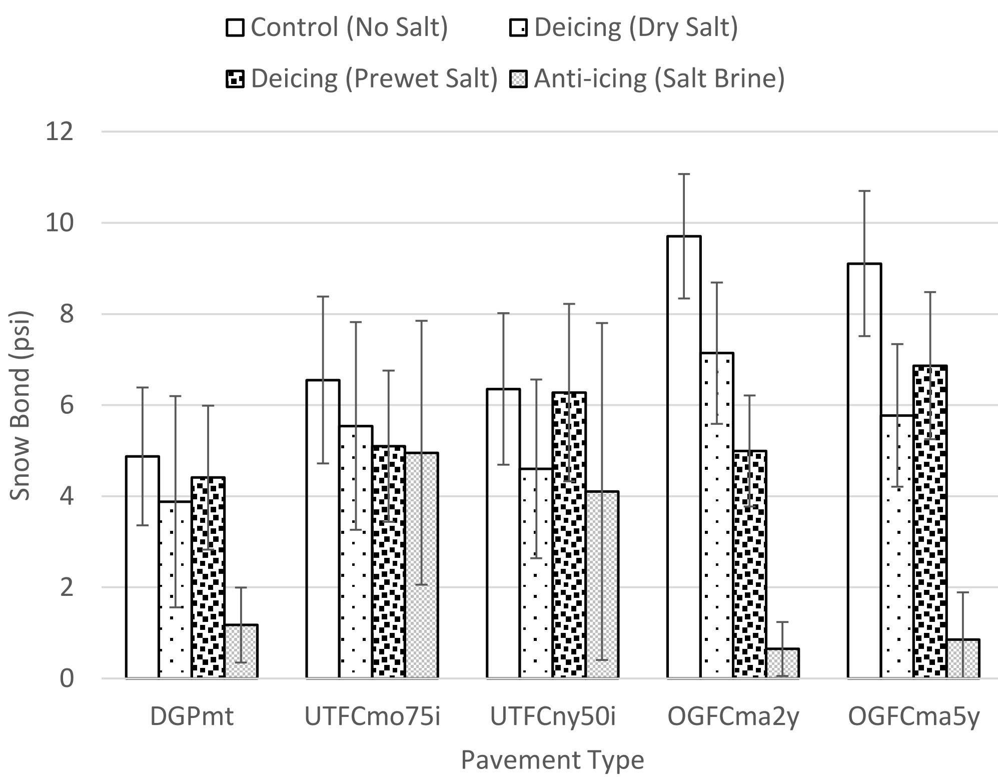


Figure 14: Snow-pavement bond test results for each pavement type (average value ± 1 standad deviation).

Measurement of Friction

Surface friction on the pavement surface was measured using a custom-made friction tester immediately after measuring the force required to shear the snow from the pavement (Figure 15). The static friction tester had a ¼-in. thick, 2 in. square neoprene rubber contact surface (durometer rating of 30A). The apparatus was pulled horizontally across the pavement surface at the same location as the sheared snow, and the force needed to overcome static friction was measured with a spring scale. The coefficient of static friction is defined as the ratio of the horizontal pulling force to the weight of the friction tester. Friction was measured on the pavement samples prior to each experiment on clean, dry pavement (baseline friction), on the compacted snow before trafficking (snow friction), and after shearing the snow (residual friction).

Figure 15: Friction tester.

Similar to snow-pavement bond strength, the residual friction measured in the laboratory with the static friction tester was not correlated to vehicle tire-to-pavement friction. The residual friction allows relative assessments of which pavement types or salting strategies have greater friction; however, specific values are not used to establish limits for “good” or “safe” road conditions. Friction measurement values ranged from 0.4 on compacted snow to 1.2 on clean, dry pavement (Figure 16). Obviously, greater values approaching 1.2 are better, while values nearer 0.4 are poorer. Baseline friction on the OGFC pavements was greater than DGP and UTFC pavements. Friction on compacted snow was similar amongst all pavements because the snow was thick enough such that the snow surface was unaffected by the pavement characteristics. Residual friction results shown in Figure 16 are the average of the control tests where no salt was applied, and was typically greater than compacted snow friction, particularly for the PPPs.

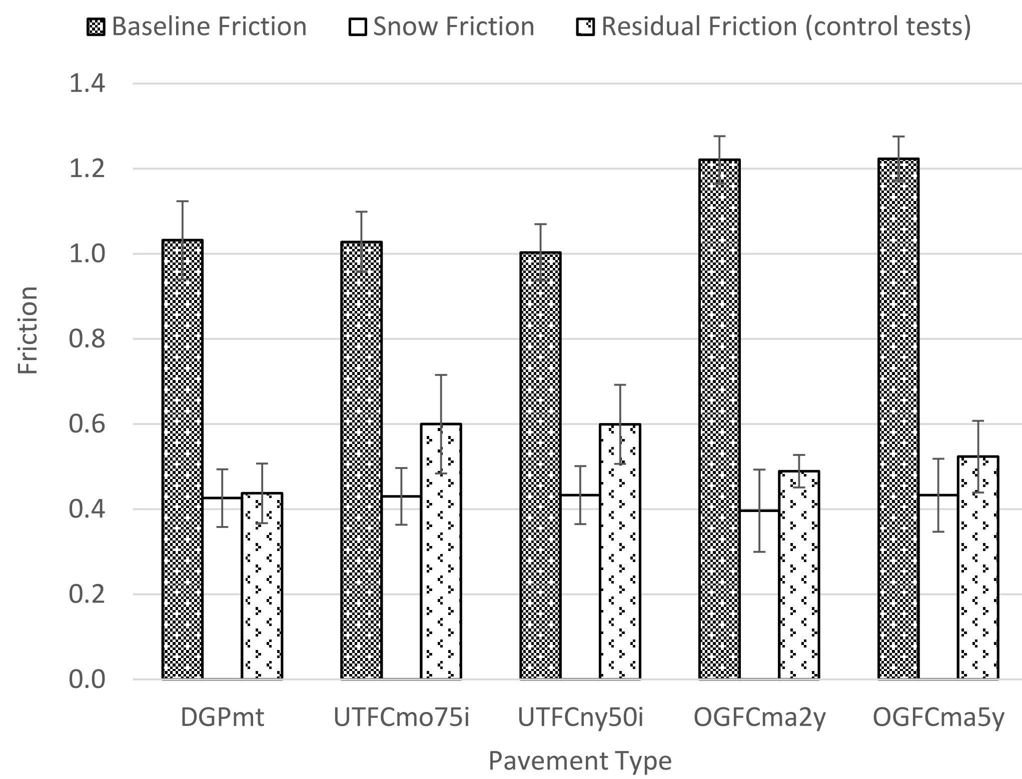


Figure 16: Results of baseline, compacted snow, and residual friction measurements for each pavement type (average ± 1 standard deviation).

The results of residual friction measurements for all pavement types organized by treatment type (control, deicing with dry salt, deicing with pre-wet salt, and anti-icing with salt brine) are shown in Figure 17. Residual friction of control tests generally ranged from 0.45 to 0.6, and treated tests from 0.5 to 0.65. These friction values are significantly less than baseline friction values (1.0 – 1.2), but greater than compacted snow friction (average = 0.43).

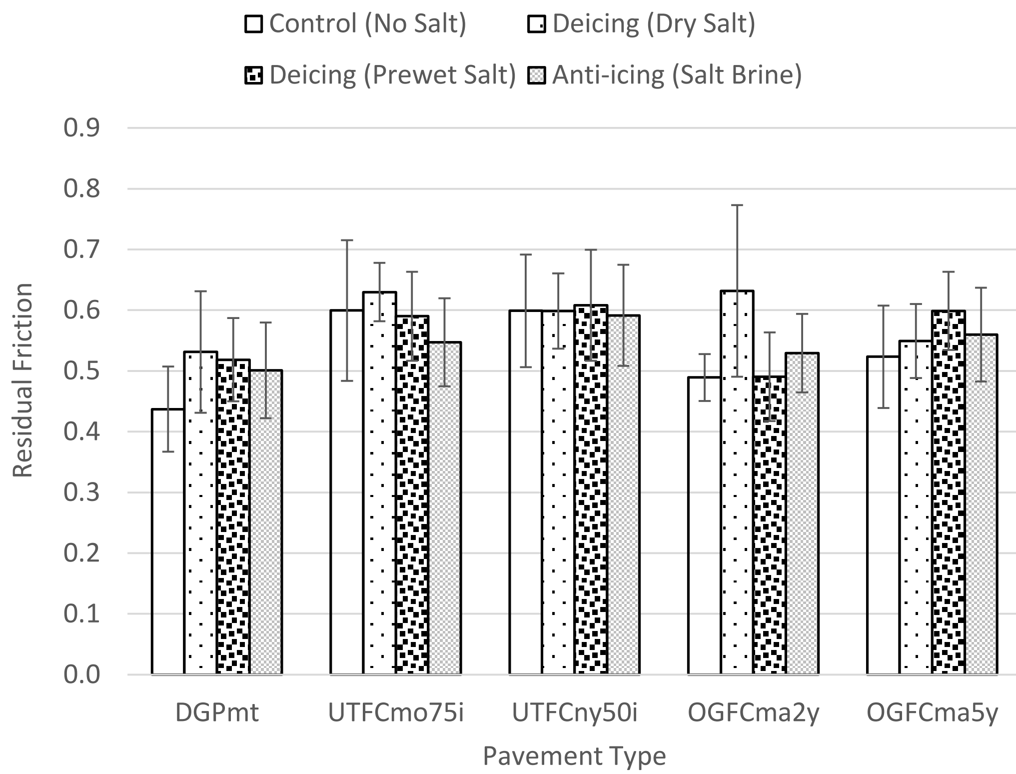


Figure 17: Residual friction results with respect to pavement type and treatment type (average ± 1 standard deviation)

Optical Friction and Salt Residue Measurements

Five lab tests were conducted in which friction and surface state were measured using an optical, non-contact mobile surface condition sensor (Mobile Ice Sight, manufactured by Innovative Dynamics, Inc). Three control (no salt) and two dry salt deicing tests were conducted. The snow sheared from the pavement during the deicing tests was collected and chloride concentration in the plowed, melted snow was measured. This measurement provided data needed to determine how much snow remained on the pavement surface after plowing. The results of these tests is shown in Table 3. Residual static friction ranged from 0.52 to 0.86 depending on pavement type and use of salt. Friction was higher on PPP samples than DGP, and higher with salt deicing than control (no salt) tests. Residual optical friction was 0.2 for all tests, regardless of pavement type or use of salt. The surface state after plowing was “snow” for all PPPs (because snow remained trapped in the pores, which the Mobile Ice Sight accurately detected) and “ice” for the DGPs. The chloride measurements in the plowed snow indicated a similar amount of salt remained on the pavement for both the DGP and PPP, however only two deicing tests were conducted.

Table 3: Static and Optical Friction and Chloride Results from Five Additional Lab Tests with Photos of Pavement Sample after Simulated Plowing

DGPmt Control (no salt)

Parameter	Initial	Residual
Static friction	0.89	0.52
Optical friction	0.5	0.2
Surface state	Damp	Ice
% salt removed by plowing	—	—
% salt remaining on pavement	—	—

UTFCny50i Control (no salt)

Parameter	Initial	Residual
Static friction	1.10	0.66
Optical friction	0.8	0.2
Surface state	Dry	Snow
% salt removed by plowing	—	—
% salt remaining on pavement	—	—

UTFCmo75i Control (no salt)

Parameter	Initial	Residual
Static friction	1.08	0.80
Optical friction	0.8	0.2
Surface state	Dry	Snow
% salt removed by plowing	—	—
% salt remaining on pavement	—	—

DGPmt Deicing Dry Salt

Parameter	Initial	Residual
Static friction	0.96	0.72
Optical friction	*	0.2
Surface state	*	Ice
% salt removed by plowing	—	69%
% salt remaining on pavement	—	31%

UTFCny50i Deicing Dry Salt

Parameter	Initial	Residual
Static friction	1.12	0.86
Optical friction	0.5	0.2
Surface state	Damp	Snow
% salt removed by plowing	—	75%
% salt remaining on pavement	—	25%

— Not applicable, * measurement not recorded (operator error)

Salt residue measurements with a computed tomography (CT) scanner located in the Subzero facility was also attempted. However, despite using small samples (1 in diameter cores from the pavement samples) and including a "tracer" (ISOVIEW-300, iodine solution used in medical CT scans) the CT scan resolution was too coarse to identify chloride ions (they are just too small to see) amongst the pavement components (asphalt and aggregate) and we were unable to develop a technique to quantify the amount of chloride in the pavement using the CT scanner.

3. Data Analysis

A matrix of laboratory tests was conducted to evaluate the performance characteristics of various treatment types on different types of pavements, namely snow-bond strength and surface friction. Meaningful comparisons were made to identify the effect of pavement type and treatment type on the performance. The comparison matrix included three pavement categories (DGP, UTFC, and OGFC) and four winter maintenance treatments (control, anti-icing with salt brine, deicing with dry salt, and deicing with pre-wet salt), as illustrated in Figure 18, where the control is when no treatment was applied to the pavement surface. The following comparisons were made to evaluate differences between the various pavement types: DGP vs. UTFC, DGP vs. OGFC, and UTFC vs. OGFC. Two types of UTFCs (½ in. and ¾ in.) and two types of OGFCs (new and old) were also incorporated in the analysis to refine these comparisons. The winter maintenance strategy comparisons that were made included: control vs. salt, anti-icing vs. deicing, and dry salt vs. pre-wet salt. These comparisons are shown by the arrows in Figure 18. In some comparisons, test results are combined. For instance when using "deicing" in a comparison it includes tests results of both dry salt and pre-wet salt tests, because dry and pre-wet are simply modifications of the treatment strategy referred to as "deicing." Another example of combining test results is the group of "salt" tests, which includes the salt brine, dry salt, and pre-wet salt tests. Figure 18 shows which specific tests feed into the combinations by the thin lines that delineate the sub-categories.

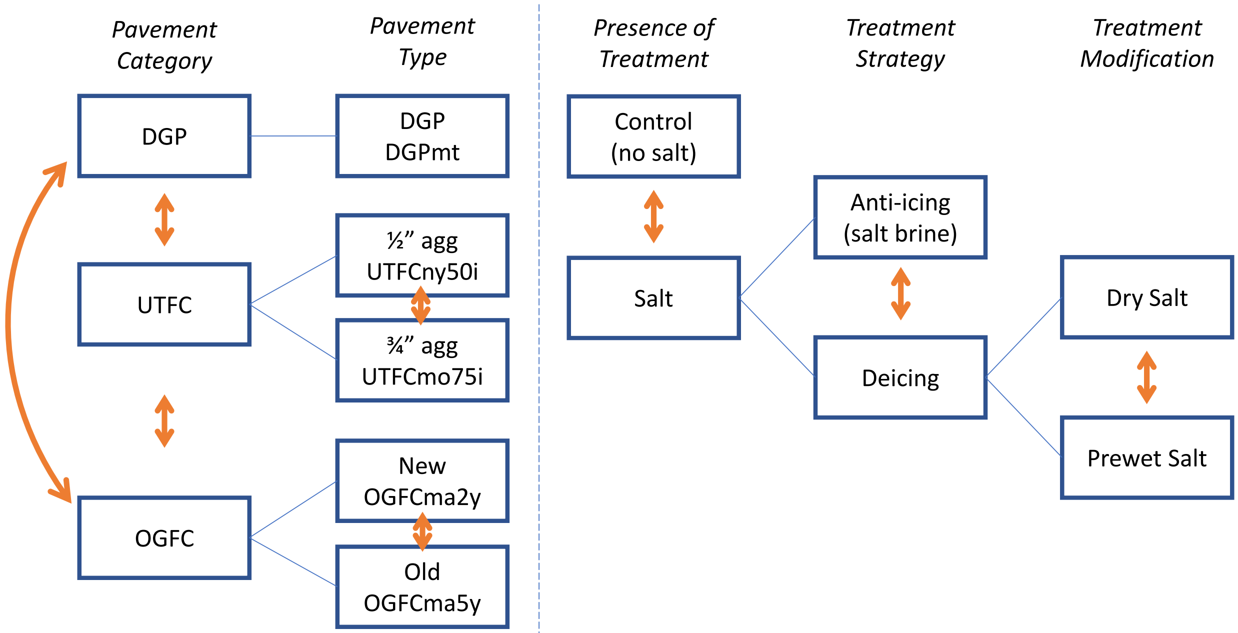


Figure 18: Matrix of comparisons made with respect to pavements and treatments

A two-sided t-test (for samples having unequal variance) was used as the statistical method to determine whether apparent trends in measured laboratory test results represent true differences between pavement category, treatment type, etc. The two-sample t-test is a statistical test used to determine if the averages of the two data sets are statistically different from one another based on a mathematical evaluation of the data scatter. In cases where the averages are statistically different, a direct comparison of the mean values indicates which value is greater. Otherwise, the means are considered statistically equal.

The output from this analysis is a parameter called a p-value. In this report, the p-value ranges from 0.50 to 1.00 (based on the one-tailed distribution). Although not typically shown this way, the p-values can be used to determine how two averages compare to one another. P-values closer to 0.5 indicate that the means are statistically more similar to one another and p-values closer to 1.0 indicate the means are statistically more different from one another. For the purposes of comparison in this project, and taking into consideration the relative variability typically observed in winter maintenance lab test data, a p-value greater than 0.90 was selected to indicate that the two means were statistically different from one another, while p-values between 0.50 and 0.90 indicated that the means were statistically the same. Certainly, the range of comparisons depends on the tolerance level of the analyst. Raw values are published below to allow the reader to analyze the data in a manner that best suits him or her.

Comparisons of Results Made with Respect to Pavement Type

Quantitative data collected during the lab tests included snow bond and residual friction, as described above. The combined mean values for the pavement categories (DGP, UTFC and

OGFC) and pavement types (UTFC ½”, UTFC ¾”, OGFC new, and OGFC old) for control tests and salt tests are shown in Table 4. The p-values of the comparisons of the mean snow bond and residual friction for the pavement categories and pavement types are shown in Table 5. The p-values from comparisons between DGP and UTFC, DGP and OGFC, and UTFC and OGFC ranged from 0.98 – 1.0, indicating each pavement category is clearly different from the others in terms of snow bond and residual friction. Therefore, mean values summarized in Table 4 can be used to make direct comparisons in the performance measures. To determine which pavement category has greater or less residual friction one must refer to the mean values, shown in Table 4 and also in Figure 19. Figure 19 shows the relative magnitude of snow bond and residual friction for the pavement categories for control tests and tests that used some form of salt. A summary of the differences between the different pavement types, based on Figure 19 are as follows:

- Snow bond was lowest on DGP pavements and greater on OGFC pavements, which is consistent with the findings of the literature review which found snow and ice can become integrally “keyed” into PPPs.
- Residual friction was lowest on DGP sample and greater on both PPPs – also consistent with findings from the literature review.
- Snow bond was greatest on OGFC pavements in control tests and UTFC pavements in salt tests.
- OGFC pavements exhibited the greatest reduction in snow bond from salt application.
- UTFC pavements had the greatest residual friction, in both control and salt tests.
- Improvements in residual friction from salt application compared to control tests were similar for DGP and OGFC pavements.
- No differences between the UTFC ½” and UTFC ¾”.

Table 4: Combined Mean Values for Pavement Type Comparisons

	Mean Value: Snow Bond (psi)	Mean Value: Residual Friction		Mean Value: Snow Bond (psi)	Mean Value: Residual Friction
Control Tests			**Salt Tests**		
DGP	4.9	0.44	DGP	3.5	0.52
UTFC	6.5	0.60	UTFC	5.0	0.59
OGFC	9.4	0.51	OGFC	4.4	0.56
UTFC ½”	6.4	0.60	UTFC ½”	4.9	0.60
UTFC ¾”	6.5	0.60	UTFC ¾”	5.2	0.59
OGFC new	9.7	0.49	OGFC new	4.3	0.55
OGFC old	9.1	0.52	OGFC old	4.5	0.57

Table 5: T-Statistic for Pavement Type Comparisons

	P-Value: Snow Bond (psi)	P-Value: Residual Friction		P-Value: Snow Bond (psi)	P-Value: Residual Friction
Control Tests			**Salt Tests**		
DGP vs UTFC	**1.00**	**1.00**	DGP vs UTFC	**1.00**	**1.00**
DGP vs OGFC	**1.00**	**1.00**	DGP vs OGFC	**1.00**	**1.00**
UTFC vs OGFC	**1.00**	**1.00**	UTFC vs OGFC	**0.98**	**1.00**
UTFC ½” vs ¾”	0.79	0.51	UTFC ½” vs ¾”	0.73	0.79
OGFC new vs old	**0.99**	**0.98**	OGFC new vs old	0.67	**0.91**

Numbers greater than 0.90 are **bolded**

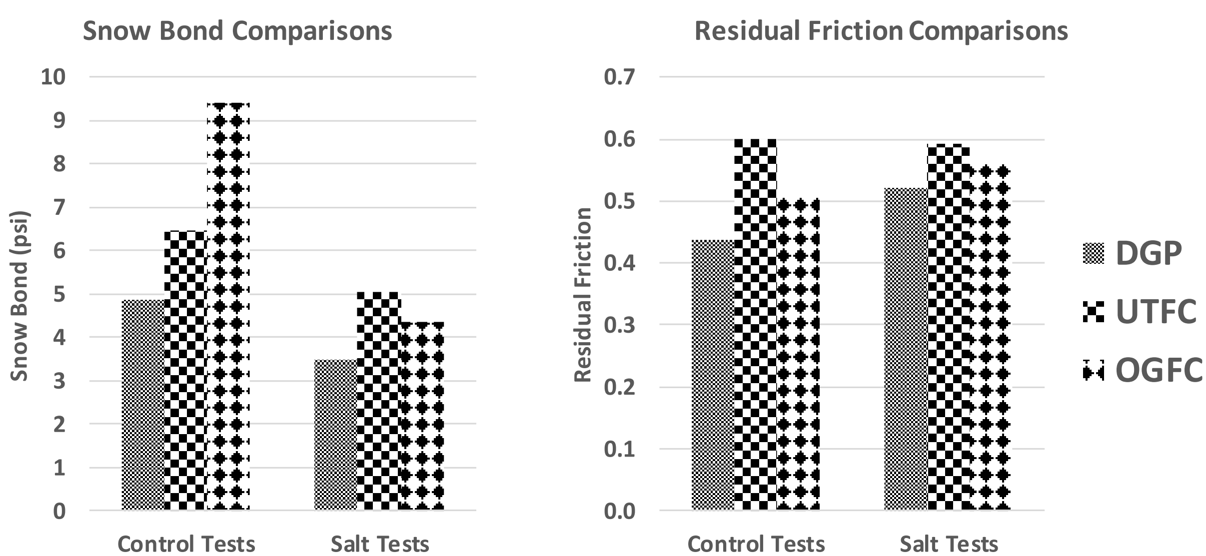


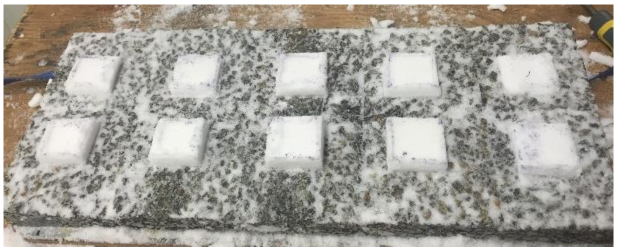
Figure 19: Snow bond and residual friction for pavement type comparisons.

Various attributes of the pavements were compared between the two UTFCs (½-in. vs. ¾-in. maximum aggregate size) and two OGFCs (new vs. old) with results provided in Table 4 (means) and Table 5 (p-values). The differences between ½-in. and ¾-in. UTFCs were not statistically different (p-values of 0.79 and 0.51 for control tests and 0.73 and 0.79 for salt tests – all less than 0.90). This means that the snow bond and residual friction from the ½-in. and ¾-in. UTFCs were similar, and could therefore be grouped together for the next analysis in which effective winter maintenance strategies were identified. When the two types of OGFCs (new and old) were compared to one another, the snow bond results were mixed – some p-values were greater than 0.90 and some less (0.99 and 0.67). However, with respect to residual friction, there were consistent statistically relevant differences between the two OGFCs (p-values of 0.98 and 0.91). The magnitude of the differences in terms of the actual values themselves is not relevant in this application (specifically residual friction of 0.49 vs. 0.52), where a difference of 0.03 does not represent appreciable difference in the two values. With respect to snow bond, a high p-value for the comparison between the control tests indicated that the bond strength in the new OGFC (9.7 psi) is stronger than the old OGFC (9.1 psi). However, comparisons between the newer and older treated OGFC samples indicated that the new and old OGFC had similar mean snow bond values.

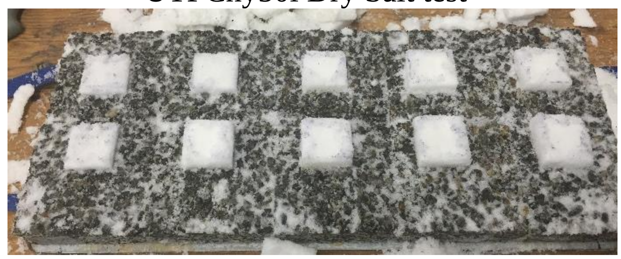
Visual observations made throughout the lab testing also provided qualitative indications of performance between DGP and PPPs that may have significant implications for winter maintenance. Perhaps most notably, the PPPs appeared significantly more "snowy" than the DGPs after the snow was sheared from the pavement; however, the snow remaining on the PPPs was trapped in the pore space of the pavement surface. So, despite appearing white and snowy, the PPP samples had higher residual friction than the DGP samples. Photos of control and dry salt tests run on a UTFC and OGFC (Figure 20) and a DGP (Figure 21) show that the PPPs have more visible snow on the pavement surface after removing snow than DGPs. Also noteworthy, is how similar the surface of the treated and untreated DGP sample appeared (Figure 21); however, the results of those treated with salt generally had significantly higher residual friction (about 0.5 instead of 0.4). The importance of this information is to illustrate that decisions on whether or not to treat a road surface should not be based solely on visual inspections. As an example, PPPs appear to need more treatment than DGPs, despite PPPs having higher friction after snow removal. These results should be verified prior to establishing a reliable protocol within each organization.

UTFCny50i Control test

UTFCny50i Dry Salt test

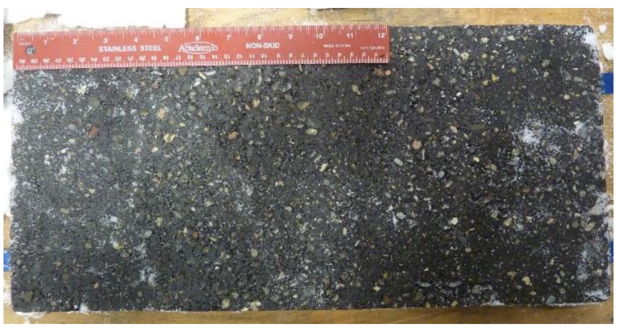


OGFCma5y Control test



OGFCma5y Dry Salt test

Figure 20: Photos showing the "snowiness" of PPPs after shearing snow (control tests on left, dry salt tests on right; UTFCs on top, OGFCs on bottom).



DGPmt Control test

DGPmt Dry Salt test

Figure 21: Photos showing the "snowiness" of DGP sample after shearing snow (left: control test, right: dry salt test).

Analysis of Results to Identify Effective Winter Maintenance Strategies

For a given pavement type, comparing various salting strategies to the control or other strategies can help determine the most effective winter maintenance strategies. The specific comparisons made within each pavement type are: control vs. salt, control vs. anti-icing, control vs. deicing, anti-icing vs. deicing, and dry salt vs. pre-wet salt).

The combined means and p-values for the tests on DGP samples are shown in Table 6. The control tests (i.e., no salt treatment) had the worst performance in terms of residual friction and second-worst for snow bond, indicating salt application provided significant benefits in terms of reduced snow bonding and improved friction. Anti-icing resulted in the lowest snow bond (1.2 psi) while deicing resulted in the greatest friction (0.53). The p-values comparing dry salt and prewet salt were 0.89 (for snow bond) and 0.77 (for residual friction), indicating insignificant differences between the treatment modification. The deicer application rate for these laboratory tests was 250 lb/LM, chosen in consultation with the project technical panel. This application rate was higher than typical for winter maintenance on DGPs at 28°F, thus three tests (providing 30 data points each for snow bond and residual friction) were run on this pavement at a reduced application rate. The salt grains were the same size (so deicer penetration was unchanged), but they were applied with greater spacing corresponding to 125 lb/LM. Interestingly, the reduced dry salt application had greater snow bond and lower residual friction than the greater salt application, which corresponds to intuition. However, compared to the control, snow bonding was greater on the reduced salt than no-salt scenario, which is counter-intuitive.

Table 6: Combined Means and T-Statistic for Winter Maintenance Strategy Comparisons on DGP

	Mean Value			**P-Value**	
Treatment	Snow Bond (psi)	Residual Friction	**Comparison**	Snow Bond (psi)	Residual Friction
Control	4.9	0.44	Control vs Salt	**1.00**	**1.00**
Salt	3.5	0.52	Control vs Anti-icing	**1.00**	**1.00**
Anti-icing	1.2	0.50	Control vs Deicing	**1.00**	**1.00**
Deicing	4.0	0.53	Anti-icing vs Deicing	**1.00**	**0.93**
Dry salt	3.9	0.53	Dry salt vs Pre-wet salt	0.89	0.77
Pre-wet salt	4.4	0.52	Dry salt vs Dry salt (½)	**1.00**	**1.00**
Dry salt (½)*	6.9	0.46			

*Dry salt test with reduced application rate (125 lb/LM instead of 250 lb/LM)

The combined means and p-values for the tests on UTFC samples are shown in Table 7. Because earlier comparisons between the two types of UTFCs (½" and ¾") indicated similar behavior, their results were grouped together for the analysis. Applying salt (whether salt brine, dry salt, or pre-wet salt) provided a statistically significant reduction in snow bond, but not a consistent improvement in residual friction. Because snow bond doesn't correlate to "ease of plowing" the practical implications of any reduction in snow bond are difficult to ascertain. The differences in residual friction are statistically significant with some strategies, but the overall range in friction is small (0.57 to 0.61), suggesting in practical terms, that friction across all the tests was similar, despite the statistical analyses indicating there were true differences.

Table 7: Combined Means and T-Statistic for Winter Maintenance Strategy Comparisons on UTFC

	Mean Value			P-Value	
Treatment	Snow Bond (psi)	Residual Friction	**Comparison**	Snow Bond (psi)	Residual Friction
Control	6.5	0.60	Control vs Salt	**1.00**	0.70
Salt	5.0	0.59	Control vs Anti-icing	**1.00**	**0.97**
Anti-icing	4.6	0.57	Control vs Deicing	**1.00**	0.73
Deicing	5.3	0.61	Anti-icing vs Deicing	0.89	**1.00**
Dry salt	5.1	0.61	Dry salt vs Pre-wet salt	0.87	0.79
Pre-wet salt	5.7	0.60			

The combined means and p-values for tests on the two OGFC samples ("new" in Table 8 and "old" in Table 9) are presented in separate tables because 1) some of the previous comparisons indicated differences between the two OGFC pavements, and 2) the literature review and interviews conducted in earlier tasks indicated newer/younger OGFC pavements needed greater salt application than older OGFC pavements. The comparisons of winter maintenance strategies for both OGFC pavements had several similar results: 1) the control tests had the greatest snow bond and lowest residual friction, and 2) anti-icing with salt brine resulted in the lowest snow bond while providing a modest increase in friction. Deicing with dry salt for the "new" OGFC and pre-wet salt for the "old" OGFC yielded the greatest residual friction.

Table 8: Combined Means and T-Statistic for Winter Maintenance Strategy Comparisons on OGFC-new

	Mean Value			P-Value	
Treatment	Snow Bond (psi)	Residual Friction	**Comparison**	Snow Bond (psi)	Residual Friction
Control	9.7	0.49	Control vs Salt	**1.00**	**1.00**
Salt	4.3	0.55	Control vs Anti-icing	**1.00**	**1.00**
Anti-icing	0.6	0.53	Control vs Deicing	**1.00**	**1.00**
Deicing	6.1	0.56	Anti-icing vs Deicing	**1.00**	**0.94**
Dry salt	7.1	0.63	Dry salt vs Pre-wet salt	**1.00**	**1.00**
Pre-wet salt	5.0	0.49			

Table 9: Combined Means and T-Statistic for Winter Maintenance Strategy Comparisons on OGFC-old

	Mean Value	
Treatment	Snow Bond (psi)	Residual Friction
Control	9.1	0.52
Salt	4.5	0.57
Anti-icing	0.9	0.56
Deicing	6.3	0.57
Dry salt	5.8	0.55
Pre-wet salt	6.9	0.60

	P-Value	
Comparison	Snow Bond (psi)	Residual Friction
Control vs Salt	**1.00**	**0.99**
Control vs Anti-icing	**1.00**	**0.96**
Control vs Deicing	**1.00**	**1.00**
Anti-icing vs Deicing	**1.00**	0.79
Dry salt vs Pre-wet salt	**0.99**	**1.00**

4. Summary of Laboratory Testing and Analysis

The lab test performed for this project provided a consistent methodology for comparing the use of salt applied in various ways and measuring its effect on snow bond and friction. The suite of pavement specimens included the most common porous and permeable pavement surfaces: open-graded friction course and ultrathin friction course. The OGFC samples were made from cores of in-service pavements and are fairly representative of OGFCs in general, but state specifications vary throughout the U.S. and the samples used in this project were only from one state. The two UTFC samples were made from pavement mix from two different states, but were made into slabs using the same machine, which should be taken into consideration.

The results of the laboratory tests indicate PPPs have higher friction, require greater force to shear snow from the surface, and had much visible snow trapped in the pores after scraping snow. A summary of significant results from the laboratory testing are as follows:

- PPPs appear more snow-covered after scraping snow from the surface.
- Friction on PPPs is significantly greater than on DGPs.
- Snow bond is generally stronger on PPPs than DGPs.
- Anti-icing generally provides the greater reduction in snow bond.
- Friction on PPPs was only slightly greater on salt tests compared to control tests.