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De-icing Operations for Permeable Interlocking Concrete Pavements

Prepared for: Interlocking Concrete Pavement Institute Foundation for Education and Research

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EXECUTIVE SUMMARY

Permeable interlocking concrete pavements (PICP) allow stormwater to infiltrate directly through aggregate-filled joints. Best practices for the winter operation of PICP is poorly understood. Unlike conventional impervious pavements, melted snow and ice infiltrates directly through the PICP joints to underlying aggregate layers, underdrains or native soils.

The University of Toronto conducted this study at a PICP test pad, constructed in 2017, located at the Toronto and Region Conservation Authority's (TRCA) Kortright Centre for Conservation in Vaughan, Ontario. The test pad included four 2 m by 2 m (6.6 ft by 6.6 ft) PICP cells constructed with a generic grey paver arranged in a herringbone pattern and one 2 m by 2 m (6.6 ft by 6.6 ft) asphalt control cell. A perforated pipe drained the PICP cells. The asphalt cell was drained via a catch basin. Concrete curbs between cells prevent the inter-mixing of flows.

De-icing practices were tested over two winter seasons in 2018 and 2019. Two PICP cells received road salt at medium 0.049 kg/m^2 (10 lb/1000 ft^2) and low 0.024 kg/m^2 (5 lb/1000 ft^2) application rates and two cells received road salt pre-wetted with beet juice also at medium and low application rates. The asphalt control cell received road salt at a medium application rate. Surface friction, surface temperature and water quality were measured.

Study Findings

The results of this study indicate that the PICP provides equivalent or higher levels of safety compared with asphalt when treated with de-icing products at medium or low application rates. Re-freezing of melted snow and ice after sunset was observed on the asphalt surface creating black ice but not on the PICP cells. Consequently, compared to asphalt pavements, **PICP surfaces will require use of less deicers and will have lower risk of slips and falls for pedestrians and lower risk of skidding for vehicles throughout the winter.**

Key findings of this research include the following:

- **Surface Friction under Dry Pavement Conditions**: PICP and asphalt surfaces have equivalent levels of surface friction under dry conditions.
- **Shovelled Snow followed by De-icing:** The PICP surfaces had lower surface friction than the asphalt surface after shovelling. This is not surprising, as the PICP surfaces have a monolithic texture that likely caused the thin layer of snow to have a more consistent thickness. In contrast, the asphalt had a more rugged and irregular texture that allowed for the snow to settle into surface depressions. Both pavement surfaces treated with a medium application rate of road salt (0.049 kg/m^2 or 10 lb/1000 ft^2) provide similar levels of safety soon after snow begins to melt. PICP treated with a low application rate of road salt (0.024 kg/m^2 or 5 lb/1000 ft^2) provided similar levels of safety as PICP treated with a medium application rate of road salt. This research demonstrates that, under mild conditions, road salt applications on PICP surfaces can be reduced by 50% while maintaining the same level of safety for pedestrians and vehicles. Pre-wetting road salt with beet juice did not provide any additional benefit under the tested conditions.
- **De-icing under Icy Conditions**: Under icy conditions, the PICP and asphalt surfaces had similar levels of surface friction prior to salting. Melting and drying of the PICP surfaces

occurred more rapidly with the medium application rate or when using road salt pre-wetted with beet juice. Re-freezing of melted snow and ice after sunset was observed on the asphalt surface but not on the PICP cells.

- **Melting of Undisturbed Snow and Surface Temperatures**: Pavement thermal properties (e.g. colour), not drainage characteristics drive melting processes of undisturbed snow and surface temperature. Melting occurred more rapidly on the black asphalt as opposed to the grey PICP. Despite this, refreezing of meltwater near the catch basin frequently occurred on the asphalt.
- **Water Quality**: Conductivity measurements demonstrated that the PICP attenuated and buffered the release of de-icing materials in stormwater discharge. Peak conductivity levels were reduced by over 85% by the PICP. Chloride concentrations in sampled asphalt runoff exceeded USEPA chronic chloride concentration limit of 230 mg/L and an acute chloride concentration limit of 860 mg/L to sustain aquatic life by several magnitudes. Sampled PICP discharge never exceeded the acute concentration limit. Despite having clayey soils, significant exfiltration to the underlying soils occurred which will allow de-icers to migrate into subsurface systems. The ultimate pathway and fate of de-icers remain unclear, but as with conventional pavements, impacts to both surface and groundwater resources are likely.

Recommendations for further research on winter snow and ice management are provided.

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1.0 BACKGROUND AND OBJECTIVES

Permeable pavements provide on-site quantity and quality stormwater control. Quantity control is achieved through infiltration, temporary detention and some evaporation of stormwater. Quality control is achieved through several processes including stormwater capture, filtration, sorption, and biodegradation. Researchers have evaluated long term quantity and quality performance [1]–[5], surface infiltration rates [6], permeable pavement types [7], infiltration over low permeability soils [8], clogging [9]–[11] and urban heat island effects [12], [13]. In Ontario, the benefits of permeable interlocking concrete pavements (PICP) on parking lot stormwater quality have been demonstrated at the Kortright Centre for Conservation [14]–[16]. Monitoring of this site revealed that, relative to asphalt runoff, permeable pavement effluent contains substantially reduced concentrations of many common pollutants, including suspended solids, heavy metals, petroleum-based hydrocarbons, and some nutrients [14]. Despite the proven environmental benefits, PICP remains a niche product in Canada. Due to a lack of national regulations providing an incentive for PICP use, the Canadian interlocking paver industry lags dramatically behind the U.S. and, in the United States, 4.8% of all pavers sold are permeable pavers, whereas in Canada, only 1.8% of sold pavers are permeable [17]. Uptake of permeable pavements has been slow in Canada because consumers are concerned about winter performance and long-term operational and maintenance costs.

A lack of consensus regarding winter best management practices leaves designers, manufacturers and property owners uncertain as to whether or not salting or sanding is necessary for, or possibly detrimental to, permeable pavements. Researchers [18], [19] have made anecdotal observations that permeable pavements require less application of de-icers than traditional pavements. The safety benefits of permeable pavements have not yet been scientifically or rigorously verified or quantified. Chloride concentrations in asphalt runoff and permeable pavement outflow are often comparable during the summer months [14] but maybe significantly different during the winter when road salting occurs [18], [20], [21]. Roseen et al. [22] successfully demonstrated that, relative to traditional asphalt, porous asphalt requires substantially less salt (64 to 77%) while simultaneously providing higher skid resistance. However, comparable research of permeable interlocking concrete pavers or concrete pavements has not been performed. Furthermore, there are no winter performance evaluations in Canadian jurisdictions. Without regionally specific peer-reviewed published evidence, property owners and government policymakers are skeptical towards implementing new winter operational practices that *reduce* de-icing application rates out of concern for increased liability.

From an environmental perspective, de-icing materials pose a significant threat to natural waterways and biological systems. It would be economically and environmentally beneficial to reduce our reliance on roughly 5 million tonnes of road salts that are applied to Canadian roadways each year. Due to the environmentally hazardous effects of road salts, Canadian municipalities that apply more than 500 tonnes of road salt per year must implement costly preventative practices outlined in the Road Salt Code of Practice [23]. Despite these efforts, long-term environmental data indicates that chloride concentrations in Ontario rivers are still increasing [23]. Developing *customized best management practices* for permeable pavements presents the opportunity for high-impact environmental benefits through reducing the volume and frequency of road salt applications.

The objective of this research is developing and testing effective operational practices for Permeable Interlocking Concrete Pavements (PICP) during the winter. This study addresses the following objectives:

1. Investigate the indicator pavement parameters for pedestrian and vehicle uses (e.g. slip tests, time to bare pavement, etc.) under different de-icing pavement operations for PICP.
2. Investigate the environmental impacts (e.g. timing, concentration and loading) of de-icing/anti-icing pavement operations for PICP on winter stormwater quality.
3. Develop best management practices for winter operations of PICP in cold climates.

Anti-icing operations were not investigated throughout the study. The location of the experimental test pad was not accessible overnight, and consequently, anti-icing treatments could not be tested.

2.0 STUDY SITE

An outdoor pavement test pad was constructed in August 2017 at the Toronto and Region Conservation Authority (TRCA) Kortright Centre for Conservation located in Vaughan, Ontario. The test pad (as shown in Figure 2-1 and Figure 2-2) consisted of four 2 m by 2 m (6.6 ft by 6.6 ft) PICP cells and an asphalt control cell. The names displayed in Figure 2-2 for each pavement cell correspond to their respective pavement type, de-icer type, and application rate, as later described in subsequent sections of this report. Each pavement cell was enclosed within an impervious concrete barrier such that water below the surface was unable to flow between the cells. All four PICP cells were constructed with a level surface, whereas the asphalt cell was sloped at 2% to allow for meltwater to drain to a catch basin. The cells were installed within an open field where they received no pedestrian or vehicular traffic throughout the study period. Table 2-1 outlines the thermal properties of the PICP and asphalt materials.

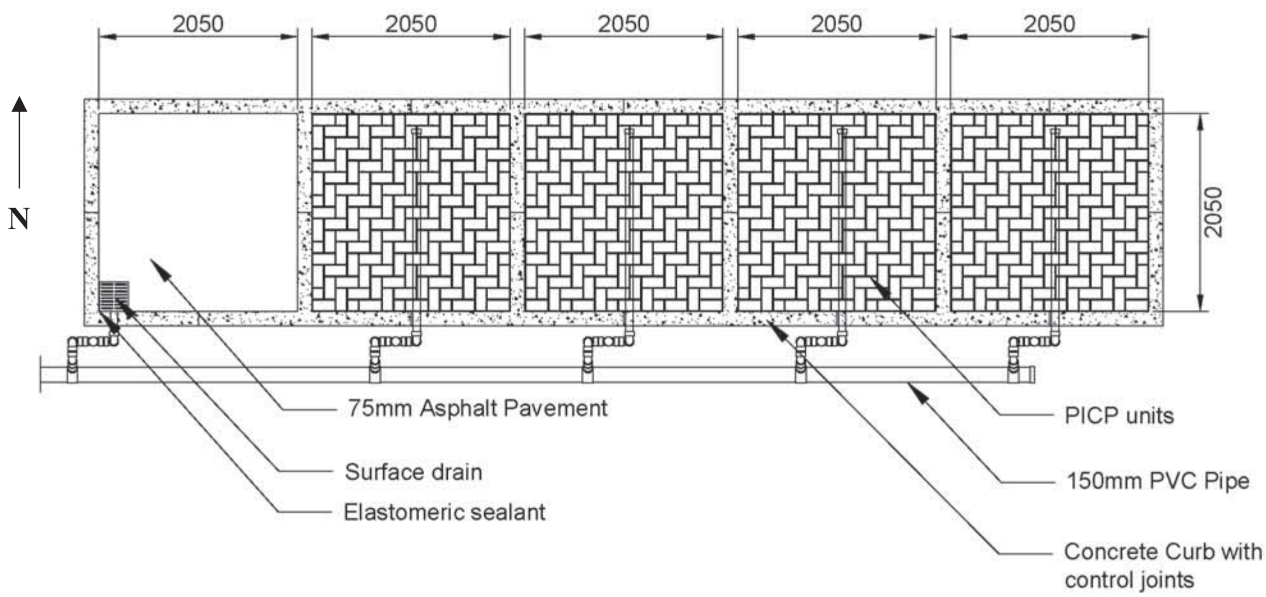


Figure 2-1: Test Pad Layout. Dimensions are presented in mm.

Figure 2-2: Surface layout of the outdoor pavement test site (facing south).

Table 2-1: Thermal properties of PICP and asphalt

Pavement Type	Albedo	Emissivity	Thermal Conductivity (W/m-°C)
PICP	0.26[a]	0.97[a]	1.83[b] (1.69)
Asphalt[b]	0.09	0.80	1.73 (0.74)

[a] Value provided by the manufacturer for PICP product.

[b] Values estimated based on a review of pavement surfaces [24].

Cross-sectional layouts of the PICP and asphalt cells are provided in Figure 2-3. The PICP cells followed design recommendations outlined by the Interlocking Concrete Pavement Institute (ICPI) [25]. Paver materials used for the PICP cells were 80 mm (3.15 in) thick , 120 mm by 240 mm (4.72 in by 9.45 in) grey Enviro Midori concrete paving stones with a 7.5 mm (0.30 in) spacer bar laid out in a 90° herringbone pattern with 8.1 ± 0.6 mm (0.32 ± 0.02 in) joint spaces filled with ASTM No. 8 crushed stone. Appendix A provides a drawing of the paver. The pavers were installed above a 50 mm (2 in) thick bedding layer that was also comprised of ASTM No. 8 crushed stone. A 100 mm (4 in) thick base layer consisting of ASTM No. 57 crushed stone and a 150 mm (6 in) thick subbase layer consisting of ASTM No. 2 crushed stone were installed below the bedding layer. All aggregate materials were washed. The total depth from the PICP surface to the native soil was 380 mm (15 in), which places the installation well above the typical winter frost line in Vaughan, Ontario of approximately 1.4 m (4.6 in) [26]. A 75 mm (30 in) diameter perforated underdrain was installed in an approximately 100 mm (4 in) deep sump below the subbase and bedded within ASTM No. 57 stone. A permeable, nonwoven geotextile with a permittivity of 1.2 per second was installed below the subbase and underdrain to separate the aggregates from the native soil. The PICP cells allowed for partial infiltration into the native soil, which had a measured saturated hydraulic conductivity of approximately 2 mm/hr (0.08 in/hr).

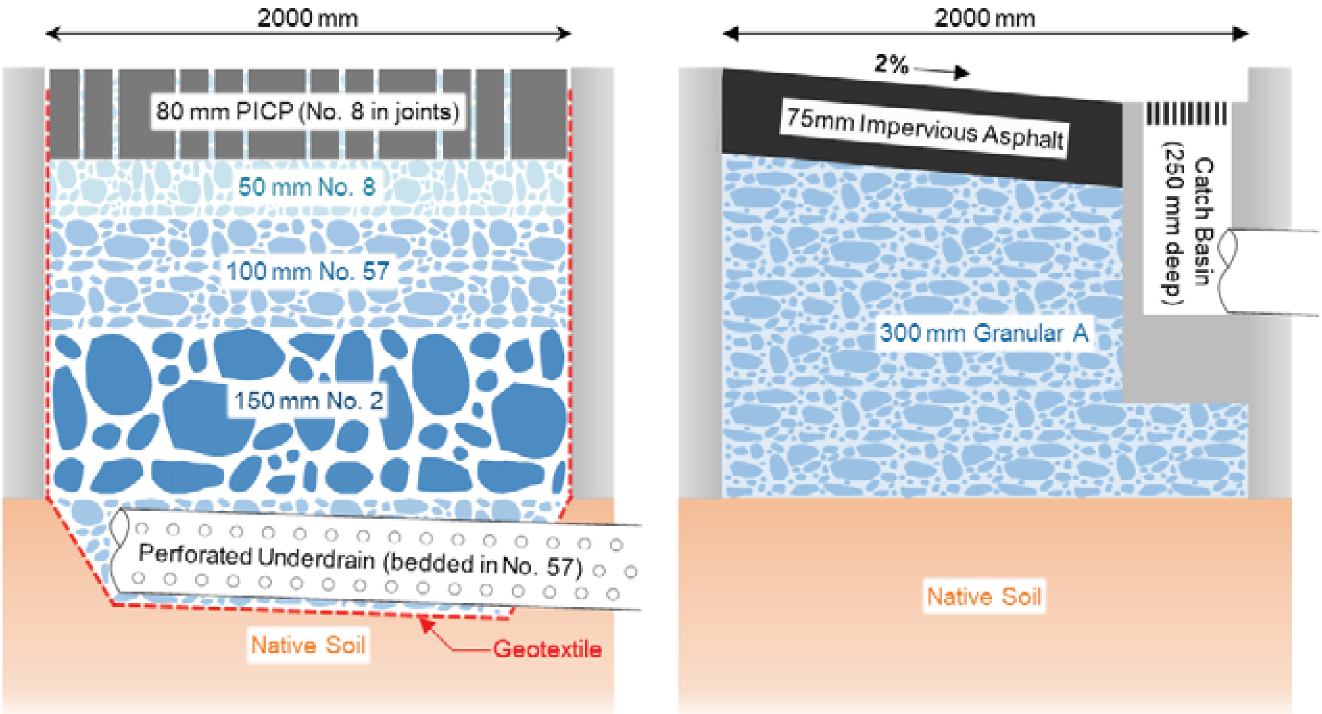


Figure 2-3: Cross-sectional layout of PICP (left) and asphalt test cells (right).

The asphalt cell consisted of a 75 mm (3 in) thick hot mix asphalt pavement layer installed above a 300 mm (12 in) thick Granular A aggregate layer. This specification was typical of local residential driveway installations. The catch basin had a surface area of 250 mm by 250 mm (10 in by 10 in) and a depth of 250 mm (10 in) with no sump, representing a shallow catch basin installation often found on private properties. A 75 mm (3 in) diameter pipe was used for the catch basin outlet. Both the catch basin outlet pipe and the PICP underdrains were sloped at 1% from the cells into individual traps for water quality monitoring before connecting to the downstream drainage system.

3.0 METHODS

3.1 Snow Clearing and Compaction

A variety of snow clearing and de-icing practices created different types of surface cover conditions on the PICP and asphalt pavements. These practices generally consisted of shovelling snow from the pavement surfaces with or without prior compaction of the snow and then applying de-icing chemicals to each pavement cell. A summary of the winter maintenance activities carried out during the two winters is provided in Table 3-1. The term *salting* in the table refers to the application of de-icing chemicals. Shovelling and salting activities were carried out during the daytime hours after the cells were clear of all shadows and precipitation.

Table 3-1: Winter maintenance activities carried out on pavement cells.

Date	Snow Compaction	Shovelling (to a thin layer of snow or ice)	Shovelling (to a dense layer of snow or ice)	Salting
17/Jan/2018		✓		✓
01/Feb/2018		✓		
05/Feb/2018		✓		✓
08/Feb/2018		✓		✓
12/Feb/2018	✓		✓	
15/Apr/2018		✓		✓
18/Jan/2019	✓			
19/Jan/2019	✓			
21/Jan/2019	✓	✓		✓
28/Jan/2019	✓			
29/Jan/2019	✓		✓	✓
30/Jan/2019		✓		✓
07/Feb/2019		✓		✓
13/Feb/2019	✓			
14/Feb/2019	✓			
16/Feb/2019			✓	✓
28/Feb/2019	✓			
03/Mar/2019			✓	
04/Mar/2019			✓	✓

Snow compaction was carried out by repeatedly walking over the cells using a regular walking pattern until maximum compaction was visually observed. The number of passes required to achieve maximum compaction varied between events based on the thickness and condition of the snow. The purpose of the snow compaction was to simulate winter pavement conditions where vehicles and pedestrians pass over snow-covered surfaces before or while the surfaces are plowed or shovelled.

Several other snowfalls and mixed precipitation events of varying magnitudes occurred throughout the two winters where melting occurred the following day due to positive air and surface temperatures (i.e. ≥ 0 °C). While no maintenance was carried out for these events, these events provided information on how snow melts on PICP surfaces when left undisturbed.

3.2 De-Icing Treatments

Pavement de-icing treatments are outlined in Table 3-2. Two PICP cells received road salt (RS) at a medium (M) or low (L) application rates and two cells received road salt pre-wetted with beet juice (BJ) at a medium or low application rates. The asphalt control cell received road salt at a medium application rate. The medium 0.049 kg/m^2 (10 lb/1000ft^2) and low 0.024 kg/m^2 (5 lb/1000 ft^2) application rates used in this study were based on equipment calibration values used in the *Salt Application Verified Equipment* (SAVE) program administered by the Sustainable Technologies Evaluation Program (STEP) [27]. Although not used in this study, for reference, a high application rate is 0.073 kg/m^2 (15 lb/1000 ft^2) [27].

The road salt used in this study was a locally available commercial product (Sifto® Safe Step® Ice Salt™) composed of pure sodium chloride (NaCl). The beet juice product used in this study to pre-wet the road salt was Fusion™ Liquid De-Icer. Pre-wetting was carried out by mixing the beet juice and the road salt and at a ratio of 14 L of beet juice to one metric tonne of road salt, as recommended by the manufacturer.

The purpose of using road salt that has been pre-wetted with beet juice was to evaluate a common and more environmentally friendly de-icing alternative to pure NaCl, and the product manufacturer claims that using beet juice to pre-wet road salt can reduce the amount of road salt that is needed. Beet juice also lowers the freezing point of water to lower values than NaCl, allowing ice and snow to melt when temperatures are too low for pure NaCl to function. Despite the potential salt reduction benefits of pre-wetting with beet juice, the low and medium application rates were kept the same between both treatment types such that the potential salt reduction benefits of beet juice on PICP could be directly compared.

Table 3-2: De-icer type and application rate for each test cell.

Test Cell	De-Icer	Application Rate (lb/1000 ft^2)[a]	Effective Temperature (°C)[b]
PICP-RS-M	Road Salt	10	-15
PICP-RS-L	Road Salt	5	-15
PICP-BJ-M	Road Salt Pre-Wetted with Beet Juice	10	-27
PICP-BJ-L	Road Salt Pre-Wetted with Beet Juice	5	-27
Asph-RS-M	Road Salt	10	-15

[a] Unit for application rate is pounds of de-icer per 1000 square feet.
[b]Effective temperature as reported by the manufacture.

3.3 Surface Friction Measurements

Surface friction was measured on the pavement cells using two devices, SlipAlert and Slip-Test Mark IIIB (referred to hereafter as the Mark IIIB). Photos of the two devices are shown in Figure 3-1. SlipAlert is a British tribometer adopted by BS 8204 (British Standards Institution 2003) that measures the dynamic coefficient of friction (DCOF) by simulating the sliding action of a vehicle. Mark IIIB is an American tribometer certified to ASTM F2508 (ASTM International 2016) that measures the transitional coefficient of friction (TCOF) by simulating the biomechanical movement of a pedestrian when slipping on a surface. Measurements are collected at a single location when using Mark IIIB, whereas measurements are collected over the sliding distance of the instrument when using SlipAlert. While all TCOF measurements on the asphalt cell were able to be collected across its slope, corrections were made to sloped DCOF measurements using conversions provided by the manufacturer.

With practice, field crews were able to predict based on site conditions (i.e. icy, snowy, wet, dry) an appropriate initial foot angle for the Mark IIIB that was slightly steeper than when a slip would occur. The foot angle would be adjusted down by one unit until a slip occurred. If the initial angle selected was too shallow and the foot slipped on the first trial the device would be moved to a different location and repeated in the same general area on the pavement.

(a) **(b)**

Figure 3-1: Friction measuring devices in use on ice-covered PICP surfaces: (a) SlipAlert and (b) Mark IIIB.

Surface friction was measured after shovelling, 10 – 20 minutes after salting, until the pavements were dry or experienced no further changes in surface cover (generally 1 – 2 hours after salting, but in some instances up to 24 hours after salting), as well as before and after sunset if refreezing conditions occurred. Each friction measurement set consisted of collecting five replicate measurements with each friction device per cell at locations that provided overall spatial representations of the pavement surfaces. The cell order in which the measurements were collected was randomized each day, and measurements were collected at approximately the same time on all cells. The SlipAlert measurements were collected before the Mark IIIB measurements for each measurement set. The purpose of this data collection procedure was to equally account for any changes to surface cover that may occur during a measurement set. This was important because surface conditions can change within minutes, whereas the friction measurement sets took approximately 10 minutes to collect using SlipAlert and 20 minutes to collect using Mark IIIB.

Two additional SlipAlert measurements were collected on the asphalt cell, one across the top of the slope on the east side where drying would typically first occur, and one diagonally across the cell towards the catch basin. Additional Mark IIIB measurements were collected if the five measurements did not cover all observed types of surface cover, such as isolated patches of ice or dry spots.

SlipAlert classifies the risk of slip as low when the DCOF is greater than 0.4 this corresponds to the Pendulum Test Value of 40 [28] specified by BS 8204 [29] which is required for pedestrian safety on indoor flooring.

Pavement cells were first shovelled to a thin layer of snow or ice pellets and then treated with de-icing chemicals for six experiments. Friction measurements were collected during the shovelled snow experiments within 30 minutes after shovelling (Test 1), within 30 minutes after salting (Test 2), and one to two hours after salting (Test 3). Statistical comparisons of DCOF and TCOF for each of the three tests were carried out by combining the data from all experiments. For reasons outlined in Table 3-3, statistical hypothesis tests only included four, three, and two of the experiments for Test 1, Test 2, and Test 3, respectively.

Table 3-3: List of included and excluded data from shovelled snow experiments.

Experiment Date	Data Included?			Reason for Excluding Data
	Test 1	Test 2	Test 3	
01/Feb/2018				shadows, no salting due to positive temperatures
05/Feb/2018	✓	✓	✓	(all tests included)
08/Feb/2018				de-icers from previous experiment still present
21/Jan/2019	✓	✓	✓	(all tests included)
30/Jan/2019	✓	✓		blowing snow conditions after Test 2
07/Feb/2019	✓			freezing drizzle conditions after Test 1

Shovelling and salting activities were carried out during the daytime hours after the cells were clear of all shadows and precipitation. Cells were most impacted by shadows created by a solar panel system located to the south during the mornings and late afternoons from November to January.

3.4 Surface Temperature and Surface Condition Monitoring

Surface-mount thermistors were installed on the corner of each cell to continuously monitor pavement surface temperatures every five minutes throughout the winter periods. Sensors were placed on the northern side of the cells to avoid shadows from solar panel structure located to the south of the test pad. These data helped to identify surface conditions and the potential for the ice and snow to melt. Ambient air temperature data were collected from a climate station operated by the TRCA located approximately 500 m from the study site.

Surface conditions were monitored by capturing photos of the site using a field camera and by manually capturing photos with handheld cameras during site visits. The field camera was equipped with infrared lighting also to capture photos during the night.

The amount of surface cover was visually estimated from each photo and grouped into one of the four following categories: full cover (> 99% covered), partial cover (> 5% covered), trace cover (< 5% cover), and clear (< 1% cover). The camera photos were also used to determine when each of the temperature sensors were impacted by surface cover throughout the monitoring period to eliminate the impacts of ice, snow, and slush on surface temperatures.

3.5 Water Quality: Conductivity and Chloride

Conductivity was continuously monitored in the outflow from the four PICP underdrains (installed at the bottom of each cell) and from the outlet pipe of the catch basin on the asphalt cell using CT2X sensors. Two-point calibration was performed on each sensor using conductivity solutions of 1,413 and 12,880 µS/cm. The sensors were installed within U-shaped rubber pipe traps connected to the PICP underdrains and catch basin outlet pipe. Rubber traps with clamp connections were used such that the traps could withstand soil expansions and contractions throughout the winter period without leaking, and monitoring wells were connected to the traps such that the sensors could be installed and accessed. The traps were bedded in a 400 mm deep layer of ASTM No. 8 washed aggregates to minimize movement of the traps, and the bedding layer was covered with 2 inches of foam insulation to minimize frost penetration. The native soil was backfilled above the insulation. Trap installation was completed on 31/Oct/2019. A photo of the traps during installation before being covered and backfilled is provided in Figure 3-2.

Figure 3-2: Installation of traps for housing conductivity sensors.

Within the traps, the conductivity sensors were submerged within a permanent pool of water that was approximately 300 mm (12 in) deep and stored approximately 1.2 L of water, and conductivity was measured approximately 110 mm (4.3 in) from the bottom. Measurements were collected every five minutes throughout the 2018/2019 winter beginning on November 8, 2018. While flows were not monitored, the sensors also measured water depth and temperature. Changes in these data were used to identify the presence of flows. Water depth varied throughout the monitoring period as a result of periodic water sampling but was always kept at above 200 mm (8 in) to maintain submergence of the sensors.

Water samples were collected in each trap using a 15 mL bottle attached to a swing sampler. For each sample, the 15 mL bottle was dipped into the bottom of the trap next to the conductivity sensor, removed, and then poured into a larger 250 mL sampling bottle. This process was repeated a minimum of five times for each well such that sample volumes of 75 mL or greater were collected. A new 15 mL bottle was used for each trap to prevent contamination. Between samples, the swing sampler was washed with reverse osmosis water and then quickly dried using a space heater to prevent ice from forming on the sampler during the frigid outdoor temperatures. Water samples were sent to AGAT Laboratories, and tested for chloride concentrations within 28 days of sampling. Water samples were first collected on 14/Jan/2019 to identify background chloride concentrations in each trap prior to the first application of de-icing treatments. Sampling was completed whenever changes in conductivity occurred after rainfall events or melting periods.

As a reference, Canadian Water Quality Guidelines for the protection of aquatic life recommend a long-term chloride concentration limit of 120 mg/L and a short-term chloride concentration limit of 640 mg/L [30].

4.0 STUDY FINDINGS

4.1 Surface Friction

Summary tables of measurements collected with the SlipAlert and Mark IIIB are provided in Appendix B.

4.1.1 Dry pavement conditions

Surface friction measurements were collected during dry pavement conditions (Figure 4-1). **No significant differences in DCOF or TCOF were found between the four PICP cells or between the PICP cells and the asphalt cell under dry conditions.** Mean DCOF of the PICP surfaces was measured to be 0.74 and mean TCOF was 0.72.

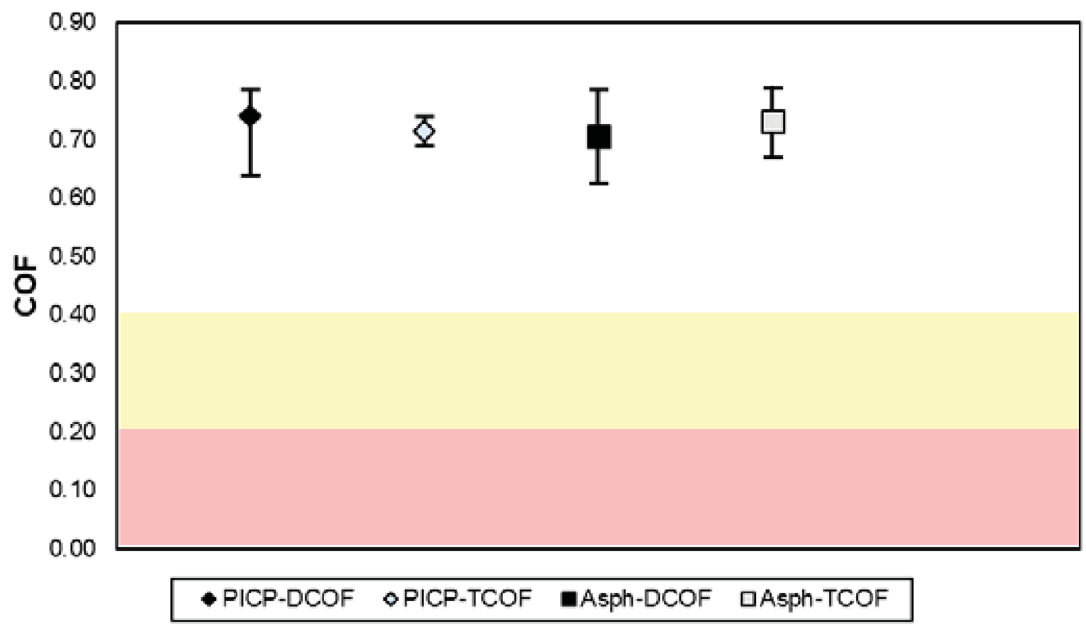


Figure 4-1: Surface friction during dry pavement conditions.

Red shading indicates high risk of slip (DCOF < 0.2) and yellow shading indicates moderate risk of slip (0.2 ≤ DCOF < 0.4).

4.1.2 Shovelled snow experiments

Mean DCOF and TCOF values are provided in **Error! Reference source not found.**. Friction means and ranges for each pavement cell are plotted in Figure 4-2. Surface friction soon after shovelling (Test 1) was always statistically significantly lower on the PICP cells than on the asphalt cell. Lower friction on the PICP surfaces after shovelling is not surprising, as the PICP surfaces have a monolithic texture that likely caused the thin layer of snow to have a more consistent thickness. In contrast, the asphalt had a more rugged and irregular texture that allowed for the snow to settle into microtexture surface depressions (Figure 4-3). Surface friction soon after salting (Test 2) and one to two hours after salting (Test 3) was statistically similar between the asphalt and PICP cells that both received 10 lb/ 1,000 ft^2 of road salt. These results demonstrate that **both pavement surfaces provide similar levels of safety soon after snow begins to melt.**

Mean DCOF and TCOF were statistically similar between all PICP cells regardless of application rate and de-icer type. **<u>The addition of beet juice did not provide any benefit under these conditions. The reduced de-icer application rate (5 lb/1000 ft^2) provided similar levels of safety as the medium application rate (10 lb/1000 ft^2).</u>**

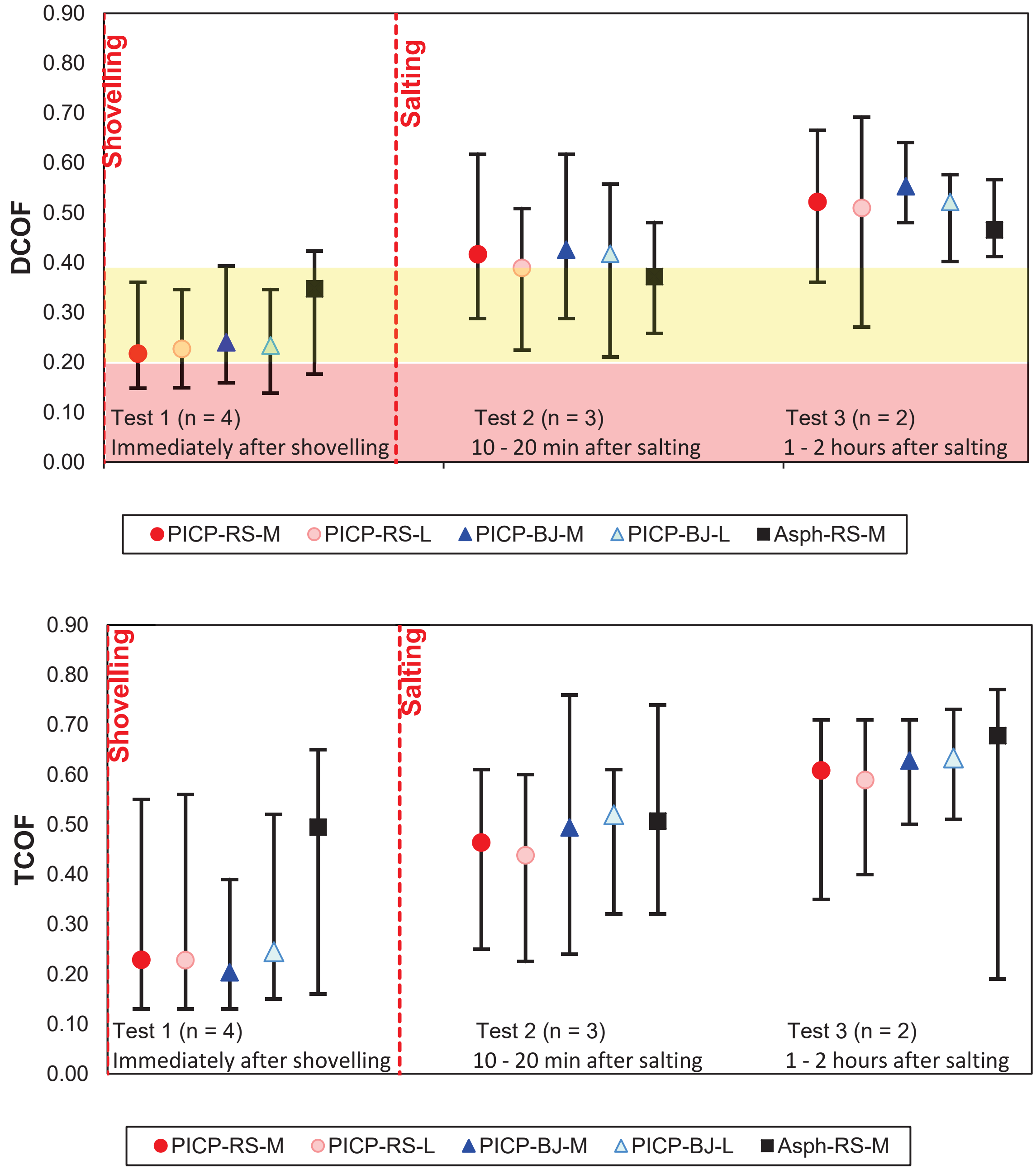


Figure 4-2: Means and ranges of DCOF (top) and TCOF (bottom) measurements for shoveled snow experiments.

In the top figure red shading indicates high risk of slip (DCOF < 0.2) and yellow shading indicates moderate risk of slip (0.2 ≤ DCOF < 0.4).

Table 4-1: Mean DCOF and TCOF values for shovelled snow experiments.

Pavement Cell[1]	Test 1 (n = 4) Immediately after shovelling		Test 2 (n = 3) 10 – 20 min after salting		Test 3 (n = 2) 1 – 2 hours after salting	
	Mean DCOF	Mean TCOF	Mean DCOF	Mean TCOF	Mean DCOF	Mean TCOF
PICP-RS-M	0.22	0.23	0.42	0.46	0.52	0.61
PICP-RS-L	0.23	0.23	0.39	0.44	0.51	0.59
PICP-BJ-M	0.24	0.20	0.43	0.49	0.55	0.63
PICP-BJ-L	0.23	0.25	0.42	0.52	0.52	0.63
Asph-RS-M	0.35	0.48	0.37	0.51	0.47	0.68

[1]Pavemnt Cell abbreviations are: (1) to describe pavement type: PICP - Permeable Interlocking Concrete Pavement and Asph – Asphalt, (2) to describe dicing product: RS – Road Salt and and BJ - Road Salt pre-wetted with Beet Juice, and (3) application rate: M - Medium (10 lb/1000 ft^2) and L – Low (5 lb/1000 ft^2).

Figure 4-3: Comparison of pavement textures between PICP (left) and asphalt (right).

4.1.3 Ice cover experiments

Two ice cover experiments, where compacted snow had partially melted and then refroze to form a dense layer of ice on the pavement cells, were completed. During the first experiment on 16/Feb/2019, the pavement cells were salted in the morning, and friction measurements were collected throughout the day from before salting until after sunset. DCOF and TCOF measurements collected during the 16/Feb/2019 experiment are presented in Figure 4-4, and percent coverages of ice and snow throughout the experiment calculated from site photos are provided in Figure 4-5. Table 4-2 summarizes the findings of statistical comparisons.

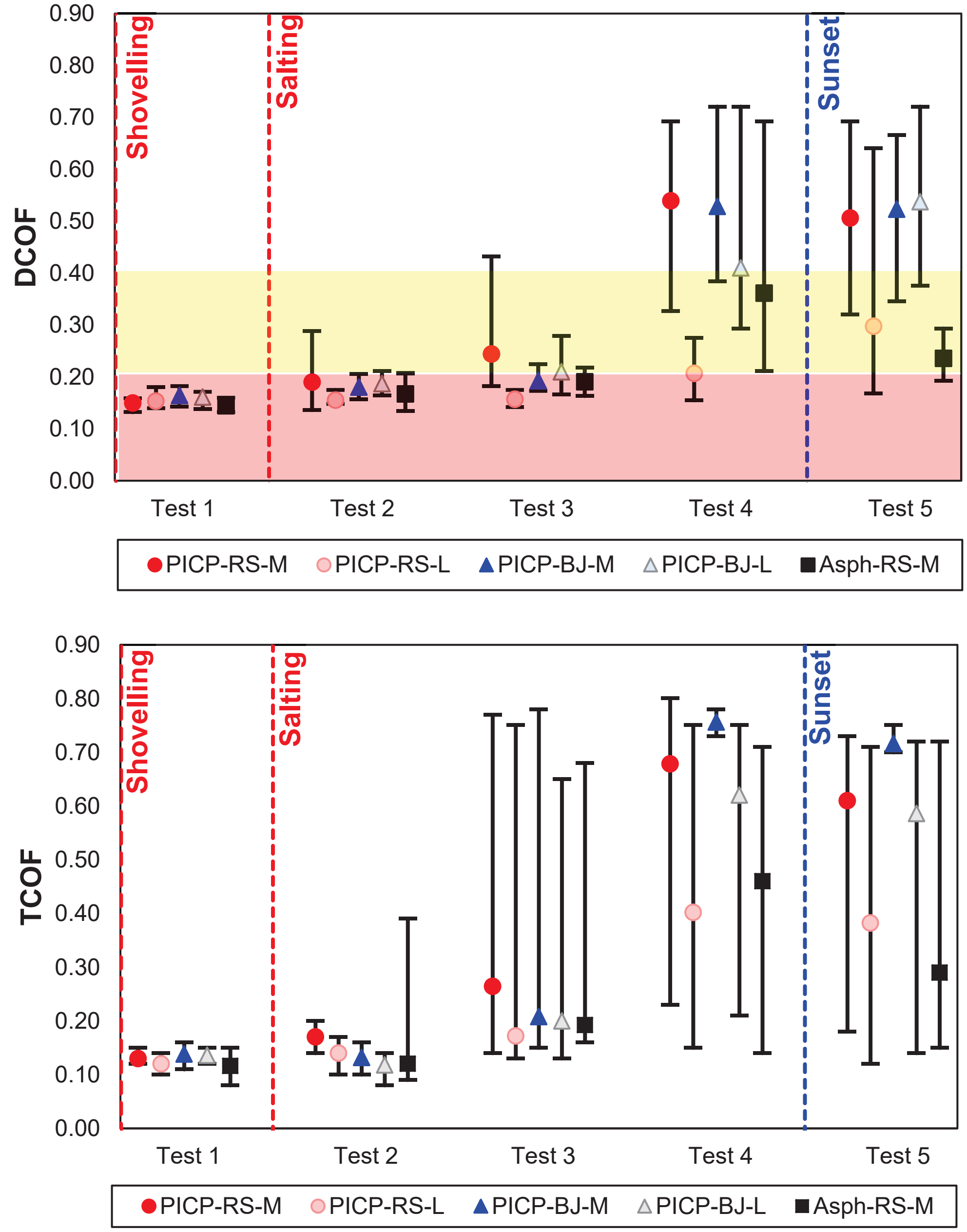


Figure 4-4: Means and ranges of DCOF (top) and TCOF (bottom) measurements collected during 16/Feb/2019 experiment.

In the top figure red shading indicates high risk of slip (DCOF < 0.2) and yellow shading indicates moderate risk of slip (0.2 ≤ DCOF < 0.4).

Timing of measurements is as follows: Shovelling occurred at 8:43, Salting began at 9:23 hr, Sunset was at 17:49 hr, Test 1 is immediately after shoveling (started at 8:48 hr, Test 2 is 10 – 20 minutes after salting (started at 9:35 hr), Test 3 is ~ 1 hours after salting (started at 11:36 hr), Test 4 is ~ 6 hours after salting (started at 15:32 hr), and Test 5 is 10 minutes after sunset (started at 18:02 hr).

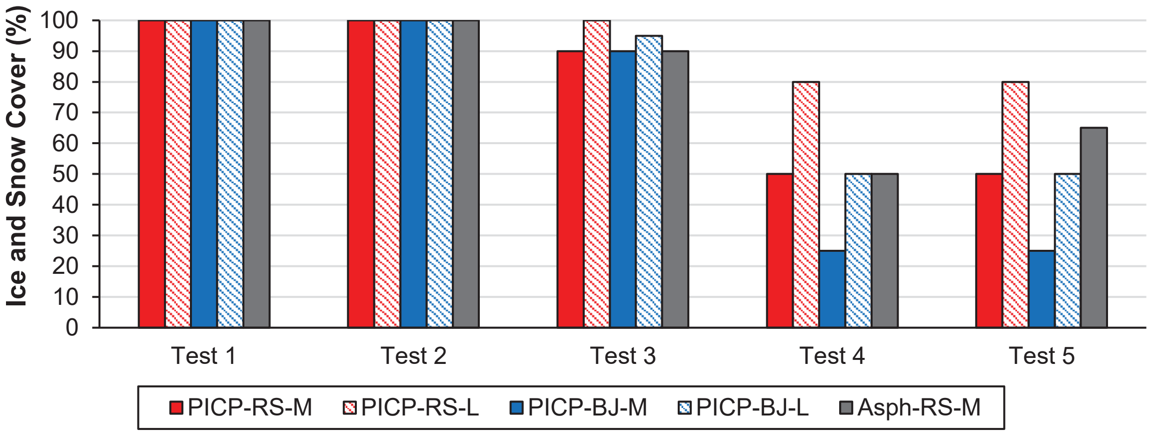


Figure 4-5: Ice and snow coverage during melting and refreeze on 16/Feb/2019.

There were no significant differences in surface friction between the pavement surfaces before salting (Test 1). Within 30 minutes after salting (Test 2), all surfaces remained ice-covered except for a few small pockets of partially clear pavement on the asphalt cell (< 1% of cell area). Regardless of these patches frictions levels on the asphalt and PICP surface were similar. Statistically significant differences in DCOF were identified between the PICP cells treated with 5 lb/1000 ft^2 of beet juice wetted road salt and 5 lb/1000 ft^2 of regular road salt demonstrating that **the beet juice facilitated more rapid melting under icy conditions**.

During Test 3 (approximately 2 hours after salting), drastic changes in maximum TCOF occurred on all cells due to various pockets of dry and semi-dry patches. As a result, maximum TCOF ranged from 0.65 to 0.78 for the PICP cells and was 0.68 for the asphalt cell. TCOF measurements were statistically similar on all surfaces. The PICP cell that received treated with 5 lb/1000 ft^2 of beet juice wetted road salt continued to have statistically significantly higher DCOF levels than the PICP cell treated with 5 lb/1000 ft^2 of regular road salt. Similarly, the PICP with the higher road salt treatment (10 lb/1000 ft^2) had higher DCOF levels than the PICP with the lower (5 lb/1000 ft^2) road salt treatment, demonstrating that **under icy conditions the higher road salt application facilitated a more rapid melting of surface ice.**

During Test 4 (approximately 6 hours after salting), the advantage of the beet-juice additive was evident. Snow and ice still covered 80% of the PICP surface treated with 5 lb/1000 ft^2 of road salt. The asphalt surface and PICP cells treated with 10 lb/1000 ft^2 of road salt and 5 lb/1000 ft^2 of beet-juice wetted road salt were approximately 50% covered with ice and snow. And, only 25% of the PICP surface treated with 10 lb/1000 ft2 of beet-juice-wetted road salt remained covered with ice or snow.

Table 4-2: Comparison of friction between pavement cells for the 16/Feb/2019 experiment.

Pavement Cell Comparison	Significant Difference ($p < 0.05$)?[a]									
	Test 1		Test 2		Test 3		Test 4		Test 5	
	DCOF	TCOF	DCOF	TCOF	DCOF	TCOF	DCOF	TCOF	DCOF	TCOF
PICP-RS-M vs. PICP-RS-L					✓		✓			
PICP-BJ-M vs. BJ-M-L								✓		
PICP-RS-M vs. BJ-BJ-M										
PICP-RS-L vs. PICP-BJ-L			✓		✓		✓			
PICP-RS-M vs. Asph-RS-M								✓	✓	

[a] Calculated using two-tailed Mann-Whitney U Test. A "✓" symbol indicates a significant difference ($p < 0.05$).

Several areas of the PICP pavements had dried while the asphalt surface remained wet (Figure 4-6). As a result, even though the asphalt and PICP surfaces treated with 10 lb/1000 ft^2 of road salt had similar amounts of clear pavement, frictions levels were significantly higher on the PICP pavement.

During Test 5, which was carried out within the hour after sunset, 25% of the asphalt surface that was previously cleared of ice and snow became covered in a thin sheet of ice as a result of meltwater refreezing. Refreeze of melted ice and snow along its drainage path is a typical occurrence on impervious sidewalks, as snow residing on properties often melts and drains onto sidewalks during the day and then refreezes during the night. As a result of the meltwater refreeze on Asph-RS-M, the mean DCOF decreased from 0.34 to 0.22 and the mean TCOF decreased from 0.46 to 0.29. Notably, TCOF near the catch basin was reduced from 0.67 to 0.21 after the meltwater refroze. No refreeze of previously melted ice occurred on the PICP cells, as all remaining wet areas rapidly drained and evaporated. The refrozen ice on the asphalt cell remained on the surface the next morning.

An attempt was made to repeat the ice condition experiment during the first week of March. Salting was carried out on 04/Mar/2019 on the compacted snow and ice to expedite melting and to evaluate its impacts. On the days following salting, clear spots formed along the meltwater path of the asphalt cell near the catch basin and in the middle of the cell that experienced refreeze during the nights. Friction measurements carried out on 07/Mar/2019 before and after sunset showed that meltwater refreezes on the asphalt surface decreased TCOF as wet pavement became icy. At one location, TCOF decreased from 0.47 to 0.08. At the second location, TCOF decreased from 0.46 to 0.19.

Over the next two days, the compacted snow on the PICP surfaces would partially melt and refreeze whenever temperatures went above zero then dropped again. However, none of the "wet" areas (i.e. the locations where the snow layer had completely melted) refroze after sunset or when temperatures dropped, as any melted water drains rapidly and has a short overland path to follow (i.e. one paver length to the nearest open joint). While pavers did become damp during the day, no ice form and melt water evaporated. This is very different from the drainage and wetting/drying processes observed on the asphalt pavement which had a thick layer of water and a constant creeping flow along a meltwater path that freezes into black ice at night.

(a)

(b)

(c)

Figure 4-6: Surface conditions after ice cover melting on 16/Feb/2019.

(a) before sunset when PICP surfaces were slightly damp at locations where ice had just melted while the meltwater path along the asphalt surface remained wet, (b) after sunset when damp areas on the PICP surfaces were reduced while meltwater had refrozen on the asphalt surface, (c) the next morning when all previously damp area on PICP surfaces were dry while refrozen meltwater remained on the asphalt surface at locations where the ice was thickest.

During the two ice cover experiments, surface ice appeared to adhere to the asphalt surface more than the PICP surfaces. As shown in Figure 4-7 and Figure 4-8, gaps between ice and PICP surfaces are present at the perimeter of ice patches. In contrast, the ice spatially transitioned into a liquid state on the asphalt surface without losing contact. Similar observations occurred on 15/Apr/2018 after the sleet and freezing rain event, where ice pellets were notably easier to shovel down to a thin layer on the PICP cells compared to the asphalt cell.

Figure 4-7: Ice cover characteristics on 16/Feb/2019: partially detached ice cover on PICP (left) and ice transition into wet pavement on asphalt (right)

Figure 4-8: Refreeze of partially melted compacted snow at sunset on 09/Mar/2019 following rapid melting during the afternoon.

4.2 Melting Processes during Undisturbed Snow Conditions and other Observations

A total of fifteen melt events occurred throughout the two winters where snow was left undisturbed on the pavement surfaces. Pavement melt times to trace snow cover conditions (between 95% and 99% clear) and entirely clear conditions (> 99% clear) are provided in Appendix C. During these events, an even melting pattern through the joint spaces occurred on the PICP cells. In contrast, an uneven and radial melting pattern usually occurred on the asphalt cell. Melting always began in the morning or before peak daytime air temperatures. For all events, melting began first on the asphalt cell. Melting to trace cover conditions also always occurred sooner on the asphalt cell than on the PICP cells, whereas clear conditions occurred sooner on the asphalt cell for only one-third of the events. The longer times to achieve entirely clear conditions on the asphalt cell were a result of snow remaining at the low point around the catch basin for extended periods. Snow at the catch basin was unable to melt by the end of the day for 47% of the melt events. An example of the melting patterns described above is shown in Figure 4-9.

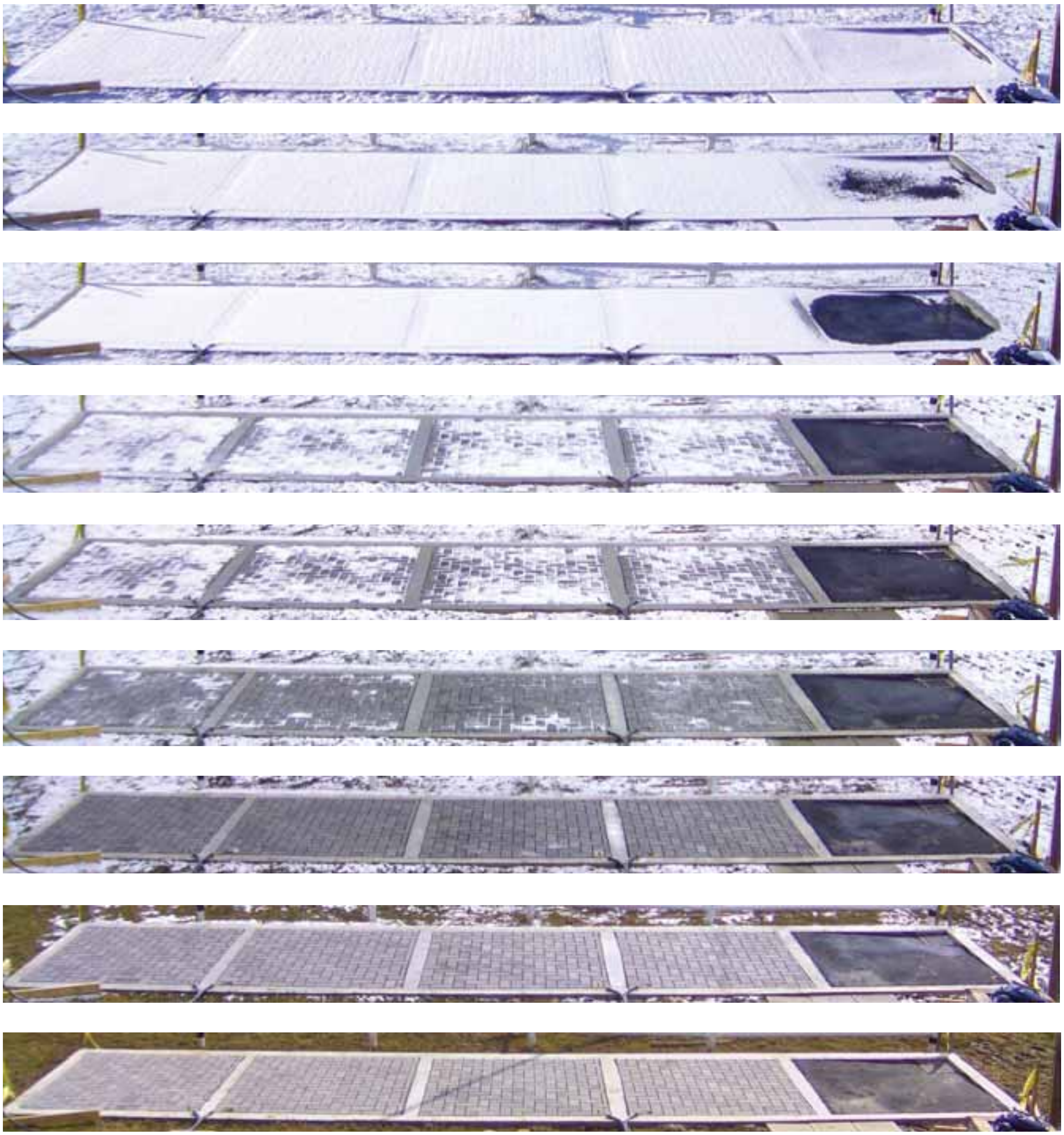


Figure 4-9: Snowmelt over time on 13/Mar/2018 under undisturbed site conditions.

Melting occurs on the asphalt cell before the PICP cells. Melting on the asphalt cell begins along its slope, whereas melting on the PICP cells is evenly distributed.

Flooding of the asphalt cell occurred during a rainfall event on 24/Feb/2019 as a result of ice accumulation in the catch basin and outlet pipe (Figure 4-10). The ice formed after three days of air temperatures fluctuating above and below 0 °C while snow on the surface was gradually melting. Manual ice removal was carried out on 25/Feb/2019 so that winter observations and experiments could continue. No surface flooding on the PICP cells occurred through the study.

(a)

(b) **(c)**

Figure 4-10: Flooding of asphalt cell on 24/Feb/2019 caused by frozen catch basin.

(a) flooded asphalt cell and partially wet PICP cells on 24/Feb/2019 after rainfall event, (b) ice in catch basin during clean-out, and (c) ice in catch basin outlet pipe during clean-out.

Undissolved salt particles remained on the five pavement cells after the shovelled snow experiments. Some of the salt particles entered the joint spaces where meltwater drains vertically around the aggregates instead of radially over the pavers inhibiting the overall salt dissolution on the PICP surfaces. After meltwater had evaporated from the pavement surfaces, a portion of the dissolved salt remained as a precipitate. This salt created anti-icing conditions for subsequent snowfall events when there was no rainfall to flush it away (Figure 4-11). Precipitated salt particles were more widespread and concentrated on the asphalt cell because of its slope and increased salt dissolution. Snow accumulation rates were slower on the asphalt surfaces when leftover salt was present, as the precipitated salt coverage on the asphalt cell was more representative of liquid brine-based anti-icing treatments.

(a)

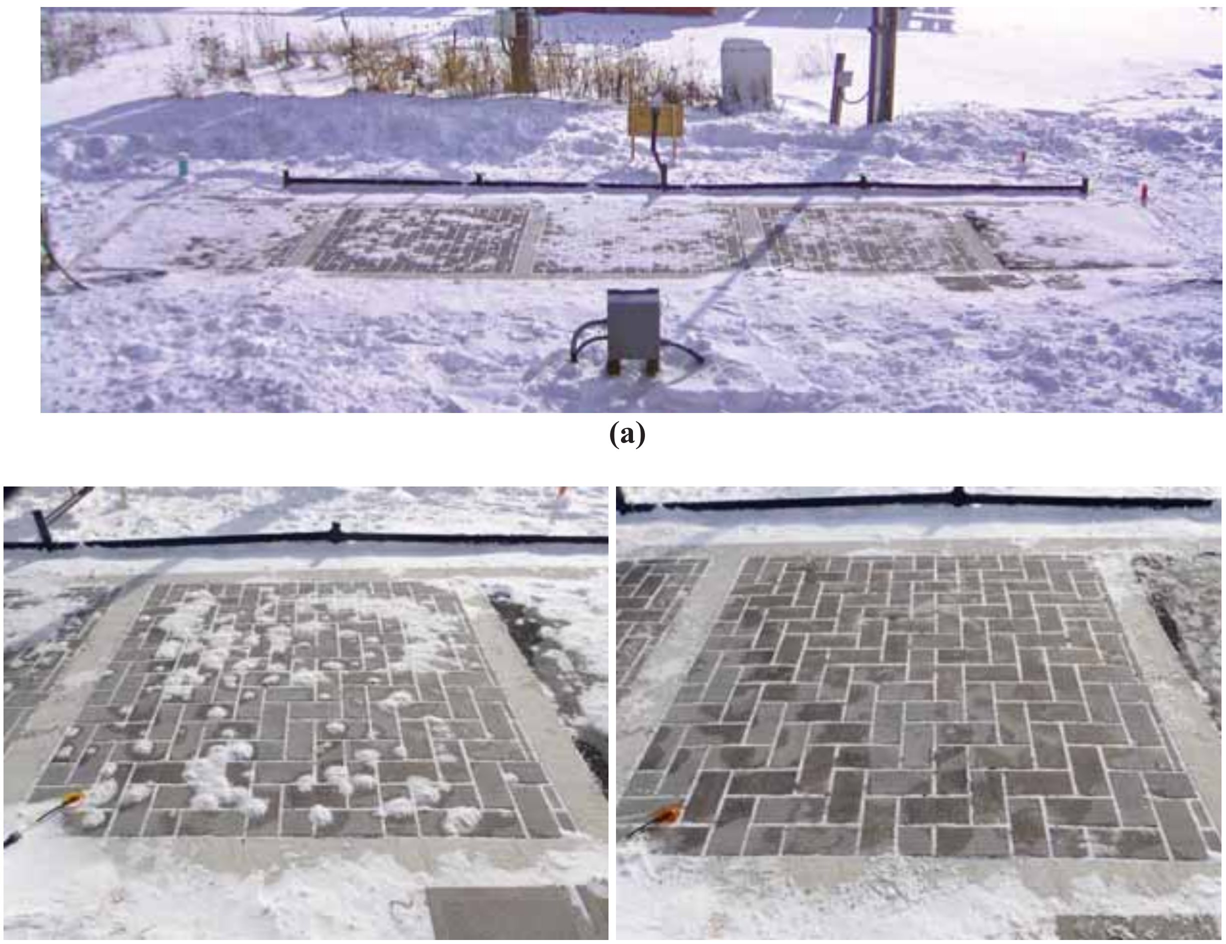
(b)

(c)

Figure 4-11: Impacts of leftover salt particles from 08/Feb/2018 de-icing treatment after the snow had melted and meltwater had drained and evaporated.

(a) larger salt particles remained on PICP surfaces, (b) most salt particles dissolved and precipitated on the asphalt surface, (c) the leftover salt particles impact snow accumulation rates the next day.

Both the undissolved and the precipitated salt particles created isolated patches of ice during temperatures below -15 °C where blowing snow would adhere to the salt, partially melt, and refreeze (Figure 4-12). On 31/Jan/2019, almost the entire asphalt cell was covered in ice due to its more widespread coverage of precipitated salt particles that had been applied the previous day. In contrast, ice on the PICP cells was limited to the locations where there were leftover salt particles. Cells that received medium de-icer application rates were covered 90% in ice, while cells that received a low de-icer application rate were covered 50% by ice. Friction measurements collected after shovelling the blown snow to a thin layer reflect slippery conditions created by the higher ice coverage (Figure 4-13). Despite surface temperatures on these days being below the operational range for road salt, no reduction in ice or increase in friction occurred on the cells that received road salt pre-wetted with beet juice, as most of the beet juice coating drained off during the 30/Jan/2019 experiment. Observations during these blowing snow conditions exemplify the safety hazards of using road salt when temperatures are below its operational range.

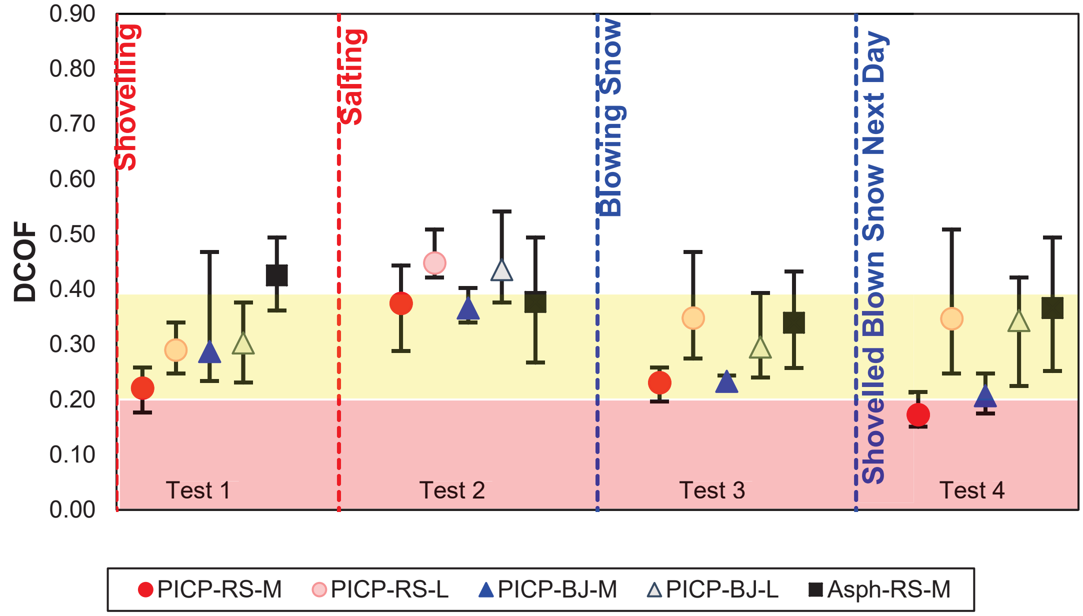


(a)

(b) (c)

Figure 4-12: Impacts of blowing snow on 31/Jan/2019 after salt particles remained on pavement surfaces.

(a) comparison of blown snow quantities based on spatial coverage of salt particles and pavement topography, (b) blown snow on PICP, (c) ice patches on PICP where blown snow was shovelled.



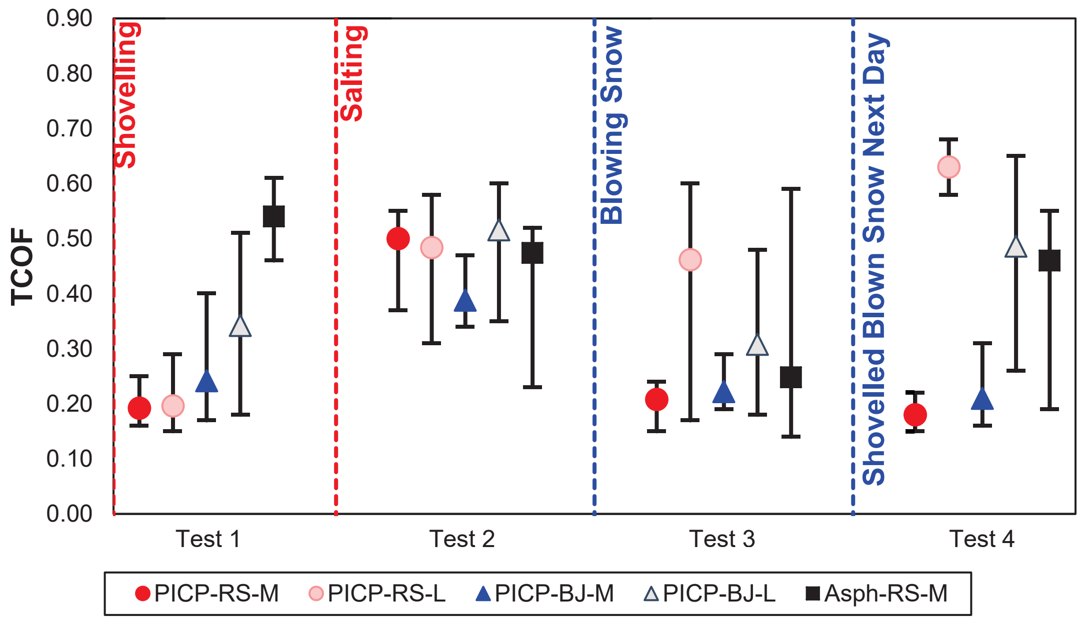


Figure 4-13: DCOF (top) and TCOF (bottom) data collected on 30/Jan/2019 and 31/Jan/2019 after cells were shovelled to a thin layer of snow.

In the top figure red shading indicates high risk of slip (DCOF < 0.2) and yellow shading indicates moderate risk of slip (0.2 ≤ DCOF < 0.4).

Blowing snow partially covered cells after Test 2 and again after Test 3. Timing of measurements is as follows: Shovelling occurred at 11:35 hr, Salting began at 12:09 hr, Test 1 is immediately after shoveling (started at 11:42 hr, Test 2 is 10 – 20 minutes after salting (started at 12:19 hr), and Test 3 is ~ 1.5 hours after salting after blowing snow occurred (started at 13:50 hr). Blown snow was shoveled on 31/Jan/2019 to thin patches of ice that formed where the blown snow had previously melted by salt particles and then refroze. Shoveling on 31/Jan/2019 created thin layers of snow that partially covered PICP-RS-L and PICP-BJ-L, and that fully covered PICP-RS-M, PICP-BJ-M, and Asph-RS-M.

4.3 Surface Temperatures

Surface temperatures on the four PICP cells were averaged because surface temperatures were significantly different between individual cells. Box plots of all surface temperature and of sunset temperatures are plotted in Figure 4-14. Air temperatures at the research site were colder during the 2018/2019 winter than climate normal values (Table 4-3).

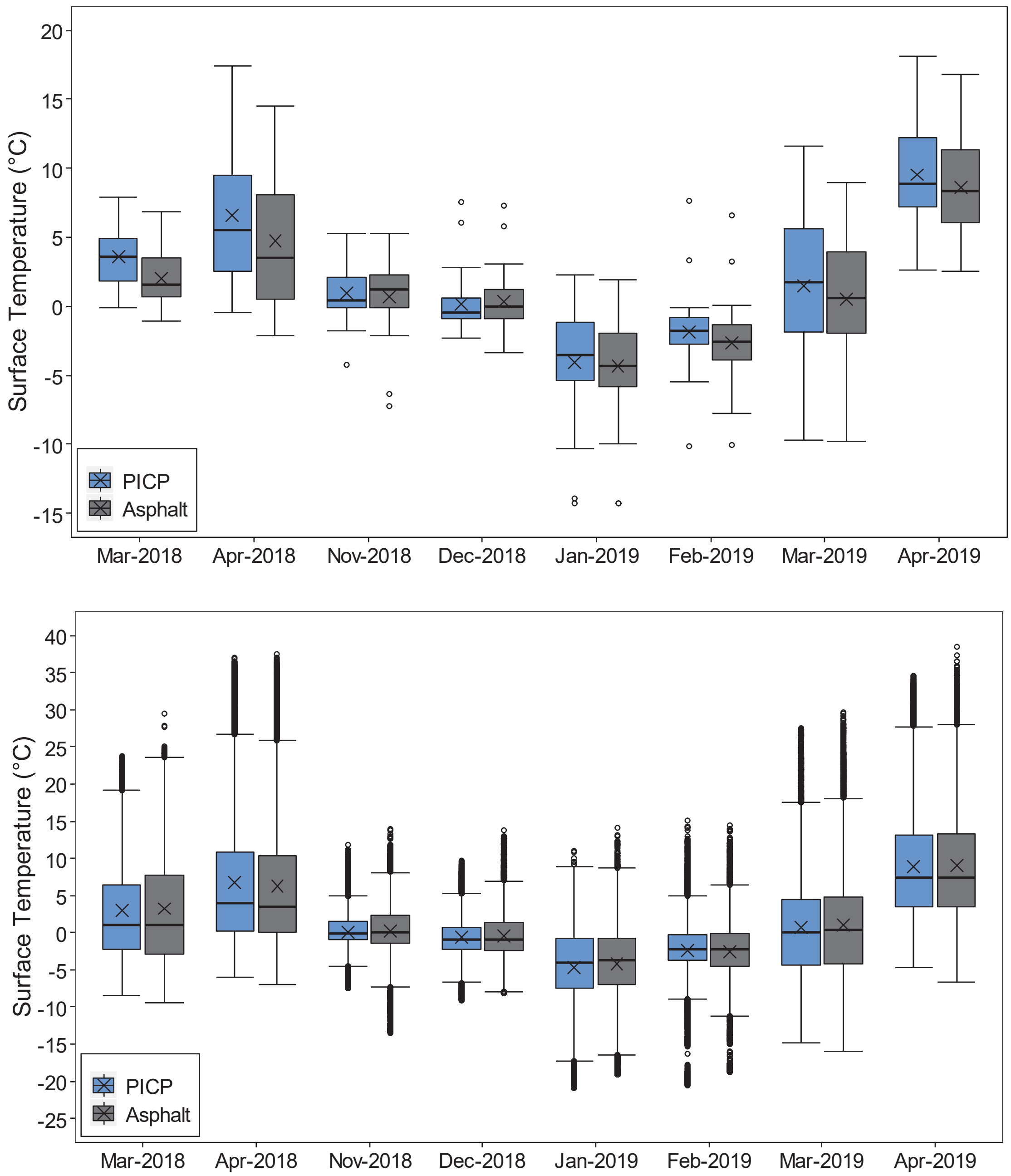


Figure 4-14: Box plots of surface temperatures at sunset (top) and overall (bottom)

Table 4-3: Comparison of air temperatures at research site with climate normal values.

Month	Daily Mean Air Temperature (°C)		Daily Maximum Air Temperature (°C)		Daily Minimum Air Temperature (°C)	
	Climate Normal[a]	2018/2019 Period[b]	Climate Normal[a]	2018/2019 Period[b]	Climate Normal[a]	2018/2019 Period[b]
Nov	3.1	0.7	6.9	3.6	-0.8	-2.5
Dec	-2.8	-0.9	0.8	2.2	-6.4	-4.3
Jan	-6.6	-7.6	-2.5	-3.3	-10.7	-12.4
Feb	-4.8	-5.0	-0.5	-0.7	-9.2	-9.7
Mar	-0.4	-1.8	4.3	3.1	-5.2	-6.7
April	6.6	5.7	12.0	10.4	1.2	0.8

[a] Climate normal values are from the Woodbridge climate station operated by Environment Canada. The station is located approximately 6 km away from the research site.
[b] 2018/2019 temperatures are from a climate station operated by the TRCA. The station is located approximately 500 m away from the research site.

Daily mean surface temperatures were similar between the Asphalt and PICP surfaces but maximum surface temperatures for this winter were slightly lower (typically 1 to 2°C lower) on the PICP cells (Figure 4-15). The lower maximum temperatures were not surprising since the PICP cells were grey has have a lower albedo than the black asphalt.

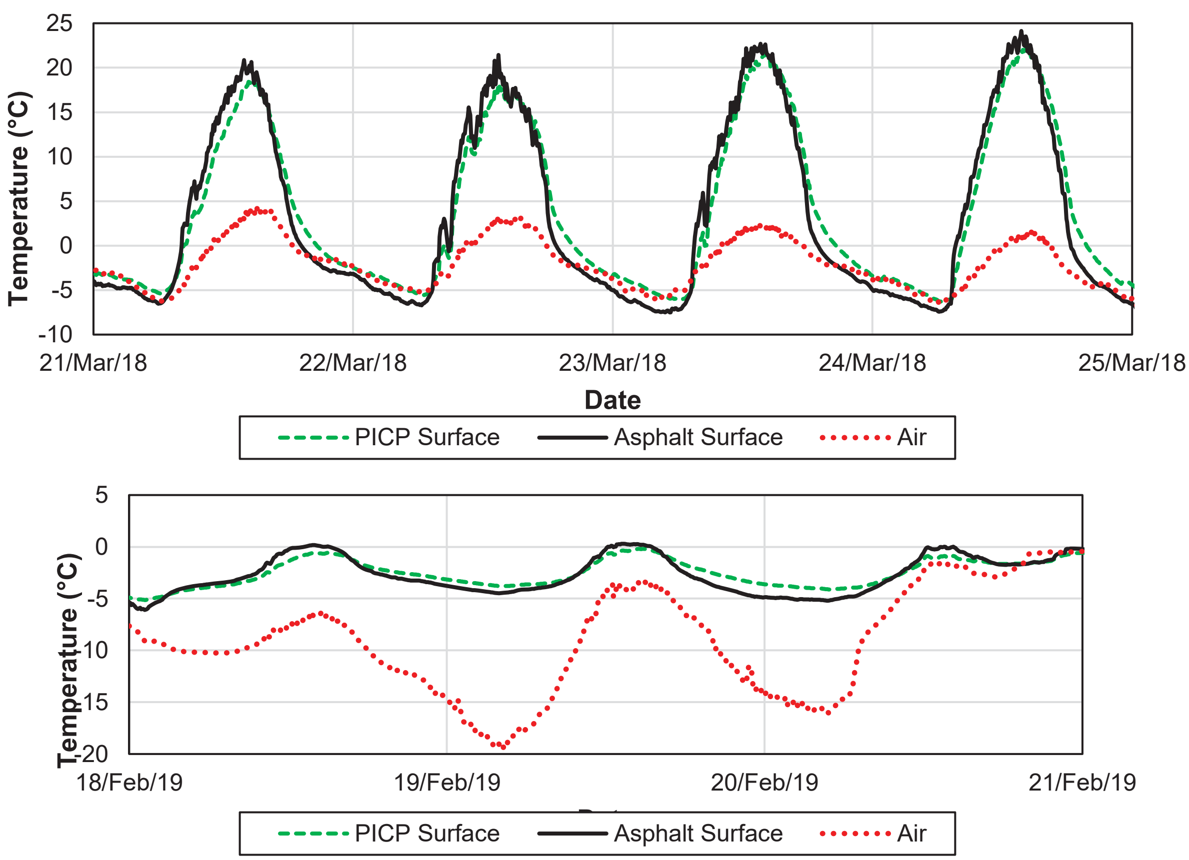


Figure 4-15: Air and surface temperatures during a typical diurnal pattern in March 2018 (top) and during a snow-covered period in February 2019 (bottom).

While daily minimum surface temperatures of the asphalt were not significantly lower than the PICP surfaces during the winter, asphalt surface temperatures were significantly lower at sunset. As shown in Figure 4-15, asphalt temperatures dropped more rapidly than PICP temperatures beginning mid-afternoon when air temperatures and solar radiation rapidly decrease. Surface temperatures then remained higher on the PICP cells until the early hours of the following day when air temperatures and solar radiation begin to increase.

4.4 Water Quality

4.6.1 Conductivity

Conductivity is a general measure of water quality and an indirect measurement of the saltiness of water. It measures the ability of water to pass an electric current. It is measured with a probe that applies voltage between two electrodes. The basic unit of measurement is called *mho* because it is the inverse of *ohm* [31]. The basic unit mho/cm is known as 1 Siemens. In natural waters conductivity occus at one millionths (micro-) scale hence conductivity is measured as micro siemens per centimetre (μS/cm) [31]. High conductivity is associated with high amounts of dissolved solids. In Canada a common target for conductivity in surface water systems is 500 μS/cm [32]. Conductivity measurements collected from the middle of January to the end of May are presented in Figure 4-16, and background and peak winter conductivities are presented in Table 4-4. Conductivity spikes were found to be more closely associated with rainfall rather than snowfall, as larger flows occurred during rainfall events.

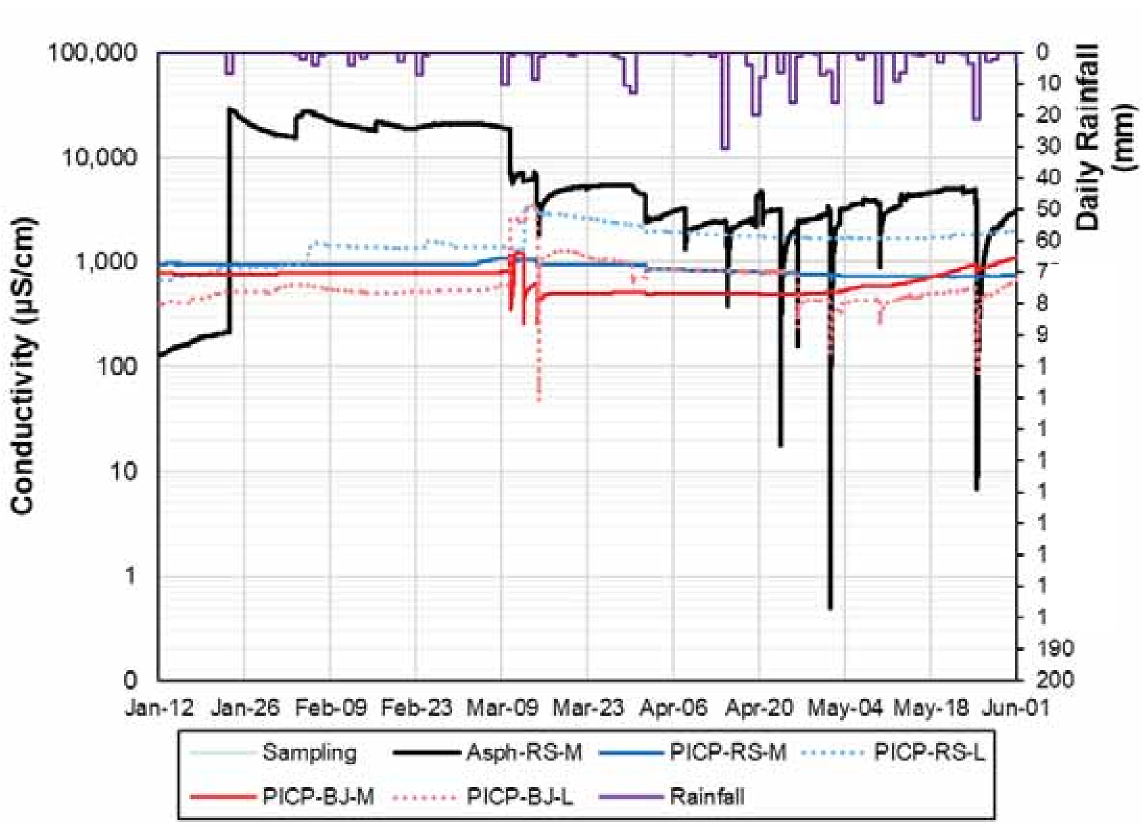


Figure 4-16: Conductivity measurements collected during the 2019 winter and spring.

Table 4-4: Background and peak winter conductivities in pavement cell outflows.

Test Cell	Background Conductivity (µS/cm)	Peak Conductivity (µS/cm)	Peak Conductivity Reduction[a]	Peak Measurement Date
PICP-RS-M	908	1,090	96%	09/Mar/2019
PICP-RS-L	649	3,450	88%	14/Mar/2019
PICP-BJ-M	774	1,240	96%	11/Mar/2019
PICP-BJ-L	383	3,450	88%	14/Mar/2019
Asph-RS-M	155	29,400	-	23/Jan/2019

[a] Percentage of peak conductivity in the respective PICP cell to that of the asphalt cell.

The peak winter conductivity in the asphalt cell outflow was measured at 29,400 µS/cm and occurred after the first rainfall event that followed the first de-icing treatment. Similar conductivity levels were then observed in the asphalt cell outflow until after the last de-icing treatment was carried out on 04/Mar/2019. Beginning on 10/Mar/2019, rainfall events began to result in peak minima conductivity values rather than peak maxima conductivity values, indicating that very little road salt was left either on the pavement surface or in the catch basin.

For the two PICP cells that received medium de-icer application rates, peak winter conductivities in the underdrain outflows were 4% of those in the asphalt cell outflow. For the two PICP cells that received low de-icer application rates, peak winter conductivities in the underdrain outflows were 12% of those in the asphalt cell outflows. It is unclear why conductivity in discharge from PICP cells treated with less de-icers were higher.

While peak winter conductivities in the asphalt outflows occurred immediately after the first de-icing treatment, peak winter conductivities in the PICP outflows occurred in March after rainfall events became more frequent and temperatures began to rise. The PICP cells were therefore found to both reduce and delay the peak winter conductivity spikes. From 14/Mar/2019 onward, peak minima conductivities were observed in the PICP outflows whenever the traps received flows. Similar to the asphalt cell, this likely occurred as a result of low quantities of the salt remaining in the system, or the denser water containing dissolved salts not fully flushing out of the traps.

Salinity estimated from conductivity measurements is described using the practical salinity scale and measurements values have the suffix psu (practical salinity unit). Figure 4-17 plots the salinity of discharge water from the asphalt pavement and PICP drains. Asphalt runoff was 10 psu or higher throughout much of January and February (for context sea water has a salinity of approximately 35 psu) while the salinity of PICP discharge remained relatively constant (2 psu or less) throughout the entire study.

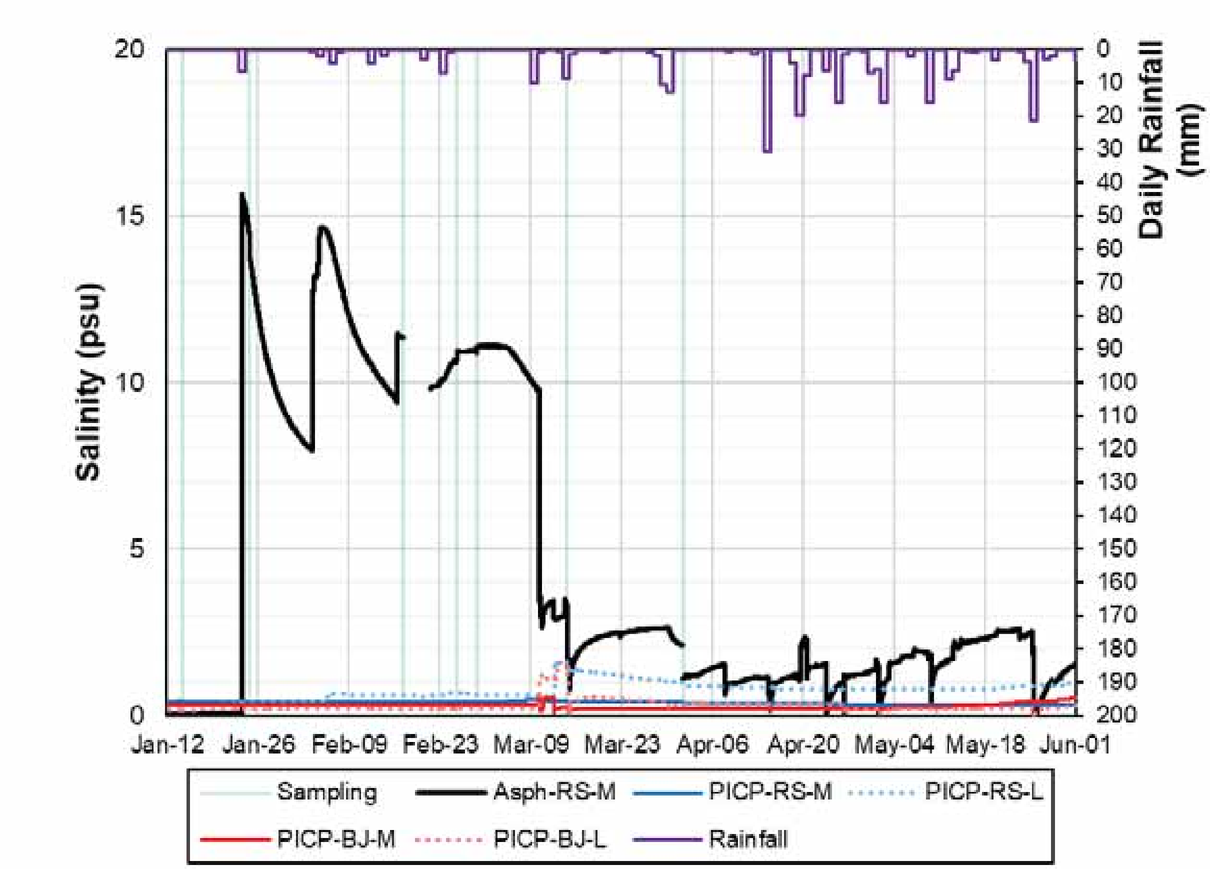


Figure 4-17: Salinity of discharge water in winter and spring 2019

4.6.2 Chloride

Chloride concentrations measured in the collected water samples are presented in Table 4-5. Baseline chloride concentrations prior to any de-icing activities were found to be higher in the PICP outflows (30 mg/L on average) compared to the asphalt outflows (1.6 mg/L). These chloride concentrations are, however, much lower than the current USEPA chronic limits. While no chloride sources were identified in the PICP cells, low levels of chlorides were likely leaching from the fresh aggregate materials into the underdrains.

Table 4-5: Chloride concentrations measured in water samples.

Test Cell	Sample Number	Sample Date	Chloride Concentration (mg/L)	Conductivity Measurement (µS/cm)
PICP-RS-M	1	14/Jan/2019	43.9	978
	2	14/Mar/2019	29.9	1,040
	3	01/Apr/2019	32.9	936
PICP-RS-L	1	14/Jan/2019	16.1	671
	2	28/Feb/2019	786	1,500
	3	14/Mar/2019	766	3,213
	4	01/Apr/2019	413	2,195
PICP-BJ-M	1	14/Jan/2019	30.6	779
	2	14/Mar/2019	44.9	496
	3	01/Apr/2019	26.2	520
PICP-BJ-L	1	14/Jan/2019	28.7	427
	2	14/Mar/2019	674	3,169
	3	01/Apr/2019	143	722
Asph-RS-M	1	14/Jan/2019*	1.62	151
	2	24/Jan/2019	610	26,411
	3	17/Feb/2019	2,910	21,375
	4	28/Feb/2019	3,390	20,699
	5	14/Mar/2019	110	6,881
	6	01/Apr/2019	185	4,393

*Identified as an outlier

For the asphalt cell (Asph-RS-M in Table 9), the chloride concentration measured on 24/Jan/2019 after the first de-icing treatment and subsequent rainfall event was 610 mg/L. However, large amounts of suspended sediment were observed in the sample, which may have impacted its chloride content. Turbidity of the asphalt outflows was visually observed to decrease as the winter progressed. The source of the turbidity was likely sediment leftover from construction activities during installation of the traps and from atmospheric deposition before the winter season.

Asphalt chloride concentrations exceeded Canadian Environmental Quality Guideline short- and long-term concentration by several magnitudes on 17/Feb/2018 and 28/Feb/2018 after additional de-icing treatments and rainfall events. For the two PICP cells that received medium de-icer application rates (PICP-RS-M and PICP-BJ-M in Table 9), the water samples provided no evidence that chloride levels had increased during the conductivity monitoring period. The absence of increased chloride levels on 14/Mar/2019 also indicates that most chlorides were rapidly flushed out of the system during the previous rainfall events associated with the peak winter conductivity observations. Slush was observed in water samples collected from the PICP cells that received low de-icer application rates, indicating that partially frozen conditions in the traps may have impacted the conductivity readings and chloride concentrations in the water samples. The presence of frozen water in the traps also indicates that ice may have accumulated in the PICP underdrains and aggregate layers.

5.0 CONCLUSIONS

5.1 Study Findings

The results of this study indicate that the PICP provides equivalent or better levels of safety compared with asphalt when treated with dicing products at medium or low application rates.

Key findings of this research include the following:

- PICP and asphalt surfaces have equivalent levels of surface friction under dry conditions.
- PICP treated with a low application rate of road salt (5 lb/1000 ft^2) provided similar levels of safety as PICP treated with a medium application rate of road salt. This demonstrates that road salt applications on PICP surfaces can be reduced while maintain the same level of safety for pedestrians and vehicles. The PICP surfaces had lower surface friction after shovelling than the asphalt surface after shovelling. This is not surprising, as the PICP surfaces have a monolithic texture that likely caused the thin layer of snow to have a more consistent thickness, whereas the asphalt had a more rugged and irregular micro-texture that allowed for snow to settle into surface depressions. Both pavement surfaces treated with medium application rate of road salt (10 lb/1000 ft^2) provide similar levels of safety soon after snow begins to melt. Pre-wetting road salt with beet juice did not provide any additional benefit under the tested conditions.
- Re-freezing of melted snow and ice after sunset was observed creating black ice on the asphalt surface but not on the PICP cells. Prior to salting the PICP and asphalt surfaces had similar levels of surface friction under icy conditions. Melting and drying of the PICP surfaces occurred more rapidly with the medium application rate or when using road salt pre-wetted with beet juice.
- Surface ice was less bonded to the PICP and was easier to shovel and remove compared to the asphalt surface.
- Melting processes of undisturbed snow and surface temperature is driven by pavement thermal properties (e.g. color) not drainage characteristics. Melting occurred more rapidly on the black asphalt as opposed to the grey PICP. Despite this, refreezing of meltwater near the catch basin frequently occurred on the asphalt.
- The PICP attenuated and buffered the release of de-icing materials in stormwater discharge. Peak conductivity levels were reduced by over 85% by the PICP. Chloride concentrations in sampled asphalt runoff exceeded USEPA chronic chloride concentration limit of 230 mg/L and an acute chloride concentration limit of 860 mg/L to sustain aquatic life by several magnitudes. Sampled PICP discharge never exceeded the acute concentration limit. Despite having clayey soils, significant exfiltration to the underlying soils occurred which will allow de-icers to migrate into subsurface systems. The ultimate pathway and fate of de-icers remain unclear, but as with conventional pavements, impacts to both surface and groundwater resources are likely.

5.2 Best Management Practices

Based on the experiences gained throughout this study, the following recommendations should be implemented for winter operations for PICP:

- To minimize the use of de-icers, which are environmentally harmful, shovelling and plowing of snowy and icy pavements should always be attempted before applying de-icers. De-icers are not very effective when used on thick snow. Additionally, ice may be less bonded to a PICP surface compared to the conventional pavement and easily removed. If ice can only be removed in some areas, this may limit the areas where de-icers are needed and allow less de-icers to be applied.
- Under mild winter conditions it is **not necessary** to apply de-icers at medium (10 lb/1000 ft^2) or high (15 lb/1000 ft^2) application rates to achieve low risk surface conditions for slipping or skidding. A low application rate (5 lb/1000ft^2) provides similar levels of safety as medium and high application rates.
- Under icy conditions, a medium application rate (10 lb/1000 ft^2) of deicers is appropriate. In this study, road salt pre-wetted with beet juice provided more rapid melting and drying of the PICP than road-salt alone.
- Although not explicitly demonstrated in this study, road salt pre-wetted with beet juice has a lower effective temperature and is an appropriate alternative to road-salt only for temperatures between -15°C (5°F) and -27°C (-16°F).
- Re-freezing of melted snow and ice after sunset was observed on the asphalt surface, creating black ice but not on the PICP cells. Consequently, compared to asphalt pavements, **PICP surfaces will require use of less deicers and will have a lower risk of slips and falls for pedestrians and lower risk of skidding for vehicles throughout the winter.**

5.3 Future Research

It is recommended that winter testing of winter operational practices continue to expand and improved best management practices. Additional questions that should be considered in future research include:

- *Can application rates be reduced using smaller particle-sized de-icing products?* Throughout this study, it was observed that road salt granular would often not fully dissolve, especially under thin snow/ice conditions. Smaller particle sizes may allow for improved coverage and more rapid melting.
- *How do PICP surfaces respond to the use of brine-based anti-icing products?* Due to site accessibility, anti-icing products were not evaluated in this study. This is an increasingly popular operational approach and should be evaluated.
- *Can safe pavement conditions be achieved throughout the winter using aggregates (i.e. joint-sized chip stone) instead of de-icers?* ICPI recommends joint material as an alternative to de-icing/anti-icing during the winter. To our knowledge surface friction and ice coverage on PICP surfaces has not been rigorously examined or tested.

6.0 REFERENCES

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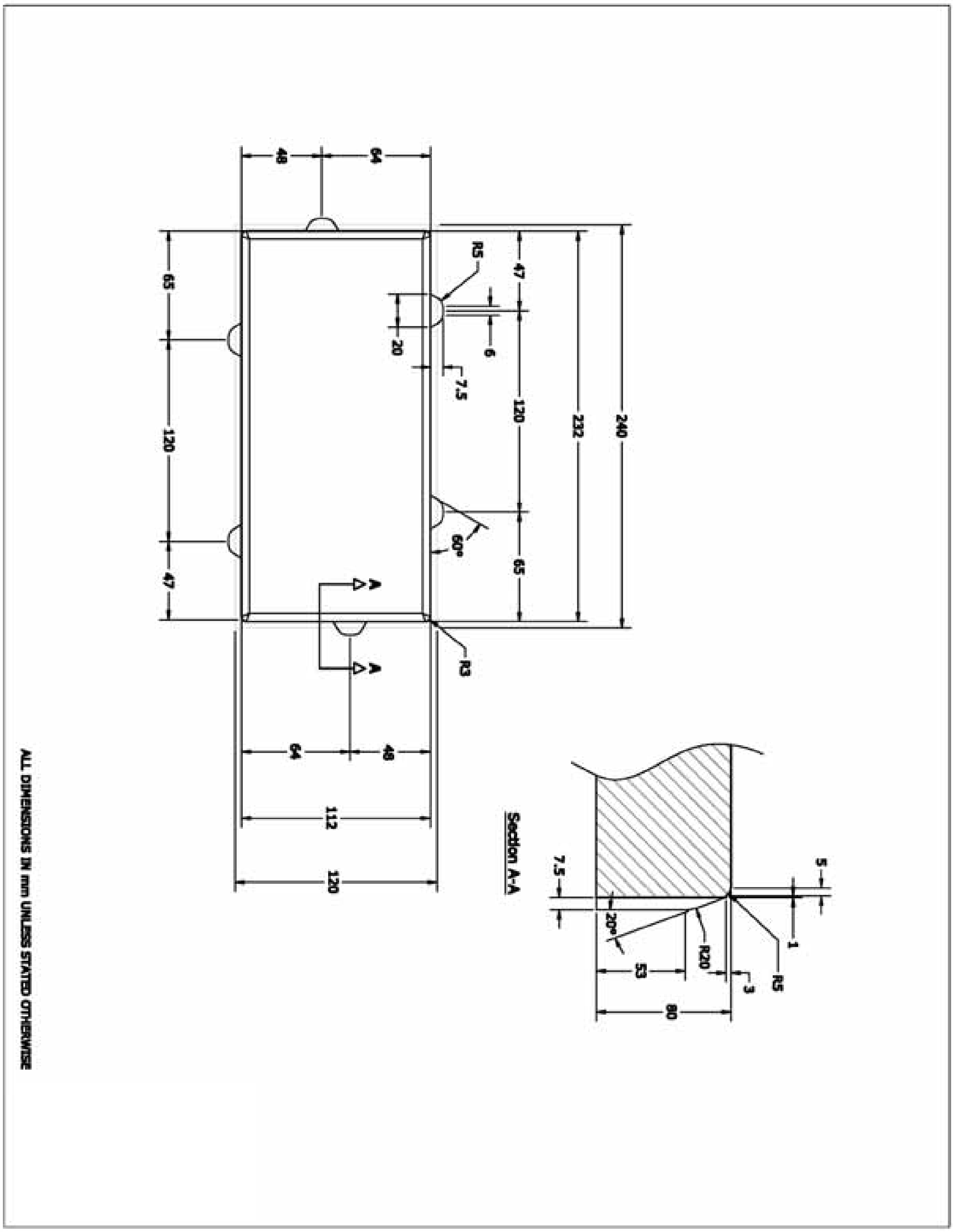
APPENDICES

Appendix A PICP Drainage Paver



Appendix B Surface Friction Data

January 17th and 18th, 2018

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		15:15	Start Time:		16:20	Start Time:		11:20
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	μ	μ	STV	μ	μ	STV	μ	μ
PICP 1	16:14	**1**	168	0.22	0.24	126	0.46	0.49	117	0.60	0.73
		2	130	0.41	0.34	125	0.47	0.56	118	0.58	0.63
		3	144	0.31	0.31	122	0.51	0.55	117	0.60	0.66
		4	171	0.21	0.26	121	0.52	0.64	114	0.67	0.72
		5	129	0.42	0.23	120	0.54	0.59	117	0.60	0.72
PICP 2	16:13	**1**	126	0.46	0.23	115	0.64	0.64	114	0.67	0.71
		2	142	0.32	0.23	115	0.64	0.62	116	0.62	0.74
		3	148	0.29	0.23	115	0.64	0.61	119	0.56	0.72
		4	119	0.56	0.23	116	0.62	0.68	113	0.69	0.74
		5	128	0.43	0.22	117	0.60	0.65	118	0.58	0.61
PICP 3	16:12	**1**	208	0.14	0.27	124	0.48	0.27	117	0.60	0.68
		2	171	0.21	0.26	117	0.60	0.42	117	0.60	0.58
		3	155	0.26	0.30	120	0.54	0.40	119	0.56	0.56
		4	134	0.38	0.28	118	0.58	0.44	115	0.64	0.64
		5	138	0.35	0.25	120	0.54	0.44	119	0.56	0.63
PICP 4	16:11	**1**	129	0.42	0.17	117	0.60	0.65	118	0.58	0.64
		2	138	0.35	0.20	117	0.60	0.66	119	0.56	0.67
		3	140	0.33	0.23	117	0.60	0.61	118	0.58	0.66
		4	129	0.42	0.23	121	0.52	0.63	120	0.54	0.67
		5	122	0.51	0.18	120	0.54	0.65	125	0.47	0.66
Asphalt	16:10	**1**	144	0.31	0.49	125	0.47	0.52	122	0.51	0.63
		2	149	0.28	0.45	132	0.39	0.55	123	0.49	0.59
		3	156	0.27	0.29	152	0.29	0.53	126	0.48	0.46
		4	157	0.28	0.46	157	0.28	0.40	134	0.41	0.50
		5	157	0.29	0.52	146	0.34	0.39	135	0.41	0.56
		6	163	0.23		134	0.38		123	0.49	0.19
		7	175	0.23		157	0.29		129	0.46	0.48

February 1st, 2018

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		10:41	Start Time:		11:29	Start Time:		13:02
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	μ	μ	STV	μ	μ	STV	μ	μ
PICP 1	11:18	**1**	173	0.20	0.16	122	0.51	0.55	117	0.60	0.52
		2	198	0.16	0.16	129	0.42	0.30	118	0.58	0.65
		3	150	0.28	0.19	121	0.52	0.57	117	0.60	0.63
		4	145	0.30	0.13	132	0.39	0.54	114	0.67	0.65
		5	150	0.28	0.55	116	0.62	0.50	117	0.60	0.65
PICP 2	11:20	**1**	176	0.20	0.17	135	0.37	0.41	114	0.67	0.54
		2	188	0.17	0.16	128	0.43	0.30	116	0.62	0.68
		3	191	0.17	0.16	134	0.38	0.54	119	0.56	0.62
		4	163	0.23	0.17	128	0.43	0.58	113	0.69	0.56
		5	160	0.24	0.13	122	0.51	0.55	118	0.58	0.65
PICP 3	11:22	**1**	187	0.17	0.16	132	0.39	0.41	117	0.60	0.50
		2	165	0.22	0.16	121	0.52	0.54	117	0.60	0.60
		3	176	0.20	0.14	124	0.48	0.76	119	0.56	0.57
		4	132	0.39	0.13	116	0.62	0.56	115	0.64	0.67
		5	141	0.33	0.13	119	0.56	0.55	119	0.56	0.67
PICP 4	11:23	**1**	213	0.14	0.21	128	0.43	0.55	118	0.58	0.58
		2	189	0.17	0.16	120	0.54	0.54	119	0.56	0.64
		3	181	0.19	0.20	125	0.47	0.46	118	0.58	0.59
		4	162	0.23	0.43	119	0.56	0.58	120	0.54	0.65
		5	138	0.35	0.18	126	0.46	0.55	125	0.47	0.63
Asphalt	11:16	**1**	137	0.35	0.57	124	0.48	0.55	122	0.51	0.59
		2	150	0.28	0.55	125	0.47	0.50	123	0.49	0.65
		3	141	0.35	0.55	131	0.42	0.55	126	0.48	0.63
		4	141	0.36	0.31	141	0.36	0.45	134	0.41	0.64
		5	162	0.27	0.51	152	0.31	0.40	135	0.41	0.70
		6	144	0.31	0.31	127	0.44	0.40	123	0.49	0.57
		7	133	0.42	N/A	131	0.44	N/A	129	0.46	N/A

Febuary 8th, 2019

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		11:47	Start Time:		12:38	Start Time:		16:30
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ	STV	µ	µ
PICP 1	12:31	**1**	189	0.17	0.45	119	0.56	0.48	115	0.64	0.43
		2	192	0.17	0.18	121	0.52	0.49	115	0.64	0.63
		3	185	0.18	0.19	119	0.56	0.49	115	0.64	0.57
		4	191	0.17	0.63	119	0.56	0.57	115	0.64	0.49
		5	165	0.22	0.56	121	0.52	0.54	114	0.67	0.63
PICP 2	12:33	**1**	171	0.21	0.22	122	0.51	0.53	124	0.48	0.62
		2	193	0.16	0.27	136	0.36	0.56	117	0.60	0.67
		3	192	0.17	0.38	122	0.51	0.63	115	0.64	0.61
		4	185	0.18	0.19	124	0.48	0.56	116	0.62	0.46
		5	175	0.20	0.50	122	0.51	0.56	115	0.64	0.64
PICP 3	12:35	**1**	155	0.26	0.23	122	0.51	0.43	116	0.62	0.45
		2	186	0.18	0.21	128	0.43	0.49	116	0.62	0.63
		3	178	0.19	0.17	118	0.58	0.43	120	0.54	0.60
		4	169	0.21	0.18	122	0.51	0.44	116	0.62	0.43
		5	148	0.29	0.18	119	0.56	0.55	115	0.64	0.62
PICP 4	12:37	**1**	175	0.20	0.30	128	0.43	0.50	118	0.58	0.70
		2	197	0.16	0.20	139	0.34	0.55	116	0.62	0.67
		3	173	0.20	0.20	125	0.47	0.50	118	0.58	0.56
		4	151	0.27	0.19	122	0.51	0.47	119	0.56	0.58
		5	178	0.19	0.16	119	0.56	0.61	116	0.62	0.70
Asphalt	12:29	**1**	133	0.38	0.61	122	0.51	0.60	123	0.49	0.61
		2	133	0.38	0.61	123	0.49	0.51	121	0.52	0.69
		3	130	0.43	0.59	125	0.49	0.58	126	0.48	0.74
		4	133	0.42	0.50	128	0.47	0.50	125	0.51	0.64
		5	133	0.43	0.54	143	0.36	0.59	129	0.47	0.75
		6	126	0.46	0.41	122	0.51	N/A	138	0.35	N/A
		7	126	0.50	N/A	131	0.44	N/A	119	0.60	N/A

April 15th, 2018

Plot	Time of Salting	Test	Test 1			Test 2		
			Start Time:		9:56	Start Time:		11:14
			SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	μ	μ	STV	μ	μ
PICP 1	11:09	**1**	205	0.15	0.17	180	0.19	0.16
		2	203	0.15	0.17	154	0.26	0.13
		3	178	0.19	0.16	151	0.27	0.20
		4	203	0.15	0.15	168	0.22	0.14
		5	190	0.17	0.16	144	0.31	0.17
PICP 2	11:10	**1**	220	0.13	0.16	182	0.18	0.14
		2	207	0.15	0.16	168	0.22	0.17
		3	210	0.14	0.15	157	0.25	0.17
		4	205	0.15	0.16	160	0.24	0.14
		5	211	0.14	0.15	161	0.24	0.15
PICP 3	11:11	**1**	201	0.15	0.16	155	0.26	0.13
		2	204	0.15	0.18	138	0.35	0.16
		3	196	0.16	0.16	152	0.27	0.15
		4	204	0.15	0.15	152	0.27	0.19
		5	205	0.15	0.15	157	0.25	0.21
PICP 4	11:12	**1**	207	0.15	0.17	159	0.24	0.14
		2	194	0.16	0.18	146	0.30	0.15
		3	202	0.15	0.16	150	0.28	0.14
		4	190	0.17	0.14	157	0.25	0.15
		5	191	0.17	0.16	163	0.23	0.16
Asphalt	11:08	**1**	207	0.15	0.16	157	0.25	0.13
		2	214	0.14	0.15	172	0.21	0.14
		3	208	0.16	0.16	170	0.23	0.11
		4	210	0.17	0.16	185	0.21	0.12
		5	255	0.14	0.16	182	0.22	0.16
		6	205	0.15		169	0.21	
		7	213	0.17		186	0.21	

May 29th, 2018

Plot	Time of Salting	Test	Test 1		
			Start Time:		
			SlipAlert		Slip-Test
			STV	µ	µ
PICP 1		1	112	0.72	0.69
		2	112	0.72	0.70
		3	115	0.64	0.73
		4	110	0.79	0.73
		5	110	0.79	0.73
PICP 2		1	111	0.75	0.71
		2	113	0.69	0.71
		3	113	0.69	0.73
		4	110	0.79	0.70
		5	110	0.79	0.71
PICP 3		1	115	0.64	0.74
		2	110	0.79	0.71
		3	112	0.72	0.70
		4	110	0.79	0.73
		5	111	0.75	0.70
PICP 4		1	110	0.79	0.71
		2	111	0.75	0.70
		3	111	0.75	0.73
		4	112	0.72	0.74
		5	111	0.75	0.71
Asphalt		1	112	0.72	0.72
		2	110	0.79	0.67
		3	114	0.69	0.79
		4	114	0.71	0.75
		5	118	0.63	0.73
		6			
		7			

January 21st, 2019

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		12:50	Start Time:		13:30	Start Time:		14:56
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	μ	μ	STV	μ	μ	STV	μ	μ
PICP 1	13:27	**1**	205	0.15	0.16	131	0.40	0.26	129	0.42	0.63
		2	178	0.19	0.19	147	0.29	0.25	136	0.36	0.35
		3	182	0.18	0.37	128	0.43	0.60	125	0.47	0.67
		4	154	0.26	0.50	137	0.35	0.61	126	0.46	0.71
		5	136	0.36	0.17	128	0.43	0.27	124	0.48	0.62
PICP 2	13:23	**1**	197	0.16	0.20	146	0.30	0.32	152	0.27	0.70
		2	183	0.18	0.20	162	0.23	0.16	145	0.30	0.45
		3	170	0.21	0.48	165	0.22	0.60	136	0.36	0.58
		4	138	0.35	0.56	136	0.36	0.46	119	0.56	0.71
		5	161	0.24	0.27	135	0.37	0.23	123	0.49	0.40
PICP 3	13:25	**1**	197	0.16	0.39	121	0.52	0.57	119	0.56	0.69
		2	179	0.19	0.17	144	0.31	0.24	121	0.52	0.58
		3	180	0.19	0.20	132	0.39	0.60	122	0.51	0.65
		4	168	0.22	0.17	139	0.34	0.56	122	0.51	0.71
		5	136	0.36	0.24	129	0.42	0.68	124	0.48	0.64
PICP 4	13:29	**1**	210	0.14	0.17	132	0.39	0.46	121	0.52	0.64
		2	208	0.14	0.19	170	0.21	0.32	119	0.56	0.51
		3	207	0.15	0.17	143	0.31	0.54	119	0.56	0.68
		4	154	0.26	0.52	152	0.27	0.60	131	0.40	0.73
		5	140	0.33	0.15	127	0.44	0.61	126	0.46	0.68
Asphalt	13:22	**1**	138	0.35	0.46	133	0.38	0.57	122	0.51	0.77
		2	129	0.42	0.45	155	0.26	0.52	122	0.51	0.75
		3	142	0.34	0.65	136	0.38	0.57	132	0.41	0.68
		4	141	0.36	0.53	146	0.33	0.56	133	0.42	0.65
		5	142	0.36	0.52	157	0.29	0.56	126	0.50	0.72
		6	131	0.40		138	0.35	0.32	126	0.46	0.19
		7	137	0.39		138	0.38	0.74	121	0.57	

January 29th, 2019

Plot	Time of Salting	Test	Test 1			Test 2		
			Start Time:		12:20	Start Time:		13:59
			SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ
PICP 1	12:51	1	156	0.25	0.30	148	0.29	0.26
		2	161	0.24	0.27	149	0.28	0.26
		3	160	0.24	0.22	159	0.24	0.25
		4	159	0.24	0.20	156	0.25	0.27
		5	172	0.21	0.22	160	0.24	0.28
PICP 2	12:47	1	142	0.32	0.30	149	0.28	0.29
		2	171	0.21	0.24	166	0.22	0.30
		3	159	0.24	0.21	167	0.22	0.28
		4	170	0.21	0.22	168	0.22	0.25
		5	156	0.25	0.16	170	0.21	0.25
PICP 3	12:53	1	145	0.30	0.30	163	0.23	0.26
		2	162	0.23	0.26	156	0.25	0.25
		3	148	0.29	0.20	154	0.26	0.23
		4	140	0.33	0.23	138	0.35	0.26
		5	155	0.26	0.21	134	0.38	0.24
PICP 4	12:55	1	160	0.24	0.25	166	0.22	0.26
		2	167	0.22	0.23	165	0.22	0.27
		3	149	0.28	0.20	144	0.31	0.24
		4	155	0.26	0.21	146	0.30	0.25
		5	162	0.23	0.14	159	0.24	0.26
Asphalt	12:49	1	145	0.30	0.37	149	0.28	0.29
		2	166	0.22	0.30	165	0.22	0.28
		3	161	0.26	0.13	148	0.31	0.18
		4	162	0.27	0.21	165	0.26	0.25
		5	181	0.23	0.14	164	0.27	0.22
		6	162	0.23		154	0.26	
		7	166	0.26		162	0.27	

January 30th and 31st, 2019

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		11:42	Start Time:		12:19	Start Time:		13:50
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	μ	μ	STV	μ	μ	STV	μ	μ
PICP 1	12:09	**1**	174	0.20	0.25	148	0.29	0.55	155	0.26	0.15
		2	186	0.18	0.17	138	0.35	0.54	176	0.20	0.22
		3	163	0.23	0.21	131	0.40	0.37	158	0.25	0.19
		4	155	0.26	0.17	127	0.44	0.55	170	0.21	0.24
		5	161	0.24	0.16	132	0.39	0.49	160	0.24	0.24
PICP 2	12:18	**1**	145	0.30	0.17	127	0.44	0.31	142	0.32	0.51
		2	139	0.34	0.29	128	0.43	0.47	125	0.47	0.60
		3	144	0.31	0.15	122	0.51	0.55	135	0.37	0.17
		4	158	0.25	0.17	129	0.42	0.51	144	0.31	0.50
		5	157	0.25	0.20	128	0.43	0.58	151	0.27	0.53
PICP 3	12:13	**1**	156	0.25	0.40	139	0.34	0.34	159	0.24	0.23
		2	158	0.25	0.17	137	0.35	0.36	164	0.23	0.19
		3	125	0.47	0.18	134	0.38	0.37	160	0.24	0.29
		4	162	0.23	0.29	136	0.36	0.40	161	0.24	0.19
		5	162	0.23	0.17	131	0.40	0.47	168	0.22	0.21
PICP 4	12:11	**1**	138	0.35	0.23	125	0.47	0.51	143	0.31	0.18
		2	134	0.38	0.51	120	0.54	0.52	132	0.39	0.27
		3	162	0.23	0.18	134	0.38	0.35	160	0.24	0.22
		4	163	0.23	0.34	132	0.39	0.60	153	0.27	0.39
		5	141	0.33	0.45	131	0.40	0.60	154	0.26	0.48
Asphalt	12:15	**1**	134	0.38	0.61	123	0.49	0.52	135	0.37	0.22
		2	123	0.49	0.46	132	0.39	0.50	128	0.43	0.26
		3	125	0.49	0.57	158	0.27	0.47	145	0.32	0.27
		4	141	0.36	0.57	144	0.34	0.38	165	0.26	0.26
		5	136	0.40	0.49	138	0.39	0.50	151	0.32	0.23
		6	126	0.46		148	0.29	0.23	140	0.33	0.14
		7	132	0.43		134	0.41		144	0.35	0.59

January 30th and 31th, 2019 Continued

Plot	Time of Salting	Test	Test 4		
			Start Time:		14:24
			SlipAlert		Slip-Test
			STV	μ	μ
PICP 1	12:09	**1**	186	0.18	0.17
		2	197	0.16	0.16
		3	169	0.21	0.20
		4	193	0.16	0.22
		5	203	0.15	0.15
PICP 2	12:18	**1**	158	0.25	0.61
		2	129	0.42	0.65
		3	146	0.30	0.68
		4	155	0.26	0.63
		5	122	0.51	0.58
PICP 3	12:13	**1**	187	0.17	0.16
		2	187	0.17	0.31
		3	169	0.21	0.19
		4	165	0.22	0.19
		5	158	0.25	0.20
PICP 4	12:11	**1**	129	0.42	0.55
		2	133	0.38	0.35
		3	139	0.34	0.26
		4	138	0.35	0.65
		5	165	0.22	0.62
Asphalt	12:15	**1**	135	0.37	0.23
		2	123	0.49	0.55
		3	146	0.32	0.45
		4	167	0.25	0.54
		5	137	0.40	0.53
		6	156	0.25	0.19
		7	140	0.37	

February 7th, 2019

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		08:51	Start Time:		09:30	Start Time:		11:11
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ	STV	µ	µ
PICP 1	09:22	1	191	0.17	0.22	149	0.28	0.24	124	0.48	0.62
		2	180	0.19	0.23	144	0.31	0.48	119	0.56	0.79
		3	190	0.17	0.19	168	0.22	0.18	128	0.43	0.78
		4	184	0.18	0.22	168	0.22	0.23	142	0.32	0.77
		5	189	0.17	0.17	155	0.26	0.27	117	0.60	0.66
PICP 2	09:18	1	204	0.15	0.25	174	0.20	0.18	127	0.44	0.64
		2	186	0.18	0.21	167	0.22	0.18	120	0.54	0.70
		3	182	0.18	0.22	179	0.19	0.18	137	0.35	0.72
		4	169	0.21	0.21	160	0.24	0.18	160	0.24	0.75
		5	167	0.22	0.18	170	0.21	0.17	127	0.44	0.48
PICP 3	09:24	1	183	0.18	0.22	149	0.28	0.25	132	0.39	0.66
		2	185	0.18	0.18	137	0.35	0.19	127	0.44	0.79
		3	178	0.19	0.21	161	0.24	0.32	128	0.43	0.71
		4	172	0.21	0.18	166	0.22	0.19	134	0.38	0.80
		5	181	0.19	0.18	159	0.24	0.28	115	0.64	0.65
PICP 4	09:29	1	177	0.19	0.19	164	0.23	0.19	125	0.47	0.65
		2	176	0.20	0.20	170	0.21	0.19	118	0.58	0.78
		3	166	0.22	0.21	136	0.36	0.22	124	0.48	0.72
		4	165	0.22	0.19	159	0.24	0.15	126	0.46	0.73
		5	165	0.22	0.18	162	0.23	0.21	115	0.64	0.62
Asphalt	09:27	1	148	0.29	0.35	130	0.41	0.45	135	0.37	0.64
		2	155	0.26	0.35	140	0.33	0.64	130	0.41	0.63
		3	151	0.29	0.44	146	0.32	0.65	130	0.43	0.59
		4	168	0.25	0.29	146	0.33	0.26	134	0.41	0.63
		5	157	0.29	0.28	155	0.30	0.55	138	0.39	0.66
		6	162	0.23		158	0.25		124	0.48	
		7	179	0.22		158	0.28		139	0.38	

February 16th, 2019

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		08:48	Start Time:		09:35	Start Time:		11:36
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ	STV	µ	µ
PICP 1	09:28	1	204	0.15	0.15	183	0.18	0.17	179	0.19	0.21
		2	198	0.16	0.12	215	0.14	0.14	182	0.18	0.14
		3	219	0.13	0.14	186	0.18	0.14	183	0.18	0.65
		4	197	0.16	0.12	192	0.17	0.20	163	0.23	0.18
		5	201	0.15	0.12	148	0.29	0.20	128	0.43	0.14
PICP 2	09:26	1	210	0.14	0.12	202	0.15	0.14	210	0.14	0.21
		2	184	0.18	0.12	187	0.17	0.10	204	0.15	0.19
		3	212	0.14	0.14	201	0.15	0.17	195	0.16	0.16
		4	210	0.14	0.10	204	0.15	0.14	187	0.17	0.17
		5	194	0.16	0.12	205	0.15	0.15	198	0.16	0.13
PICP 3	09:25	1	186	0.18	0.15	198	0.16	0.10	186	0.18	0.15
		2	190	0.17	0.15	189	0.17	0.16	188	0.17	0.23
		3	203	0.15	0.11	189	0.17	0.14	187	0.17	0.24
		4	183	0.18	0.16	176	0.20	0.13	165	0.22	0.21
		5	209	0.14	0.12	172	0.21	0.13	169	0.21	0.21
PICP 4	09:31	1	213	0.14	0.15	185	0.18	0.13	192	0.17	0.18
		2	189	0.17	0.13	180	0.19	0.14	180	0.19	0.18
		3	192	0.17	0.12	193	0.16	0.12	179	0.19	0.16
		4	191	0.17	0.15	170	0.21	0.12	165	0.22	0.35
		5	195	0.16	0.13	178	0.19	0.08	150	0.28	0.13
Asphalt	09:30	1	200	0.15	0.12	175	0.20	0.12	170	0.21	0.21
		2	219	0.13	0.13	200	0.15	0.18	194	0.16	0.24
		3	210	0.16	0.08	180	0.21	0.10	175	0.22	0.16
		4	255	0.13	0.15	255	0.13	0.09	214	0.17	0.17
		5	255	0.14	0.10	255	0.14	0.11	201	0.19	0.18
		6	214	0.14		183	0.18	0.39	180	0.19	
		7	246	0.14		219	0.17		200	0.19	

February 16th, 2019 (Continued)

Plot	Time of Salting	Test	Test 4			Test 5		
			Start Time:		15:32	Start Time:		18:02
			SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ
PICP 1	09:28	1	119	0.56	0.78	118	0.58	0.73
		2	141	0.33	0.80	138	0.35	0.73
		3	121	0.52	0.80	142	0.32	0.71
		4	117	0.60	0.23	117	0.60	0.18
		5	113	0.69	0.78	113	0.69	0.70
PICP 2	09:26	1	171	0.21	0.24	148	0.29	0.18
		2	200	0.15	0.23	190	0.17	0.19
		3	185	0.18	0.64	191	0.17	0.71
		4	167	0.22	0.75	166	0.22	0.71
		5	151	0.27	0.15	115	0.64	0.12
PICP 3	09:25	1	119	0.56	0.77	114	0.67	0.75
		2	131	0.40	0.78	138	0.35	0.71
		3	112	0.72	0.73	115	0.64	0.71
		4	133	0.38	0.75	126	0.46	0.71
		5	118	0.58	0.75	122	0.51	0.70
PICP 4	09:31	1	139	0.34	0.71	121	0.52	0.72
		2	147	0.29	0.21	134	0.38	0.14
		3	145	0.30	0.71	131	0.40	0.69
		4	132	0.39	0.72	114	0.67	0.70
		5	112	0.72	0.75	112	0.72	0.68
Asphalt	09:30	1	136	0.36	0.71	147	0.29	0.72
		2	170	0.21	0.59	178	0.19	0.15
		3	151	0.29	0.67	172	0.23	0.21
		4	168	0.25	0.19	188	0.20	0.18
		5	115	0.69	0.14	165	0.26	0.19
		6	136	0.36		165	0.22	
		7	162	0.27		178	0.23	

March 4th, 2019

Plot	Time of Salting	Test	Test 1			Test 2			Test 3		
			Start Time:		09:58	Start Time:		11:15	Start Time:		16:36
			SlipAlert		Slip-Test	SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ	STV	µ	µ
PICP 1	10:37	1	162	0.23	0.24	148	0.29	0.22	149	0.28	0.18
		2	161	0.24	0.20	154	0.26	0.22	150	0.28	0.19
		3	172	0.21	0.23	151	0.27	0.25	151	0.27	0.22
		4	172	0.21	0.28	151	0.27	0.20	144	0.31	0.22
		5	153	0.27	0.20	151	0.27	0.27	142	0.32	0.24
PICP 2	10:35	1	166	0.22	0.21	151	0.27	0.25	155	0.26	0.21
		2	162	0.23	0.21	158	0.25	0.22	147	0.29	0.23
		3	158	0.25	0.20	157	0.25	0.27	148	0.29	0.21
		4	161	0.24	0.24	150	0.28	0.20	144	0.31	0.19
		5	160	0.24	0.20	145	0.30	0.22	145	0.30	0.18
PICP 3	10:40	1	152	0.27	0.22	149	0.28	0.23	139	0.34	0.22
		2	156	0.25	0.22	144	0.31	0.24	137	0.35	0.21
		3	148	0.29	0.21	153	0.27	0.24	138	0.35	0.21
		4	149	0.28	0.22	138	0.35	0.27	136	0.36	0.19
		5	161	0.24	0.19	149	0.28	0.20	143	0.31	0.18
PICP 4	10:38	1	153	0.27	0.25	149	0.28	0.25	141	0.33	0.22
		2	153	0.27	0.20	148	0.29	0.21	146	0.30	0.22
		3	148	0.29	0.20	138	0.35	0.22	138	0.35	0.23
		4	147	0.29	0.23	147	0.29	0.29	140	0.33	0.19
		5	146	0.30	0.23	136	0.36	0.21	143	0.31	0.21
Asphalt	10:42	1	164	0.23	0.12	168	0.22	0.17	168	0.22	0.12
		2	177	0.19	0.20	163	0.23	0.20	156	0.25	0.22
		3	180	0.21	0.19	176	0.22	0.15	179	0.21	0.07
		4	198	0.19	0.20	195	0.19	0.23	203	0.18	0.18
		5	196	0.20	0.21	190	0.21	0.20	196	0.20	0.18
		6	188	0.17		159	0.24	0.59	164	0.23	0.59
		7	180	0.22		182	0.22		161	0.27	

March 7th, 2019

Plot	Time of Salting	Test	Test 1			Test 2		
			Start Time:		15:53	Start Time:		17:29
			SlipAlert		Slip-Test	SlipAlert		Slip-Test
			STV	µ	µ	STV	µ	µ
PICP 1		1	143	0.31	0.21	146	0.30	0.19
		2	123	0.49	0.18	143	0.31	0.16
		3	139	0.34	0.22	137	0.35	0.20
		4	141	0.33	0.22	141	0.33	0.17
		5	137	0.35	0.23	137	0.35	0.20
PICP 2		1	152	0.27	0.26	141	0.33	0.20
		2	148	0.29	0.20	142	0.32	0.17
		3	147	0.29	0.26	145	0.30	0.17
		4	139	0.34	0.21	141	0.33	0.18
		5	137	0.35	0.25	141	0.33	0.18
PICP 3		1	139	0.34	0.19	139	0.34	0.22
		2	133	0.38	0.25	134	0.38	0.20
		3	132	0.39	0.26	141	0.33	0.22
		4	132	0.39	0.21	138	0.35	0.17
		5	138	0.35	0.23	137	0.35	0.18
PICP 4		1	141	0.33	0.23	141	0.33	0.17
		2	136	0.36	0.26	134	0.38	0.16
		3	129	0.42	0.27	134	0.38	0.20
		4	133	0.38	0.26	137	0.35	0.17
		5	136	0.36	0.25	131	0.40	0.18
Asphalt		1	151	0.27	0.69	153	0.27	0.69
		2	144	0.31	0.20	155	0.26	0.13
		3	151	0.29	0.47	162	0.25	0.08
		4	141	0.36	0.22	163	0.26	0.09
		5	193	0.20	0.46	197	0.20	0.19
		6	122	0.51		168	0.22	
		7	138	0.38		155	0.29	

Appendix C: Time to Bare Pavement

Melt Event	Time to Trace Snow Cover (minutes)[a,b,c]					Time to Fully Clear (minutes)[a,b,c]				
	PICP-RS-M	PICP-RS-L	PICP-BJ-M	PICP-BJ-L	Asph-RS-M	PICP-RS-M	PICP-RS-L	PICP-BJ-M	PICP-BJ-L	Asph-RS-M
13/Mar/2018	165	170	165	160	**85**	180	195	195	**175**	**175**
14/Mar/2018[e]	250	215	215	235	**210**	275	**215**	235	255	1,520
05/Apr/2018	105	105	105	100	**55**	125	**105**	115	110	155
24/Nov/2018[d,e]	7,000	7,045	7,045	7,085	**6,365**	7,105	7,165	7,170	7,260	**6,640**
28/Nov/2018	60	50	50	50	**35**	100	**80**	**80**	**80**	125
07/Dec/2018[e]	-	-	-	-	**120**	-	-	-	-	-
08/Dec/2018[e]	-	-	-	1,720	**60**	-	-	-	**3,055**	-
12/Dec/2018[e]	-	-	-	-	**105**	-	-	-	-	-
14/Dec/2018[d]	1,380	1,390	1,375	1,350	**1,155**	1,395	1,405	1,390	**1,370**	1,505
24/Dec/2018	-	-	-	-	**75**	-	-	-	-	**175**
31/Dec/2018[d]	475	475	475	475	**40**	480	480	480	480	**220**
05/Jan/2019[e]	-	-	-	-	**1,285**	-	-	-	-	**2,225**
11/Jan/2019[e]	720	720	720	720	**310**	1,925	2,005	1,885	**1,730**	-
17/Mar/2019	375	375	375	375	**325**	**390**	**390**	**390**	**390**	445
31/Mar/2019	-	-	-	-	**275**	-	-	-	-	**295**

[a] Time from when melting began on the asphalt cell.
[b] Bold text indicates that the cell had the lowest time for each event.
[c] No data indicates that the respective surface cover conditions were not observed before the next snowfall event.
[d] Melting was influenced by rainfall.
[e] Snow remained at the catch basin on the asphalt cell at the end of the day.