Fall 2008

Winter performance assessment of permeable pavements: A comparative study of porous asphalt, pervious concrete, and conventional asphalt in a northern climate

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WINTER PERFORMANCE ASSESSMENT OF PERMEABLE PAVEMENTS

A COMPARATIVE STUDY OF POROUS ASPHALT, PERVIOUS CONCRETE, AND CONVENTIONAL ASPHALT IN A NORTHERN CLIMATE

BY

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THESIS

Submitted to the University of New Hampshire

in Partial Fulfillment of

the Requirements for the Degree of

Master of Science

in

Civil Engineering

September, 2008

This thesis has been examined and approved.

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8/22/08
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ACKNOWLEDGEMENTS

This research was supported by funding from the National Oceanic and Atmospheric Administration (NOAA) through the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET). Additional support was received from the University of New Hampshire, the Northern New England Concrete Promotion Association (NNECPA), the Northeast Cement Shippers Association, and the National Ready Mix Concrete Association (NRMCA).

I would like to thank my advisors, Dr. Thomas Ballestero and Dr. Robert Roseen, for all of their knowledge and guidance along the way. They have been invaluable resources and I hope that our efforts together will continue for years to come. I would like to thank everyone at the UNH Stormwater Center - Jamie, Pedro, George, Josh, Iulia, Tim, Jay, Heather, and Alison - for their willingness to help in all conditions and for providing a constant supply of fun and good humor. I would like to thank the final member of my committee, Douglas Heath, for his insight and notable contributions to my research. Many more have assisted me during my time at UNH, including: Jon Kuell of NNECPA, Thomas Byron and the UNH Grounds & Roads Dept., Maddy Wasiewski, Kelly Hinton, and countless others in the Environmental Research Group.

Finally, I would like to offer a special thank you to my family – Mom, Dad, Kelly, Katie, Willie, Brian – and my girlfriend Abigail, who have supported me in so many ways over the years.

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LIST OF ABBREVIATIONS

ADAT	Average daily air temperature
ASTM	American Society for Testing and Materials
BMP	Best Management Practice
BPN	British Pendulum Number
BPT	British Pendulum Tester
BRG	Bank Run Gravel
CICEET	Cooperative Center for Coastal and Estuarine Environmental Technology
Cl	Chloride
CRREL	Cold Regions Research and Engineering Laboratory
DI	De-ionized (water)
DMA	Dense Mix Asphalt
DRI	Double Ring Infiltrometer
IC	Infiltration Capacity
MPCA	Minnesota Pollution Control Agency
n	Number of samples
Na	Sodium
NCDC	National Climatic Data Center
NH	New Hampshire
NHDES	New Hampshire Department of Environmental Services
NHSCO	New Hampshire State Climate Office
NNECPA	Northern New England Concrete Promotion Association
NOAA	National Oceanic and Atmospheric Agency
NPDES	National Pollutant Discharge Elimination System
NRMCA	National Ready-Mix Concrete Association
OGFC	Open Graded Friction Course
PA	Porous Asphalt
PC	Pervious Concrete
PVC	Poly-vinyl Chloride
SC	Specific Conductivity
SCS	Soil Conservation Service
SI	Surface Inundation (Test)
SR	Standard Reference (parking lot)
TMDL	Total Maximum Daily Load
UNH	University of New Hampshire
UNHSC	University of New Hampshire Stormwater Center
USBLS	United States Bureau of Labor Statistics
USEPA	United States Environmental Protection Agency
WE	West Edge (Lot)

ABSTRACT

WINTER PERFORMANCE OF PERMEABLE PAVEMENTS

by

Kristopher M. Houle

University of New Hampshire, September 2008

This study presents the findings from two active parking lots constructed of permeable pavements: porous asphalt and pervious concrete. Focus is given to the performance of these pavements in a cold-climate setting. Winter places great demands on pavements so it is of particular interest to evaluate how they compare to conventional designs. Analyses include measurements of frost penetration, surface infiltration rates, snow and ice cover, skid resistance, chloride retention, and effective salt loads. Infiltration rates were retained in winter conditions and with frost depths as high as 27-inches. A 75% average reduction in annual salt use was observed for porous asphalt based on low amounts of snow and ice cover and high skid resistance. 'Black-ice' did not form on pervious concrete, eliminating the need for salt during thawing-refreezing conditions. Pavement color and shading were found to be major factors influencing the amount and duration of snow/ice cover. A comparison of project costs is discussed.

CHAPTER 1

INTRODUCTION

Permeable pavements are a low impact development (LID) stormwater management technology that is at the forefront of today's industry. These strategies not only function as transportation surfaces but serve as self-contained treatment systems that require almost no additional land for development. Historically, there has been skepticism and misinformation on how these technologies perform in cold climates due to concerns over freeze-thaw damage as well as clogging from deicing sand and salt treatments. The objective of this research stems from these concerns and addresses the winter performance of two types of permeable pavements: porous asphalt and pervious concrete. The two pavements are compared against conventional, impermeable asphalt to reveal any advantages or disadvantages that exist between strategies. A series of performance metrics are used to measure the effectiveness of the pavements in a range of weather conditions. The study is broken down into chapters highlighting two winters of evaluation, beginning with 2006-2007 in Chapter 2 and continuing with 2007-2008 in Chapter 3. The reason for this method of organization was to develop two independent research papers that could be submitted for publication to a peer-reviewed journal.

The first paper presented focuses primarily on the ability of porous asphalt to reduce the amount of salt needed for typical parking lot winter maintenance operations. Analyses of snow and ice cover, skid resistance, and recoverable chloride mass are used to quantify the effectiveness of varying salting rates and to present recommendations for adequate maintenance. In order to provide a basis for interpretation, results are directly compared to an adjacent impermeable asphalt parking lot.

The second paper is a continuation of the first but with the majority of the research taking place in the 2007-2008 winter season. The study is expanded to include pervious concrete pavement in addition to porous asphalt and dense-mix asphalt. Results from analyses similar to those in Chapter 2 are presented, in addition to measurements of frost penetration, surface infiltration capacity, and chloride retention. Comparisons are made to assess the overall winter performance of the different parking lot materials.

Chapter 4 of this document consists of an analysis of design, construction, and material costs of the three pavements. Material and project costs are presented as both total costs and costs per unit area, weight, and volume. Supplementary supporting tables and figures for all chapters are presented in the Appendices.

CHAPTER 2

A WINTER PERFORMANCE ASSESSMENT OF POROUS ASPHALT AND ITS FUNCTION FOR CHLORIDE SOURCE CONTROL

Abstract

This study examined the effectiveness of using reduced salting strategies on a porous asphalt parking lot compared with a standard dense-mix asphalt lot. Chloride is an integral component of winter maintenance and safe usage of transportation surfaces. Anti-icing and deicing is routinely needed to control both ice development caused by the pooling and freezing of meltwater and the accumulation of compacted snow and ice not removed by standard winter maintenance procedures (plowing). Chloride laden runoff from impervious surfaces threaten aquatic habitat and degrade drinking water supplies. Research at the University of New Hampshire Stormwater Center has identified parking lot runoff with chloride concentrations in excess of 5,000 mg/L over extended periods annually, exceeding regulatory standards. No existing stormwater management technology is designed to reduce chloride, leaving source control or deicing substitutes as the only viable chloride best management practices. This study identified porous asphalt as a potential strategy for minimizing the use of deicing chemicals for winter maintenance. Following de-icing, excess salt crystals remained on the porous pavement for longer durations and in greater amounts than the standard asphalt. Analyses quantify snow and ice cover, skid resistance, recoverable chloride mass, and effective salt loads.

Results demonstrate that porous asphalt requires considerably less salt for winter maintenance than standard asphalt. The lack of standing water on porous asphalt greatly reduces the frequency and mass of salt applications needed during winter precipitation or freeze-thaw periods. The annual median snow/ice surface cover amounts on the DMA lot were at least three times greater than on the PA lot. On an event basis, snow/ice surface cover on the PA was lower 60% of the time and equal 12% of the time. The low amounts of snow and ice cover and a higher exhibited skid resistance contributed to a 77% reduction in annual salt load for porous asphalt.

Introduction

For as many as six months out of a year, transportation surfaces in much of New England require winter maintenance operations that emphasize deicing by means of chemical treatment (road salt). Typically, the objective is to provide high levels of safety on trafficked (vehicle and pedestrian) surfaces during winter weather conditions consisting of periods of snow, ice, and/or freezing rain. The common strategy for treatment of roadways and parking lots often involves wide-spread application of salt ($NaCl$). Salt is effective as a deicing agent on impermeable surfaces because it melts through the snow or ice and forms a layer of highly saline water (brine) that melts the surrounding ice (Trost et al., 1987). Furthermore, the brine coats the pavement surface impeding ice development and delaying additional snow accumulation. One of the major problems with this strategy is the potential impact on freshwater resources. When salt crystals are applied to paved surfaces and react with the snow and ice, they tend to dissociates into sodium (Na^+) and chloride (Cl^-) ions. Chloride can contaminate receiving water bodies and groundwater supplies through runoff or by infiltrating underlying aquifers (Wegner & Yaggi, 2001). At the University of New Hampshire Stormwater Center (UNHSC), chloride concentrations from a nine-acre, impervious parking lot that is subjected to standard winter maintenance practices have been measured as high as 5,000 mg/L (Avellaneda, 2005). Monitoring of a first-order receiving stream in Durham, NH has identified chloride levels that regularly exceed regulatory standards (Houle, 2007). Chronic exposure levels for chloride are not to exceed 230 mg/L for a 96 hour period more than once every three years on average, while acute exposure levels must not exceed 860 mg/L for a one hour period more than once every three years on average (U.S. EPA, 1988). Similar conditions have been observed in southern New Hampshire and have fueled the implementation chloride TMDLs (Total Maximum Daily Loads) for four different watersheds. These TMDLs state that each stream flow in the four-day-average flow duration curve should not exhibit chloride concentrations exceeding 207 mg Cl per liter, or 90 percent of the regulatory chronic exposure level (Trowbridge, 2007a, 2007b).

One of the easiest, cost-effective, and most practical methods for minimizing potential chloride contamination is through source control of deicing constituents (i.e. using fewer chemicals). This study examines the effectiveness of reduced salt application rates on a porous asphalt parking lot. Conclusions are made by directly comparing the results to similar data collected on an adjacent standard dense-mix asphalt lot. Both qualitative and quantitative analyses were used to evaluate the different strategies.

Background

Porous asphalt was first developed in the 1970s. It differs from standard dense-mix asphalt in that the 'fines' (particles smaller than 600 microns) are removed from the aggregate mix, thereby allowing the formation of pores for water to pass (Cahill et al., 2003; Ferguson, 2005). In reference to cold climates, sources have reported that porous asphalt appears to become free of ice and snow quicker than standard pavement. One such observation specifically documented the lack of ice formation that is common in 'freeze-thaw' climates (MacDonald, 2006). Similar assessments were made at the UNHSC facility prior to this study, but were only confirmed anecdotally.

Site Description

This study was performed at the University of New Hampshire Durham campus. The porous asphalt (PA) site is located along the eastern perimeter of a nine-acre commuter parking lot (West Edge Lot), but is hydrologically isolated from the rest of the parking area. The PA lot is approximately 4,500-ft^2 and contains 17 parking spaces. Immediately adjacent, but also hydrologically separated, is an identically-sized, standard dense-mix asphalt (DMA) lot. This DMA lot was used as the control with which to compare the porous asphalt data.

The winter climate (January through March) in Durham, NH generally consists of average temperatures near 27.7 °F, with maximum and minimum temperature of 37.5 °F and 17.3 °F, respectively. Total precipitation during this time period is approximately 16.4 inches and snowfall is around 63.1 inches (NHSCO, 2008).

Methodology

Frost Depth Penetration

It has been documented in literature that the temperature of porous asphalt can be governed mainly by ambient air temperature, which in some cases may lower the temperature of PA faster than that of standard impermeable pavement (Noort, 1996; Shao et al., 1994). However, research has also demonstrated that porous asphalt may be more resistant to freezing due to high water content in the sub-base and associated latent heat levels (Backstrom, 2000). To evaluate this phenomena frost depth penetration within the porous asphalt system was measured using a "field assembled frost gage" (Ricard et al., 1976) installed in a screened, PVC groundwater monitoring well. Frost depth was determined by measuring the depth of frozen water-methylene blue solution. Frost depth and air temperature were recorded regularly over the 2006-2007 winter season.

Surface Infiltration Capacity

As a measure of PA hydraulic performance, the surface infiltration capacity was measured on a near-monthly basis since installation. The test performed was a modification of a falling head surface inundation (SI) test as explained by Bean (2004). It involved placing a cylinder of known diameter onto the pavement surface and sealing the edge with pliable foam. The ring was situated within a square, plywood base which provided a small platform for loading weights in order to improve the pavement seal to the equipment. Water was poured into the cylinder up to a predetermined depth and volume and the time required for all the water to enter the pavement was recorded (Briggs, 2006). The result was a rate in length per time of the surface infiltration capacity (IC) of the pavement surface.

Three randomly selected locations (A, B, & C) within the 4,500-ft^2 surface were tested beginning in November 2004. Location C near the entrance of the site exhibited an infiltration rate that was too slow to be accurately represented by the SI test; leakage during the test was common. In response to this problem, a double-ring infiltrometer (DRI) test was utilized for this location (Briggs, 2006). The DRI test is a constant-head test that is typically used for measuring infiltration rates of soils. It can provide more representative results than the SI test due to dual columns of infiltrating water (Bean, 2004). The method used followed ASTM Standard D 3385-03. SI data is presented from 2004 to 2008 in order to more clearly demonstrate long-term variations.

Salt Application

The PA and DMA lots were both divided into four equally-sized areas (Figure 1), each to receive a different salt application rate. Rates applied were 100%, 50%, 25%, and 0% (as a control) of the recommended standard of practice rate of 3.0-lbs per 1000-ft^2 of application area (MPCA, 2006). The method for applying salt was designed to mimic municipal anti-icing and de-icing strategies by applying salt prior to and immediately following (as needed) winter precipitation events. The salt used in the study was standard rock salt with less than 10% added fines by mass; it was taken from the stockpile at the UNH Grounds & Roads Department.

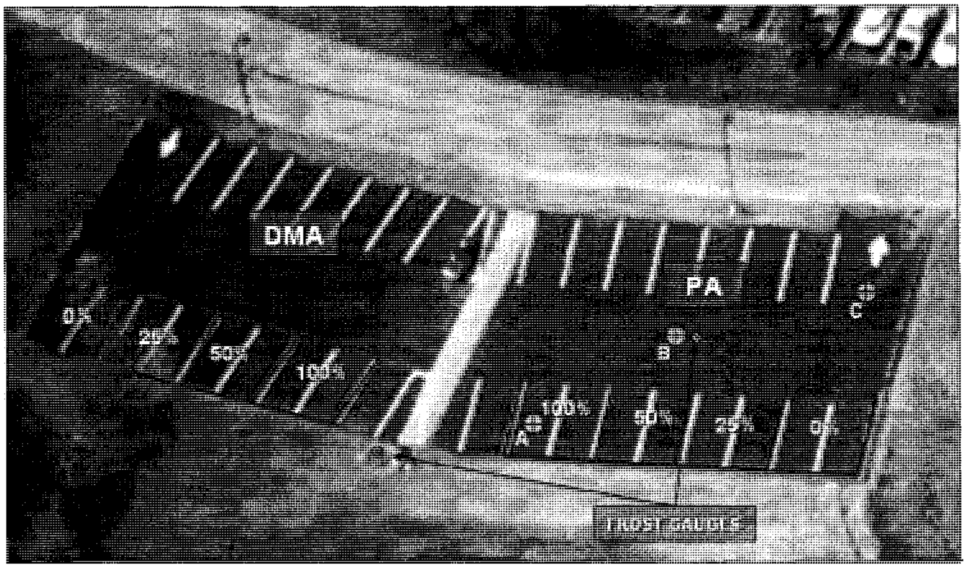

Figure 1: Porous asphalt (PA) and dense mix asphalt (DMA) study areas ('06-'07)

(Salt application rates, frost gauge and IC locations also shown)

Visual Observations and Documentation

Before, during, and after storm events, photos were taken of each study area and the specific event characteristics were recorded. Pavement conditions, type, and amount of surface cover, and weather conditions were of primary interest. Apparent effects from shading or direct sunlight was taken into consideration. Photo documentation was necessary to substantiate the findings and to display comparative results of the two pavements. Evaluations typically occurred at various times during and up to three days after precipitation events.

Pavement Friction Measurements

The main goal of anti-icing is to break the bond between snow or ice and the pavement surface in order to facilitate removal and enhance public safety. One way to measure the effectiveness of this strategy is to compare the frictional properties of snow and ice covered pavements to standard dry pavement. In this fashion one can quantitatively demonstrate a fractional loss in pavement safety under the impaired conditions. Pavement frictional measurements were performed in this study using a Munro Stanley London British Pendulum Skid Resistance Tester.

The British Pendulum Tester (BPT) is a dynamic pendulum impact device used to measure the energy loss by a rubber slider edge swung over a test surface (ASTM, 2004). It produces a skid resistance number, or British Pendulum Number (BPN), ranging from 0 to 150, and can be related to pavement coefficient of friction by dividing by 100 (Munro Environmental, 2007). The higher the frictional resistance of the surface, the greater the resulting BPN. The method used for operating the BPT followed ASTM Standard E 303–93.

Skid resistance measurements were taken at various locations within each study area, repeated five times, and seasonally averaged in order to characterize the variability in friction between each type of pavement cover (ice, snow, wet, and dry). The mean values were then multiplied by their respective surface cover type percentages in order to develop a weighted skid resistance value for each observation. The significance of the weighted skid resistance value was to obtain a number that can easily be related to safety for each of the varying salt application rates.

<u>Chloride Recovery</u>

Past observations at the UNH Stormwater Center concluded that after winter storm events, salt would often remain on the surface of the PA longer than on the DMA. To corroborate this claim, residual salt mass was recovered from parking stalls on both pavements and measured. These parking stalls were coned-off to prevent vehicle tracking of salt in order to maintain a consistent treatment rate in the observation areas. A portable wet/dry vacuum was used for recovering the undissolved salt mass. The method was sufficient at capturing much of the particles that remained on or, in the case of PA, near the pavement surface.

The recovered mass, which also contained sediments and other parking lot debris, was diluted with 500-mL of warm, deionized water (DI), and mixed on a stir plate for approximately 1.5-minutes. The mixing time was found sufficient for dissolving all recoverable salt crystals. Specific conductivity (SC) readings were taken on each sample with a portable YSI 556 MPS water quality meter. The chloride mass per sample was calculated using a chloride concentration regression equation that was developed for the West Edge parking lot in 2005 (Avellaneda).

Statistical Comparison Methods

A 'Student's t' means comparison test was employed for all portions of this study that include statistical assessment. These analyses include surface infiltration capacity, snow & ice cover, and skid resistance. The Student's t-test is a test to determine differences in central location (mean) for two independent groups (Helsel and Hirsh, 2002). Group comparisons with p-values less than 0.05 (with a 95% confidence interval) were deemed statistically different.

Results and Discussion

Frost Depth Penetration

Frost depth penetration from November 2006 to April 2007 within the porous asphalt system is presented in Figure 2. It is plotted against frost depth observed at a reference location and average daily air temperature (on a reverse axis). The reference location for this study was a nearby tree-filter stormwater treatment unit that consisted of a typical bioretention soil-mix. The maximum frost penetration within the PA was approximately equal to the depth measured at the reference location; 27.25-inches to 27.5-inches, respectively, demonstrating that porous asphalt can exhibit comparable frost penetration to soil or other existing stormwater BMPs, even with several inches of open-graded surface material. Conversely, the data shows that frost depth in PA is highly influenced by air temperature and abrupt changes in the temperature are quickly reflected within the system. On 1/17/07, the average air temperature dropped to 7.1 °F and the PA frost penetration reached about ten inches one day later, while the reference site only increased to four inches. A greater frost depth in the PA was observed until the systems equalized around 1/31/07. These frost depths remained nearly equal until the PA rapidly thawed in early March, approximately two-weeks prior to the reference location. Backstrom (2000) observed rapid thawing in a porous asphalt parking lot studied in Sweden and hypothesized that it was due to latent heat and energy content of infiltrated water and convection of air through the asphalt pores. The thawing of the UNHSC PA lot also correlated with two March rain events on 3/2/07 and 3/11/07. The rapid thawing of the PA is a significant finding given that much skepticism over the use of porous asphalt exists concerning its durability in 'freeze-thaw' climatic conditions. If the system is thawing weeks earlier than expected, much of the "problematic" freeze-thaw time period is reduced, helping to decrease the risk of pavement failure. In addition, it should be noted that after four winters of observation (2004-2008), no noticeable heaving of the porous asphalt surface has been witnessed. Finally, when the porous asphalt freezes, it becomes a frozen porous media that possesses an extremely high infiltration rate. If and when surface water does occur on the PA, it rapidly infiltrates and thaws the frozen portions of the system.

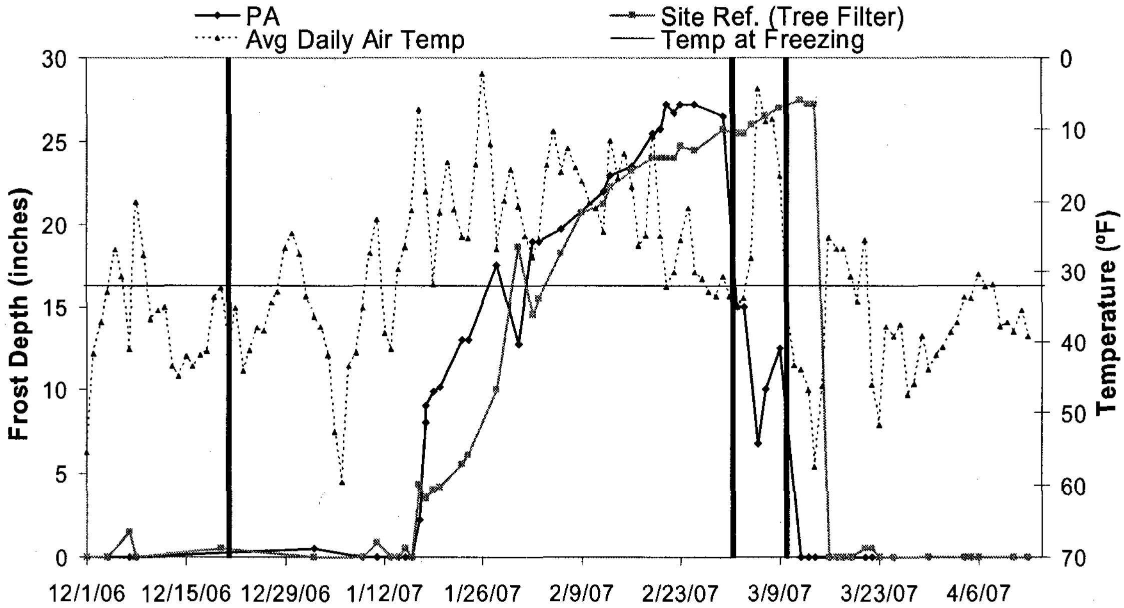

Figure 2: Frost depth penetration in the porous asphalt system (11/06 to 4/07)
(PA = porous asphalt; Occurrence of rain events shown with vertical, black lines)

Surface Infiltration Capacity

The surface infiltration capacity was measured at three locations in the porous asphalt study area beginning immediately after its installation in November 2004 and continuing until May 2008. A time-series plot of the results is displayed in Figure 3(a) (Briggs, 2006). Each point on the figure represents a mean IC measurement; the location and testing method used is indicated by the different markers. Prior to 1/7/08, the SI device used was a 12-inch aluminum cylinder and 5-gallons of water were infiltrated during the test. After this date, the device was modified to 4-inch acrylic cylinder in order to reduce the amount of water used. The volume of water needed for the modified test to remain equivalent to the original SI test was 0.56-gallons.

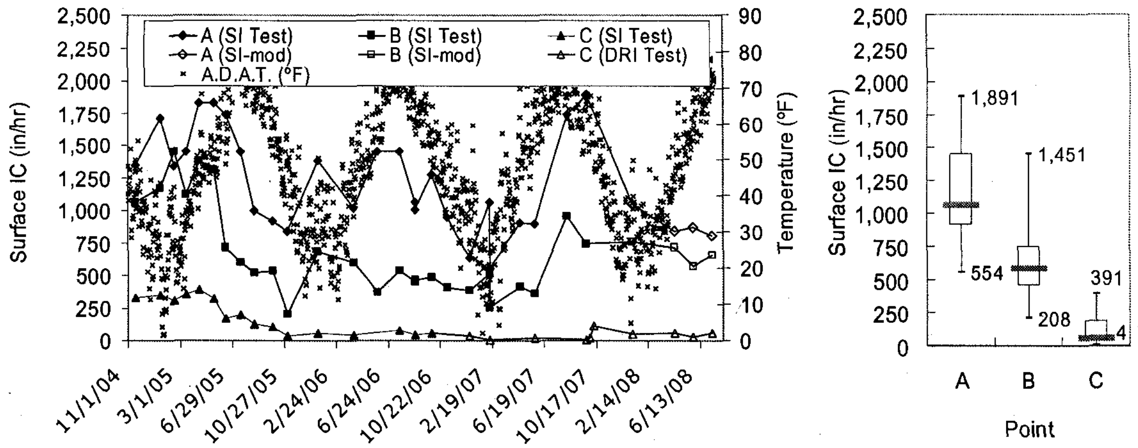

Figure 3: Porous asphalt surface infiltration capacity ('04-'08) (Briggs, 2006)

(3a) Time-series plot of surface IC (left); (3b) Box and whisker plots of surface IC (right) (SI = surface inundation; DRI = double-ring infiltrometer; ADAT = avg. daily air temp.) (Pavement cleaning prior to 9/23/07 IC measurements)

The infiltration rates of the three locations, which are corrected for any device leakage during tests, each vary by about 500-in/hr, with the fastest area exhibiting a median rate of 1,060 in/hr (shown by the gray bar through the 'boxed' segment of the data). Box and whisker plots are displayed in Figure 3(b) to characterize the variation between locations and measurements. The maximum and minimum observations are represented by the upper and lower whiskers, respectively. An interesting finding from this study is that the infiltration capacity of the pavement is retained during the winter and spring seasons, even with measureable depths of frost penetration.

When the data for each study location is compared by season and observation year several trends become apparent. Table 1 displays a statistical summary of all IC data broken down into six-month winter and summer periods. The data was compared using a Student's t-test with a 95% confidence interval and if the resulting p-values were less than 0.05 then the groups were identified as being statistically different. For the first year of evaluation (11/04-10/05), the highest infiltration rates were observed during the winter/spring months immediately following installation. Sharp declines were then measured beginning in June 2005 and continuing into November 2005. Ferguson (2005) made similar assessment on numerous PA pavements and attributed the finding to drain-down of the asphalt binder during hot summer months. It is hypothesized that the decline in IC observed at the UNHSC lot is due in part to binder drain-down. This hypothesis is supported by the analyzing the binder content in core samples taken at each of the three study locations (A, B, and C). The four-inch core samples were cut in half horizontally in order to assess the extent of any drain-down. Figure 4 displays the average binder content in the top and bottom sections of six cores at each location. The results show drain-down occurring at all three areas and ranging from 0.3% to 0.5%; Jackson (2003) recommends drain-down in PA be less than 0.3%.

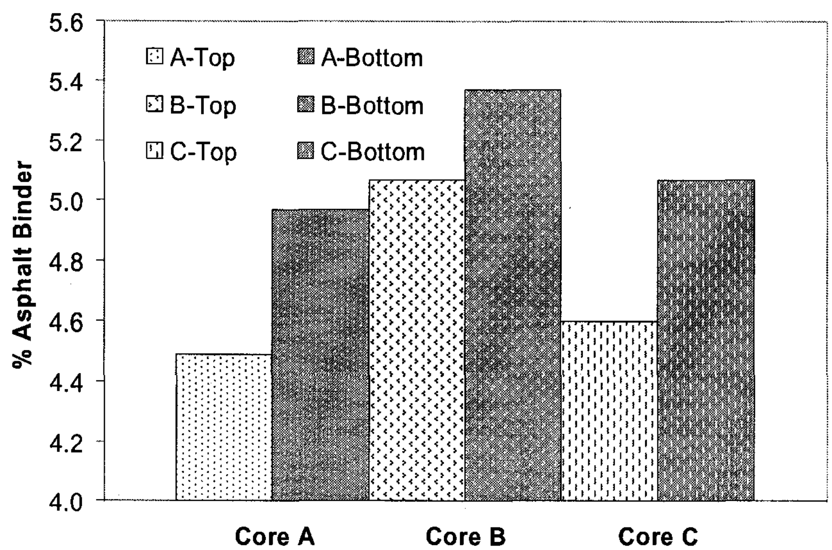

Figure 4: Analysis of asphalt binder content in PA core samples (Briggs et al., 2007)

Table 1: Seasonal statistical comparison of porous asphalt surface infiltration capacity (in/hr) using a Student's t-test

(W = November - April; S = May - October)
(n = Number of samples; SD = Standard deviation; COV = Coefficient of variation)

Period	11/04 - 10/05		11/05 - 10/06		11/06 - 10/07		11/07 - 7/08	
Season	W	S	W	S	W	S	W	S
Location A								
Device	SI		SI		SI		SI-mod	
n	5	5	3	5	5	3	2	2
Mean	1,537	1,390	1,080	1,248	820	1,511	943	838
Min.	1,337	919	840	1,003	554	896	838	808
Max.	1,838	1,838	1,379	1,451	1,058	1,891	1,047	867
SD	228	421	274	211	215	538	148	42
COV	0.15	0.30	0.25	0.17	0.26	0.36	0.16	0.05
Summary	W>S		S>W		S>>W		W>S	
P-value	0.451		0.457		0.005		0.733	
Diff. (p<0.05)?	No		No		Yes		No	
Location B								
Device	SI		SI		SI		SI-mod	
n	5	5	3	5	5	3	2	2
Mean	1235	736	496	459	396	688	732	614
Min.	1,058	521	208	368	259	364	709	572
Max.	1,451	1,313	683	531	514	957	755	656
SD	171	331	253	59	91	300	33	59
COV	0.14	0.45	0.51	0.13	0.23	0.44	0.04	0.10
Summary	W>>S		W~S		S>W		W>S	
P-value	0.001		0.808		0.063		0.569	
Diff. (p<0.05)?	Yes		No		No		No	
Location C								
Device	SI		SI		DRI		DRI	
n	5	5	3	3	2	4	2	2
Mean	345	183	45	60	23	41	54	44
Min.	306	105	38	43	8	4	48	31
Max.	391	317	57	80	37	116	60	56
SD	32	83	11	19	21	51	8	18
COV	0.09	0.46	0.23	0.31	0.91	1.24	0.15	0.40
Summary	W>>S		S>W		S>W		W>S	
P-value	0.000		0.713		0.666		0.829	
Diff. (p<0.05)?	Yes		No		No		No	

It is hypothesized that the majority of the asphalt drain-down occurred during the first summer after installation but then stabilized contributing to long-term conditions that appear to be correlated with the cyclical trend of average daily air temperature (A.D.A.T.) (Figure 3). Several laboratory studies have suggested that the IC of porous asphalt may decline by about 50% in below-freezing temperatures but will remain sufficient as long as the pavement is not completely covered with ice or clogged by sand (Stenmark, 1995; Backstrom and Bergstrom, 2000). Declining infiltration rates from measurements on 2/12/07 to 2/13/07 demonstrate the effect of air temperature on IC. During this time, the A.D.A.T. decreased by 13°F and the IC decreased by about 50% at locations A and B. The apparent correlation of IC with air temperature continued until April 2008 when the IC rates at locations A and B stabilized around 850-in/hr and 650-in/hr, respectively. This final trend change may be due in part to the modification of the SI testing device.

In addition to possible binder drain-down, the low-infiltrating area at Point C may be the result of several other factors. It is known that the area was compacted more during construction than Points A or B and therefore possessed the lowest infiltration rate for the lot since this time. Secondly, it is located approximately five-feet from one of the main driving lanes in the main DMA West Edge parking lot so it is likely that sediments and other debris from local winter sanding operations was continually blown or tracked onto the area. Points A and B are more representative of the typical infiltration capacity of the entire PA lot; Point C can be considered an anomaly.

It should also be noted that since its construction and throughout the duration of this study, vacuum maintenance of this PA lot occurred only once on 9/22/07 and was completed with a combination of an Elgin Whirlwind MV 'sweeper-vac' and a Billy Goat yard vacuum. This treatment may have contributed to the increases in IC at locations A and C between the 8/10/07 and 9/23/07 measurements. The only other vacuuming to occur was with a low pressure utility vacuum used to collect salt at locations where IC rates where not measured, therefore having no impact on the surface infiltration data.

Winter Storm Event Characteristics

For all analyses of winter performance, one season of precipitation events were evaluated. The types of observed storms consisted of light to heavy snowfall, sleet, freezing rain, rain, and various combinations of each, with air temperatures ranging between -2°F to 70°F (UNHWS, 2008). A summary of weather conditions for each event occurring in the present study is displayed in Table 2. Also shown at the bottom of the table are monthly average weather statistics for Durham, NH (NHSCO, 2008).

Table 2: Winter storm event characteristics ('06-'07)

(S = Snow; R = Rain; I = Ice) (NCDC, 2008; NHSCO, 2008; UNHWS, 2008)

Date	Precipitation Type	Snow Depth (in.)	Water Equivalent Depth (in.)	Max Temp (°F)	Min Temp (°F)
12/8/2006	S	2.00	0.02	40	16
12/30/2006	S/R	2.50	0.13	28	17
1/8/2007	R	0.00	1.11	44	33
1/15/2007	I	0.50	0.49	39	24
1/19/2007	S	1.00	0.12	35	26
1/23/2007	S	1.75	0.05	31	19
1/28/2007	S	0.25	0.01	36	18
2/3/2007	S	3.00	0.26	32	24
2/14/2007	S	7.60	0.81	18	12
2/23/2007	S	0.50	0.01	36	23
3/2/2007	S/R	5.50	1.84	49	25
3/16/2007	S	8.00	1.51	34	19
3/25/2007	S/R	2.00	0.30	51	32
4/5/2007	S	5.00	1.03	42	29
4/12/2007	S/I	0.76	0.86	47	32
Nov. avg.	-	14.4	4.84	49.1	29.3
Dec. avg.	-	14.4	4.46	36.8	18.2
Jan. avg.	-	19	4.11	33.4	13
Feb. avg.	-	16.9	3.48	35.4	14.4
Mar. avg.	-	12.8	4.31	44.4	23.7

Visual Observations

Photo documentation was used in the study to record instantaneous pavement conditions. Figure 5 is a series of photos that depict a scenario that was often observed between the PA and DMA pavements following snow events. These photos demonstrate surface conditions between 10AM and 11AM with an air temp of 25°F. Photos (5a) and (5c) were taken at 10AM immediately before plowing while photos (5b) and (5d) where taken at 11AM, about 45-minutues after plowing. Notice in (5b) how the porous asphalt is completely clear of snow even in below freezing temperatures. Part of the reason for this is that melting snow and ice can instantly drain through the pavement surface. This photo may also suggest that percentage of cover on porous asphalt is more a function of snow removal by plowing rather than salt application since all study areas appear to have similar amounts of clear pavement. Conversely, in (5d) snow appears to accumulate and remain on all DMA well after plowing. In below freezing air temperatures, solar radiation can melt remaining snow/ice and the melted water is able to then freeze on the DMA surface, consequently slowing down the melting process. The resulting weighted skid resistance value based on surface cover percentages was 14% higher for PA than DMA. The process for determining the weighted skid resistance for the pavements is explained in more detail later in the paper.

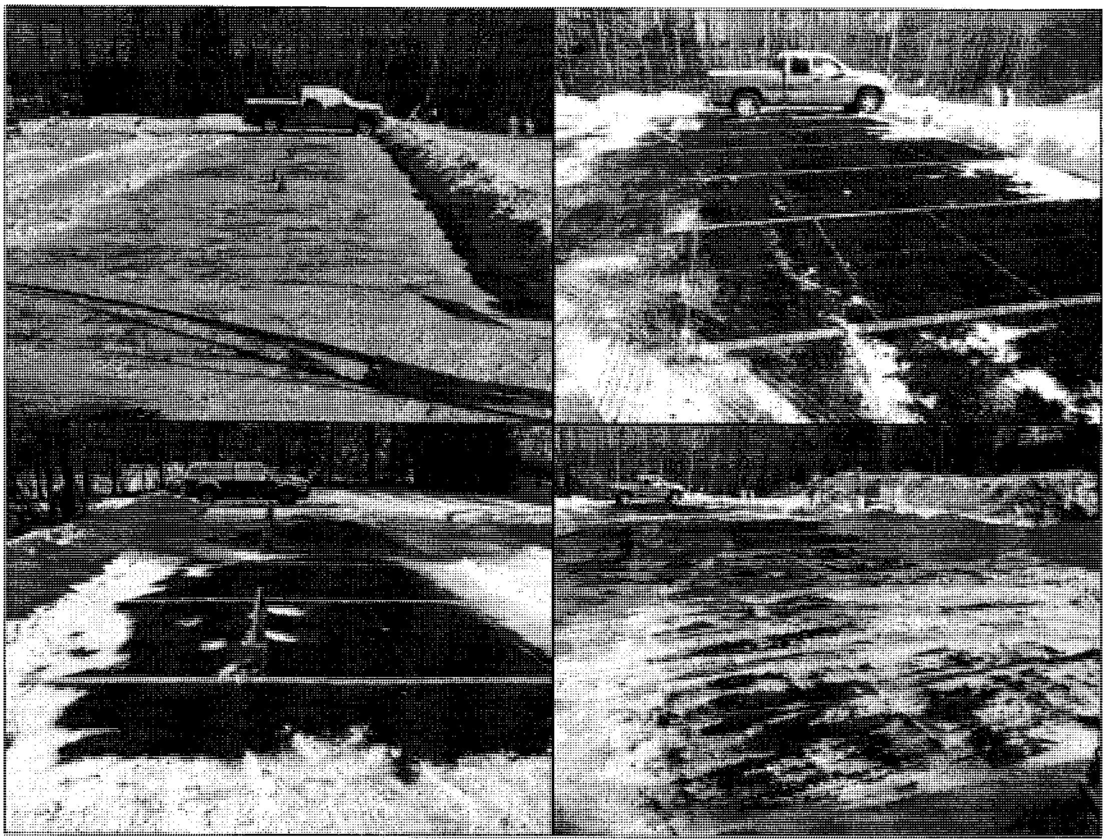

Figure 5: Pavement conditions before and after plowing (2/3/07)

(5a) PA at 10AM (top-left); (5b) PA at 11AM (top-right);
(5c) DMA at 10AM (bottom-left); (5d) DMA at 11AM (bottom-right)

Figure 6 demonstrates a theme that was commonly observed during cyclical freezing-thawing conditions. The photos were taken at 9AM, one-day after a snow-event. Any precipitation that remained on the porous asphalt immediately drained through the pavement (6a). The opposite was true on the standard asphalt (6b). Melt-water refroze overnight creating icy conditions that morning. It is common during a New England winter for salt spreading operations to apply chemical on a near-daily basis to combat (black) ice formation caused by these conditions. The resulting weighted skid resistance was 10% higher for the PA than the DMA.

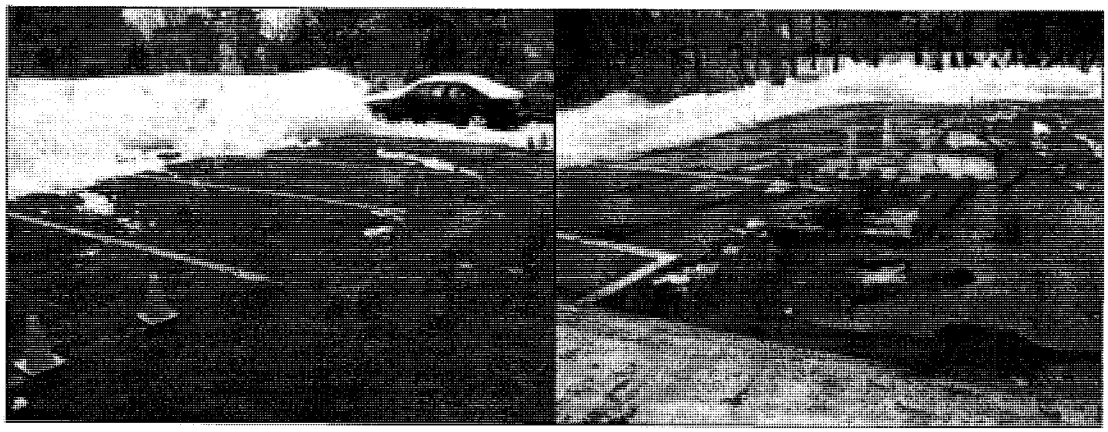

Figure 6: Instantaneous pavement conditions after thawing and refreezing of meltwater (3/18/07)

(6a) PA at 9AM (left); (6b) DMA at 9AM (right)

Snow/Ice Surface Cover Analysis

Quantifying the amount of snow and ice accumulation on the study areas was of considerable interest for this study. During and after storm events, an evaluation of surface cover (type and amount) was performed for each varying salt application. Snow and ice cover was typically significantly lower on PA study areas than was observed on DMA. Figure 7 presents the snow and ice cover for each of the eight study areas; the median surface cover percentages are displayed next to each data set. The salt application rates for each study are specified as 100%, 50%, 25%, or 0% of the recommended application rate (3.0-lbs per 1000-ft^2; MPCA, 2006).

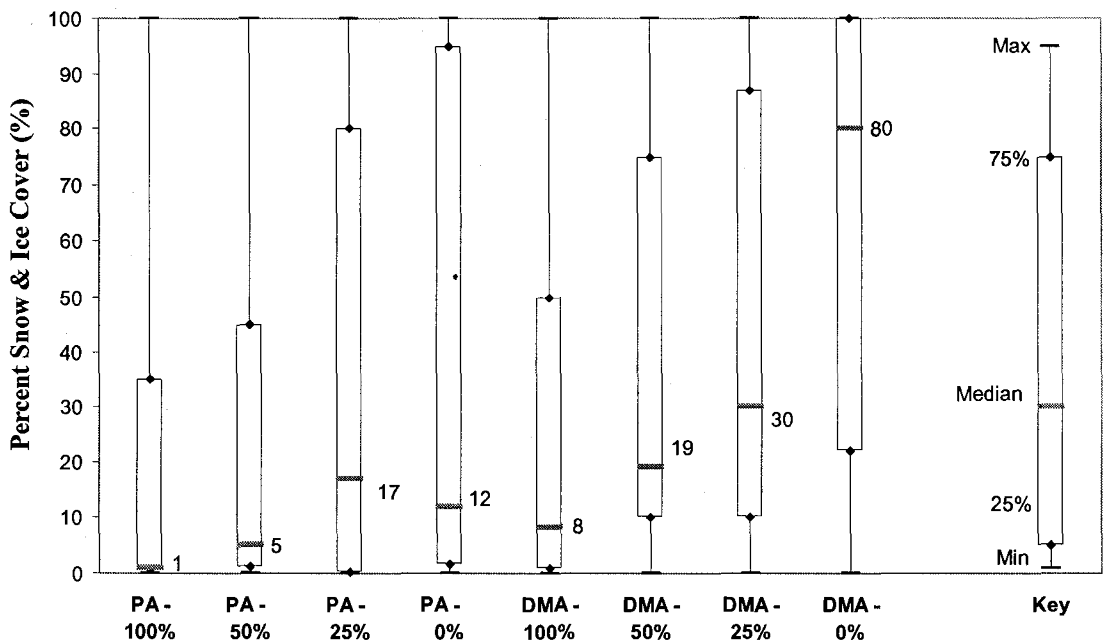

Figure 7: Comparison of percent snow & ice cover for each study area ('06-'07)
(Pavement type and salt application rate as percentage of 3-lbs/sf shown on x-axis)

As one might expect, there is an increasing trend in snow and ice cover with the decrease in salt application rate for all pavement types. This supports the assumption that applying more salt will affectively melt more snow and ice. It is significant to note that the median snow/ice surface cover for the DMA lot is at least three times greater for all salt applications than the same salt application rates on the PA lot. On an event basis, snow/ice surface cover on the PA was lower 60% of the time and equal 12% of the time. Also of importance are the consistently low snow/ice surface cover observations for both the 50% and 100% salt application rates on porous asphalt. Because of the high standard deviations, no significant statistical differences in surface cover were found between study areas (based on a p-value of 0.05). However, the fact that no statistical difference exists between the 100% DMA salt application and the 0% PA salt application is of importance because it suggests that using no salt on a porous asphalt surface may produce comparable results to the standard of practice application on conventional dense-mix asphalt. Monitoring characteristics for the varying salt applications are shown in Table 3 and a comparison of p-values for the different study areas (obtained using a Student's t-test) is shown in Table 4.

Table 3: Snow & ice cover monitoring characteristics for all study areas ('06-'07)

(n = number of samples; PA = porous asphalt; DMA = dense-mix asphalt)

Salt Application Rate	Pavement Type	n	Mean	Median	Min.	Max.	Standard Deviation	Coefficient of Variation
100	PA	21	24.6	1.0	0	100	39.0	1.585
	DMA	21	27.7	8.3	0	100	36.6	1.321
50	PA	21	25.3	5.0	0	100	38.3	1.514
	DMA	21	38.0	19.0	0	100	36.2	0.953
25	PA	21	34.5	17.0	0	100	40.1	1.162
	DMA	21	44.8	30.0	0	100	40.9	0.913
0	PA	21	41.0	12.0	0	100	45.6	1.112
	DMA	20	59.3	80.0	0	100	43.1	0.727

Table 4: Student's t-test p-value comparison of snow & ice cover ('06-'07)

Parking Lot & Salt App. Rate	PA - 100%	PA - 50%	PA - 25%	PA - 0%	DMA - 100%	DMA - 50%	DMA - 25%	DMA - 0%
PA - 100%	-	0.951	0.422	0.185	0.800	0.279	0.105	0.006
PA - 50%	0.951	-	0.459	0.206	0.848	0.307	0.118	0.008
PA - 25%	0.422	0.459	-	0.599	0.583	0.779	0.409	0.050
PA - 0%	0.185	0.206	0.599	-	0.283	0.806	0.764	0.148
DMA - 100%	0.800	0.848	0.583	0.283	-	0.407	0.170	0.013
DMA - 50%	0.279	0.307	0.779	0.806	0.407	-	0.585	0.092
DMA - 25%	0.105	0.118	0.409	0.764	0.170	0.585	-	0.249
DMA - 0%	0.006	0.008	0.050	0.148	0.013	0.092	0.249	-

Frictional Properties of Pavement Surfaces

Frictional measurements were taken on both pavement types with the British Pendulum Tester during and after storm events. Four types of pavement conditions were evaluated, including dry, wet, snow-covered, and ice-covered pavement. Statistical differences (p-values less than 0.05) were observed between most pavements and surface cover conditions when measured using a Student's t-test. Therefore, all measurements on the PA and DMA were paired by surface cover type and compared graphically with box and whisker plots in Figure 8. Table 5 summarizes the testing parameters for the different data sets.

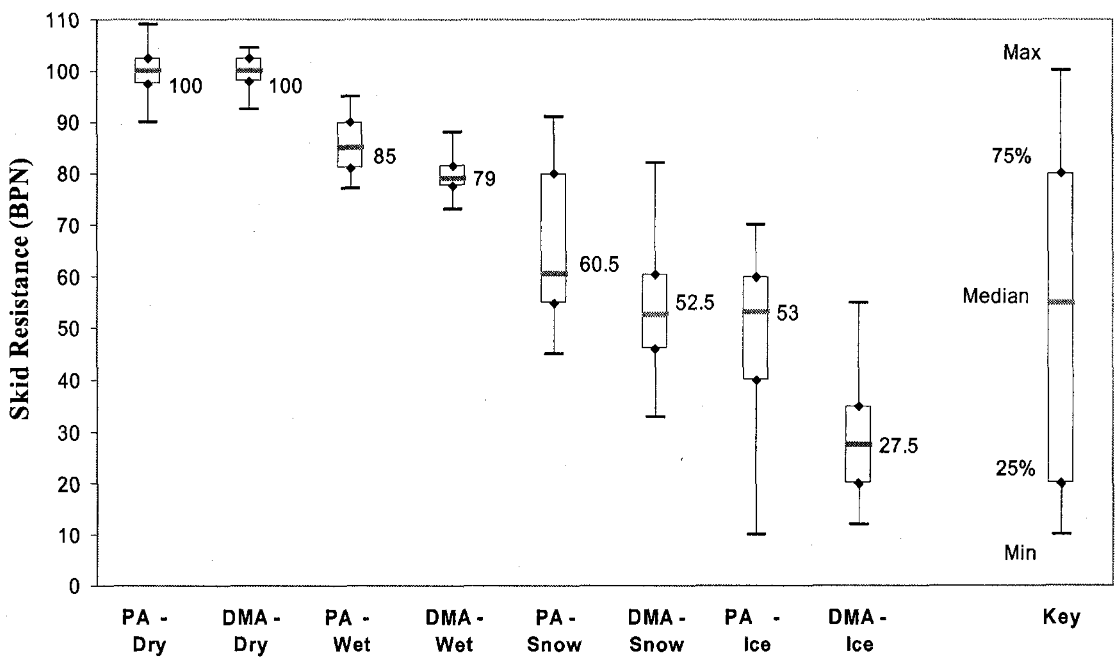

Figure 8: Skid resistance for PA and DMA pavements and all winter surface conditions ('06-'07)

(Median skid resistance value displayed under each group)

Table 5: Skid resistance descriptive statistics for PA and DMA pavements and winter surface conditions ('06-'07)

(n = number of samples)

Surface Cover Condition	Pavement Type	n	Mean	Median	Min.	Max.	Standard Deviation	Coefficient of Variation	P-value	Stat. Diff. (p<0.05)?
Dry	PA	45	99.7	100.0	90.0	109.0	4.57	0.046	0.669	No
	DMA	60	100.0	100.0	92.5	104.5	2.85	0.029		
Wet	PA	75	85.2	85.0	77.0	95.0	4.91	0.058	0.0001	Yes
	DMA	75	79.4	79.0	73.0	88.0	3.19	0.040		
Snow	PA	140	65.4	60.5	45.0	91.0	14.15	0.216	0.0001	Yes
	DMA	165	54.0	52.5	33.0	82.0	11.01	0.204		
Ice	PA	35	48.0	53.0	10.0	70.0	17.4	0.363	0.0001	Yes
	DMA	80	27.8	27.5	12.0	55.0	10.62	0.382		

The median skid resistance values observed on porous asphalt was greater than that for dense-mix asphalt for all types of surface cover (excluding dry pavement). This may be explained by a greater surface roughness for the porous asphalt, as was observed in separate studies performed in Texas and Japan. The Texas study found that porous asphalt had a greater coefficient of friction than standard asphalt under wet conditions (Diniz, 1980) and the Japanese study found that porous asphalt exhibited greater skid resistance in black-ice conditions (Manuba et al., 2007).

The mean skid resistance values were multiplied by their respective surface cover type percentages in order to develop a weighted skid resistance value for each observation. The significance of the weighted skid resistance value was to obtain a number that can easily be related to safety for each of the varying salt application rates. This process was done for each storm event evaluation (most events included 2-3 evaluations) and statistically compared for all pavement types and salt application rates. When compiling the data sets for the surface cover evaluations it was important not to include observations when all parking lot study areas were entirely dry because a bias would have been introduced leading the weighted skid resistance toward higher values.

Trends observed in Figure 9 include a decreasing trend in weighted skid resistance as salt application is reduced for both pavement types; one might expect to see this result based on the strategy behind roadway deicing. Secondly, porous asphalt exhibits only a 4% difference in median skid resistance between the 100% and the 0% salt application rates while standard asphalt demonstrates a 27% decrease in friction. These observations are supported statistically with the PA Student's t-test comparison exhibiting a greater p-value than the DMA comparison (Table 7).

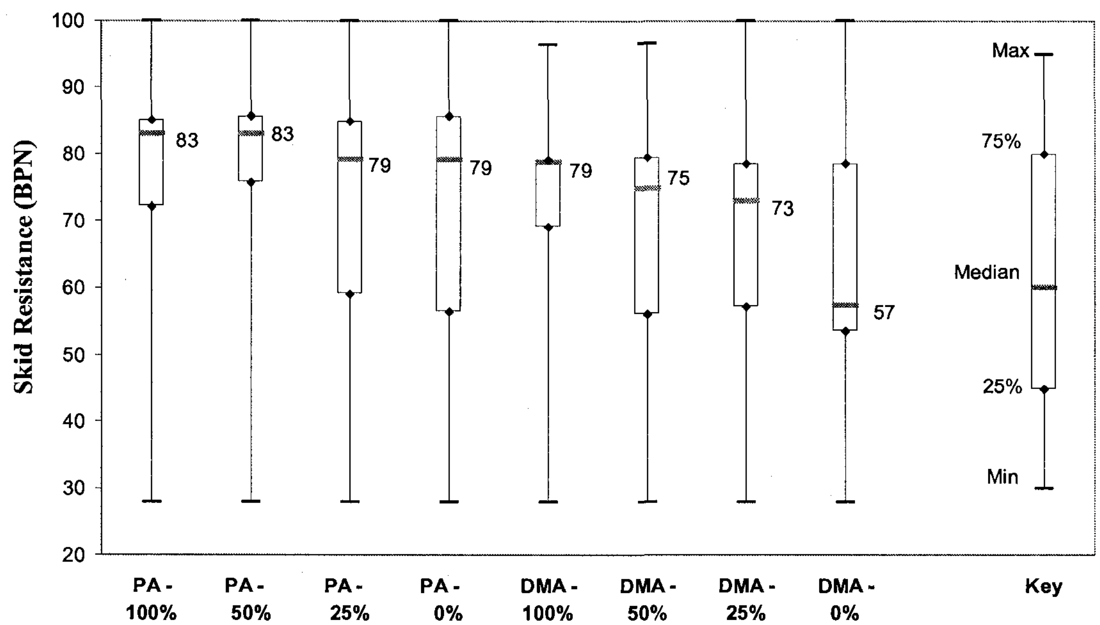

Figure 9: Weighted skid resistance as a function of snow & ice cover ('06-'07)
(Pavement type and salt application rate as percentage of 3-lbs/sf shown on x-axis)

Table 6: Weighted skid resistance descriptive statistics for all study areas ('06-'07)

(n = number of surface cover observations)

Salt Application Rate	Pavement Type	n	Mean	Median	Min.	Max.	Variance	Standard Deviation	Coefficient of Variation
100	PA	21	77.7	83.0	28.0	100.0	341	18.5	0.238
	DMA	21	71.6	78.8	28.0	96.4	428.7	20.7	0.289
50	PA	21	77.7	83.0	28.0	100.0	335.2	18.3	0.236
	DMA	21	68.1	74.8	28.0	96.6	440.2	21	0.308
25	PA	21	74.8	79.0	28.0	100.0	350.8	18.7	0.250
	DMA	21	66.2	72.8	28.0	100.0	513.7	22.7	0.343
0	PA	21	73.5	79.0	28.0	100.0	389.5	19.7	0.268
	DMA	20	63.8	57.3	28.0	100.0	596.2	24.4	0.382

Table 7: Student's t-test p-value comparison for weighted skid resistance ('06-'07)

Parking Lot & Salt App. Rate	PA - 100%	PA - 50%	PA - 25%	PA - 0%	DMA - 100%	DMA - 50%	DMA - 25%	DMA - 0%
PA - 100%	-	1.000	0.653	0.515	0.338	0.133	0.073	0.032
PA - 50%	1.000	-	0.653	0.515	0.338	0.133	0.073	0.032
PA - 25%	0.653	0.653	-	0.840	0.610	0.291	0.178	0.088
PA - 0%	0.515	0.515	0.840	-	0.759	0.393	0.252	0.132
DMA - 100%	0.338	0.338	0.610	0.759	-	0.584	0.402	0.228
DMA - 50%	0.133	0.133	0.291	0.393	0.584	-	0.770	0.505
DMA - 25%	0.073	0.073	0.178	0.252	0.402	0.770	-	0.705
DMA - 0%	0.032	0.032	0.088	0.132	0.228	0.505	0.705	-

When comparing study areas in Table 7, p-values less than 0.05 indicate that a statistical difference may exist between weighted skid resistance data sets; however, only few significant differences are present. The p-value between PA with a 100% salt application and DMA with no salt is 0.032, suggesting a possible difference. Of somewhat greater significance are certain data sets that are not statistically different. For instance, the PA study areas with 25% or 0% salt applications demonstrate high p-values when compared to DMA with the 100% application. What this means is that the weighted skid resistance, or safety, of the PA parking lot is likely to exceed that of the DMA lot even with one-fourth of the amount of salt used on the PA.

Chloride Recovery

As a way to measure the amount of salt that was affectively melting snow and ice, the chloride mass retained on the pavement surface was determined. Figure 10 shows the total percentage of chloride recovered versus the total mass applied over the course of one winter. The West Edge parking lot chloride regression (Avellaneda, 2005) and the stoichiometric relationship of chloride to NaCl were used to quantify the result. At least 30% more chloride mass was recovered from the porous asphalt than from the standard asphalt for each salt application rate. On an event basis, porous asphalt had a greater recoverable chloride mass 82% of the time for the 100% application rate, 88% of the time for the 50% rate, and 67% of the time for the 25% rate.

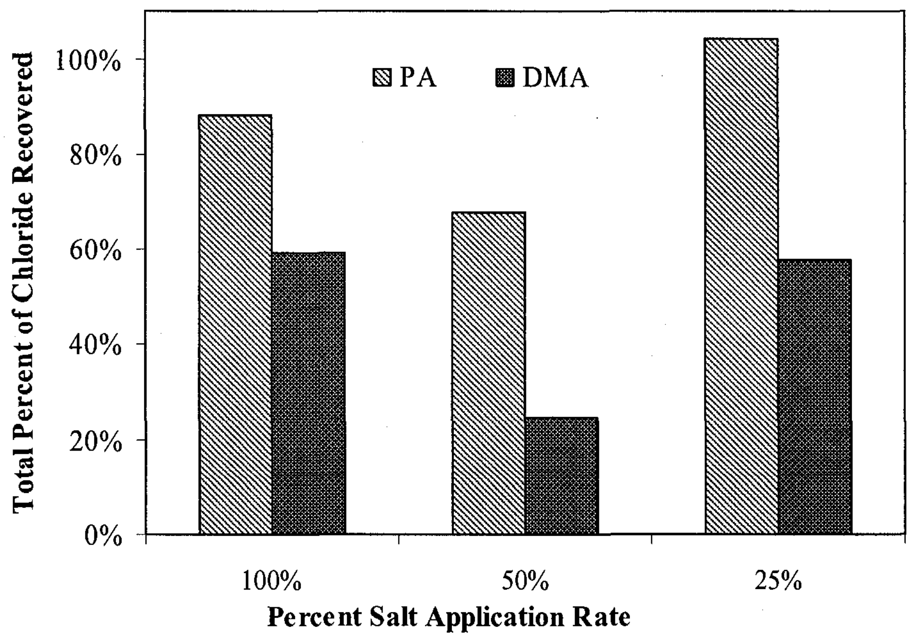

Figure 10: Comparison of recovered chloride for PA and DMA lots ('06-'07)

The greater amount of recoverable chloride and salt mass for the PA lot may be explained in a number of ways. Salt is effective as a deicing agent because it melts a hole through the snow or ice and forms a layer of highly saline water that melts the surrounding ice (Trost et al, 1987). On porous asphalt this layer of meltwater cannot form because it instantly drains through the pavement, leaving behind more of the original salt crystal. A second explanation may be based on the idea that runoff from the impermeable lot washes away any residual salt mass. This, of course, does not occur on porous asphalt. If salt crystals remain on the surface of porous asphalt then reductions can be made at least for anti-icing practices. Additional reductions are possible for deicing applications done strictly for freeze-thaw ice conditions.

Salt Load Reductions

Total possible salt load reductions were quantified by revisiting the surface cover data and determining which events necessitated deicing salt applications. If substantial snow or ice (>5%) existed on the pavement then it was decided that at least one deicing salt application was necessary. The majority of events required that either both lots be deiced, or in some cases, just the DMA pavement. Often times the porous asphalt was nearly clear of all snow and ice well before the standard. Certain events however, such as icing or freezing-rain, typically required equal salting maintenance for both lots. The total number of deicing applications for each lot were summed and added to the number of necessary anti-icing applications (assumed to be equal to the number of storm events) to come up with the total annual salt load reflective of all four application rates (Table 8).

Table 8: Required salt loads and possible salt reductions on porous asphalt ('06-'07)

Pavement Type	Anti-Icing Applications	Deicing Applications	Required Salt Load Depending on Application Rate (lbs/acre/yr)			
			100%	50%	25%	0%
DMA	15	14	3790	1895	947	0
PA	15	6	2744	1372	882	0
Possible Salt Reductions on Porous Asphalt Per Year Per Application Rate (%)						
			28%*	64%*	77%	100%

* Reduction possible with no loss in skid resistance (safety)

By combining this data with the results from the weighted skid resistance analysis, the possible annual salt reductions for porous asphalt with no change in pavement skid resistance or safety was calculated to be as high as 64% depending on application rate. Reductions on porous asphalt may exceed 77% and still produce conditions that are comparable to the standard of practice for conventional asphalt. This finding is significant considering that the proposed chloride TMDLs in NH call for an annual salt reduction of 20 to 40% for parking lots in order to meet the imposed load allocations (Trowbridge, 2007a, 2007b); a goal that could be met purely by the fewer number of deicing applications required for porous asphalt.

Conclusions

Aside from the large advantage that porous asphalt possesses as a stormwater management technology, this research shows that porous asphalt has significant winter maintenance advantages over the current impermeable asphalt standard of practice. Not only does PA preserve functionality hydraulically and stand up well to the adverse weather conditions, but considerable reductions in salt use can be achieved. The resources invested in an average winter for maintaining parking lots and keeping pavements clear of ice and snow can be staggering. UNH spent a total of $65,000 purely on deicing salt during the '07-'08 winter (Byron, 2008). Estimates in a 10 square-mile watershed in southern NH suggest that up to 50% of the total salt usage for winter operations can be directly attributed to parking lot treatments. Additionally, with NPDES Phase II water quality requirements and chloride TMDLs on the verge of implementation, cities and municipalities will be forced to reduce contaminant loads from transportation surfaces (Trowbridge, 2007a, 2007b). Since there is currently no commonly employed stormwater BMP that can remove chloride from stormwater runoff, and conventional systems (swales, ponds, catch-basin retrofits) have been shown to be ineffective, and in some cases export contaminants (Ballestero et al., 2000; Roseen et al., 2006), permeable pavements may be the most viable option. Future research will consist of additional winter performance monitoring of the porous asphalt system. The study will also be expanded to evaluate another type of permeable pavement, pervious concrete, in order to make comparisons between other existing technologies.

CHAPTER 3

A WINTER PERFORMANCE COMPARISON OF POROUS ASPHALT, PERVIOUS CONCRETE, AND CONVENTIONAL ASPHALT PAVEMENTS

Abstract

In northern climates, runoff from impermeable pavements has varying seasonal effects on the surrounding environment. During the winter and spring, deicing practices result in high levels of chloride-laden runoff that is both toxic to aquatic biota and degrades drinking water supplies. The use of permeable pavements for parking lots, roads, and sidewalks for new and redevelopment projects is one strategy that can mitigate watershed impacts associated with stormwater runoff. This study presents the findings from two active parking lot permeable pavements: porous asphalt and pervious concrete. The two lots were designed, constructed, maintained, and studied by the University of New Hampshire Stormwater Center. Winter, in particular, places great demands on pavements; however, the well-drained nature of permeable pavement systems, including their porous reservoir base, limits the freeze-thaw effects that can reduce the lifespan of conventional pavement applications. Frost penetration was observed to reach depths of eighteen inches; however, surface infiltration capacities remained in excess of 200-in/hr. Analysis of snow and ice cover and pavement skid resistance demonstrated that up to 72% less salt was needed for porous asphalt to maintain equivalent or better surface conditions as impermeable asphalt. The annual median snow and ice surface cover for

the PA lot was only 6% higher than the DMA lot even though the DMA lot received a salt application rate four times as great as the PA. The annual median weighted skid resistance for the PA lot was 12% greater than the DMA lot when measured with a British Pendulum Tester. Pervious concrete did not demonstrate substantial salt reduction capabilities during storm events; however, 'black-ice' formation did not occur during freeze-thaw conditions indicating possible annual reductions. Pavement color and shading were found to be major factors influencing the amount and duration of snow and ice cover on the PC lot. Overall, pervious pavements were observed to exhibit a high level of functionality during winter conditions for surface infiltration, skid resistance, and salt reduction.

Introduction

The implementation of the National Pollutant Discharge Elimination System (NPDES) Phase II regulations has helped to fuel the research, development, and implementation of innovative Best Management Practices (BMP) for managing and treating stormwater runoff. Since 2003, the University of New Hampshire Stormwater Center (UNHSC) has set out to evaluate over twenty types of BMPs in a fully-monitored field setting. One class of BMP that is at the forefront of the industry and is being adopted in both the public and private sectors is permeable pavements. One of the major benefits of permeable pavements is their dual function as a transportation surface and self-contained stormwater management device. In addition, research has demonstrated that porous asphalt may allow for a 77% annual salt reduction for winter maintenance over conventional practices on impermeable asphalt (Houle, 2008). To date, the UNH

Stormwater Center (UNHSC) has constructed and tested two types of permeable pavement parking lots: porous asphalt and pervious concrete, both of which are located at the UNH campus in Durham, NH. The objective of this study is to compare and contrast a series of winter performance metrics of porous asphalt (PA) and pervious concrete (PC). This paper is the second phase of a research project that was initiated in 2006. Topics discussed include design details, frost penetration, hydraulic performance as measured by infiltration capacity, winter performance and maintenance requirements, and salt reduction opportunities. Historically, there has been some debate among the engineering community on how permeable pavements perform in northern climates; part of this debate stems from the confusion between a true porous asphalt stormwater management system (as is described in this paper) versus open-graded friction course (OGFC), for example, which is typically used in highway application and differs from PA by its impermeable asphalt base (Kandhal and Mallick, 2002). This paper to addresses these misconceptions and identifies the potential benefits of permeable pavements.

Background

Permeable pavements differ from standard dense-mix asphalt in that the "fines" (particles smaller than 600 microns) are removed from the aggregate mix, thereby allowing the formation of pores for water to pass (Cahill et al., 2003; Ferguson, 2005). Porous asphalt typically consists of stone aggregate, binder material, and other modifiers and should demonstrate a void space of 18% to 20% (Briggs, 2006). Pervious concrete, on the other hand, consists of hydraulic cement, stone aggregate, water, and a combination of various chemical additives (admixtures) to enhance the performance, strength, and ease of placement. Typical void space of a pervious concrete pavement should be between 15% and 25% (NRMCA, 2007). In the case of the UNHSC designs, the porous asphalt lot was placed in one, four-inch lift while the pervious concrete lot was poured to a six-inch depth. Both of these surfaces were placed over a choker (stone) course underlain by 12-inches or more of a bank run gravel filter course.

The aggregate gradations and particle-size distributions (PSD) for the two pavement mixes are shown in Figure 11 to display the differences. The PA mix is coarser than the PC for the upper 90% of the gradation (by weight). The PC mix is slightly smaller than the specification for the lowest 50% of the gradation; however, even if it was within the spec the PA mix would still be coarser.

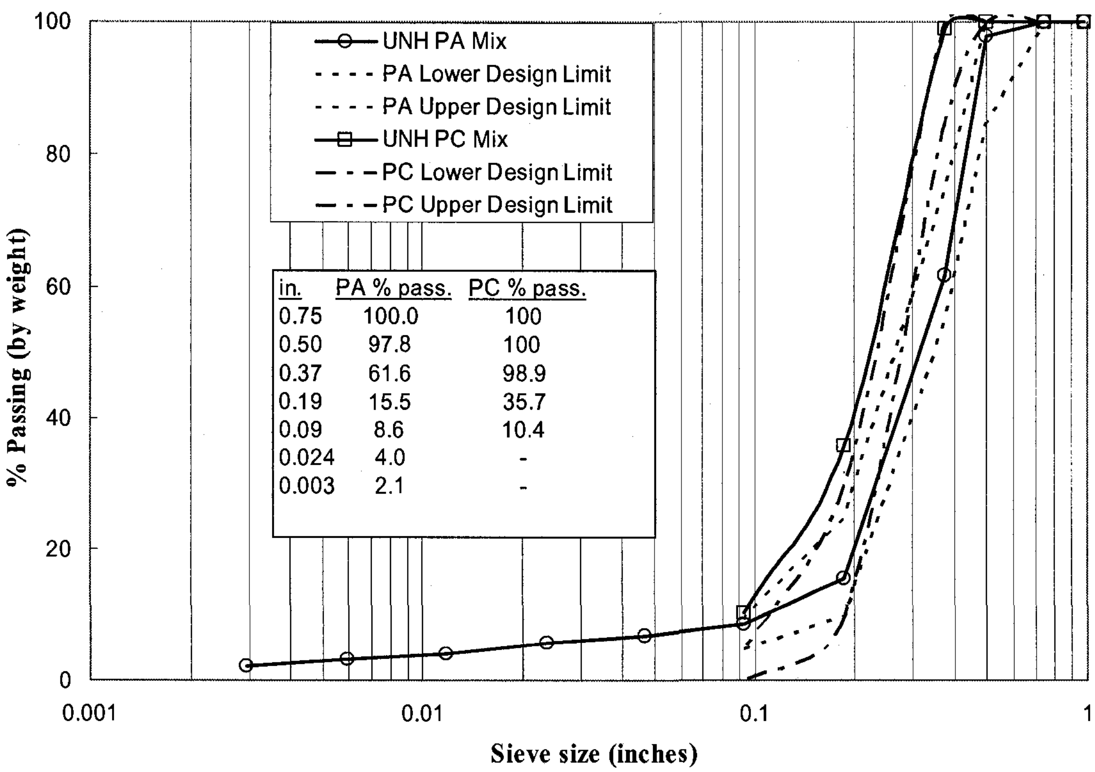

Figure 11: Particle-size distributions for PA and PC aggregate mixes

Many of the sub-base design considerations for porous asphalt and pervious concrete stormwater management systems are similar to those that would be inherent of most infiltration-based BMPs. For instance, both UNHSC designs consist of a bank-run-gravel (BRG) filter course underlain by crushed-stone reservoir layer. The thicknesses of these layers vary between systems, ranging from 14-inches (PC) to 24-inches (PA) of filter course and 4-inches (PC) to 21-inches (PA) of crushed-stone reservoir. The total sub-base depth of the PA site was greater than the PC design in order to meet seasonal-high-groundwater separation restrictions and due to the presence of a less permeable native sub-grade soil. Historically, the sub-base of many porous asphalt systems consisted of only crushed stone; however, with the addition of the filter course, the water quality performance of the porous asphalt system is substantially improved, resulting in the removal of most stormwater contaminants (hydrocarbons, microorganisms, sediment, metals) (Roseen et al., 2007). The major differences between these systems (PA and PC, in general) are primarily in the wearing course mix designs.

The UNHSC porous asphalt (PA) site is a hydraulically isolated 4,500-ft^2, 17-space parking lot that was installed in 2004. Directly adjacent to this PA lot is an equally-sized dense-mix asphalt (DMA) parking area that is also hydraulically isolated. The DMA lot was constructed concurrently with the PA site to serve as a control for most performance metrics. Both lots are located along the perimeter of a nine-acre, asphalt commuter parking lot.

The UNHSC pervious concrete (PC) site was installed in August, 2007. It is approximately 20,000-ft^2 and includes 75 parking stalls. It serves as a parking lot for several nearby dormitories and is used to capacity primarily from September to May. Adjacent to the PC site, is a university-maintained standard asphalt lot that was used as an additional reference location for the study.

The winter climate (January through March) in Durham, NH generally consists of average temperatures near 27.7 °F, with maximum and minimum temperature of 37.5 °F and 17.3 °F, respectively. Total precipitation during this time period is approximately 16.4 inches and snowfall is around 63.1 inches (NHSCO, 2008).

Methodology

The methodology for this research was designed to mimic strategies outlined in Houle (2008) but altered as needed. References to this previous study are provided where appropriate.

Frost Depth Penetration

Frost depth penetration within the two types of permeable pavement was measured using a "field assembled frost gauge" (Ricard et al., 1976) installed in a screened, PVC groundwater monitoring well. Frost depth was determined by measuring the depth of frozen water-methylene blue solution. Frost depth and air temperature were recorded regularly from December 2007 to April 2008.

Surface Infiltration Capacity

Hydraulic performance of the permeable pavements was evaluated by measuring the surface infiltration capacity (IC) on a near-monthly basis beginning soon after installation. A falling head surface inundation (SI) test (Bean, 2004) was used for this process. This involved pouring a known volume of water into a cylinder and measuring the time required for the water to enter the pavement surface. Measurements were taken at three randomly selected locations (A-C) on the PA lot beginning in 2004, and at six locations (A-F) on the PC lot beginning in 2007. A double-ring infiltrometer (DRI) test was used at one location at the PA lot (Point C) because the IC rate was too low to be accurately represented with the SI device (Briggs, 2006). Further explanation can be referenced in Houle (2008).

Salt Application

Salt was applied to the parking lots in a manner designed to mimic municipal anti-icing and de-icing strategies, and consistent with the general practices employed by the University of New Hampshire. Application rates were selected based on percentages of the recommend standard of practice rate of 3.0-lbs per 1000-ft^2 of application area (MPCA, 2006). The rates used in Houle (2008) (100%, 50%, 25%, and 0%) were applied to 20-ft by 20-ft sections of the driving lane through the pervious concrete lot (Figure 12). The remaining driving lane area received a 100% application rate. The salt used was standard rock salt with less than 10% added fines by mass; it was identical to the mix used in the '06-'07 study.

The number of salt application rates for the porous asphalt and dense-mix asphalt lots was altered from the previous winter. The entire PA lot received a rate of 25% of the standard of practice while the DMA lot received a 100% rate (Figure 13). Evaluation areas included isolated parking stalls, as was the case in Houle (2008) and the lots as a whole. This change in methodology was performed in order to quantify any differences that may exist between driving lanes and parking stalls.

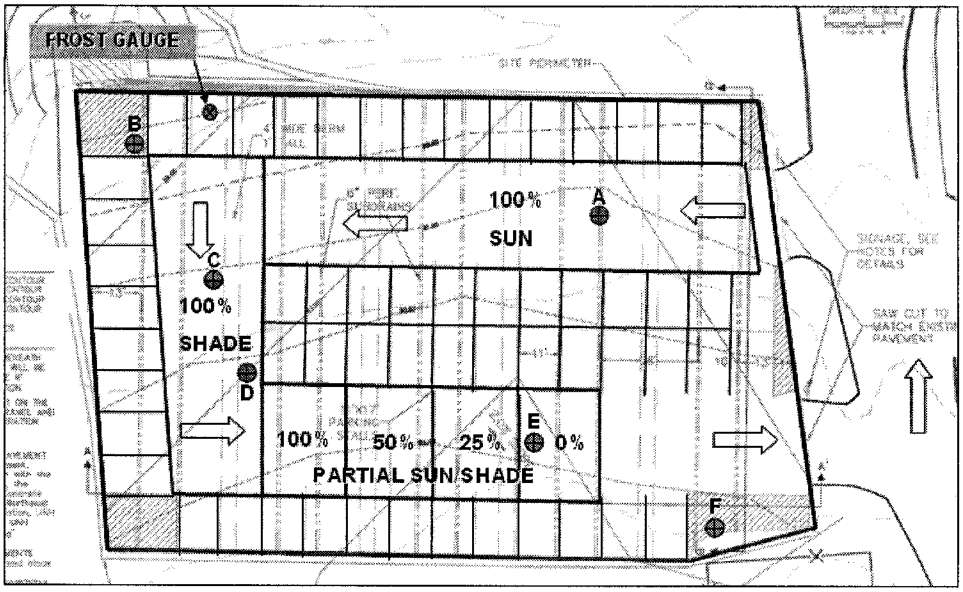

Figure 12: Pervious concrete (PC) study areas ('07-'08)

(Salt application rates, frost gauge and IC locations also shown)

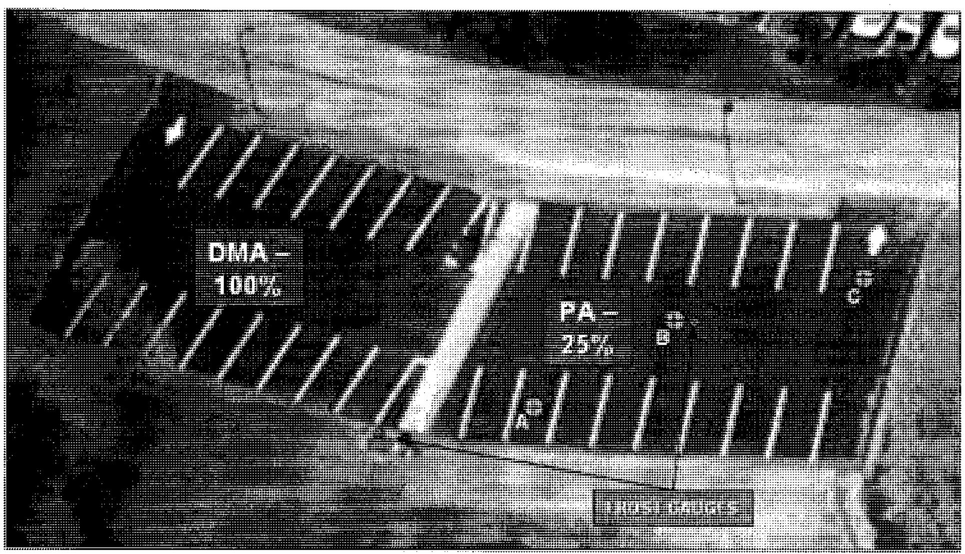

Figure 13: Porous asphalt (PA) and dense mix asphalt (DMA) study areas ('07-'08)

(Salt application rates, frost gauge and IC locations also shown)

<u>Visual Observations and Documentation</u>

Before, during, and after storm events, photos were taken of each study area and the specific event characteristics were recorded. Pavement conditions, type and amount of cover, and weather conditions were of primary interest. Apparent effects from shading or direct sunlight was also recorded. Photo documentation was necessary to substantiate the findings and to display comparative results of the different pavements. Evaluations typically occurred at various times during and up to three days after precipitation events.

Friction Measurements

The skid resistance of all pavement types was measured using a Munro Stanley London British Pendulum Skid Resistance Tester. Each measurement was classified based on the form of surface cover that was present during the reading, including: dry, wet, snow, slush, compacted-snow, and ice covered pavement. The method for using the skid resistance tester followed ASTM Standard E 303–93 (2004). As explained in Houle (2008), the device measures the energy loss of a rubber slider as it is swung against the test surface. A British Pendulum Number, or BPN, is generated and can be directly related to a pavement coefficient of friction (Munro Environmental, 2007). The higher the frictional resistance of the surface, the greater the resulting BPN.

Skid resistance measurements were taken at various locations within each study area, repeated five times, and seasonally averaged in order to characterize the variability in friction between each type of pavement cover. The mean values were then multiplied by their respective surface cover type percentages in order to develop a weighted friction value for each observation. The significance of the weighted friction value was to obtain a number that can easily be related to safety for each of the varying salt application rates.

Chloride Mass Balance

During rain or melt events, water infiltrates through the permeable pavement systems and either infiltrates the underlying soil and/or fills up the sub-surface stone reservoirs. Providing there is sufficient rainfall and the stone reservoir sub-base is filled to the perforated sub-drains, water will discharge the systems through the sub-drain to where it is then monitored and sampled with an automated 6712SR Isco sampler outfitted with a bubbler-weir flow meter and a YSI Model 600XL Sonde that records several real-time parameters at regular intervals, including: pH, temperature, dissolved oxygen, and specific conductance. By measuring the specific conductance of the effluent leaving the systems and knowing the total salt mass applied for anti-icing and deicing practices, a chloride mass balance for each lot was performed. Real-time chloride concentrations were obtained by converting the specific conductance levels with a regression relationship developed by the UNHSC (Avellaneda, 2005); chloride mass was determined using the recorded flow measurements. A chloride mass balance is of interest to investigate the ability of permeable pavement to reduce the peak chloride discharge and the mass load that would be typical with runoff from conventional impermeable pavements. Research at the UNHSC has measured chloride concentrations of parking lot runoff to be in excess of 5,000 mg/L for most of the winter season (Avellaneda, 2005), levels far above regulatory standards. Chronic exposure levels for chloride are not to exceed 230 mg/L for a 96 hour period more than once every three years on average, while acute exposure levels must not exceed 860 mg/L for a one hour period more than once every three years on average (U.S. EPA, 1988). Any way to reduce these levels may help to better manage the risks that chloride poses to the environment and drinking water supplies.

Statistical Comparison Methods

A 'Student's t' means comparison test was employed for all portions of this study that include statistical assessment. These analyses include surface infiltration capacity, snow & ice cover, and skid resistance. The Student's t-test is a test to determine differences in central location (mean) for two independent data sets (Helsel and Hirsh, 2002). Group comparisons with p-values less than 0.05 (with a 95% confidence interval) were deemed statistically different.

Results and Discussion

Frost Depth Penetration

A time-series from November 2007 to April 2008, displaying frost depth in the porous asphalt and pervious concrete lots, is shown in Figure 14. Frost depth within the systems is plotted against average daily air temperature (on a reverse axis) and frost depth at two reference locations, one in a tree-filter stormwater treatment unit adjacent to the PA lot consisting of a typical bioretention soil-mix and one in soil adjacent to the PC study areas. It is apparent from the figure that the PC responded quicker to lower air temperatures and maintained a greater frost depth than the PA system until early February when a sudden decrease in depth of frost was observed. It is believed that the rapid decrease in frost depth was due to a rain-event on 2/5/08 that thawed the systems, which is consistent with findings by Backstrom (2000) and Houle (2008). Shortly after this rapid thawing process, the PA lot refroze to a frost depth of about thirteen inches while the frost depth in PC lot stayed nearly constant at eight-inches. A possible explanation for this may be due to water levels and latent heat within the two systems. The PC frost gauge well is located at the low-point of the lot and in an area where the total system depth is about 30-inches. At the time of observation, the water level was consistently about 26-inches below the pavement surface (at the base of four-inch perforated sub-drains). The water level in the PA lot on the other hand, was approximately 37-inches below the pavement surface. Researchers in Sweden discovered that high water content in the sub-soils beneath permeable pavements creates a high level of latent heat within the system, which can help resist freezing of the sub-base materials (Backstrom, 2000). The higher ground water level in the pervious concrete system may have supplied enough latent heat to minimize its frost depth.

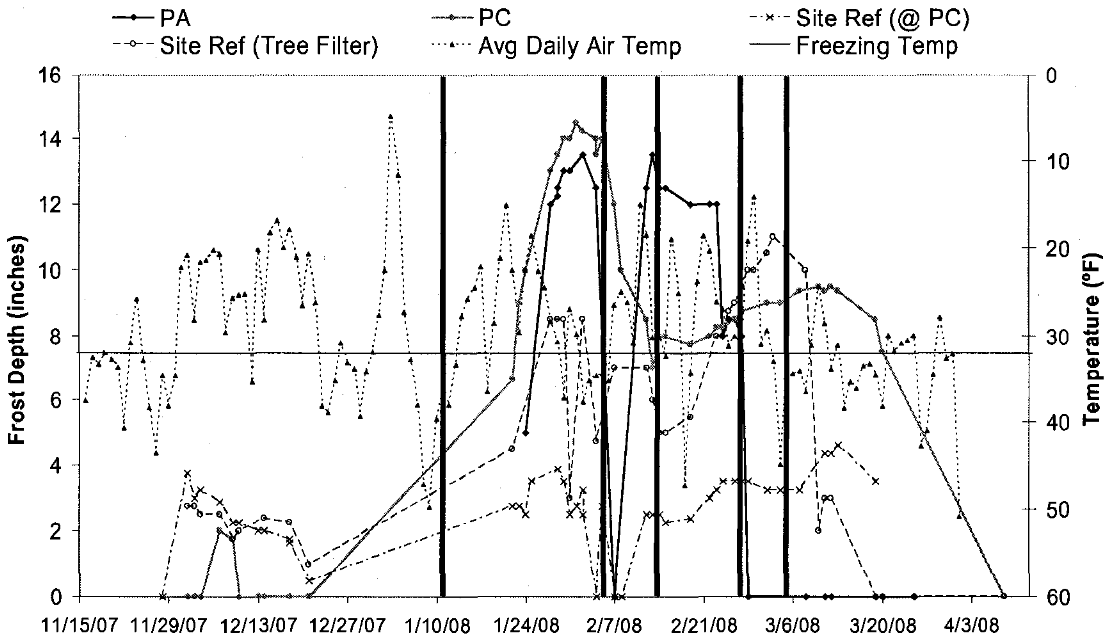

Figure 14: Frost depth penetration comparison between permeable pavements and reference soil sites (11/07 – 4/08)

(Rain events shown with vertical, black lines)

Another interesting finding from this data is that frost depth in the PA system reached zero, and was sustained, two to three weeks earlier than the PC lot. This discovery can be explained by the fact that the black PA surface possesses low albedo and therefore retains more solar energy in the winter than lighter colored surfaces. Concrete pavements have been shown to exhibit surface temperatures up to 10-degrees Fahrenheit lower than asphalt pavements when subjected to similar sun exposure conditions (Cambridge Systematics, 2005). Shading of the PC lot may have also contributed to the longer frost depth duration.

In addition, the permeable pavements demonstrated similar freezing depths to the tree filter treatment unit, suggesting that frost penetration can be comparable to other existing stormwater BMPs, even with several inches of open-graded surface material (Houle, 2008). The one major difference between the pavements and the tree filter is the time it took to reach the maximum frost depths. The lag of the tree filter may be attributed to snow-pack insulation that was present much of the winter. It is also worth noting that no damage or heaving due to freeze-thaw was observed at these lots since their respective installations.

Surface Infiltration Capacity

The surface infiltration capacity was measured at both permeable pavement lots. Figure 15 is a time series and box and whisker plot of the IC data for the PA lot. In the time series plots, each point on the figure represents an average IC measurement; the location and testing method used is indicated by the different markers. The average daily air temperature (A.D.A.T.) is also shown on the figure. In the box and whisker plots, the maximum and minimum observations are represented by the upper and lower whiskers, respectively, and the median values are shown by the gray bar through the 'boxed' segment of the data. The infiltration rates for the PA lot were typically found to be greater than 500 in/hr (Houle, 2008). During the first year of study, IC rates were highest during the winter and spring seasons, even with frost penetration reaching up to six-inches (Briggs, 2006). Since the first year of testing, higher IC rates were typically observed during the summer months; however, winter rates never dropped below 250 in/hr at Locations A and B. Asphalt binder drain-down of approximately 0.5% was identified (Houle, 2008) and thought to contribute to the infiltration rate decline observed during the first summer of study. The low infiltration capacity at Location C was determined to be an anomaly due to over-compaction during placement and clogging from tracked/blown sediments. Further explanation of the IC results can be referenced in Houle (2008) and Briggs (2006).

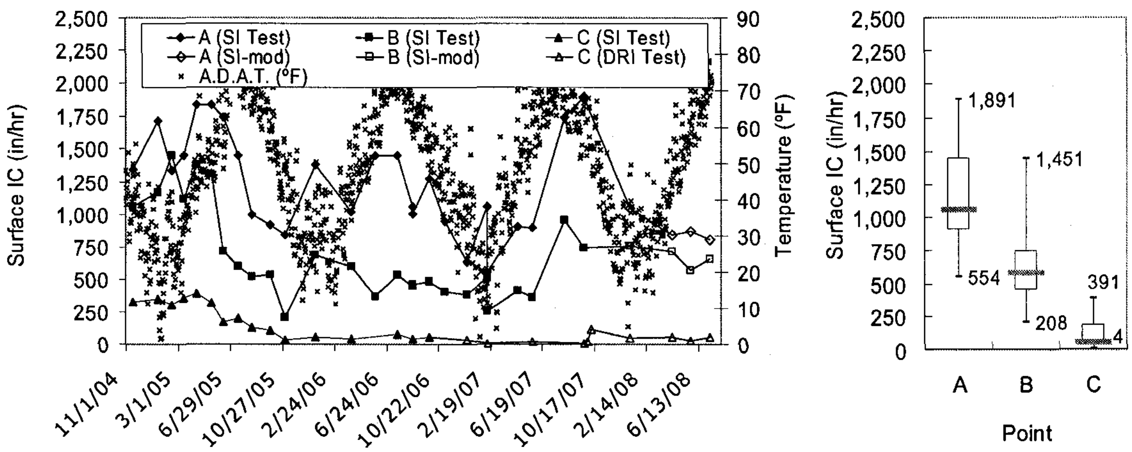

Figure 15: Porous asphalt surface infiltration capacity (Houle, 2008; Briggs, 2006)

(15a) Time-series of surface IC (left); (15b) Box and whisker plots of surface IC (right) [(SI = surface inundation; DRI = double-ring infiltrometer; SI-mod. = modified SI), (Mod. SI appears to report lower infiltration rates, further study needed for correlation), (Pavement cleaning prior to 9/23/07 IC measurements)]

The IC testing at the PC lot was monitored at six locations. Even though considerable variability existed between locations, five of the six sites exhibited median IC rates in excess of 1,600-in/hr (Figure 16b), nearly matching the highest values recorded on the PA lot. The only site below this value was near the entrance of the lot, a location where sand and other debris was commonly tracked and deposited from the nearby roadway. Nevertheless, all of the observed rates surpass rainfall intensities that one might experience in New England. [The 50-yr rainfall intensity for a 5-minute time of concentration in Strafford County, NH is approximately 8.0-inches per hour (NHDES, 1992)].

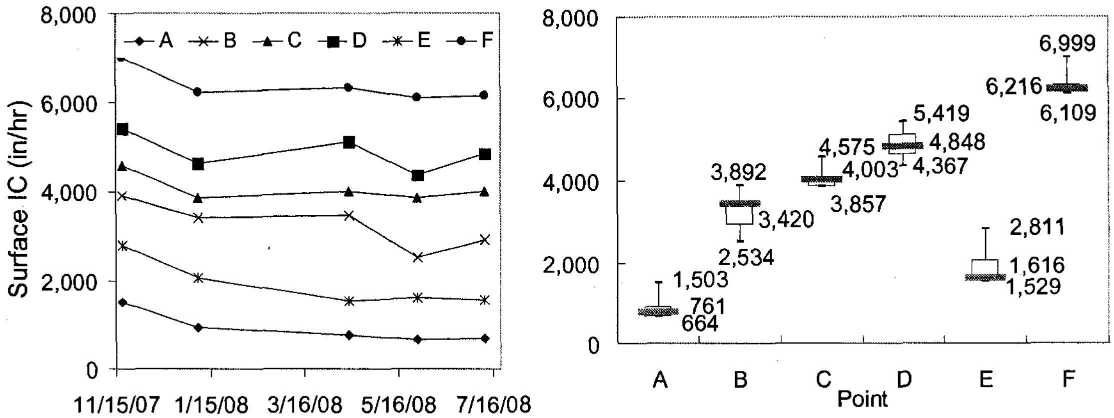

Figure 16: Pervious concrete surface infiltration capacity ('07-'08)

(16a) Time-series of surface IC (left); (16b) Box and whisker plots of surface IC (right)

<u>Winter Storm Event Characteristics</u>

The results for one season of winter precipitation events are presented beginning in December 2007 and ending in March 2008. The types of storms evaluated during this season consisted of light to heavy snowfall, sleet, freezing rain, rain, and various combinations of each, with air temperatures ranging between -5°F and 62°F (UNHWS, 2008). A summary of weather conditions for each event studied is displayed in Table 9. Also shown at the bottom of the table are monthly average weather statistics for Durham, NH (NHSCO, 2008).

Table 9: Winter storm event characteristics ('07-'08)

(S = Snow; R = Rain; I = Ice) (NCDC, 2008; NHSCO, 2008; UNHWS, 2008)

Date	Precipitation Type	Snow Depth (in.)	Water Equivalent Depth (in.)	Max Temp (°F)	Min Temp (°F)
11/20/2007	S	1.5	0.19	35	30
12/3/2007	S	5.5	0.74	33	21
12/10/2007	S	1.5	0.13	34	14
12/12/2007	I	0.04	0.35	44	31
12/14/2007	S	5	0.13	39	17
12/16/2007	S/I	8	0.99	19	10
12/20/2007	S	7	0.39	29	21
12/27/2007	S/R	2	0.21	35	29
12/31/2007	S	13	1.3	36	14
1/14/2008	S	7	0.47	36	12
1/18/2008	S/R	2	0.67	44	18
1/27/2008	S	3	0.31	28	17
2/1/2008	I/R	0.5	1.23	44	33
2/5/2008	S/R	0.75	1.66	37.5	32
2/8/2008	S	4	0.51	29	21
2/10/2008	S	2	0.29	35	16
2/13/2008	S/R	5	2.77	36	21
2/22/2008	S	5	0.36	26.5	13
2/26/2008	S/R	3	0.94	39.5	20
3/1/2008	S	3	0.44	35	21
3/11/2008	S/R	1	0.21	41	17
3/15/2008	S/R	1	0.69	40	33
3/28/2008	S	4	1.02	42	32
Nov. avg.	-	14.4	4.84	49.1	29.3
Dec. avg.	-	14.4	4.46	36.8	18.2
Jan. avg.	-	19	4.11	33.4	13
Feb. avg.	-	16.9	3.48	35.4	14.4
Mar. avg.	-	12.8	4.31	44.4	23.7

Visual Observations

Provided that plowing occurred shortly after the end of snow events, it was commonly observed that the PA pavement became clear of snow and ice earlier than the dense-mix asphalt lot. This observation is exemplified by the photos in Figures 17 and 18. Figure 17(a) and 17(c) show the PA and DMA lots, respectively, at 11:20AM after morning plowing. A thin layer of snow is present on both lots because most plowing operations have difficulty removing all cover due to vehicular compaction and irregularities of the pavement surface as well as the plow blade itself. Figure 17(b) and 17(d) show the same lots one-hour and forty-minutes later. The PA lot is distinctively clear of snow and ice while the conditions of the DMA lot only exhibit minimal melting. Estimates of surface cover amounts at 1PM were 15% snow for the PA lot and 50% snow for the DMA lot. Air temperatures ranged from 31.3°F at 11:20AM and 37.6°F at 1PM. These observations correlate well with assessments made during the 2006-2007 winter on the same parking lots (Houle, 2008).

Figure 18 shows the two pavements after a freezing-rain event (air temperature of 42.3°F). It is clear from these photos that the ice on PA had melted and drained through the pavement far earlier than the DMA lot based on the amount of standing water and ice on the DMA surface in 18(b). Standing water on pavements is a problem because it will often refreeze during the night creating unsafe surface conditions that require deicing salt applications. Standing water was never observed on the porous asphalt lot. It should be noted that freezing-rain events often created icy conditions on both the PA and DMA pavements when air temperature remained near or below 32°F. When temperatures exceeded this point, the porous asphalt typically responded quicker than the DMA, as is the case in the photos of Figure 18.

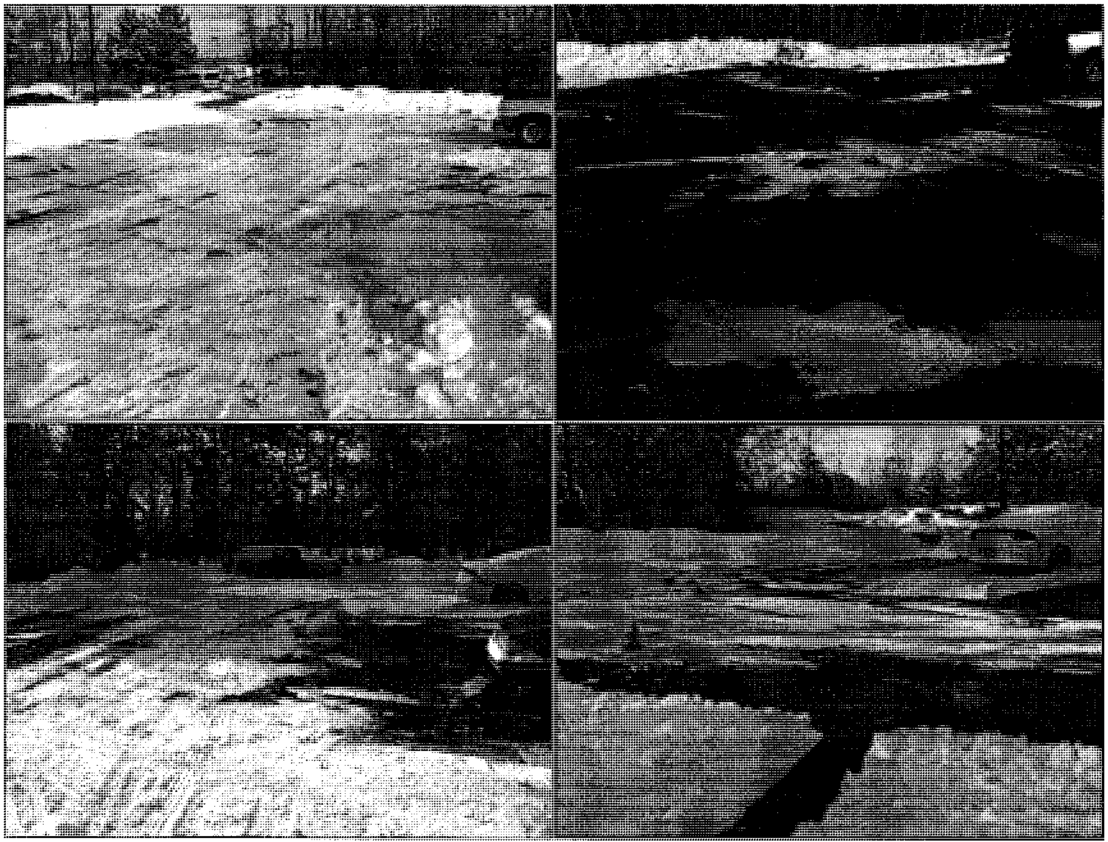

Figure 17: Changing pavement conditions with time: PA vs. DMA

(12/14/07) (17a) PA at 11:20AM (top-left); (17b) PA at 1PM (top-right); (17c) DMA at 11:20AM (bottom-left); (17d) DMA at 1PM (bottom-right)

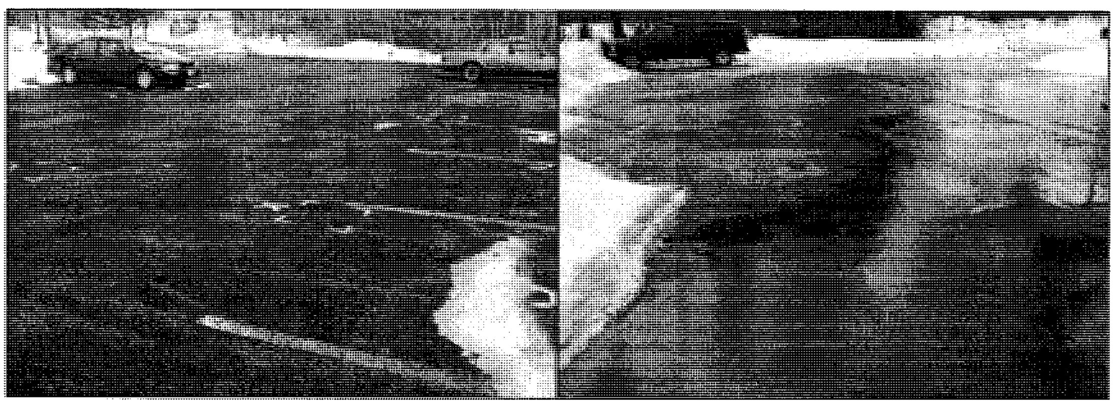

Figure 18: Instantaneous pavement conditions after freezing-rain: PA vs. DMA

(1PM on 2/2/08) (18a) PA (left); (18b) DMA (right)

The PC lot demonstrated mixed results based on the amount of shading that each section of the lot received. Much of the lot was shaded due to dense fir tree cover around the perimeter; some areas were in shade at all times of the day. The lot was divided up into three main sections in order to characterize this spatial variation. The photos in Figure 19 demonstrate the shading trends that were common through the majority of the winter; all were taken concurrently at 11AM on 2/27/08. Figure 19(a) shows the driving lane that was typically in the sun with clear weather conditions; notice the primarily clear pavement. Figure 19(b) shows a driving lane that received partial sunlight depending on the time of day; this is also the area that included the four different salt application rates. Figure 19(c) is an image of the driving lane in the back of the parking lot; this area was almost always in the shadow of the surrounding trees; notice the heavy snow cover.

Figure 19: Pervious concrete surface conditions with varying levels of shading (11AM on 2/27/08) (19a) In sun (left); (19b) In partial sun (center); (19c) In shade (right)

Despite the difficulties created by shading, the PC lot performed extremely well during freezing and thawing weather conditions as measured by the amount of black ice formation. Figure 20 is a comparison the PC lot and the adjacent standard asphalt reference lot that is maintained by the university. Photo 20(a) shows a driving lane of the PC lot that is completely dry and nearly free of snow while the nearby standard lot in

20(b) is almost entirely covered with black-ice and water. These photos were taken at 12:50PM on 2/16/08 when the air temperature was approximately 22.5°F; a low of 14°F was reached at 7:15AM (UNHWS, 2008). The standard winter maintenance practice for the UNH Grounds & Roads Dept. is that when nightly air temperatures are below freezing, salt is applied to most roads and parking lots to combat the formation of black ice. The lot in 20(b) was treated in this manner. Conversely, no salt was needed on the PC pavement under these weather conditions since standing water was never an issue. In these photos, snow is observed in the parking stalls. The stalls are not plowed because often cars remain there before, during, and after snowfall events.

Figure 20: Pavement conditions after thawing and refreezing of meltwater (12:50PM on 2/16/08) (20a) PC at 12:50PM (left); (20b) Stnd. Ref. lot at 12:50PM (right)

<u>Snow/Ice Surface Cover Analysis</u>

The amount and type of snow/ice surface cover (dry, wet, slush, snow, compacted-snow, or ice) that was observed on each study area after storm events was recorded in order to make comparisons between salt applications and pavement type. Data for the entire '07-'08 winter season was grouped and compared statistically and graphically. Figure 21 presents the snow and ice cover for all study areas; the median surface cover percentages are displayed next to each data set. Monitoring characteristics for the varying salt applications are shown in Table 10 and a comparison of p-values for the different study areas (obtained using a Student's t-test) is shown in Table 11. The salt application rates for each study area are specified as 100%, 50%, 25%, or 0% of the recommended application rate (3.0-lbs per 1000-ft^2; MPCA, 2006).

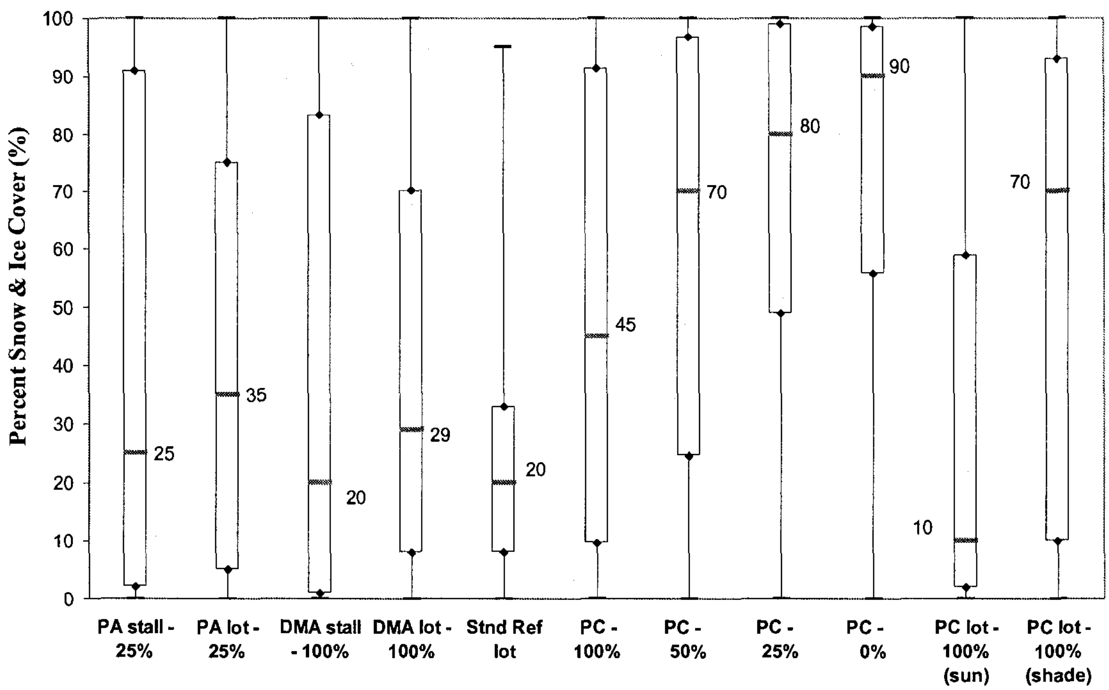

Figure 21: Comparison of snow & ice percent cover for all study areas ('07-'08)
(Pavement type and salt application rate as percentage of 3-lbs/sf shown on x-axis)

A significant finding from these observations is that the median snow/ice surface cover at the "DMA lot" is not significantly different (6% less) than at the "PA lot" even though the DMA received a salt application rate four times as great as the PA. A slightly higher application rate on the PA surface may have produced equivalent results between the two pavements.

When comparing the parking "stall" snow and ice cover data to the "lot" data in Figure 21, a difference of about 10% is shown for both the PA and DMA pavements even though each received the same salting rate. This disagreement can be explained by the amount of vehicular snow compaction at each observation area. The driving lanes, which make up a portion of the area included in the "lot" snow/ice surface cover observations, often experienced longer melting times than the parking stalls due to the difference in traffic and amount of snow compaction. Despite this disparity, no statistical difference in snow/ice surface cover was found between the data sets for the "lot" and "stall" areas at either the PA or DMA site (based on a p-value of 0.05).

Table 10: Snow & ice cover monitoring characteristics for all study areas ('07-'08)

(n = number of samples; PA = porous asphalt; DMA = dense-mix asphalt)

Pavement Type & Area	Salt Application Rate (%)	n	Mean	Median	Min.	Max.	Standard Deviation	Coefficient of Variation
PA - stall	25	43	40.8	25.0	0.0	100.0	40.59	0.994
PA - lot		48	42.0	35.0	0.0	100.0	37.08	0.883
DMA - stall	100	45	37.7	20.0	0.0	100.0	39.70	1.053
DMA - lot		48	39.5	28.8	0.0	100.0	33.62	0.850
Stnd Ref lot	100	17	22.4	20.0	0.0	95.0	25.32	1.133
PC	100	40	47.9	45.0	0.0	100.0	39.43	0.823
PC	50	40	59.4	69.8	0.0	100.0	36.92	0.621
PC	25	40	69.2	80.0	0.0	100.0	34.59	0.500
PC	0	40	70.8	90.0	0.0	100.0	34.23	0.483
PC - lot (sun)	100	44	30.3	10.0	0.0	100.0	39.57	1.305
PC - lot (shade)		45	54.5	70.0	0.0	100.0	39.02	0.716

The snow/ice surface cover measurements for the PC lot were considerably higher than the PA and DMA lots, but as one might expect, snow/ice surface cover increases with decreasing salt use. As mentioned previously, a possible explanation for the dramatic difference can be attributed to shading of the PC lot. The four PC study areas were located in an area that received only partial sunlight. This claim is supported when comparing the data sets for the PC lot that were in the sun and in the shade. A strong statistical difference exists between the sunny and shaded study areas at the PC lot (p =

0.001) demonstrating that a factor other than salt application was contributing to the amount of snow/ice surface cover.

Table 11: Student's t-test p-value comparison of snow & ice cover ('07-'08)

	PA stall - 25%	PA lot - 25%	DMA stall - 100%	DMA lot - 100%	Stnd Ref Lot	PC - 100%	PC - 50%	PC - 25%	PC - 0%	PC lot - 100% (sun)
PA stall - 25%	-	0.882	0.692	0.871	0.084	0.385	0.023	0.001	0.000	0.131
PA lot - 25%	0.882	-	0.577	0.749	0.062	0.456	0.029	0.001	0.000	0.089
DMA stall - 100%	0.692	0.577	-	0.808	0.149	0.205	0.007	0.000	0.000	0.258
DMA lot - 100%	0.871	0.749	0.808	-	0.102	0.293	0.013	0.000	0.000	0.165
Stnd Ref Lot	0.084	0.062	0.149	0.102	-	0.018	0.001	0.000	0.000	0.552
PC - 100%	0.385	0.456	0.205	0.293	0.018	-	0.168	0.011	0.006	0.019
PC - 50%	0.023	0.029	0.007	0.013	0.001	0.168	-	0.242	0.172	0.000
PC - 25%	0.001	0.001	0.000	0.000	0.000	0.011	0.242	-	0.845	0.000
PC - 0%	0.000	0.000	0.000	0.000	0.000	0.006	0.172	0.845	-	0.000
PC lot - 100% (sun)	0.131	0.089	0.258	0.165	0.552	0.019	0.000	0.000	0.000	-
PC lot - 100% (shade)	0.085	0.105	0.032	0.053	0.003	0.416	0.544	0.070	0.045	0.001

Frictional Properties of Pavement Surfaces

Frictional measurements were taken on all pavements with the British Pendulum Tester during and after storm events. All types of pavement conditions observed were evaluated, including dry, wet, snow-, slush-, compacted snow-, and ice-covered pavement. The data were grouped by pavement type and analyzed statistically to determine median skid resistance values for each type of surface cover (Figure 22). The median values for each group are displayed on the figure below each data set. Table 12 summarizes the testing parameters for the different data sets. Student's t-tests were performed to show how porous asphalt and pervious concrete compare to the conventional pavements in this study.

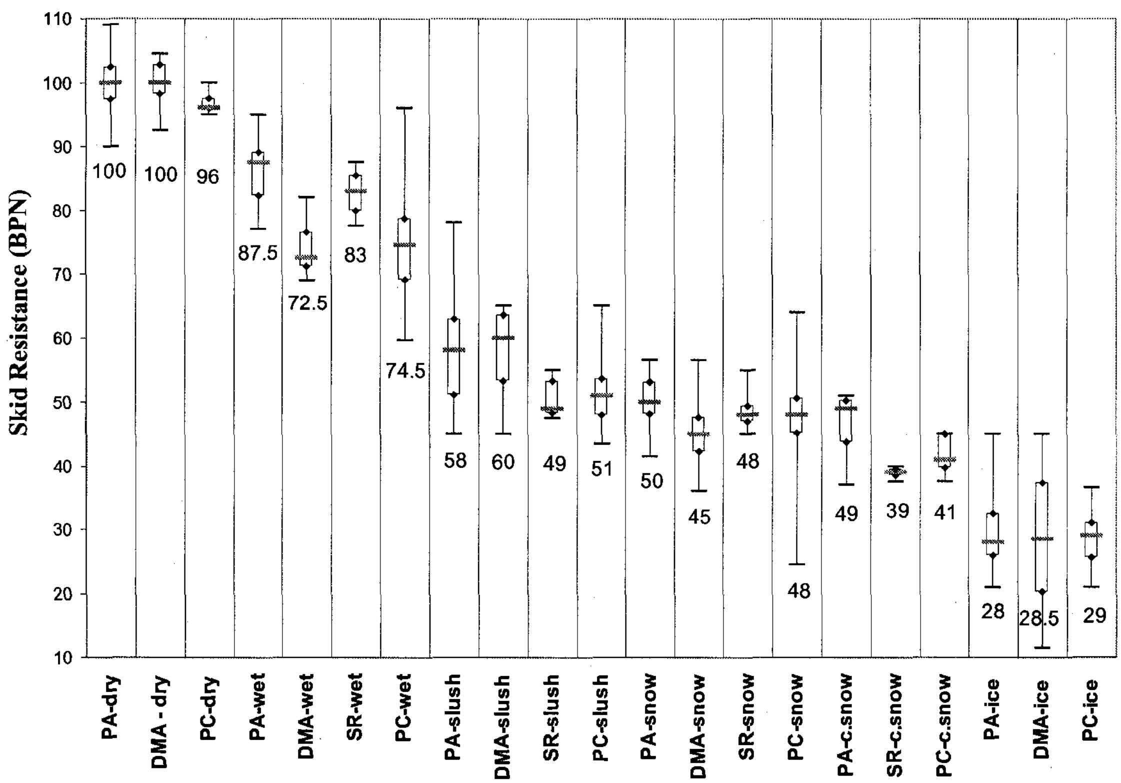

Figure 22: Skid resistance for all pavements and winter surface conditions ('07-'08)

[(PA = porous asphalt; DMA = dense-mix asphalt; PC = pervious concrete; SR = standard (asphalt) reference), (Median skid resistance value displayed under each group)]

Table 12: Skid resistance descriptive statistics for all pavements and winter surface conditions ('07-'08)

Surface Cover Condition	Pavement Type (Col. 2)	n	Mean	Median	Min.	Max.	Standard Deviation	Coefficient of Variation	P-value (Lot in Col. 2 vs. PA)	P-value (Lot in Col. 2 vs. PC)
Dry	PA	45	99.7	100.0	90.0	109.0	4.57	0.046	-	0.1024
	DMA	60	100.0	100.0	92.5	104.5	2.85	0.028	0.6651	0.0667
	PC	5	96.9	96.0	95.0	100.0	1.95	0.020	0.1024	-
Wet	PA	55	86.0	87.5	77.0	95.0	4.47	0.052	-	0.0001
	DMA	55	73.6	72.5	69.0	82.0	3.39	0.046	0.0001	0.7758
	SR	40	82.5	82.8	77.5	87.5	3.14	0.038	0.0024	0.0001
	PC	70	73.9	74.5	59.5	96.0	8.05	0.109	0.0001	-
Slush	PA	100	51.4	51.0	43.5	65.0	4.91	0.096	-	0.0001
	DMA	45	58.1	58.0	45.0	78.0	9.48	0.163	0.6852	0.0002
	SR	20	57.4	59.8	45.0	65.0	7.16	0.125	0.0001	0.4390
	PC	20	50.2	49.3	47.5	55.0	2.78	0.055	0.0001	-
Snow	PA	220	47.5	48.0	24.5	64.0	6.29	0.132	-	0.0001
	DMA	90	50.4	50.3	41.5	56.5	3.56	0.071	0.0001	0.0001
	SR	100	45.2	45.0	36.0	56.5	4.36	0.097	0.0087	0.2662
	PC	70	48.3	48.0	45.0	55.0	2.27	0.047	0.0001	-
Comp-acted Snow	PA	20	46.4	48.8	37.0	51.0	4.81	0.104	-	0.0008
	SR	5	38.9	39.0	37.5	40.0	0.96	0.025	0.0004	0.1810
	PC	15	41.6	41.0	37.5	45.0	2.68	0.064	0.0008	-
Ice	PA	49	29.6	28.0	21.0	45.0	6.00	0.203	-	0.4413
	DMA	45	29.1	28.5	11.5	45.0	10.87	0.373	0.7297	0.6842
	PC	50	28.5	28.8	21.0	36.5	4.02	0.141	0.4413	-

Of the four pavement types studied, porous asphalt was found to have the highest skid resistance for wet, snow-, and compacted snow-covered pavement, this is likely due to the large aggregate gradation (Figure 11) and the lack of fine particles in the mix. Literature suggests that coarser aggregate gradations will produce rougher pavement surface textures (Asi, 2007; Manuba et al., 2007). The PC demonstrated moderate skid resistance values for dry, wet, and snow-covered pavement. The smooth PC surface finish may have also contributed to the lower skid resistance when compared to the tackiness of asphalt mixes. It is significant to note the similarities in skid resistance for PA and DMA between this winter and the '06-'07 winter presented in Houle (2008). The median values exhibit only slight differences between seasons, some of this variation may be due in part to the inclusion of additional snow/ice surface cover types (slush and compacted snow) in the '07-'08 winter.

By multiplying the mean skid resistance values by the snow and ice surface cover percentages a weighted skid resistance value was developed (Figure 23). The purpose of a weighted skid resistance was to assign a single number that can describe the pavement safety when compared to standard, dry conditions. The median skid resistance for the "PA lot" was 12% higher than the "DMA lot" even though the salt application rate was a quarter of that which was applied to the DMA surface. Similarly, the standard reference lots, which received regular plowing and salting by the UNH Grounds & Roads Dept., also demonstrated lower frictional resistance than the porous asphalt lot. The weighted skid resistance for the PA "stall" measurements in Figure 23 correlate extremely well with the data from the '06-'07 winter (Figure 9). A median value of 77 BPN was observed for the '07-'08 winter with the 25% salt application rate, whereas for the '06-'07 winter, a BPN of 79 was shown. The "stall" measurements serve best for making comparisons between winters because the '06-'07 study focused only on areas that were not utilized for parking. A p-value of 0.662 was calculated between winters for the PA lot, suggesting that annual differences in weather conditions did not statistically change the results. The difference between the two seasons for the DMA parking stall study areas was 7 BPNs with a p-value of 0.298, also suggesting no statistical difference between winters.

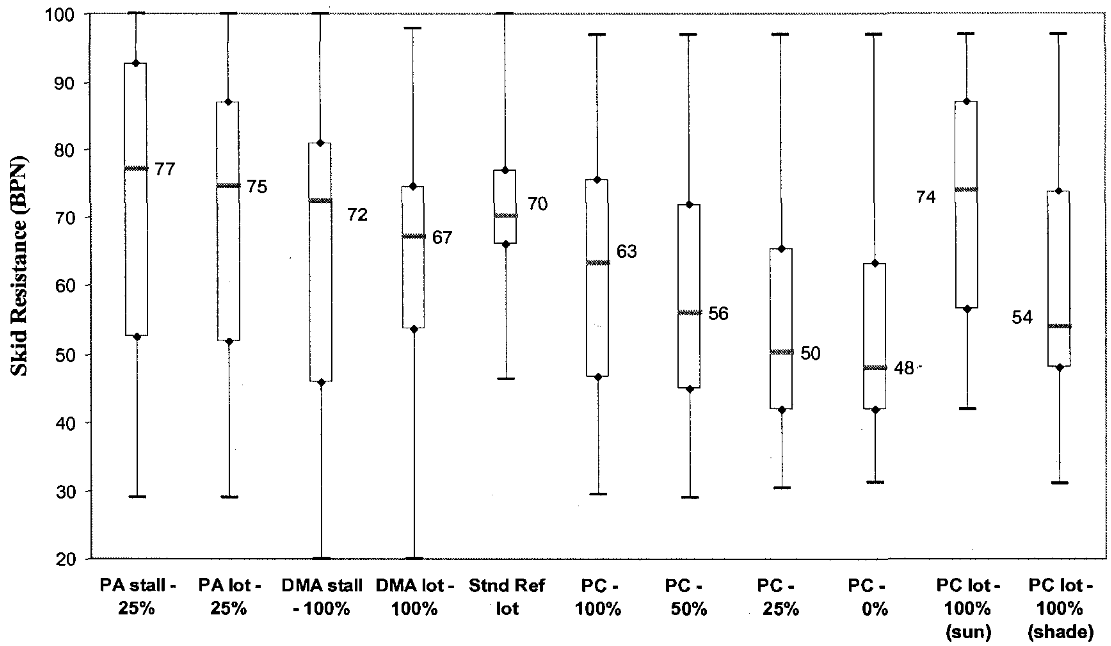

Figure 23: Weighted skid resistance as a function of surface cover ('07-'08)

(Pavement type and salt application rate as percentage of 3-lbs/sf shown on x-axis)

Table 13: Weighted skid resistance descriptive statistics for all study areas ('07-'08)

(n = number of surface cover observations)

Pavement Type & Area	Salt Application Rate (%)	n	Mean	Median	Min.	Max.	Standard Deviation	Coefficient of Variation
PA - stall	25	43	72.3	77.1	29.0	100.0	22.66	0.313
PA - lot		48	71.6	74.6	29.0	100.0	20.23	0.282
DMA - stall	100	45	65.1	72.4	8.9	100.0	24.48	0.376
DMA - lot		47	64.1	67.0	10.0	97.9	22.15	0.346
Stnd Ref lot	100	16	69.8	70.1	46.5	100.0	12.85	0.184
PC	100	40	64.1	63.1	29.5	97.0	18.62	0.291
PC	50	40	59.4	56.0	29.0	97.0	18.03	0.304
PC	25	40	54.4	50.2	30.4	97.0	16.72	0.307
PC	0	40	53.7	48.0	31.3	97.0	16.68	0.311
PC - lot (sun)	100	44	72.4	74.0	42.0	97.0	17.82	0.246
PC - lot (shade)		45	60.5	54.0	31.0	97.0	16.07	0.266

The weighted skid resistance values for the pervious concrete parking lot study areas were considerably lower than both the PA and DMA pavements, despite salt application. This is likely due in part to a number of factors. As mentioned previously, the four main study areas did not receive as much sunlight as the other pavements because of a heavily wooded perimeter. Additionally, the pervious concrete lot is a much more trafficked parking lot due to its proximity to three adjacent dormitories; therefore, vehicle compaction of snow cover prior to plowing was often a problem. Operational constraints limited plowing maintenance for this project to one time per storm event. For this reason it was not uncommon for snow in the lanes to be driven on for several hours before plowing ensued. Lastly, the measured skid resistance values for most types of pavement cover on the PC were lower than the other pavements, which will inherently produce lower weighted skid resistance values. Conversely, when looking at the data for the section of the PC lot that did receive sunlight, the skid resistance is similar to the results for the PA data set. This is a significant finding considering that permeable pavements may be most applicable for large, commercial settings where heavy tree cover is uncommon.

P-values less than 0.05 indicate that a statistical difference may exist between weighted skid resistance data sets. As shown in Table 14, some significant differences are present. When comparing the results for PA to DMA using a Student's t-tests, the p-values are only slightly greater than 0.05, suggesting that the data sets may be marginally different and that PA with a 25% salt application may be safer than DMA with the recommended 100% application rate. This finding is consistent with results from Houle (2008). When comparing the PC study area that is primarily in the sun to the study area primarily in the shade a p-value of 0.004 is shown, suggesting a strong difference. Also of importance are certain data sets that are not statistically different. The PC lot study area in the sun compared to the PA lot demonstrate very similar weighted skid resistance results ($p = 0.847$). This is a notable finding because it shows that pervious concrete may exhibit similar surface conditions to porous asphalt if used under more typical site conditions (i.e. few surrounding trees). A comparison between results for the DMA lot and for the Standard Reference Lot also exhibits a high p-value. This fact helps to verify that the winter maintenance methods used in this study were similar to the methods used by UNH Grounds & Roads.

Table 14: Student's t-test p-value comparison for weighted skid resistance ('07-'08)

	PA stall - 25%	PA lot - 25%	DMA stall - 100%	DMA lot - 100%	Stnd Ref Lot	PC - 100%	PC - 50%	PC - 25%	PC - 0%	PC lot - 100% (sun)
PA stall - 25%	-	0.860	0.083	0.046	0.657	0.056	0.003	0.000	0.000	0.989
PA lot - 25%	0.860	-	0.109	0.061	0.748	0.074	0.004	0.000	0.000	0.847
DMA stall - 100%	0.083	0.109	-	0.801	0.410	0.817	0.184	0.012	0.008	0.079
DMA lot - 100%	0.046	0.061	0.801	-	0.312	0.992	0.273	0.021	0.015	0.043
Stnd Ref Lot	0.657	0.748	0.410	0.312	-	0.327	0.074	0.008	0.006	0.648
PC - 100%	0.056	0.074	0.817	0.992	0.327	-	0.287	0.026	0.018	0.053
PC - 50%	0.003	0.004	0.184	0.273	0.074	0.287	-	0.245	0.194	0.003
PC - 25%	0.000	0.000	0.012	0.021	0.008	0.026	0.245	-	0.891	0.000
PC - 0%	0.000	0.000	0.008	0.015	0.006	0.018	0.194	0.891	-	0.000
PC lot - 100% (sun)	0.989	0.847	0.079	0.043	0.648	0.053	0.003	0.000	0.000	-
PC lot - 100% (shade)	0.005	0.006	0.259	0.374	0.101	0.388	0.816	0.153	0.116	0.004

Chloride Mass Balance

A mass balance of chloride was performed for the PA and PC parking lots. Applied chloride (salt) mass was recorded for the duration of the study; beginning in December 2006 for the PA lot and December 2007 for the PC lot. Effluent chloride concentration following rain and melt events was measured in five-minute intervals. A background chloride level of 20 mg/L was subtracted from all measurements. This background value was determined by selecting the lowest continuous observed concentration during the late summer months when chloride input and export from winter maintenance operations is essentially zero. A cumulative plot of applied and measured chloride mass from the two systems is shown in Figure 24.

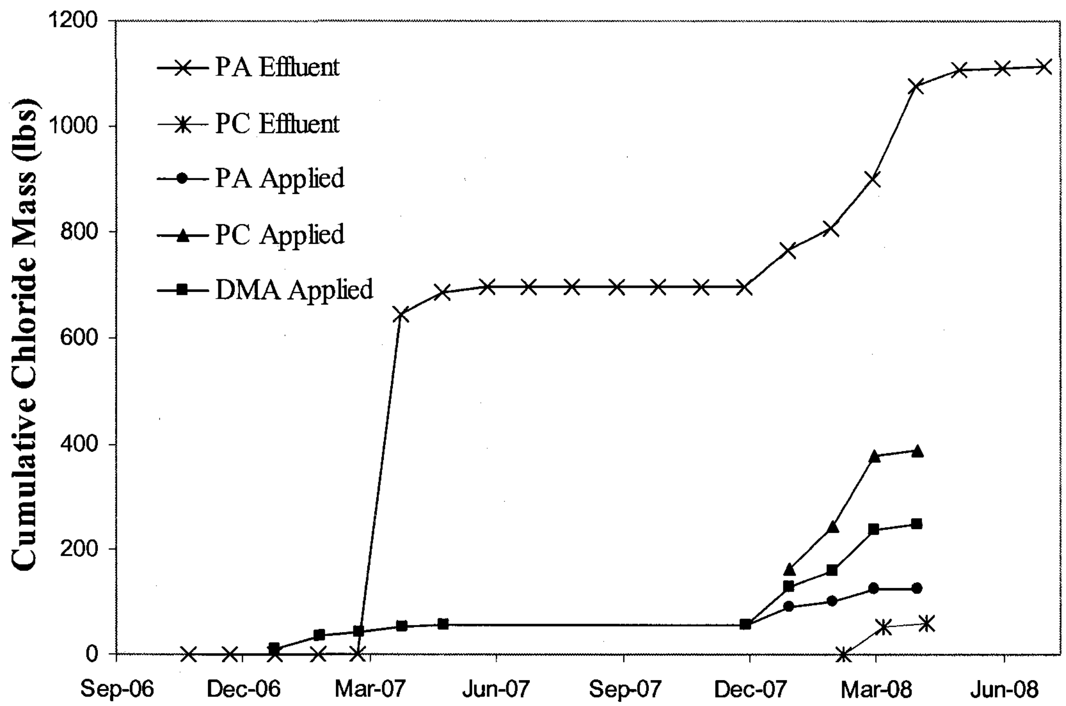

Figure 24: Cumulative chloride mass balance for PA and PC systems (10/06-6/08)

Data for this plot begins in October 2006 to show that the chloride load leaving the porous asphalt system prior to the study was negligible. It took until March 2007 to observe the first substantial discharge of chloride from the PA even though salt was applied regularly since December 2006. The centriod of applied mass occurred in January demonstrating an approximate lag-time of two to three months for chloride to pass through the filter media. Exportation of chloride was observed through May 2007.

It is likely that a 7.5-inch rain event that occurred on 4/16/07 contributed to the abrupt flushing of the system.

During the '06-'07 winter a total of 56.1-lbs of chloride (92.5-lbs of salt) was applied to the PA lot, while 696-lbs Cl^- was measured in the effluent. Possible explanations for this discrepancy may be related to chloride inputs through groundwater movement into the system. It is probable that road salt from seasonal use infiltrated through up-gradient soils (from salting of nearby Route 155A and the nine-acre West Edge lot) penetrated the PA sub-surface reservoir, which then exited the system through the perforated drains during rainfall events. Seasonal increases in atmospheric deposition, water softeners, and mineral weathering may account for additional chloride entering the system (Trowbridge, 2007a, 2007b). There is a septic system up-gradient of the PA lot. Flow metering measurement errors and inaccuracies in the chloride-specific conductance regression curve may have led to the underestimation of background chloride levels. Calibrating the flow/depth measuring instruments and verifying that the chloride-specific conductance relationship, which was developed for the West Edge Parking Lot runoff, is also valid for groundwater may help provide further insight. Research is currently underway at the UNHSC to address these chloride balance issues.

Similar mass-balance errors were observed with the PA system for the '07-'08 winter. A total of 68.5-lbs of chloride was applied, whereas 416-lbs Cl^- were measured. One major difference between study years concerns the lag-time of the chloride leaving the PA systems. Almost no lag in chloride mass was observed at the start of the winter; measurable chloride was present the same month as when salt applications commenced (December, 2007). At the end of the season, elevated chloride (measured as specific conductance) was observed in the effluent two-months after the last salt application, suggesting that the system has a capacity to store and then distribute the chloride load over a longer time period than would be observed on a standard, impermeable asphalt pavement, therefore reducing acute levels at the receiving water.

The PC lot showed the ability to reduce the effluent chloride load. A total of 390.5-lbs of chloride was applied from Dec. '07 to April '08 whereas only 60-lbs were measured leaving the system through the subdrains. Part of the reason for this is that effluent did not exit through the sub-drains until Feb. '08. The PC lot is situated on an SCS Type B soil that has the ability to infiltrate water substantially faster than the D soils located at the PA site. This fact will reduce chloride levels in surface waters, thereby improving conditions for fish and other species, but may negatively impact groundwater systems if they are recharged by the chloride laden infiltration waters. Specific conductance was not measured at the PC lot until March so it is likely that chloride mass did leave the system during two February rain events, accounting for some of the discrepancy. Effluent flow has not been observed through the PC system sub-drains between April and June 2008. Additional monitoring of all systems, including monthly sampling of perimeter wells, should be performed in order to refine future annual mass balances and better quantify chloride reduction and/or lag capabilities.

Salt Load Reductions

Possible annual salt load reductions were estimated by determining which events required deicing salt applications. If substantial snow or ice (>5%) existed on the pavement during the surface cover evaluation then it was decided that at least one deicing salt application was necessary. The majority of events required that all lots be deiced with at least one salt application. In some cases, the PA and PC pavements required more than one application in order to facilitate timely deicing and match the surface conditions exemplified by the standard of practice rate on the DMA lot. The total number of deicing applications needed to clear the pavements of snow and ice were summed for each lot and added to the number of required anti-icing applications (assumed to be equal to the number of storm events) to develop the expected total annual salt load for each of the four varying application rates (Table 15).

Table 15: Required salt loads & possible salt reductions for each pavement ('07-'08)

Pavement Type	Anti-Icing App.	De-Icing App.	Required Salt Load For Each Application Rate (lbs/acre/yr)				Reductions Possible when Compared to DMA with 100% App. Rate	
			100%	50%	25%	0%	App. Rate	Mass Reduction*
DMA	23	22	5881	2940	1470	0	100%	0%
PA	23	27	6534	3267	1634	0	25%	72%
PC - shade	23	31	7057	3528	1764	0	100%	-20%
PC - sun	23	23	6011	3006	1503	0	100%	-2%

* Reductions possible with no loss in skid resistance (safety)

The weighted skid resistance results in Figure 23 show that the PA study areas and the PC driving lane in the sun have median values that exceed that of the DMA lot suggesting that reductions in annual salt load may be possible while maintaining equal or better pavement conditions. The percent mass reduction was determined by dividing the required load for the proper application rate by the required salt load for the DMA lot. All loads were normalized by area to make the comparisons. It was determined that a 72% reduction in annual salt mass on the PA lot would produce better and safer surface conditions than would be observed on standard asphalt with no reduction. This correlates well with the findings from the '06-'07 winter, which demonstrated a 77% salt reduction for the PA lot. This is significant considering that proposed chloride TMDLs in NH will require that parking lot salt use be reduced by 20 to 40% in order to improve water quality in several receiving streams (Trowbridge, 2007a, 2007b). The PA lot was the only pavement studied that demonstrated a possible salt mass reduction. However, the section of the PC lot that was primarily in the sun required only 2% more salt use than was needed at the DMA lot (based on the MPCA recommended salting rate of 3.0-lbs per 1000-ft^2) and produced skid resistance conditions exceeding those measured at the DMA lot. It is likely that the conditions of the two pavements would be similar if a slight salt mass reduction on the PC lot took place because salt crystals were often observed on the pavement surface long after storm events (Houle, 2008).

Conclusions

In summary, two years of winter performance evaluations have demonstrated that PA can perform extremely well in northern climates. Frost depth penetration and freeze-thaw temperature cycles have not compromised the integrity of the system structurally, visually, or hydraulically. Research has shown (both through literature and field testing) that PA exhibits greater frictional resistance and can become clear of snow and ice faster than conventional pavements. Substantial reductions in annual salt loads for anti-icing/deicing practices were observed, reaching over 70% during the study. Providing that plowing was regularly performed, salting was needed only for events where freezing rain created icy conditions. No salt was required on days when refreezing of meltwater was a problem on standard asphalt.

The results obtained from studying PC varied from PA but showed strengths in other areas. The surface infiltration rates measured on the PC lot exceeded those that were observed on the PA. The benefit of this is that the PC will have a greater tolerance for clogging if sand or organic debris is present at the site. Additionally, binder drain-down is not a consideration with PC, as is the case with some PA mixes, making for a possible longer service life. Overall, the skid resistance and salt reduction capabilities for the PC lot were not as great as was shown for the PA. It is suspected that shading was the main contributing factor for this finding. The reasoning for this can be explained when looking at sections of PC pavement where shading was not as prominent and trees did not obstruct direct sunlight. Under these conditions the results drastically improve and the weighted skid resistance is shown to surpass that of the DMA lot (Figure 23). In addition to the shading, it is believed that the white pavement color of the PC contributed to the high levels of surface cover. White pavements are more efficient at reflecting radiation, which can be beneficial in the summer months by lowering surface and air temperatures and consequently reducing the urban 'heat island' effect often associated with black, asphalt-based pavements, but non-ideal during the winter since the absorption of heat into the pavement will help to melt snow and ice (U.S. EPA, 2007). Salt reductions during freeze-thaw events were achievable provided the lot was adequately plowed after storm events, an important consideration for all pavements not just PC.

The use of innovative stormwater management technologies is necessary for communities to comply with current regulations such as NPDES Phase II requirements as well as the numerous surface water TMDLs in place today. This research has shown that permeable pavements are an improvement over conventional parking lot designs and can be used to help meet these imposed guidelines. The ability of permeable pavements to not only serve as self-contained stormwater management/treatment systems but to also demonstrate winter performance improvements over impermeable designs, including annual salt reductions, make them attractive in a variety of climates and settings.

CHAPTER 4

AN ANALYSIS OF PROJECT COSTS

An analysis of the project costs for porous asphalt (PA), dense-mix asphalt (DMA), and pervious concrete (PC) parking lots is presented in this chapter. The cost itemizations were derived from the invoices submitted by the contractors that performed specific construction tasks. Each project consisted of project management, site excavations and grading, placement of sub-grade materials, placement of pavement materials, perimeter construction, landscaping, and miscellaneous work associated with research and monitoring needs. All incurred costs were tabulated, summed, and broken down by several metrics, including cost per pavement weight/volume and cost per parking stall. Adjustments were made to the total costs to account for aspects that were specific to the UNHSC research designs and not necessarily part of a typical design/installation. Total costs were also adjusted for inflation from 2004 and 2007 to May 2008 U.S. dollars; an inflation rate of 15% and 4%, respectively, was assumed during those periods (U.S. BLS, 2008).

The PA and DMA lots were constructed at the same time and were consequently billed together. Therefore, the costs for each task had to be divided according to the percentage associated with each lot. Table 16 displays the allocation of costs for the two parking lots. In most instances, since the PA and DMA lots were equally sized, the itemized costs for each lot were assumed to be 50% of each billed cost except where specified. Labor and materials costs were also estimated and each was assumed to make up half of the itemized costs for each lot (i.e. 25% of the total itemized costs) (Briggs, 2006).

Costs per parking stall for the UNH installation were found to be approximately $4,455 for PA and $3,456 for DMA in May 2008 dollars. When adjusted for a typical, non-research installation, the cost for PA was reduced to $2,578, a cost that is competitive with dense-mix asphalt. Briggs (2006) quoted costs of $2,300 per parking stall for DMA at the West Edge parking lot. Costs of PA materials per ton of asphalt were determined to be $388 for the UNH installation and $223 for a typical installation. A total of 120 tons of porous asphalt material was required for this project. Further explanation of the construction cost breakdown for the PA and DMA lots can be referenced in Briggs (2006). When winter maintenance costs associated with salting operations are considered and factored into long-term project costs (or life cycle costs), PA becomes even more appealing economically. In Chapters 2 and 3, an average 75% reduction in annual salt load was shown and with salt reaching $46 per ton in 2008 (Byron, 2008), the consequent savings could be substantial for commercial-type settings that often use vast quantities of salt.

Table 16: UNHSC PA and DMA lots costs and estimation of a typical PA design (2004 $US) (Briggs, 2006)

Description of Work	Cost Billed	UNH Installation					Typical Installation		
		% as DMA	Cost as DMA	% as PA	Cost as PA	Cost as PA Mat.	% as PA	Cost as PA	Cost as PA Mat.
General Conditions									
Project Mgmnt.	$4,655	0.5	$2,328	0.5	$2,328	$0	0.5	$1,164	$0
Bonds & Insurance	$3,666	0.5	$1,833	0.5	$1,833	$0	0.5	$917	$0
Transportation	$621	0.5	$311	0.5	$311	$0	0.5	$155	$0
Site Work									
Clear & Grub	$1,327	1	$1,327	0	$0	$0	0	$0	$0
Erosion Control	$2,463	0.5	$1,232	0.5	$1,232	$616	0.33	$406	$203
Strip Top-Soil	$2,532	0.5	$1,266	0.5	$1,266	$0	0.33	$418	$0
Seed & Loam	$5,069	0.5	$2,535	0.5	$2,535	$1,267	0.25	$634	$317
Site Finish Work	$1,312	0.5	$656	0.5	$656	$0	0.25	$164	$0
Earthwork									
Create Berm for Abutters	$2,868	0	$0	0	$0	$0	0	$0	$0
Subgrade Areas	$11,588	0.25	$2,897	0.75	$8,691	$0	0.5	$4,346	$0
Rip Rap Pad	$939	0.5	$470	0.5	$470	$470	0.75	$352	$352
Paving (DMA)									
Filter Fabric & Gravel	$5,466	1	$5,466	0	$0	$0	0	$0	$0
Paving	$8,727	1	$8,727	0	$0	$0	0	$0	$0
Curbs and Speed-Bump	$1,700	0.75	$1,275	0.25	$425	$213	0	$0	$0
Pavement Markings	$642	0.5	$321	0.5	$321	$161	1	$161	$161
Paving (PA)									
Filter Fabric & Subgrade Mat.	$25,889	0	$0	1	$25,889	$25,889	0.5	$12,945	$12,945
Paving	$12,840	0	$0	1	$12,840	$6,420	1	$12,840	$6,420
Perimeter Stone Edge	$311	0	$0	1	$311	$156	1	$311	$156
Curbs	$1,252	0	$0	1	$1,252	$626	1	$1,252	$626
Piping									
Precast Tree Filter Well	$1,382	1	$1,382	0	$0	$0	0	$0	$0
Piping from Precast Well	$4,428	1	$4,428	0	$0	$0	0	$0	$0
Piping from DMA	$6,392	1	$6,392	0	$0	$0	0	$0	$0
Piping from PA	$4,129	0	$0	1	$4,129	$2,065	1	$4,129	$2,065
Electrical Work	$4,002	0.5	$2,001	0.5	$2,001	$1,001	0	$0	$0
ORIGINAL CONTRACT	$114,200		$44,845		$66,488	$38,881		$40,192	$23,163
Change Orders									
Add. Berm Work	$3,000	0	$0	0	$0	$0	0	$0	$0
Electrical Changes	$3,777	0.5	$1,888	0.5	$1,888	$944	0	$0	$0
Add. Pole Outlets	$2,714	0.5	$1,357	0.5	$1,357	$679	0	$0	$0
TOTAL CHANGE ORDERS	$9,491	-	$3,245	-	$3,245	$1,623	-	$0	$0
TOTAL	**$123,691**	**-**	**$48,090**	**-**	**$69,733**	**$40,504**	**-**	**$40,192**	**$23,163**
COST METRICS					**UNH**	**$ 2008**		**Typical**	**$ 2008**
PA Mat. Cost per Ton Asphalt	120 tons				$338	$388		$194	$223
PA Mat. Cost per Stall	18 Stalls				$2,250	$2,588		$1,291	$1,485
PA Cost per Stall	18 Stalls				$3,874	$4,455		$2,242	$2,578
DMA Cost per Stall	16 Stalls				$3,006	$3,456		$2,000	$2,300

The costs for the PC parking lot installation are summarized in a similar manner. Table 17 displays the breakdown of the various tasks associated with design and construction of the lot. Total costs were adjusted for inflation from 2007 to May 2008 U.S. dollars. Research-based expenses were accounted for and total costs for typical installations were adjusted accordingly. Total cost per cubic-yard of pervious concrete was approximately $529 in May 2008 dollars. Costs per parking stall were $2,729 with the specified design conditions. When comparing PC to other pavement materials, the cost per stall is approximately 18% greater than PA and 31% greater than DMA. However, when taking into account service life, PC may be a much more economical solution. Montalto et al. (2007) found that pervious concrete may last up to 40 years before requiring resurfacing, whereas porous asphalt and conventional asphalt may need to be replaced after 8 to 10 years. This would amount to an approximate two-thirds savings over a 40 year span if PC were to be used.

Table 17: Costs of UNHSC PC lot and cost estimation of a typical design (2007 $US)

Description of Work	Cost Billed (UNH Installation)	Cost (Typical Installation)	Cost per Parking Stall	Cost per Unit	
General Conditions	$2,844	$2,844	$37.92	$0.14	ft^2
Mobilization	$4,500	$4,500	$60.00	$0.22	ft^2
Site Work					
Grinding of Original Pavement	$3,500	$0	$0	$0.17	ft^2
Excavation to Subgrade	$15,000	$15,000	$200.00	$8.00	yd^3
Place 3/8-in. Stone Reservoir Layer & Perf. Pipe	$22,000	$22,000	$293.33	$56.88	yd^3
Place Bank Run Gravel Filter Course	$27,000	$27,000	$360.00	$25.00	yd^3
Place 1-1/2 in. Stone Choker Course	$12,000	$12,000	$160.00	$31.03	yd^3
Back-Fill & Site Clean-Up	$6,500	$6,500	$86.67	$0.31	yd^3
Perimeter Swale	$5,000	$5,000	$66.67	$10.59	ft
Place Rip-Rap around Sampling Chamber	$500	$0	$0	-	-
Change Orders					
Additional Excavation	$3,600	$3,600	$48.00	$8.00	yd^3
Bedrock Excavation	$6,780	$0	$0	-	-
Additional Placement of BRG	$9,625	$9,625	$128.33	$25.00	yd^3
Sampling Chamber	$5,350	$0	$0	-	-
Electrical Work for Shed	$3,506.16	$0	$0	-	-
PC Placement					
Materials	$35,000	$35,000	$466.67	$90.00	yd^3
Placement	$53,760	$53,760	$716.80	$2.56	ft^2
Total Contract ($US 2007)	**$216,465**	**$196,829**	**$2,624**	**$9.42**	**ft^2**
				$509	**yd^3**
Total Contract Adjusted for Inflation ($US 2008)	**$225,124**	**$204,702**	**$2,729**	**$9.80**	**ft^2**
				$529	**yd^3**

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results indicate that permeable pavements provide better functionality than impervious pavements in cold climates, and provide many improvements over conventional designs. Higher skid resistance was exemplified by PA and PC versus DMA for a range of surface conditions. The ability to reduce salt use on the permeable surfaces was greatest during the cyclical freeze-thaw conditions that are characteristic of New England winters. PA demonstrated adequate skid resistance for an average annual salt reduction of 75% below the standard of practice rate. No quantifiable salt reductions were observed for PC at the UNHSC site; however, it was determined that site shading and the light pavement color were the main reasons for this finding. It is important to note that routine plowing during and after each winter precipitation event is compulsory to achieving safe and adequate pavement conditions. Without regular winter maintenance, all parking lots, regardless of pavement type, are susceptible to snow compaction and subsequent ice formation. Even though this study shows PA excelling in these non-desirable conditions, it is not recommended to allow such a situation to occur.

Recommendations for Future Research

Even though this research was carried out over two winter seasons and identifiable trends were observed during that time, it would be beneficial to continue with certain facets of the investigation. For instance, the PC parking lot was only studied for one winter; an additional year of monitoring would provide further verification of results and allow for adjustment of the methodology to better account for the shading effects and the high traffic volume. Two years of study were adequate for obtaining comparable results for the PA lot; however, additional data collection would further substantiate the findings. Other analyses that would be useful to continue for both pavements include surface infiltration testing (to monitor long-term changes in permeability) and measurements of effluent specific conductivity for an extended chloride mass balance. Accurate quantification of applied chloride loads would be essential to perform the balance. It would also be interesting to expand the study to include conventional concrete as a fourth material for comparison. No impermeable concrete parking lots currently exist on the UNH campus in Durham, NH so arrangements would have to be made for future installation.

Salt brine for deicing was tested briefly during the 2007-2008 winter but a number of factors contributed to fairly inconclusive results. It would be interesting to continue this experiment for another winter and test other maintenance alternatives such as non-chloride salts. Additional explanation of the salt brine experiment is provided in Appendix A.

A test that may help to explain the duration of snow and ice cover and level of frost penetration would be to outfit the permeable and standard pavements with temperature probes set at various elevations below the surface. Backstrom (2000) looked at this topic in a PA system and identified that latent heat from ground- and infiltrating water produced favorable conditions for snow/ice melting. The UNH PC lot was outfitted with temperature probes during its installation, for similar analysis, but monitoring has yet to commence. Concurrent measurements of groundwater elevations within the systems would be necessary.

An analysis of life cycle costs for the different pavement types would be a beneficial supplement to the cost analysis portion of this research. This may consequently require that the study areas be assessed long-term for any substantial deterioration or degradation in order to determine reasonable estimates of pavement service lives for cold-climate settings. Costs associated with construction, maintenance, disposal and/or replacement would be inherent in such a study.

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APPENDICES

APPENDIX A

SALT BRINE USE FOR WINTER MAINTENANCE OF PERMEABLE PAVEMENTS

Introduction & Background

The effectiveness of saturated sodium-chloride brine solution was tested during the 2007-2008 winter season on the UNHSC porous asphalt and pervious concrete parking lots. It was measured against the use of standard, dry NaCl rock-salt. Research has shown that brine solution can provide a means to reduce the amount of salt spread on roadways while maintaining an adequate level of service. Other advantages over dry salt include: its ability to be active immediately after application since the salt does not blow off the pavement surface, improved control when applying material, and its functionality in temperatures down to 26.6°F (Russ et al., 2008). Application of brine should take place prior to winter precipitation events and immediately following plowing operations in order to provide the most efficient treatment. The Danish Road Directorate suggests that brine use on open-graded pavements should be avoided because it requires a heavier application than would be necessitated on conventional pavements due to the surface porosity (Knudsen et al., 2003). The objective of this study was to provide further insight into the ability of brine to reduce the impacts associated with chloride for parking lot winter maintenance.

Methodology

An area of 400-ft^2 was selected for analysis on each of the three pavement types studied: porous asphalt (PA), pervious concrete (PC), and dense-mix asphalt (DMA). The PA and DMA areas were located in parking stalls while the PC area was in one of the driving lanes. The brine application rate was based upon rates suggested in literature. Fonnesbech (2001) studied a rate of 0.94-lb NaCl / 1000-ft^2 of area (4.6-g NaCl / m^2) which was found to be the most common rate used in Funen County, Denmark. The rate used in this study was scaled up to 1.5-lb NaCl / 1000-ft^2 of area to correspond to the 50% salt application rate used in other aspects of this research so comparisons could be made. This rate falls within the range of 20-40 mL/m^2 observed by Fonnesbech.

The salt brine solution was produced by mixing a measured weight of salt with a known volume of de-ionized water in order to obtain a blend consisting of approximately 23% salt by mass. Salt is soluble in water up to 35% but 20-23% is usually used to avoid pipe and nozzle blockage in distribution trucks (Burtwell, 2001). The brine solution was applied to the study areas by hand with a pressurized garden sprayer (typically used for applying herbicides or fertilizers). Even application was achieved by calibrating a pace at which to walk back-and-forth across the study area while also ensuring to maintain adequate pressure within the sprayer bottle. Both anti-icing and deicing applications were performed for each event beginning on January 27, 2008, for a total of 12 events. A summary of event characteristics for the study period is shown in Table 19. Also shown at the bottom of the table are monthly average weather statistics for Durham, NH (NHSCO, 2008).

Table 18: Salt brine application rate parameters

Size of study area (ft^2)	400
Brine application rate (lb/1000-ft^2)	1.5
Brine application rate (mL/m^2)	32
% salt concentration (by weight)	23

Table 19: Winter storm event characteristics ('08)

(NCDC, 2008; NHSCO, 2008; UNHWS, 2008) (S = Snow; R = Rain; I = Ice)

Date	Precipitation Type	Snow Depth (in.)	Water Equivalent Depth (in.)	Max Temp (°F)	Min Temp (°F)
1/27/2008	S	3	0.31	28	17
2/1/2008	I/R	0.5	1.23	44	33
2/5/2008	S/R	0.75	1.66	37.5	32
2/8/2008	S	4	0.51	29	21
2/10/2008	S	2	0.29	35	16
2/13/2008	S/R	5	2.77	36	21
2/22/2008	S	5	0.36	26.5	13
2/26/2008	S/R	3	0.94	39.5	20
3/1/2008	S	3	0.44	35	21
3/11/2008	S/R	1	0.21	41	17
3/15/2008	S/R	1	0.69	40	33
3/28/2008	S	4	1.02	42	32
Nov. avg.	-	14.4	4.84	49.1	29.3
Dec. avg.	-	14.4	4.46	36.8	18.2
Jan. avg.	-	19	4.11	33.4	13
Feb. avg.	-	16.9	3.48	35.4	14.4
Mar. avg.	-	12.8	4.31	44.4	23.7

Results & Discussion

Effectiveness of the brine application on the different pavements was determined by quantifying the type and amount of snow/ice surface cover and then measuring the skid resistance of the study area. Evaluations were carried out with the same methodology as was discussed in Houle (2008). Figure 25 shows that the lowest median snow/ice surface cover value for the brine use resulted on the DMA lot, with the highest being observed on the PC lot. The results were similar for the weighted skid resistance comparison in Figure 26, with the DMA lot performing the best.

Possible explanation for the poor performance of the permeable pavements may be explained by a number of factors. The pervious concrete study area was located in a region that was typically shaded for much of the day, while the DMA area was primarily under direct sunlight. Sunlight was shown to play a significant role in pavement surface cover in Chapter 3. Also explained in Chapter 3 was the change in performance when analyses occur in driving lanes versus parking stalls. The better performance of the conventional asphalt may be expected based on the literature findings stating an increase in brine use may be necessary for permeable pavements.

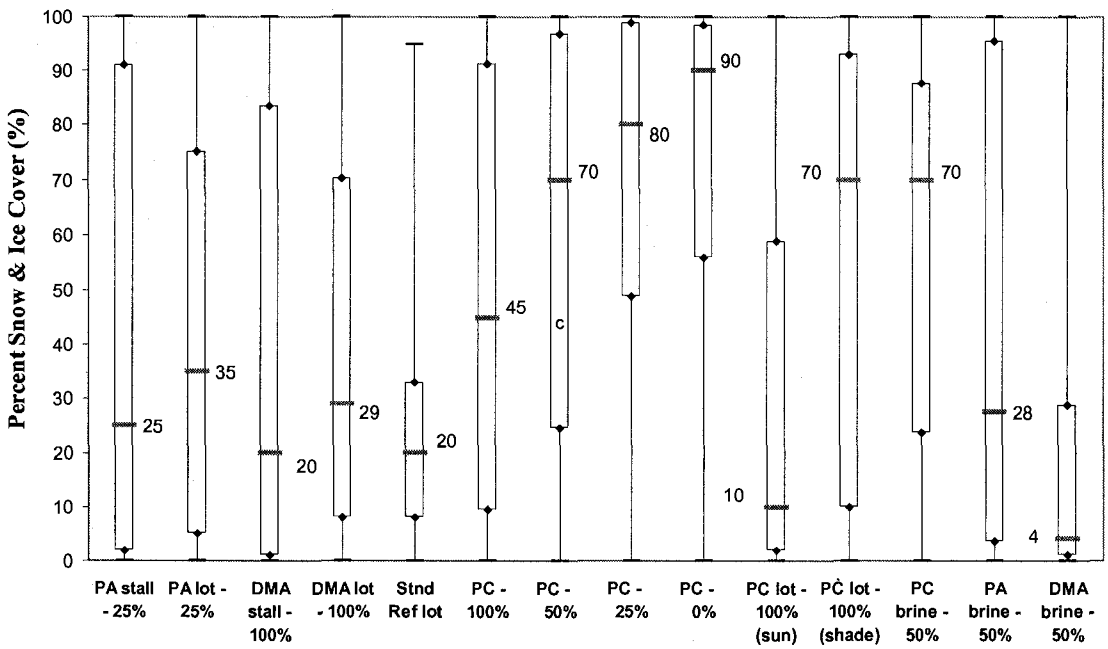

Figure 25: Comparison of snow & ice percent cover for all study areas ('07-'08)
(Pavement type and salt application rate as percentage of 3-lbs/sf shown on x-axis)

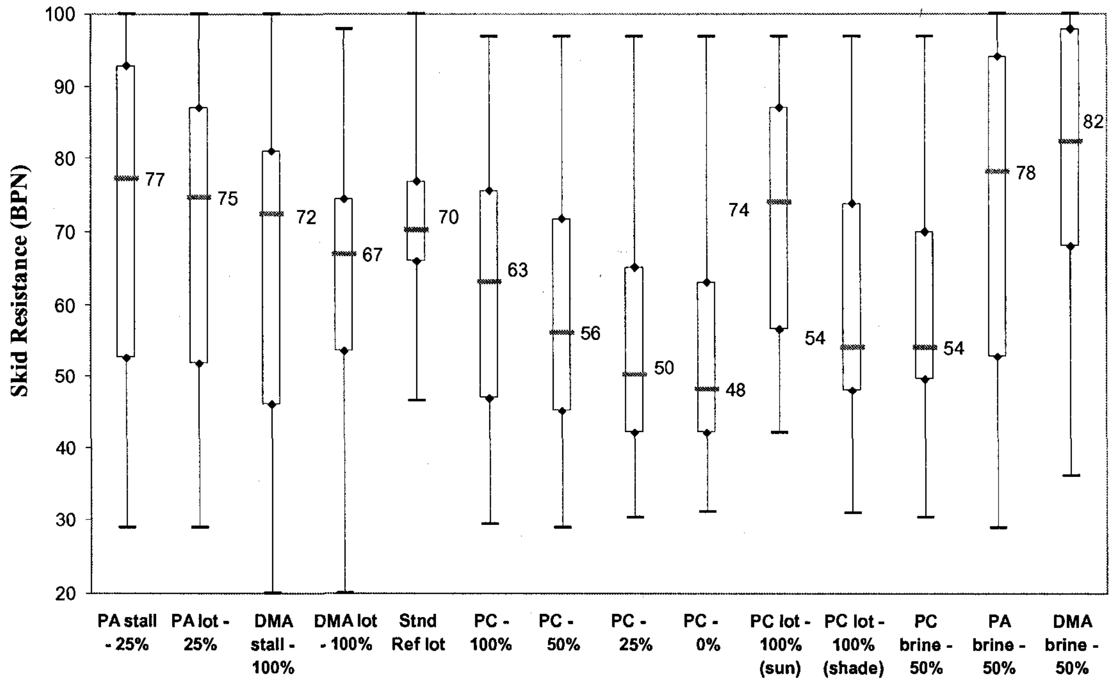

Figure 26: Weighted skid resistance as a function of surface cover ('07-'08)

(Pavement type and salt application rate as percentage of 3-lbs/sf shown on x-axis)

Conclusion

It is recommended that further testing be performed to better determine the winter performance of permeable pavements when maintained with a salt brine solution. Analyses only consisted of a two-month period (12 events) while much of the other results presented in this thesis are based on two years of data. Special attention should be paid to the selection of study areas to ensure that shading is not a factor and that all areas receive the same traffic conditions. Some data had to be discarded after discovering that vehicles had parked on the study areas at the PA and DMA lots, further complicating results. Additional salting rates beyond the 50% rate used in this study could be evaluated in order to identify optimal treatment strategies.

APPENDIX B

CROSS-SECTIONS OF UNHSC PERMEABLE PAVEMENT SYSTEMS

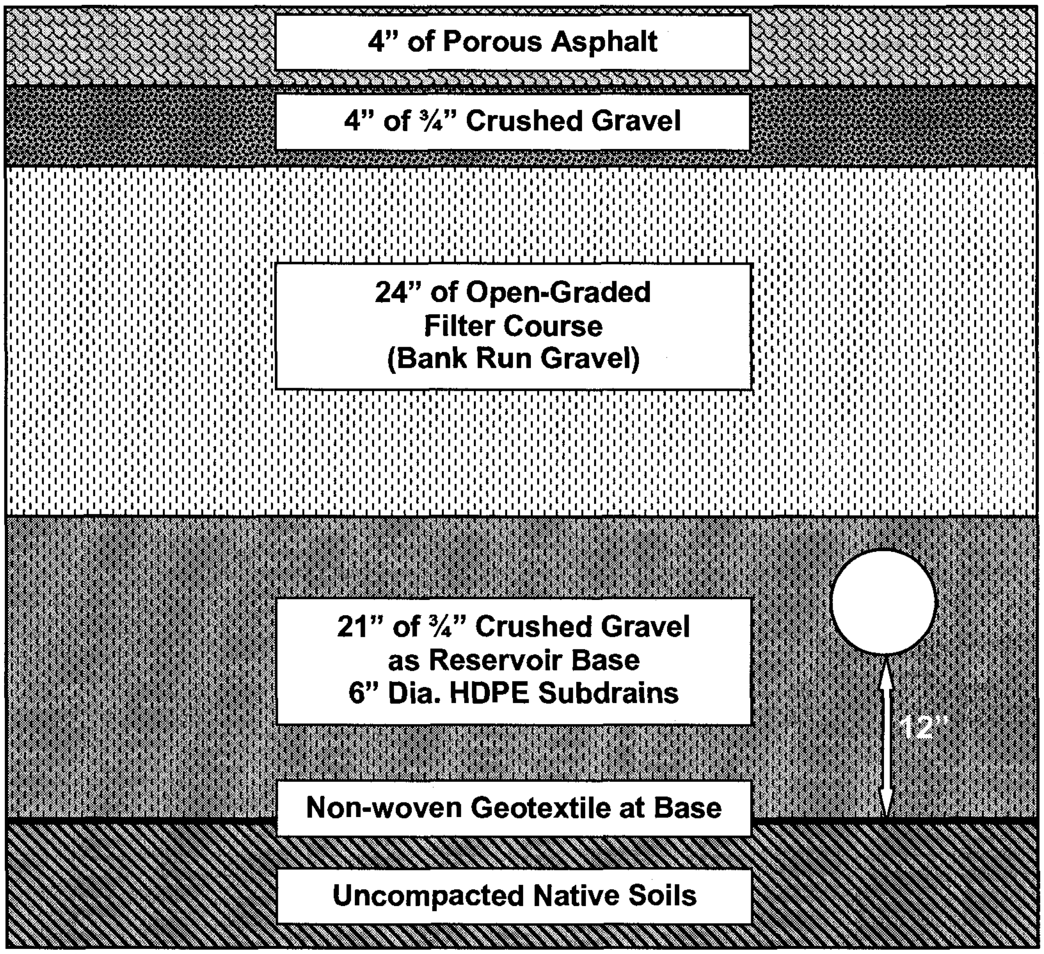

Figure 27: Cross-section of UNHSC porous asphalt parking lot

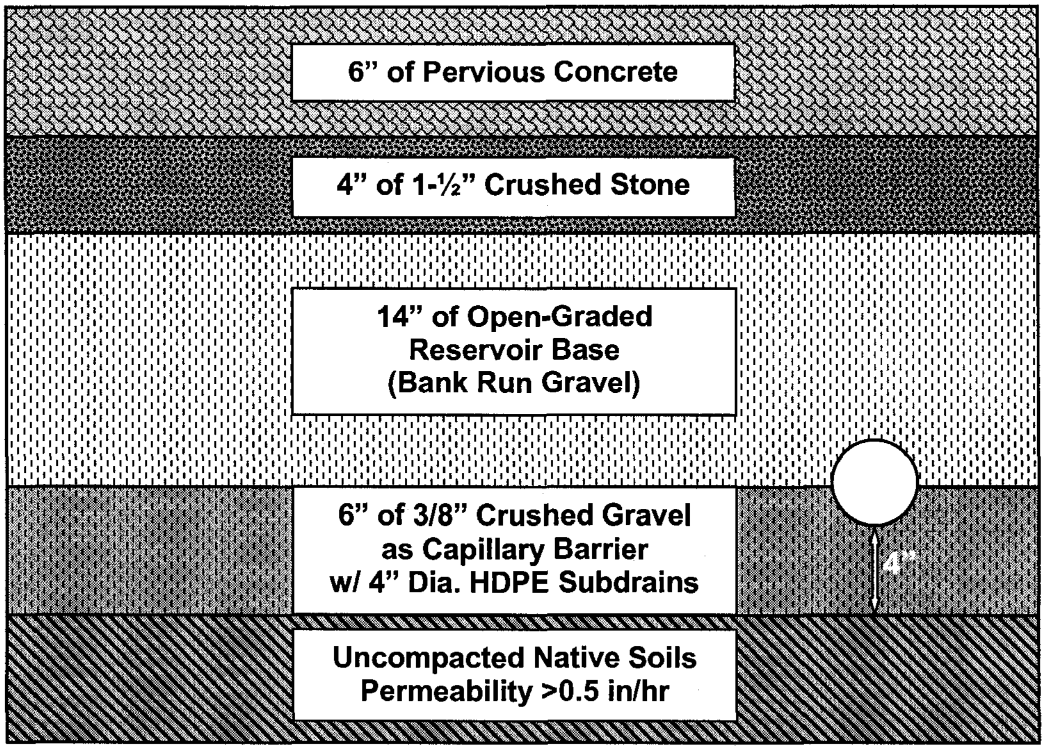

Figure 28: Cross-section of UNHSC pervious concrete parking lot

APPENDIX C

FROST DEPTH

Table 20: Frost depth raw data ('06-'07)

Date	Time	Porous Asphalt (in)	Tree Filter Reference (in)	Date	Time	Porous Asphalt (in)	Tree Filter Reference (in)
12/1/06	12:00	0.00	0.00	2/21/07	0:00	27.25	24.00
12/4/06	7:20	0.00	0.00	2/22/07	0:00	26.75	24.00
12/7/06	0:00	0.00	1.50	2/23/07	8:50	27.25	24.75
12/8/06	10:45	0.00	0.00	2/25/07	15:45	27.25	24.50
12/20/06	0:00	-	0.50	3/1/07	22:10	26.50	25.75
1/2/07	10:30	0.50	0.00	3/3/07	8:50	15.00	25.50
1/9/07	0:00	0.00	0.00	3/4/07	8:50	15.00	25.50
1/11/07	0:00	0.00	0.88	3/5/07	0:00	-	26.00
1/13/07	20:15	0.00	0.00	3/6/07	0:00	6.75	-
1/14/07	22:40	0.00	0.00	3/7/07	0:00	10.00	26.50
1/15/07	13:30	0.00	0.50	3/9/07	0:00	12.50	27.00
1/16/07	9:30	0.00	0.00	3/12/07	0:00	0.00	27.50
1/17/07	0:00	2.25	4.25	3/13/07	0:00	0.00	27.25
1/18/07	9:40	8.00	3.50	3/14/07	0:00	0.00	27.25
1/18/07	16:45	9.00	3.63	3/16/07	15:05	0.00	0.00
1/19/07	15:00	9.88	4.00	3/17/07	17:15	0.00	0.00
1/20/07	10:40	10.13	4.13	3/18/07	10:00	0.00	0.00
1/23/07	8:55	13.00	5.50	3/19/07	9:30	0.00	0.00
1/24/07	13:05	13.00	6.13	3/21/07	0:00	0.00	0.50
1/28/07	13:50	17.50	10.00	3/22/07	0:00	0.00	0.50
1/31/07	0:00	12.75	18.63	3/23/07	0:00	0.00	0.00
2/2/07	0:00	19.00	14.50	3/25/07	9:20	0.00	0.00
2/3/07	10:30	19.00	15.50	3/30/07	0:00	0.00	0.00
2/6/07	0:00	19.75	18.25	4/4/07	14:50	0.00	0.00
2/9/07	0:00	-	20.75	4/5/07	10:30	0.00	0.00
2/12/07	0:00	22.00	21.25	4/6/07	8:25	0.00	0.00
2/13/07	20:50	23.00	22.25	4/11/07	13:00	0.00	0.00
2/16/07	0:00	23.50	23.25	4/13/07	8:45	0.00	0.00
2/19/07	0:00	25.50	24.00	Max. Depth (in.)		25.75	24.00
2/20/07	10:00	25.75	24.00	Max. Duration		51 days	56 days

Table 21: Frost depth raw data ('07-'08)

Date	Time	Porous Asphalt (in)	Tree Filter (in)	Pervious Concrete (in)	PC Site Reference (in)
11/28/07	10:00	-	-	0.00	0.00
12/2/07	17:00	-	2.75	0.00	3.75
12/3/07	12:00	-	2.75	0.00	3.00
12/4/07	11:30	-	2.50	0.00	3.25
12/7/07	11:15	-	2.50	2.00	2.88
12/9/07	21:00	-	1.75	1.75	2.25
12/10/07	11:45	-	2.00	0.00	2.25
12/13/07	10:10	-	-	0.00	2.00
12/14/07	9:30	-	2.38	0.00	2.00
12/18/07	12:30	-	2.25	0.00	1.75
12/18/07	16:00	-	-	0.00	1.63
12/21/07	10:00	-	1.00	0.00	0.50
1/22/08	8:45	-	4.50	6.63	2.75
1/23/08	15:10	-	-	9.00	2.75
1/24/08	9:45	5.00	-	10.00	2.50
1/25/08	14:20	-	-	-	3.50
1/28/08	14:10	12.00	8.50	13.00	-
1/29/08	7:00	12.25	8.50	13.50	3.88
1/29/08	16:00	12.50	8.50	13.50	-
1/30/08	9:00	13.00	8.50	14.00	-
1/30/08	14:00	-	-	14.00	3.50
1/31/08	8:15	-	-	14.00	2.50
1/31/08	17:15	13.00	3.00	14.00	-
2/1/08	8:45	-	-	14.50	2.75
2/2/08	10:10	13.50	8.50	14.25	3.25
2/2/08	12:20	-	-	14.25	2.50
2/4/08	14:00	12.50	4.75	14.00	0.00
2/4/08	19:00	12.50	4.75	13.50	-
2/5/08	19:45	-	-	14.00	2.75
2/7/08	8:30	0.00	7.00	12.00	0.00
2/8/08	14:30	-	-	10.00	0.00
2/12/08	14:00	12.50	7.00	8.50	2.50
2/13/08	15:15	13.50	6.00	7.00	2.50
2/14/08	8:15	12.50	5.00	8.00	2.50
2/15/08	14:30	12.50	5.00	8.00	2.25
2/19/08	8:10	-	5.50	7.75	2.38
2/22/08	8:00	12.00	-	8.00	3.00
2/23/08	12:30	12.00	8.00	8.25	3.25
2/24/08	10:00	12.00	8.00	8.25	3.50
2/25/08	0:00	8.00	8.75	-	-

Date	Time	Porous Asphalt (in)	Tree Filter (in)	Pervious Concrete (in)	PC Site Reference (in)
2/26/08	7:40	-	-	8.50	3.50
2/26/08	14:30	8.50	9.00	8.50	3.50
2/27/08	10:15	8.50	9.50	8.75	3.50
2/28/08	14:30	8.00	10.00	-	3.50
2/29/08	8:00	8.00	10.00	-	-
3/2/08	9:45	8.25	10.50	9.00	3.25
3/3/08	0:00	1.00	11.00	-	-
3/4/08	8:00	-	-	9.00	3.25
3/7/08	13:30		-	9.38	3.25
3/8/08	0:00	0.00	10.00	-	-
3/10/08	13:40	-	2.00	9.50	-
3/11/08	17:45	0.00	3.00	9.38	4.38
3/12/08	14:45	0.00	3.00	9.50	4.38
3/13/08	9:00	-	-	9.38	4.63
3/19/08	7:00	0.00	0.00	8.50	3.50
3/20/08	8:20	0.00	0.00	7.50	-
3/25/08	0:00	0.00	0.00	-	-
4/8/08	0:00	0.00	0.00	0.00	-
Max. Depth (in.)		13.50	8.50	14.50	3.88
Max. Duration (days)		20	101	58	62

APPENDIX D

SURFACE INFILTRATION CAPACITY

Table 22: Porous asphalt mean surface infiltration capacity raw data ('04-'07) (Briggs, 2006; Briggs et al., 2007)

Date	Surface IC Rate (in/hr)			Estimated % Leakage			Corrected IC Rate (in/hr)			
	A	B	C	A	B	C	A	B	C	Mean
11/18/04	1414	1114	438	5	5	25	1,343	1,058	328	910
1/15/05	2451	1671	694	30	30	50	1,716	1,170	347	1,078
2/15/05	1671	1935	613	20	25	50	1,337	1,451	306	1,032
3/15/05	1935	1599	707	25	30	50	1,451	1,119	354	975
4/14/05	2298	1838	782	20	25	50	1,838	1,379	391	1,203
5/17/05	2298	1751	634	20	25	50	1,838	1,313	317	1,156
6/15/05	1935	836	210	10	15	20	1,742	710	168	873
7/17/05	1532	668	334	5	10	40	1,455	602	201	753
8/19/05	994	549	167	0	5	25	994	521	125	547
9/30/05	1081	668	210	15	20	50	919	535	105	520
11/4/05	1050	320	153	20	35	75	840	208	38	362
1/12/06	1838	1050	230	25	35	75	1,379	683	57	706
4/5/06	1362	919	163	25	35	75	1,021	597	41	553
5/31/06	1935	566	0	25	35	-	1,451	368		910
7/20/06	1935	817	320	25	35	75	1,451	531	80	687
8/26/06	1414	694	0	25	35	-	1,061	451		756
8/26/06	1114	549	171	10	15	75	1,003	466	43	504
10/2/06	1414	566	230	10	15	75	1,273	481	57	604
11/8/06	1050	477	0	10	15	-	945	406		676
12/28/06	668	409	37	5	5	-	635	388	37	353
2/12/07	1114	541	0	5	5	-	1,058	514	-	786
2/13/07	584	272	8	5	5	-	554	259	8	274
4/23/07	955	435	0	5	5	-	907	413	-	660
5/29/07	943	383	22	5	5	-	896	364	22	427
8/10/07	1838	1007	0	5	5	-	1,746	957	-	1,352
9/23/07	1991	782	4	5	5	-	1,891	743	4	880
10/2/07	0	0	21	-	-	-	-	-	21	21
10/10/07	0	0	116	-	-	-	-	-	116	116

Table 23: Porous asphalt surface infiltration capacity raw data ('08)

Date	Test Loc.	Rep. #	Time (sec)	Surface Temp (°F)	Water Temp (°F)	Leakage (%)	IC_{corr} (in/hr)	Mean IC (in/hr)
1/7/08	A	1	29.9	46.0	50	5	1178	1102
		2	33.0			5	1067	
		3	33.2			5	1061	
	B	1	41.4	46.2	50	5	851	794
		2	45.4			5	776	
		3	46.6			5	756	
	C	DRI Test - See CD		36.3	55	25	48	48
4/14/08	A	1	34.7	94.3	49	5	1015	882
		2	40.6			5	868	
		3	46.1			5	764	
	B	1	45.3	86.5	49	5	778	747
		2	47.2			5	746	
		3	49.2			5	716	
	C	DRI Test - See CD		69.8	49	25	20	20
5/28/08	A	1	34.7	35.8	61	5	1015	913
		2	39.8			5	885	
		3	42			5	839	
	B	1	55.8	29.4	61	5	631	602
		2	58.7			5	600	
		3	61.4			5	574	
	C	DRI Test - See CD		72.5	61	7	31	31
7/11/08	A	1	39.0	116.1	71	5	903	815
		2	44.0			5	801	
		3	47.6			5	740	
	B	1	51.5	92.1	71	5	684	662
		2	53.4			5	660	
		3	54.8			5	643	
	C	DRI Test - See CD		104	71	10	56	56

Table 24: Pervious concrete surface infiltration capacity raw data ('07-'08)

Date	Test Loc.	Trial Time (s)					Raw IC (in/hr)	Leak-age (%)	IC_{corr} (in/hr)	Water Temp (°F)	Surf. Temp (°F)
		1	2	3	4	Mean					
11/19/07	A	22.4	23.5	24.4		23.4	1,582	5	1,503	42	115.5
	B	9.2	8.7	9.0	9.3	9.1	4,097	5	3,892	49	99.9
	C	8.3	7.3	7.5		7.7	4,816	5	4,575	42	100.8
	D	6.4	6.5	6.6		6.5	5,705	5	5,419	42	103.3
	E	12.1	12.6	12.9		12.5	2,959	5	2,811	42	99.7
	F	5.0	5.0	5.1		5.0	7,367	5	6,999	42	98.4
								Mean	4,200		
1/7/08	A	38.5	38.0	38.8		38.4	965	5	917	50	42.1
	B	10.3	10.4	10.2		10.3	3,600	5	3,420	51	38.1
	C	8.8	9.5	9.1		9.1	4,060	5	3,857	49	43.9
	D	7.2	7.5	8.1		7.6	4,879	5	4,635	51	36.3
	E	16.9	17.2	16.9		17.0	2,181	5	2,072	59	40.6
	F	5.8	5.3	5.9		5.7	6,544	5	6,216	50	38.1
								Mean	3,519		
4/14/08	A	42.0	47.9	49.0		46.3	801	5	761	51	86.7
	B	9.9	10.3	10.4		10.2	3,635	5	3,454	51	55.6
	C	8.5	8.8	9.1		8.8	4,214	5	4,003	51	52.7
	D	6.8	6.8	7.0		6.9	5,400	5	5,130	51	62.2
	E	22.4	22.4	24.3		23.0	1,610	5	1,529	51	80.1
	F	5.5	5.7	5.5		5.6	6,661	5	6,328	51	76.3
								Mean	3,534		
5/28/08	A	48.3	54.6	56.2		53.0	699	5	664	61	102.9
	B	13.4	13.9	14.4		13.9	2,668	5	2,534	61	109.6
	C	9.0	9.2	9.2		9.1	4,060	5	3,857	61	110.7
	D	7.8	8.0	8.4		8.1	4,597	5	4,367	61	100.2
	E	20.5	22.5	22.4		21.8	1,701	5	1,616	61	105.6
	F	5.9	5.7	5.7		5.8	6,430	5	6,109	61	66.0
								Mean	3,191		

Date	Test Loc.	Trial Time (s)					Raw IC (in/hr)	Leak-age (%)	IC_{corr} (in/hr)	Water Temp (ºF)	Surf. Temp (ºF)
		1	2	3	4	Mean					
11/19/07	A	48.0	52.5	55.6		52.0	713	5	677	70	97.9
	B	12.0	12.0	12.0		12.0	3,090	5	2,936	70	95.4
	C	8.3	9.1	9.0		8.8	4,214	5	4,003	70	92.5
	D	7.0	7.5	7.3		7.3	5,103	5	4,848	70	92.3
	E	22.0	22.3	23.0		22.4	1,653	5	1,570	70	84.4
	F	5.5	5.8	5.9		5.7	6,467	5	6,144	70	80.2
								Mean	3,363		

APPENDIX E

SURFACE COVER AND SKID RESISTANCE

Table 25: Surface cover observations and weighted skid resistance values ('06-'07)

Date	Time	Weather/ Temp (ºF)	Study Area	Cell #	Cover Type Percentage								
					Dry	Snow	Slush	Comp -acted Snow	Ice	Stand -ing Water	Wet/ moist	% Snow/ Ice Cover	Weighted Skid Resistance (BPN)
1/14/07	9:45 PM	Cloudy, light wind	PA - 100%	All							100	0	85
			PA - 50%	All							100	0	85
			PA - 25%	All							100	0	85
			PA - 0%	All							100	0	85
			DMA - 100%	All					5	10	85	0	76
			DMA - 50%	1-4					90		10	0	56
				5-8						15	85	0	
			DMA - 25%	All					5	15	80	5	76
			DMA - 0%	1-4					90		10	90	56
				5-8						40	60	0	
1/15/07	12:30 PM	Moderate snow/ sleet, light wind	PA - 100%	All					60		40	60	63
			PA - 50%	All					60		40	60	63
			PA - 25%	All					80		20	80	55

			PA - 0%	All					95		5	95	50
			DMA - 100%	All					100			100	28
			DMA - 50%	All					80		20	80	38
			DMA - 25%	All					95		5	95	31
			DMA - 0%	All					100			100	28
1/16/07	10:45 AM	Mostly cloudy, moderate wind	PA - 100%	All					95		5	95	50
			PA - 50%	All					98		2	98	49
			PA - 25%	All					99		1	99	48
			PA - 0%	All					100			100	48
			DMA - 100%	All					98		2	98	29
			DMA - 50%	All others					98		2	98	30
				5,7					90		10	90	
			DMA - 25%	All					98		2	98	29
			DMA - 0%	All					100			100	28
1/18/07	4:15 PM	Mostly cloudy, light wind	PA - 100%	6					35		65	35	72
			PA - 50%	6					25		75	25	76
			PA - 25%	6					85		15	85	54
			PA - 0%	6					100			100	48
			DMA - 100%	6					60		40	60	48
			DMA - 50%	6					80		20	80	38
			DMA - 25%	6					99		1	99	29
			DMA - 0%	6					100			100	28
1/19/07	2:30 PM	Mostly sunny, moderate wind	PA - 100%	All		1					99	1	85
			PA - 50%	All							100	0	85
			PA - 25%	All							100	0	85

			PA - 0%	All		20					80	20	81
			DMA - 100%	All		1					99	1	79
			DMA - 50%	All		5					95	5	78
			DMA - 25%	All		5					95	5	78
			DMA - 0%	All		5					95	5	78
1/20/07	10:15 AM	Partly cloudy, strong wind, cold	PA - 100%	All	100							0	100
			PA - 50%	All	100							0	100
			PA - 25%	All	100							0	100
			PA - 0%	2,4,6	70				30			30	94
				All others	100							0	
			DMA - 100%	5,6					5		95	5	79
				All others	5						95	0	
			DMA - 50%	1,2	90				10			10	97
				All others	90						10	0	
			DMA - 25%	All	50				50			50	64
			DMA - 0%	All	70				30			30	78
1/23/07	4:30 PM	Mostly cloudy, no wind, snow that morning	PA - 100%	All	1						99	0	85
			PA - 50%	All	15						85	0	87
			PA - 25%	All	20						80	0	88
			PA - 0%	All	5						95	0	86
			DMA - 100%	All	75						25	0	95
			DMA - 50%	All	60					15	25	0	92
			DMA - 25%	All	80					5	15	0	96
			DMA - 0%	All	90						10	0	98

1/28/07	1:30 PM	Sunny, light wind, warm	PA - 100%	All	100							0	100
			PA - 50%	All	100							0	100
			PA - 25%	All	100							0	100
			PA - 0%	All	100							0	100
			DMA - 100%	All							100	0	79
			DMA - 50%	All		25					75	25	73
			DMA - 25%	All		25					75	25	73
			DMA - 0%	All		100						100	54
2/3/07	10:30 AM	Sunny, moderate/ strong winds, snowed overnight	PA - 100%	All		10					90	10	83
			PA - 50%	All		10					90	10	83
			PA - 25%	All		20					80	20	81
			PA - 0%	All		90					10	90	67
			DMA - 100%	All							100	0	79
			DMA - 50%	All	40	60						60	72
			DMA - 25%	All	20	80						80	63
			DMA - 0%	All	8	90					2	90	58
2/15/07	12:30 PM	Sunny, strong winds, very cold	PA - 100%	All							100	0	85
			PA - 50%	All							100	0	85
			PA - 25%	2,4,6, 8		100						100	75
				1,3,5, 7							100	0	
			PA - 0%	All							100	0	85
			DMA - 100%	All	85	10			5			15	92
			DMA - 50%	4,5,6	50	50						50	91
				1,2,3, 7,8	100							0	

			DMA - 25%	All	100							0	100
			DMA - 0%	All	100							0	100
2/15/07	2:40 PM	Sunny, strong winds, very cold	PA - 100%	All	95				5			5	97
			PA - 50%	All	95				5			5	97
			PA - 25%	2,4,6, 8		100						100	75
				1,3,5, 7							100	0	
			PA - 0%	All	95				5			5	97
			DMA - 100%	All	95				5			5	96
			DMA - 50%	All	85				15			15	89
			DMA - 25%	All	95				5			5	96
			DMA - 0%	All	95				5			5	96
2/23/07	8:35 AM	Mostly cloudy, light wind, sun breaking through	PA - 100%	All		10					90	10	83
			PA - 50%	All		25					75	25	80
			PA - 25%	All		40					60	40	77
			PA - 0%	All		100						100	65
			DMA - 100%	All						25	75	0	79
			DMA - 50%	All		10				60	30	10	77
			DMA - 25%	All		30				30	40	30	72
			DMA - 0%	All		100						100	54
3/3/07	11:00 AM	Partly cloudy, ~40F	PA - 100%	All		3					97	3	84
			PA - 50%	All		7					93	7	84
			PA - 25%	All		17					83	17	82
			PA - 0%	All		33					67	33	78
			DMA - 100%	All		40				10	50	40	69
			DMA - 50%	All		17				40	43	17	75

			DMA - 25%	All						40	60	0	79
			DMA - 0%	All		70				10	10	70	54
3/4/07	7:30 AM	Sunny, ~30F	PA - 100%	All	2						98	0	85
			PA - 50%	All	5						95	0	86
			PA - 25%	All	30						70	0	90
			PA - 0%	All	50						50	0	93
			DMA - 100%	All	5				25/ 45		25	0	77
			DMA - 50%	All	1				75/ 24			0	46
			DMA - 25%	All					30/ 70			0	78
			DMA - 0%	All					25/ 75			0	82
3/18/07	8:30 AM	Sunny, mod. wind, ~26F	PA - 100%	All	100							0	100
			PA - 50%	All	95				5			5	97
			PA - 25%	All	99				1			1	99
			PA - 0%	All	90				10			10	95
			DMA - 100%	All	82				18			18	87
			DMA - 50%	All	82				18			18	87
			DMA - 25%	All	70				30			30	78
			DMA - 0%	All	97				3			3	98
3/19/07	9:30 AM	Sunny, light wind, ~32F	PA - 100%	All	99	1						1	100
			PA - 50%	All	98				2			2	99
			PA - 25%	All	99	1						1	100
			PA - 0%	All	95	5						5	98
			DMA - 100%	All	99	1						1	100
			DMA - 50%	All	100							0	100

			DMA - 25%	All	99	1						1	100
			DMA - 0%	All	95	5						5	98
3/25/07	9:00 AM	Mostly cloudy, no wind, ~36F	PA - 100%	All							100	0	79
			PA - 50%	All							100	0	79
			PA - 25%	All							100	0	79
			PA - 0%	All							100	0	79
			DMA - 100%	1,2		33				67		33	77
				3,4,5, 6,7,8						10	90	0	
			DMA - 50%	1,2		50				50		50	76
				3,4,5, 6,7,8						35	65	0	
			DMA - 25%	1,2,3, 4		100						100	67
				5,6,7, 8							100	0	
			DMA - 0%	All						35	65	0	79
4/5/07	8:30 AM	Cloudy, ~33F, just snowed	PA - 100%	All		97					3	97	55
			PA - 50%	All		90					10	90	57
			PA - 25%	All		80					20	80	59
			PA - 0%	All		90					10	90	57
			DMA - 100%	All		50				50		50	67
			DMA - 50%	All		75				25		75	60
			DMA - 25%	All					75	25		75	41
			DMA - 0%	All		90				10		90	57
			DMA - 100% (2)	All						85	15	0	79
4/5/07	10:10 AM	Cloudy, ~35F, light wind	PA - 100%	All		1					99	1	79
			PA - 50%	All		5					95	5	78

			PA - 25%	All		2					98	2	79
			PA - 0%	All		2					95	2	76
			DMA - 100%	All						40	60	0	79
			DMA - 50%	All		1				39	60	1	79
			DMA - 25%	All		5				25	70	5	78
			DMA - 0%	All		5				20	75	5	78
			DMA - 100% (2)	All						70	30	0	79
4/13/07	7:30 AM	Sunny, light wind, ~30F	PA - 100%	All					100			100	28
			PA - 50%	All					100			100	28
			PA - 25%	All					100			100	28
			PA - 0%	All					100			100	28
			DMA - 100%	All					100			100	28
			DMA - 50%	All					100			100	28
			DMA - 25%	All					100			100	28
			DMA - 0%	All					100			100	28
			DMA - 100% (2)	All					100			100	28
4/13/07	8:50 AM	Mostly sunny, light wind, ~36F	PA - 100%	All		98					2	98	55
			PA - 50%	All		100						100	54
			PA - 25%	All		100						100	54
			PA - 0%	All		100						100	54
			DMA - 100%	All		10				90		10	77
			DMA - 50%	All		37				63		37	70
			DMA - 25%	All		87				13		87	57
			DMA - 0%	All		100						100	54

			DMA - 100% (2)	All						75	25	0	79
4/13/07	11:10 AM	Mostly cloudy, moderate wind, ~36F	PA - 100%	All							100	0	79
			PA - 50%	All							100	0	79
			PA - 25%	All							100	0	79
			PA - 0%	All							100	0	79
			DMA - 100%	All	25					50	25	0	84
			DMA - 50%	All	2					70	28	0	79
			DMA - 25%	All						50	50	0	79
			DMA - 0%	All		37				50	13	37	70
			DMA - 100% (2)	All						75	25	0	79

Table 26: Surface cover observations and weighted skid resistance values ('07-'08)

Date	Time	Wea-ther/ Temp (°F)	Study Area	Cover Type Percentage							% Snow /Ice Cover	Weighted Skid Resistance (BPN)
				Dry	Snow	Slush	Comp-acted Snow	Ice	Stand-ing Water	Wet/ moist		
12/5/07	11:15 AM	Sunny, no wind, ~34F	PA - stall					100			100	29
			PA - lot					100			100	29
			DMA - stall	15				85			85	40
			DMA - lot	15				85			85	40
			Stnd. Ref.	5	15					80	15	71
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (shade)									
			PC - brine									
			PA - brine									
			DMA - brine									
12/9/07	8:50 PM	Mod. snow, light wind, ~32F	PA - stall				25	49		26	74	48
			PA - lot					74		26	74	44
			DMA - stall					25		75	25	63
			DMA - lot					75		25	75	40
			Stnd. Ref.	100							0	100
			PC - 100%					23		77	23	64
			PC - 50%					38		62	38	57
			PC - 25%		70			30			100	42
			PC - 0%		70			30			100	42
			PC-lot (sun)									
			PC-lot (shade)									

			PC - brine									
			PA - brine									
			DMA - brine									
12/11/ 07	12:15 PM	Partly sunny, no wind, ~32F	PA - stall					90		10	90	35
			PA - lot					90		10	90	35
			DMA - stall			10				90	10	72
			DMA - lot			13		37		50	50	55
			Stnd. Ref.									
			PC - 100%		50		50				100	45
			PC - 50%		50		50				100	45
			PC - 25%				100				100	42
			PC - 0%				100				100	42
			PC-lot (sun)		100						100	48
			PC-lot (shade)		100						100	48
			PC - brine									
			PA - brine									
			DMA - brine									
12/11/ 07	4:30 PM	Mostly cloudy, ~34F	PA - stall		60					40	60	65
			PA - lot		73					27	73	60
			DMA - stall		1					99	1	74
			DMA - lot		28					72	28	66
			Stnd. Ref.									
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)			40				60	40	65
			PC-lot (shade)			40				60	40	65
			PC - brine									

			PA - brine									
			DMA - brine									
12/12/ 07	10:00 AM	Cloudy, light wind~3 8F	PA - stall			40				60	40	75
			PA - lot			73				27	73	65
			DMA - stall							100	0	74
			DMA - lot			15				85	15	72
			Stnd. Ref.									
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)			70				30	70	58
			PC-lot (shade)			75		20		5	95	48
			PC - brine									
			PA - brine									
			DMA - brine									
12/13/ 07	9:45 AM	Cloudy, no wind, ~27F	PA - stall	98				2			2	99
			PA - lot	95				5			5	96
			DMA - stall	100							0	100
			DMA - lot	90				10			10	93
			Stnd. Ref.	75				25			25	82
			PC - 100%	100				0			0	97
			PC - 50%	99				1			1	96
			PC - 25%	99				1			1	96
			PC - 0%	99				1			1	96
			PC-lot (sun)	99				1			1	96
			PC-lot (shade)	99				1			1	96
			PC - brine									
			PA - brine									

			DMA - brine									
12/14/ 07	10:00 AM	Sunny, no wind, ~32F	PA - stall		99					1	99	51
			PA - lot		99					1	99	51
			DMA - stall		80					30	80	58
			DMA - lot		70					20	70	46
			Stnd. Ref.									
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)		100						100	48
			PC-lot (shade)		100						100	48
			PC - brine									
			PA - brine									
			DMA - brine									
12/14/ 07	11:50 AM	Sunny, light wind, ~36F	PA - stall		25					75	25	77
			PA - lot		25					75	25	77
			DMA - stall		80					20	80	51
			DMA - lot		70					30	70	54
			Stnd. Ref.		95					5	95	46
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)									
			PC-lot (shade)									
			PC - brine									
			PA - brine									
			DMA - brine									

12/14/ 07	1 PM	Partly cloudy, light wind, ~36F	PA - stall		5					95	5	84
			PA - lot		15					85	15	81
			DMA - stall		30					70	30	65
			DMA - lot		50					50	50	60
			Stnd. Ref.									
			PC - 100%			60				40	60	61
			PC - 50%			70				30	70	58
			PC - 25%			70				30	70	58
			PC - 0%			50				50	50	63
			PC-lot (sun)									
			PC-lot (shade)									
			PC - brine									
			PA - brine									
			DMA - brine									
12/15/ 07	10 AM	Sunny, cold, no wind, ~24F	PA - stall	98				2			2	99
			PA - lot	90				10			10	93
			DMA - stall	80				20			20	86
			DMA - lot	65				35			35	75
			Stnd. Ref.									
			PC - 100%	10			90				90	47
			PC - 50%	50			50				50	69
			PC - 25%	80			20				20	86
			PC - 0%	40			60				60	64
			PC-lot (sun)									
			PC-lot (shade)									
			PC - brine									
			PA - brine									
			DMA - brine									

12/17/07	1:30 PM	Sunny, cold, no wind, ~24F	PA - stall		90					10	90	54
			PA - lot		95					5	95	52
			DMA - stall		90					10	90	48
			DMA - lot		95					5	95	46
			Stnd. Ref.									
			PC - 100%		100						100	48
			PC - 50%		100						100	48
			PC - 25%		100						100	48
			PC - 0%		100						100	48
			PC-lot (sun)		100						100	48
			PC-lot (shade)		100						100	48
			PC - brine									
			PA - brine									
			DMA - brine									
12/18/07	1:10 PM	Sunny, cold, mod wind, ~26F	PA - stall	5	45		45			5	90	53
			PA - lot	5			90			5	90	51
			DMA - stall	35			60				60	35
			DMA - lot	10			90				90	10
			Stnd. Ref.									
			PC - 100%				100				100	42
			PC - 50%				100				100	42
			PC - 25%				100				100	42
			PC - 0%				100				100	42
			PC-lot (sun)				100				100	42
			PC-lot (shade)				100				100	42
			PC - brine									
			PA - brine									
			DMA - brine									

12/19/ 07	8:30 AM	Partly sunny, cold, no wind, ~18F	PA - stall	10			90				90	52
			PA - lot	12			88				88	53
			DMA - stall	25			70	5			75	26
			DMA - lot	15			85				85	15
			Stnd. Ref.									
			PC - 100%				100				100	42
			PC - 50%				100				100	42
			PC - 25%				100				100	42
			PC - 0%				100				100	42
			PC-lot (sun)		5		95				100	42
			PC-lot (shade)		5		95				100	42
			PC - brine									
			PA - brine									
			DMA - brine									
12/19/ 07	1 PM	Partly sunny, no wind, ~30F	PA - stall				50			50	50	66
			PA - lot					65		35	65	49
			DMA - stall			18	52			30	70	33
			DMA - lot			15	45			40	60	38
			Stnd. Ref.									
			PC - 100%				85			15	85	46
			PC - 50%				99			1	99	42
			PC - 25%				95			5	95	43
			PC - 0%				95			5	95	43
			PC-lot (sun)				75			25	75	50
			PC-lot (shade)				75			25	75	50
			PC - brine									
			PA - brine									
			DMA - brine									

12/21/07	11:30 AM	Sunny, no wind, ~28F	PA - stall									
			PA - lot				85			15	85	52
			DMA - stall				85	5		10	90	9
			DMA - lot									
			Stnd. Ref.									
			PC - 100%	60	30		10				40	77
			PC - 50%	30	53		17				70	61
			PC - 25%	40	45		15				60	66
			PC - 0%	5	71		24				95	49
			PC-lot (sun)	75	25						25	85
			PC-lot (shade)									
			PC - brine									
			PA - brine									
			DMA - brine									
1/7/08	8:40 AM	Mostly cloudy, no wind, ~32F	PA - stall									
			PA - lot		50					50	50	68
			DMA - stall									
			DMA - lot		50			15		35	65	53
			Stnd. Ref.									
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)									
			PC-lot (shade)		75					25	75	54
			PC - brine									
			PA - brine									
			DMA - brine									

1/7/08	2:15 PM	Mostly cloudy, no wind, ~32F	PA - stall									
			PA - lot			20				80	20	80
			DMA - stall									
			DMA - lot			20			20	60	20	71
			Stnd. Ref.									
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)							100	0	74
			PC-lot (shade)			20				80	20	70
			PC - brine									
			PA - brine									
			DMA - brine									
1/17/08	4:30 PM	Cloudy, no wind, ~25F	PA - stall									
			PA - lot	60	40						40	80
			DMA - stall									
			DMA - lot	40	60						60	67
			Stnd. Ref.									
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)		5					95	5	73
			PC-lot (shade)		5					95	5	73
			PC - brine									
			PA - brine									
			DMA - brine									

1/18/08	11:20 AM	Sunny, light wind, ~42F	PA - stall			65				35	65	67
			PA - lot			40				60	40	75
			DMA - stall			90			10		90	59
			DMA - lot			65				35	65	63
			Stnd. Ref.							100	0	74
			PC - 100%		1	1				99	2	74
			PC - 50%		1	1				99	2	74
			PC - 25%		1	1				99	2	74
			PC - 0%		1	1				99	2	74
			PC-lot (sun)		1	1				99	2	74
			PC-lot (shade)		1	1				99	2	74
			PC - brine									
			PA - brine									
			DMA - brine									
1/19/08	11:15 AM	Sunny, light wind, ~30F	PA - stall	95				5			5	96
			PA - lot	99				1			1	99
			DMA - stall	80				25			25	87
			DMA - lot	92				8			8	94
			Stnd. Ref.	10				15		75	15	70
			PC - 100%	100							0	97
			PC - 50%	100							0	97
			PC - 25%	100							0	97
			PC - 0%	100							0	97
			PC-lot (sun)	100							0	97
			PC-lot (shade)	100							0	97
			PC - brine									
			PA - brine									
			DMA - brine									

1/28/08	8:45 AM	Partly sunny, light wind, ~22F	PA - stall		99					1	99	51
			PA - lot		99					1	99	51
			DMA - stall	15	85						85	53
			DMA - lot	20	80						80	56
			Stnd. Ref.									
			PC - 100%		50		50				100	45
			PC - 50%		35		65				100	44
			PC - 25%		25		75				100	43
			PC - 0%		25		75				100	43
			PC-lot (sun)		75		25				100	46
			PC-lot (shade)		75		25				100	46
			PC - brine		20		80				100	43
			PA - brine		70					30	70	61
			DMA - brine		97					3	97	46
1/28/08	2:20 PM	Sunny, mod wind, ~38F	PA - stall	1	20					79	20	79
			PA - lot	5		5				75	5	72
			DMA - stall	5		5				90	5	74
			DMA - lot	10					10	70	0	69
			Stnd. Ref.									
			PC - 100%			30	20			50	50	61
			PC - 50%			25	50			25	75	52
			PC - 25%			15	60			25	75	51
			PC - 0%				75			25	75	50
			PC-lot (sun)			5				95	5	73
			PC-lot (shade)			5				95	5	73
			PC - brine				70			30	70	51
			PA - brine	80						20	0	97
			DMA - brine	75						25	0	94

1/29/08	7:45 AM	Sunny, light wind, ~22F	PA - stall	10	10					80	10	84
			PA - lot	50			5			45	5	91
			DMA - stall	10				10		80	10	72
			DMA - lot	20				20		60	20	70
			Stnd. Ref.									
			PC - 100%			30	20			50	50	61
			PC - 50%			25	50			25	75	52
			PC - 25%			15	60			25	75	51
			PC - 0%				75			25	75	50
			PC-lot (sun)			5				95	5	73
			PC-lot (shade)			5				95	5	73
			PC - brine				70			30	70	51
			PA - brine	80						20	0	97
			DMA - brine	90						10	0	97
1/29/08	4 PM	Sunny, light wind, ~22F	PA - stall							100	0	86
			PA - lot		3					97	3	85
			DMA - stall			1				99	1	74
			DMA - lot						10	90	0	74
			Stnd. Ref.									
			PC - 100%			10				90	10	72
			PC - 50%				65			35	65	53
			PC - 25%				70			30	70	51
			PC - 0%				70			30	70	51
			PC-lot (sun)			2				98	2	74
			PC-lot (shade)			2				98	2	74
			PC - brine				70			30	70	51
			PA - brine							100	0	86
			DMA - brine							100	0	74

1/30/08	9:10 AM	Cloudy, no wind, fog, ~44F	PA - stall			1				99	1	86
			PA - lot			1				99	1	86
			DMA - stall						10	90	0	74
			DMA - lot			1			14	85	1	74
			Stnd. Ref.									
			PC - 100%		8					92	8	72
			PC - 50%				50			50	50	58
			PC - 25%				65			35	65	53
			PC - 0%				65			35	65	53
			PC-lot (sun)			1				99	1	74
			PC-lot (shade)			1				99	1	74
			PC - brine				60			40	60	55
			PA - brine									
			DMA - brine									
2/2/08	10:10 AM	Mostly cloudy, high wind, fog, ~40F	PA - stall			25		75			100	36
			PA - lot			24		71		5	95	39
			DMA - stall			25		75			100	36
			DMA - lot			25		75			100	36
			Stnd. Ref.									
			PC - 100%					99		1	99	29
			PC - 50%					100			100	29
			PC - 25%					97		3	97	30
			PC - 0%					95		5	95	31
			PC-lot (sun)					55		45	55	49
			PC-lot (shade)					95		5	95	31
			PC - brine					97		3	97	30
			PA - brine			25		75			100	36
			DMA - brine			25		75			100	36

2/2/08	11:30 AM	Mostly sunny, mod wind, fog, ~42F	PA - stall			2				98	2	85
			PA - lot			2				98	2	85
			DMA - stall			23		67	10		90	40
			DMA - lot			13		37	10	40	50	55
			Stnd. Ref.									
			PC - 100%					95		5	95	31
			PC - 50%					98		2	98	30
			PC - 25%					90		10	90	34
			PC - 0%					60		40	60	47
			PC-lot (sun)					5		95	5	72
			PC-lot (shade)					80		20	80	38
			PC - brine					15		85	15	67
			PA - brine							100	0	86
			DMA - brine					20		80	20	65
2/5/08	2:30 PM	Cloudy, fog, ~42F	PA - stall			25				75	25	79
			PA - lot			30				70	30	77
			DMA - stall			3			22	75	3	74
			DMA - lot			15			25	60	15	72
			Stnd. Ref.									
			PC - 100%			25	75				100	44
			PC - 50%			50	50				100	47
			PC - 25%			95	5				100	51
			PC - 0%			50	50				100	47
			PC-lot (sun)			90	10				100	51
			PC-lot (shade)			55	45				100	47
			PC - brine			87	13				100	50
			PA - brine			25				75	25	79
			DMA - brine			5			25	70	5	73

2/9/08	11:45 AM	Sunny, no wind, ~40F	PA - stall				100				100	47
			PA - lot				100				100	47
			DMA - stall			28	70			2	98	18
			DMA - lot			28	70			2	98	18
			Stnd. Ref.									
			PC - 100%				100				100	42
			PC - 50%				100				100	42
			PC - 25%				100				100	42
			PC - 0%				100				100	42
			PC-lot (sun)				100				100	42
			PC-lot (shade)				100				100	42
			PC - brine				100				100	42
			PA - brine				100				100	47
			DMA - brine				100				100	47
2/10/08	1:30 PM	Light snow falling, ~34F	PA - stall		100						100	51
			PA - lot		65	15				20	80	59
			DMA - stall		98					2	98	46
			DMA - lot		60	10				30	70	55
			Stnd. Ref.									
			PC - 100%			15				85	15	71
			PC - 50%			15				85	15	71
			PC - 25%			90				10	90	54
			PC - 0%			75	25				100	49
			PC-lot (sun)			10				90	10	72
			PC-lot (shade)		70					30	70	55
			PC - brine			60	20			20	80	54
			PA - brine		100						100	51
			DMA - brine		100						100	45

2/11/08	8:20 AM	Strong winds, sunny, cold ~18F	PA - stall					100			100	29
			PA - lot	25				75			75	47
			DMA - stall	10				90			90	36
			DMA - lot	30				70			70	50
			Stnd. Ref.									
			PC - 100%	80				20			20	83
			PC - 50%	70				30			30	77
			PC - 25%	25				75			75	46
			PC - 0%	10				90			90	36
			PC-lot (sun)	90				10			10	90
			PC-lot (shade)	30				70			70	49
			PC - brine	15				85			85	39
			PA - brine					100			100	29
			DMA - brine	20				80			80	43
2/11/08	3:20 PM	Strong winds, sunny, cold ~18F	PA - stall					100			100	29
			PA - lot	30				70			70	50
			DMA - stall	20				80			80	43
			DMA - lot	40				60			60	57
			Stnd. Ref.									
			PC - 100%	80				20			20	83
			PC - 50%	70				30			30	77
			PC - 25%	25				75			75	46
			PC - 0%	10				90			90	36
			PC-lot (sun)	90				10			10	90
			PC-lot (shade)	30				70			70	49
			PC - brine	15				85			85	39
			PA - brine	40				60			60	57
			DMA - brine	75				25			25	82

2/12/08	2:30 PM	Cloudy, light winds, ~24F	PA - stall									
			PA - lot	45				45		10	45	67
			DMA - stall	34				33		33	33	68
			DMA - lot	70				15		15	15	85
			Stnd. Ref.									
			PC - 100%	70				5		25	5	88
			PC - 50%	60				20		20	20	79
			PC - 25%	25				75			75	46
			PC - 0%	25				75			75	46
			PC-lot (sun)	49				2		49	2	84
			PC-lot (shade)	46				8		46	8	81
			PC - brine	40				20		40	20	74
			PA - brine	30				40		30	40	67
			DMA - brine	90				5		5	5	95
2/13/08	3 PM	Heavy rain, preced ed by snow, ~36F	PA - stall			10		30		60	40	66
			PA - lot			25		50		25	75	50
			DMA - stall			20		20	60		40	62
			DMA - lot			25		25	50		50	59
			Stnd. Ref.									
			PC - 100%			55		40		5	95	44
			PC - 50%			55		40		5	95	44
			PC - 25%			45		50		5	95	41
			PC - 0%			45		50		5	95	41
			PC-lot (sun)									
			PC-lot (shade)			40		40		20	80	47
			PC - brine			75		10		15	85	53
			PA - brine			see photos						
			DMA - brine			15		15	70		30	65

2/14/08	1:15 PM	Sunny, mod winds, ~34F	PA - stall	70				20		10	20	84
			PA - lot	40				30		30	30	75
			DMA - stall	25				10	25	40	10	76
			DMA - lot	45				25	15	15	25	74
			Stnd. Ref.									
			PC - 100%	5				10		85	10	71
			PC - 50%	5				20		75	20	66
			PC - 25%	5				50		45	50	53
			PC - 0%	25				50		25	50	57
			PC-lot (sun)	50				5		45	5	83
			PC-lot (shade)	10				50		40	50	54
			PC - brine	30				20		50	20	72
			PA - brine		100						100	51
			DMA - brine	55			5		15	25	5	85
2/15/08	2:30 PM	Partly cloudy, light winds, ~40F	PA - stall	93		2				5	2	98
			PA - lot	90		5				5	5	97
			DMA - stall	98						2	0	99
			DMA - lot	80		5			15		5	94
			Stnd. Ref.						50	50	0	74
			PC - 100%	40		5				55	5	82
			PC - 50%	55		5				40	5	86
			PC - 25%	10		10				80	10	74
			PC - 0%	35		5	20			40	25	74
			PC-lot (sun)	85		5				10	5	92
			PC-lot (shade)	50		10		25		15	35	72
			PC - brine	85		5				10	5	92
			PA - brine		95					5	95	52
			DMA - brine	93		2				5	2	98

2/16/08	11:30 AM	Sunny, mod wind, cold, ~24F	PA - stall	100							0	100
			PA - lot	97				2		1	2	98
			DMA - stall	99						1	0	100
			DMA - lot	93				7			7	95
			Stnd. Ref.	15				25		60	25	67
			PC - 100%	90				5		5	5	92
			PC - 50%	95				5			5	94
			PC - 25%	90				10			10	90
			PC - 0%	85				15			15	87
			PC-lot (sun)	99				1			1	96
			PC-lot (shade)	65				35			35	73
			PC - brine	100							0	97
			PA - brine	5	95						95	53
			DMA - brine	98				1		1	1	99
2/19/08	8 AM	Sunny, ~34F	PA - stall							100	0	86
			PA - lot							100	0	86
			DMA - stall					100			100	29
			DMA - lot					100			100	29
			Stnd. Ref.					60		40	60	47
			PC - 100%							100	0	74
			PC - 50%							100	0	74
			PC - 25%							100	0	74
			PC - 0%							100	0	74
			PC-lot (sun)							100	0	74
			PC-lot (shade)							100	0	74
			PC - brine									
			PA - brine									
			DMA - brine									

2/23/08	12:30 PM	Partly cloudy, no wind ~36F	PA - stall			50				50	50	72
			PA - lot		30	10				60	40	73
			DMA - stall			10			60	30	10	72
			DMA - lot			20			40	40	20	71
			Stnd. Ref.									
			PC - 100%		25					75	25	67
			PC - 50%		50	25				25	75	55
			PC - 25%		85	5				10	90	50
			PC - 0%		95					5	95	49
			PC-lot (sun)			25				75	25	68
			PC-lot (shade)			25				75	25	68
			PC - brine		85	10				5	95	49
			PA - brine			5				95	5	85
			DMA - brine	10		1			9	80	1	76
2/24/08	10:00 AM	Sunny, no wind ~40F	PA - stall	60						40	0	94
			PA - lot	40		15				45	15	87
			DMA - stall	70						30	0	92
			DMA - lot	60					10	20	0	82
			Stnd. Ref.									
			PC - 100%	50	20		15			15	35	75
			PC - 50%	15	10		75				85	50
			PC - 25%	2	2		93			3	95	44
			PC - 0%	3			95			2	95	44
			PC-lot (sun)	30			10			60	10	78
			PC-lot (shade)	30			10			60	10	78
			PC - brine	2		2	93			3	95	44
			PA - brine	90						10	0	99
			DMA - brine	100							0	100

2/25/08	8:15 AM	Sunny, no wind ~20F	PA - stall	100							0	100
			PA - lot	100							0	100
			DMA - stall	100							0	100
			DMA - lot	93				7			7	95
			Stnd. Ref.	20				20		60	20	70
			PC - 100%	95				5			5	94
			PC - 50%	40	10		50				60	64
			PC - 25%	15	5		80				85	50
			PC - 0%	10			90				90	47
			PC-lot (sun)	99	1						1	97
			PC-lot (shade)	80	20						20	87
			PC - brine	15	5		80				85	50
			PA - brine	100							0	100
			DMA - brine	100							0	100
2/26/08	3:30 PM	Light snow falling, ~32F	PA - stall							100	0	86
			PA - lot							100	0	86
			DMA - stall							100	0	74
			DMA - lot						2	98	0	74
			Stnd. Ref.							100	0	74
			PC - 100%		1					99	1	74
			PC - 50%		10	10				80	20	69
			PC - 25%		10	20				70	30	67
			PC - 0%		20	20				60	40	64
			PC-lot (sun)							100	0	74
			PC-lot (shade)							100	0	74
			PC - brine		5	10				85	15	70
			PA - brine							100	0	86
			DMA - brine							100	0	74

2/27/08	11:45 AM	cloudy, (3" of snow + rain) ~36F	PA - stall			40				60	40	75
			PA - lot		30	35				35	65	65
			DMA - stall						25	75	0	74
			DMA - lot			20			30	50	20	71
			Stnd. Ref.									
			PC - 100%			50				50	50	63
			PC - 50%			40				60	40	65
			PC - 25%			40				60	40	65
			PC - 0%			50				50	50	63
			PC-lot (sun)			15				85	15	71
			PC-lot (shade)		60	20				20	80	54
			PC - brine			25				75	25	68
			PA - brine			30				70	30	77
			DMA - brine			20			20	60	20	71
2/28/08	2:00 PM	Sunny, mod wind, (3" of snow), ~32F	PA - stall	90						10	0	99
			PA - lot	75				5		20	5	94
			DMA - stall	40				2		58	2	84
			DMA - lot	50				5	10	35	5	85
			Stnd. Ref.									
			PC - 100%			25	50			25	75	52
			PC - 50%			5	85			10	90	45
			PC - 25%				99			1	99	42
			PC - 0%				98			2	98	42
			PC-lot (sun)	25	15					60	15	76
			PC-lot (shade)			10	80			10	90	46
			PC - brine			15	45			40	60	56
			PA - brine									
			DMA - brine	80						20	0	95

2/29/08	8:00 AM	Sunny, cold, no wind, ~10F	PA - stall	100							0	100
			PA - lot	93				7			7	95
			DMA - stall	100							0	100
			DMA - lot	93				7			7	95
			Stnd. Ref.	45				10		45	10	81
			PC - 100%	25	15		60				75	56
			PC - 50%	10	20		70				90	48
			PC - 25%		2		98				100	42
			PC - 0%		5		95				100	42
			PC-lot (sun)	90			10				10	91
			PC-lot (shade)	10	30		60				90	49
			PC - brine	25	35		40				75	57
			PA - brine	85	15						15	93
			DMA - brine	97				3			3	98
2/29/08	5:30 PM	Cold, clear, ~18F	PA - stall	100							0	100
			PA - lot	98				2			2	99
			DMA - stall	100							0	100
			DMA - lot	95				5			5	96
			Stnd. Ref.									
			PC - 100%	35	5		60				65	37
			PC - 50%	15	10		75				85	20
			PC - 25%	1	4		95				99	3
			PC - 0%	3	7		90				97	6
			PC-lot (sun)	95	5						5	97
			PC-lot (shade)	20	10		70				80	25
			PC - brine	50	20		30				50	59
			PA - brine	95	5						5	97
			DMA - brine	99				1			1	99

3/2/08	9:30 AM	Sunny, mod wind ~38F	PA - stall			25		35		40	60	54
			PA - lot	63		15		7		15	22	85
			DMA - stall	45				10	45		10	81
			DMA - lot	20				30	25	25	30	66
			Stnd. Ref.					25	35	40	25	63
			PC - 100%	15	55		15	15			85	44
			PC - 50%	5	25			70			95	37
			PC - 25%	15		15		70			85	44
			PC - 0%	25		25		50			75	54
			PC-lot (sun)	80				15		5	15	88
			PC-lot (shade)	20	5		75				80	22
			PC - brine	70		10		20			30	82
			PA - brine			35		25		40	60	57
			DMA - brine	2		40			58		40	68
3/3/08	8:10 AM	Sunny, mod wind ~38F	PA - stall	100							0	100
			PA - lot	100							0	100
			DMA - stall	100							0	100
			DMA - lot	97				3			3	98
			Stnd. Ref.									
			PC - 100%	85	5			10			15	90
			PC - 50%	85	5			20			25	93
			PC - 25%	55				45			45	68
			PC - 0%	90				10			10	93
			PC-lot (sun)	98	2						2	99
			PC-lot (shade)	40			60				60	40
			PC - brine	94	2			3			5	96
			PA - brine	100							0	100
			DMA - brine	100							0	100

3/12/08	2:30 PM	Mostly cloudy, sun coming out, ~38F	PA - stall			18				82	18	71
			PA - lot			3				97	3	74
			DMA - stall						25	75	0	74
			DMA - lot			5			60	35	5	73
			Stnd. Ref.		20				80		20	68
			PC - 100%			8				92	8	73
			PC - 50%			12				88	12	72
			PC - 25%			11				89	11	72
			PC - 0%			10				90	10	72
			PC-lot (sun)			1				99	1	74
			PC-lot (shade)		40	40				20	80	56
			PC - brine			8				92	8	73
			PA - brine			1				99	1	74
			DMA - brine						25	75	0	74
3/13/08	8:30 AM	Sunny, light wind ~20F	PA - stall	100							0	100
			PA - lot	100							0	100
			DMA - stall	100							0	100
			DMA - lot	96				4			4	97
			Stnd. Ref.	20				20	10	50	20	70
			PC - 100%	98				2			2	99
			PC - 50%	99				1			1	99
			PC - 25%	98				2			2	99
			PC - 0%	100							0	100
			PC-lot (sun)	99	1						1	99
			PC-lot (shade)	80	20						20	89
			PC - brine	100							0	100
			PA - brine	100							0	100
			DMA - brine	100							0	100

3/15/08	11:45 AM	Light rain/ snow, 30F, ~1inch accum.	PA - stall									
			PA - lot			50				50	50	72
			DMA - stall									
			DMA - lot			40			60		40	67
			Stnd. Ref.		50				50		50	60
			PC - 100%									
			PC - 50%									
			PC - 25%									
			PC - 0%									
			PC-lot (sun)		100						100	48
			PC-lot (shade)		100						100	48
			PC - brine									
			PA - brine									
			DMA - brine									

APPENDIX F

SALT APPLICATION DATES

Table 27: Salt application dates on PA and DMA lots ('06-'07)

Anti-Icing	Deicing	Entire Lots	Stalls only
12/4/06	12/8/06	12/4/06	1/8/07
12/8/06	1/1/07	12/8/06	1/13/07
1/8/07	1/15/07	12/8/06	1/15/07
1/13/07	1/16/07	1/1/07	1/16/07
1/14/07	1/16/07	1/14/07	1/18/07
1/18/07	1/18/07	1/16/07	2/2/07
2/2/07	1/23/07	1/18/07	3/17/07
2/22/07	3/3/07	1/23/07	3/24/07
3/1/07	3/17/07	2/13/07	
3/13/07	1/31/07	2/22/07	
3/16/07		3/1/07	
3/24/07		3/3/07	
4/4/07		3/16/07	
4/11/07		4/4/07	
		4/11/07	
		1/31/07	
Total Applications			
14	**10**	**16**	**8**

Table 28: Salt application dates on PC, PA, and DMA lots ('07-'08)

PC Lot		PA & DMA Lots	
Anti-Icing	Deicing	Anti-Icing	Deicing
12/2/07	12/3/07	12/9/07	12/4/07
12/9/07	12/4/2007	12/13/07	12/10/07
12/13/07	12/7/07	12/15/07	12/11/07
12/15/07	12/10/07	1/17/08	12/12/07
1/17/08	12/11/07	1/22/08	12/17/07
1/17/08	12/11/07	1/31/08	12/18/07
1/22/08	12/12/07	2/4/08	12/21/07
1/31/08	12/14/07	2/6/08	1/28/08
2/4/08	12/17/07	2/12/08	2/2/08
2/6/08	12/18/07	2/22/08	2/8/08
2/12/08	1/27/08	2/26/08	2/9/08
2/22/08	1/28/08	2/29/08	2/23/08
2/26/08	1/29/08	3/11/08	2/27/08
2/29/08	2/2/08		
3/11/08	2/8/08		
	2/9/08		
	2/9/08		
	2/23/08		
	2/27/08		
	2/28/08		
Total Applications			
15	**20**	**13**	**13**

APPENDIX G

CHLORIDE RECOVERY

Table 29: Recovered chloride mass from PA and DMA lots ('06-'07)

	Recovered chloride mass per study area (lbs)							
Event Date	DMA - 100%	PA - 100%	DMA - 50%	PA - 50%	DMA - 25%	PA - 25%	DMA - 0%	PA - 0%
12/8/06	0.50	0.48	-	0.23	-	0.52	0.00	0.00
1/1/07	0.01	0.12	-	0.04	-	0.01	-	0.00
1/13/07	0.17	0.52	0.04	0.41	0.09	0.12	0.00	0.00
1/19/07	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00
1/23/07	0.52	0.40	0.29	0.17	0.29	0.07	0.00	0.00
1/23/07	0.24	0.30	0.04	0.05	0.00	0.15	0.00	0.03
2/2/07	0.00	0.01	0.00	0.00	0.11	0.00	0.01	0.00
2/14/07	0.01	0.04	0.01	0.02	0.01	0.02	0.00	0.01
2/23/07	0.11	0.25	0.01	0.07	0.11	0.11	0.00	0.01
3/2/07	0.15	0.18	0.01	0.04	0.01	0.13	0.00	0.01
3/16/07	1.09	1.73	0.17	0.50	0.07	0.12	0.00	0.00
4/13/07	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Totals	2.80	4.05	0.57	1.55	0.69	1.25	0.03	0.06

Note: All negative values changed to 0.0

Table 30: Recovered chloride mass from PC, PA, and DMA lots ('07-'08)

Event Date	Recovered chloride mass per study area (lbs)						
	PC – 100%	PC – 50%	PC – 25%	PC – 0%	PC – Brine	PA – 25%	DMA – 100%
12/14/07	0.33	0.37	0.25	0.14	0.00	0.00	0.16
1/27/08	0.12	0.02	0.04	0.00	0.04	0.26	0.04
2/1/08	1.37	0.31	0.17	0.03	0.07	0.01	0.00
2/10/08	0.06	0.01	0.00	0.00	0.01	0.00	0.00
Totals	1.87	0.72	0.44	0.17	0.12	0.28	0.20

Note: All negative values changed to 0.0