Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Strategy in a Cold Climate

Robert M. Roseen, Ph.D., P.E., D.WRE, M.ASCE[1]; Thomas P. Ballestero, Ph.D., P.E., M.ASCE[2]; James J. Houle[3]; Joshua F. Briggs[4]; and Kristopher M. Houle[5]

Abstract: This study examined the functionality of a porous pavement storm-water management system in coastal New Hampshire where 6 months of subfreezing temperatures typically occur. The usage of porous pavements for storm-water management in northern climates has many challenges, most of which relate to the extreme cold and significant frost penetration into the porous media. The porous pavement system was monitored for hydraulic and water-quality performance from 2004 to 2008. The use of porous pavements for parking lots for new and redevelopment projects are one watershed-based strategy that can both mitigate impacts for new development and reverse impacts in areas with redevelopment. Surface infiltration capacity and frost penetration were measured monthly to assess winter performance. Because of the well-drained nature of the porous pavement and reservoir base, issues related to frozen media were minimized. Significant frost penetration was observed up to depths of 71 cm without declines in hydrologic performance or observable frost heave. No consistent statistical difference was observed for seasonal hydrologic performance with mean infiltration capacity ranging from 1,490 to 2,690 cm/h. Adverse freeze-thaw effects, such as heaving, were not observed, and for that reason, the life span is expected to exceed that of typical pavement applications in northern climates. Observed hydrologic response resembled shallow depth groundwater drainage, as is the goal for low-impact development designs. Peak flows were reduced by 90% to $0.58\ \mathrm{m^3/s/km^2} \pm 0.74$ in comparison with standard impervious cover $= 5.5\ \mathrm{m^3/s/km^2} \pm 7.7$. There was exceptional water-quality treatment performance for petroleum hydrocarbons, zinc, and total suspended solids with nearly every value below detection limits. Only moderate removal was observed for phosphorous, and treatment for nitrate (NO3) was negative. **DOI: 10.1061/(ASCE)EE.1943-7870.0000459.**

CE Database subject headings: Stormwater management; Runoff; Porous media; Pavements; Cold regions; Best Management Practice; Water quality; Water treatment.

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Introduction

With the implementation of the Phase II rules under the Clean Water Act and the need for innovative storm-water management, storm-water practitioners are looking for designs that provide a high level of water-quality treatment performance and include infiltration of storm-water runoff, for which soils are useful, particularly for source control. The use of porous pavements for parking lots for new and redevelopment projects are one watershed-based strategy that can meet these requirements. Porous pavements can both mitigate impacts from new development and reverse impacts in areas with redevelopment because of the ability to cleanse and cool runoff and reduce runoff volumes. Adoption of porous pavement usage is hampered by widespread concern with regard to cost, winter performance, clogging and maintenance, and risk to groundwater quality. These concerns can be addressed effectively with appropriate designs, proper installation, long-term maintenance commitment, and quality controls for materials production. Although uncertainty exists owing to a lack of long-term performance data for porous pavements, it is obvious that conventional storm-water management is having detrimental impacts on surface waters and that future regulations require the use of innovative storm-water management.

Increased contaminant loading from various land uses with elevated levels of imperviousness is clear [USEPA 1983; Pitt et al. 2004; National Cooperative Highway Research Program (NCHRP) 2006], and conventional storm-water management is doing only a modest job at removing runoff contaminants (Roseen et al. 2006). Accumulation of heavy metals, organics, and inorganic compounds can be acute in urban snow runoff (Sansalone et al. 1996, 2002; Sansalone and Glenn 2002), leaving the need for effective winter storm-water management in northern climates. Low-impact development storm-water designs have been shown to be extremely

[1]Director, The UNH Stormwater Center; and Assistant Research Professor, Dept. of Civil Engineering, 35 Colovos Rd., Univ. of New Hampshire, Durham, NH 03824 (corresponding author). E-mail: robert.roseen@unh.edu

[2]Associate Professor, Dept. of Civil Engineering; and Principal Investigator, The UNH Stormwater Center, 35 Colovos Rd., Univ. of New Hampshire, Durham, NH 03824. E-mail: tom.ballestero@unh.edu

[3]Program Manager, The UNH Stormwater Center, 35 Colovos Rd., Univ. of New Hampshire, Durham, NH 03824. E-mail: James.Houle@unh.edu

[4]Project Engineer, Geosyntec, Acton, MA 01720. E-mail: jbriggs@geosyntec.com

[5]Project Engineer, Horsley Witten Group, Sandwich, MA 02563. E-mail: khoule@horsleywitten.com

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effective at reducing contaminant loads from impervious surfaces (Dietz and Clausen 2008; Dietz 2007), in northern climates (Oberts 2003; Roseen et al. 2009), and for reducing peak flow, lag time, and runoff volume (Hood and Clausen 2007). Porous pavement usage in cold climates has been found to be more resistant to freezing than standard pavements largely because of its disconnection to subsurface moisture and because it thaws more rapidly as a result of the rapid infiltration of meltwater (Backstrom 2000).

Background

The pavement technology for porous asphalts has been in use for decades and is known as open-graded friction course (OGFC), a pavement mix with a void content commonly in the 18–20% range, also known as permeable friction coarse (PFC). Although the two items are similar in many respects, OGFC is not equivalent to porous asphalt (PA), and many of the misconceptions about PA are with respect to OGFC (i.e., low durability, high maintenance, reduced cold-climate functionality). Porous asphalt is a full-depth pavement (typically 6.5–10 cm thick) designed to drain to the subbase. The safety and environmental benefits with porous pavements that result from the rapid infiltration of surface water during storm events include (1) improved wet pavement frictional resistance, (2) reduced hydroplaning, (3) reduced splash and spray, (4) reduced nighttime glare, (5) improved nighttime pavement marking visibility, and (6) reduced pavement noise.

Despite the current success of porous pavements in the United States and Europe, there has been a mixed history of performance associated with porous pavements in asphalt mix design, production and construction, and maintenance. These problems have been solved, in large part, because of the use of modified asphalt binders with polymers and fibers, open aggregate gradations, and quality control assurances (Kandhal and Mallick 1999). In the United States, Oregon, Washington, California, Nevada, Arizona, Florida, Vermont, and Georgia have used OGFC extensively. In Europe, it has been widely implemented since the 1980s in Germany, Netherlands, France, Italy, United Kingdom, Belgium, Spain, ASTMSwitzerland, and Austria.

Specifications can be found in a variety of places including storm-water manuals [Pennsylvania Department of Environmental Protection (PADEP) 2006], industry associations [National Asphalt Pavement Association (NAPA) 2002, 2003)], most state transportation departments, and watershed assistance groups [University of New Hampshire Stormwater Center (UNHSC) 2009a]. PA is typically recommended for parking areas and low-volume, low-use roadways. This is contrary to OGFC usage that has typically been used on large highways in the United States and Europe. Huber (2000) reported that OGFC is best used for high-volume, high-speed roadways. High traffic-intensity roads tend to maintain surface infiltration capacity (IC) of the OGFC because of the suction action of tires that removes detritus.

Structural durability and life cycle are major concerns when selecting pavement type. PA and OGFC have had a mixed record over the past 30 years. The principal cause of parking lot pavement breakdown in northern climates is freeze-thaw cycling with a typical life span of around 15 years. Potential structural durability problems for PA include rutting and distortion under heavy loads, stripping because of prolonged contact with water, and cracking and raveling because of increased photooxidative degradation. Successful examples of long-lasting pavements have accounted properly for asphalt mix design, construction practices, traffic, cold climate issues, and binder draindown and have been demonstrated to be cost-effective. By design, an open-graded, well-drained, significant depth, porous pavement system will have a longer life cycle from reduced freeze-thaw susceptibility and a greater load bearing capacity than conventional parking lot pavement.

Winter Maintenance

Most experience with winter performance and maintenance of PA has been positive, especially compared to standard pavements and in contrast to OGFC. Cahill et al. (2003) reported that PA parking lots require less plowing and that snow and ice melt faster than regular parking lots. The open pore spaces in PA permit water to freely drain through to the bed, providing rapid drainage of any snowmelt. Cahill et al. (2003), Jackson (2003), and Ferguson (2005) proposed several general guidelines for winter maintenance of PA. Ultimately, if reduced winter deicing practices are needed (UNHSC 2009b), porous asphalt could have a winter maintenance cost benefit.

Hydrologic Performance

The hydrologic benefits of the use of porous pavements have been well-documented for volume and peak flow reduction, the degree to which will be dependent on storage within the subbase and the underlying soil type (Abbott and Comino-Mateos 2003). Annual runoff volume reductions of 50–81% have been observed from infiltration in Sweden (Stenmark 1995), 97% volume reduction in Reze, France (Legret and Colandini 1999), and 100% volume reduction over 2 years of study at Pennsylvania State University (Dempsey and Swisher 2003).

Water-Quality Treatment

Several studies have examined water-quality treatment performance and pollutant retention of porous pavements. Most studies concur with the general conclusion that there exists good treatment of hydrocarbons, metals, and suspended solids. Treatment of nutrients and chloride did not appear to be significant in most examples cited. The pavement layer was critical in retention of suspended solids and metals in many studies cited. Physical, chemical, and biological mechanisms served to degrade or at least retain pollutants to a smaller extent in the porous media reservoir and at the geotextile filter (if present) and subgrade soils (if unlined). Hogland et al. (1987) reported on the first year water-quality treatment performance of snowmelt at several PA sites and found a 95% reduction in suspended solids, a 17% reduction in zinc (Zn), a 1,003% increase in nitrate (NO3) (from 0.37 to 4.3 mg/L), and a 650% increase in chloride (from 8 mg/L to 60 mg/L). Nitrate increases were attributed to the presence of residual fertilizers, decomposition of organic materials, and to nutrient leaching from the asphalt itself. Chloride increased, presumably because of winter deicing operations. Legret et al. (1994) published results of a study on the fate of heavy metals in PA from work at a site in Bègles, France. They found that the PA pavement filters out the suspended sediments, which are strongly associated with the heavy metals, lead (Pb), copper (Cu), cadmium (Cd), and zinc. They found no increase in heavy metal pollution in the subgrade soils above background conditions. Legret et al. (1996) reported results from Rezé, France from 30 rainfall events that showed a reduction of suspended solids by 64% and lead by 79%. Subgrade soil samples were not significantly contaminated after 4 years. Soil metal concentrations were close to control sample concentrations and below French regulations for agricultural soil quality standards. Legret and Colandini (1999) explained the water-quality improvement observed in the 1996 study by demonstrating retention of pollutants in the PA structure. Copper, cadmium, and zinc had a 57–85% reduction of the influent concentrations in the underlying porous media. Lead was found to be well-retained in the suspended solids of the filtered material. Dempsey and Swisher (2003) calculated soil loading rates for lead, copper, and zinc; all were well below state standards for biosolid (sludge) land application. Baladès et al. (1995) reported from two sites in Bordeaux, France that chemical oxygen demand and lead reduction ranged from 80 to 90% and 90 to 95%, respectively, and total suspended solids (TSS) reductions ranged up to 80%.

Legret et al. (1999) simulated infiltration of dissolved and particulate heavy metal polluted runoff through porous pavement in a laboratory and by computer modeling . Laboratory results confirmed retention of the metals lead, copper, cadmium, and zinc. A 50-year simulation showed slight increases in subbase soil concentrations of lead, copper, and zinc. Infiltrated water showed pollutant migration for cadmium down to 30 cm. Overall groundwater risk appeared low. A study by Brattebo and Booth (2003) in Washington showed that effluent concentrations of four permeable pavements had nondetectable concentrations for motor oil, lead, and diesel fuel for vertical flow paths of only 10 cm. Dreelin et al. (2006) reported reductions for zinc and total phosphorus (TP) of 17 and 80% and increases in total nitrogen (TN) of 43%.

Study Area

The study site is located at the UNHSC porous asphalt test facility. The PA site is located along the eastern perimeter of a 3.6 ha (9 acre) commuter parking lot (West Edge Lot). The PA lot is hydrologically isolated with an area of 465 m^2 and a surface slope of 1%. The area is frequented by passenger vehicles and is subject to frequent plowing, salting, and sanding during the winter months (typically November through April). For the period from January through March, the winter climate in Durham, New Hampshire, generally consists of average temperatures near −2.4°C, with maximum and minimum temperatures of 3.1°C and −8.2°C, respectively. Total precipitation during this time period is approximately 42 cm, and snowfall is around 160 cm. In New Hampshire, the typical maximum depth of frost ranges between 122 and 140 cm from coast to inland, respectively. For porous pavements, greater depth of frost is not the concern but rather the increase in the rate of cycling between freeze and thaw. This rate is highest near the coast (Zielinski and Keim 2005).

Methodology

Porous Asphalt Site Design

Specifications for the porous asphalt were based on guidance from the National Asphalt Pavement Association (Jackson 2003), Cahill et al. (2004), and from the Federal Aviation Administration (FAA) for the subbase design (Ferguson 2005). The PA mix design and construction details are available online [UNHSC 2004]. Pavement and subbase thickness are based on FAA guidance for runways (i.e., $\geq 0.65 \times$ design frost depth; Ferguson 2005). The porous asphalt mix was a PG64-28 with no polymer modifiers or other additives. The mix design was for 18% void space and 5.8% asphalt content. From top to bottom the PA system is a 10-cm layer of porous asphalt, 10-cm choker course of 19 mm of crushed stone, a 61-cm layer of filter course of poorly graded sand/gravel (a.k.a., bank-run gravel), and a 10-cm reservoir course of crushed stone. The fine gradation of the filter course is for enhanced filtration and water-quality improvement and delayed water release. The high air void content of the uniformly graded crushed stone reservoir course maximizes storage of infiltrated water and creates a capillary barrier to the vertical transport of water, thereby inhibiting winter freeze-thaw action. The 15-cm underdrain in the reservoir course is for hydraulic relief and raised 30 cm off the bottom of the stone layer to enhance groundwater recharge during and in between storms. Nonwoven geotextile filter fabric was used along the bottom and sides of the system. However, this is no longer recommended on the bottom unless needed, for structural reasons, upon poor load bearing soils. Fabrics are not recommended along the bottom for porous pavements because clogging has been reported (Boving et al. 2004) and when used as a design component for storm-water filtration (Roseen et al. 2009). Underlying soils were a combination of infill and hydrologic soil group type C soils. The seasonal high groundwater table was unclear because of infill soils. Groundwater wells were installed to monitor elevation and quality.

Monitoring Data, Sampling, and Analysis

Water-quality monitoring reported in this paper occurred from April 2005 to June 2006; however, monitoring continues to the present. Rainfall was measured at 5-min intervals with an ISCO 674 rain gauge. The rain gauge was heated during winter months. Because there exists no surface runoff from porous asphalt, the adjacent impervious watershed was monitored for influent water quality. The PA parking lot of 465 m^2 is a small fraction of the watershed monitored for influent water quality (approximately 3.6 ha). The influent hydrograph was divided proportionally by the ratio of watershed areas. Water-quality concentrations between the influent watershed and the PA effluent were compared directly. Flow-weighting of these concentrations by calculating event mean concentrations (EMC) allowed for meaningful comparisons of influent and effluent water-quality parameters. Monitoring points were located at the downstream end of subsurface collection pipes. In the 15-cm-diameter high density polyethylene (HDPE) pipe at the PA outfall, a Thel-Mar weir was placed at the outlet to measure flow. Real-time water quality parameters were measured with the YSI 6000-XL sonde for temperature, pH, specific conductivity, and dissolved oxygen, which were logged every 5 min. Samples were taken by using ISCO 6712FR automatic samplers. The sample programs consisted of two parts: Part A consisted of four samples that were typically collected at shorter time intervals to represent the first flush of contaminants; and Part B consisted of 20 samples collected at a single time step and was intended to represent the falling limb of the hydrograph. Up to 24 samples were collected in 1-L sample bags (Pro-Pak). After a storm event occurred, samples were transported to the main site, where they were heat-sealed, barcode-labeled, and placed in coolers for same-day transport for analysis. Of the maximum 24 samples collected per storm event, typically eight were sent to a local state-certified laboratory for analysis. Analyses conducted were for nitrate as nitrogen (NO_3-N) by the U.S. EPA Analytical Method E300.0A, total phosphorus as phosphorus by Method E365.3, total petroleum hydrocarbons as diesel (TPH-D) by Method 8015B, total suspended solids by Method E160.2, and zinc by Method 6010B (2011).

For all parameters, paired influent and effluent contrasts were conducted by using either the Student's t-test for normal distributions, or a nonparametric test, Wilcoxon rank sum, for nonnormal distributions (significance level of 95%).

Surface Infiltration Capacity

As a measure of PA hydrologic performance, the surface infiltration capacity was measured near-monthly since installation, from 2004 to 2008, to evaluate seasonal variations associated with temperature. The test performed was similar to that used by Bean (2005), a modification of an ASTM Standard D3385-03 (ASTM 1988). A falling head surface inundation (SI) test was used that involved placing a cylinder of known diameter onto the pavement surface, which was then sealed to the pavement surface (Briggs 2006). The cylinder was situated within a platform base and lined with pliable foam to achieve a seal when weighted. Water was poured into the cylinder up to a predetermined depth and volume, and the time required for all the water to infiltrate into the pavement was recorded. Before January 7, 2008, the SI device used was a 30.5-cm aluminum cylinder, and 18.9 L of water were infiltrated during the test. After this date, the device was modified to a 10.2-cm acrylic cylinder 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 2.1 L (0.56 gal.).

Three locations (A, B, and C) within the 465 m^2 PA surface were tested beginning in November 2004. Point A is a fast-infiltrating location in the south corner of the lot. Point B is a medium- to high-infiltrating location in a drive lane. Point C is a low-infiltrating location relative to Points A and B and is situated at the exit from the parking lot. Location C near the entrance of the site exhibited an infiltration rate that was too slow to be accurately represented by the SI test as a result of leakage during the test. In response to this problem, a modified double-ring infiltrometer (DRI) test was used 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 because of dual columns of infiltrating water. Constant temperature water was used for IC testing. Seasonal temperature-related viscosity effects were not examined; however, if water at the freezing point was used, then the IC value could be expected to be smaller by a factor of 1.82 (Mays 2001).

Frost Depth

Frost depth is defined as the depth below the pavement surface to which subfreezing temperatures exist. This was quantified in the PA pavement by using a frost gauge (Ricard et al. 1976). The frost gauge assembly was placed in a groundwater monitoring well, a 2.5-cm-diameter PVC pipe, fully screened and approximately 1.22 m deep. The well casing was stubbed into a road box and capped. Frost depth measurements for 2005 and 2006 were conducted routinely throughout the winter and on occasion before and after winter rain events. Outside air temperature and air pressure were recorded at a nearby outdoor location.

Water Balance Analysis

A water balance analysis was conducted for the study by measurement of precipitation depth in contrast to effluent flow volume from the subdrains. The total watershed area includes some fringe landscaping (520 m^2). The water balance analysis was performed for an 18-month period from April 1, 2005, to September 30, 2006. Precipitation and effluent were summed monthly, and their cumulative volumes were compared over time. A monthly ratio of precipitation to effluent volume was also computed.

Hydrologic Efficiency Analysis

Hydrologic performance was evaluated by examining hydrograph transformations as measured by the peak flow reduction coefficient (k_p), lag time, and lag coefficient (k_L) (Hood and Clausen 2007). The peak flow reduction coefficient is defined as the ratio of peak flow for the effluent to the maximum event precipitation intensity (weighted for the watershed area). Lag time was calculated as the difference between time at the effluent volume centroid and time at rainfall volume centroid. Lag coefficient is calculated as the ratio of effluent volume centroid to precipitation volume centroid.

Results and Discussion

Surface Infiltration Capacity

Observation of trends in IC for the three locations over 3 years indicates no consistent statistical difference for seasonal hydrologic performance (Fig. 1, Table 1). For two representative locations (Locations A and B in Fig. 2), the mean IC was 3,074 and 1,725 cm/h. For Year 1, at both locations a decline was observed in the first season where winter IC was significantly greater than the first summer, not the reverse, as might be expected. Although there exists a slight trend of declining IC for B and C, there was no observable drop for each winter. An overall downward trend in IC was observed for all three locations corresponding to no pavement maintenance or cleaning until September 22, 2007.

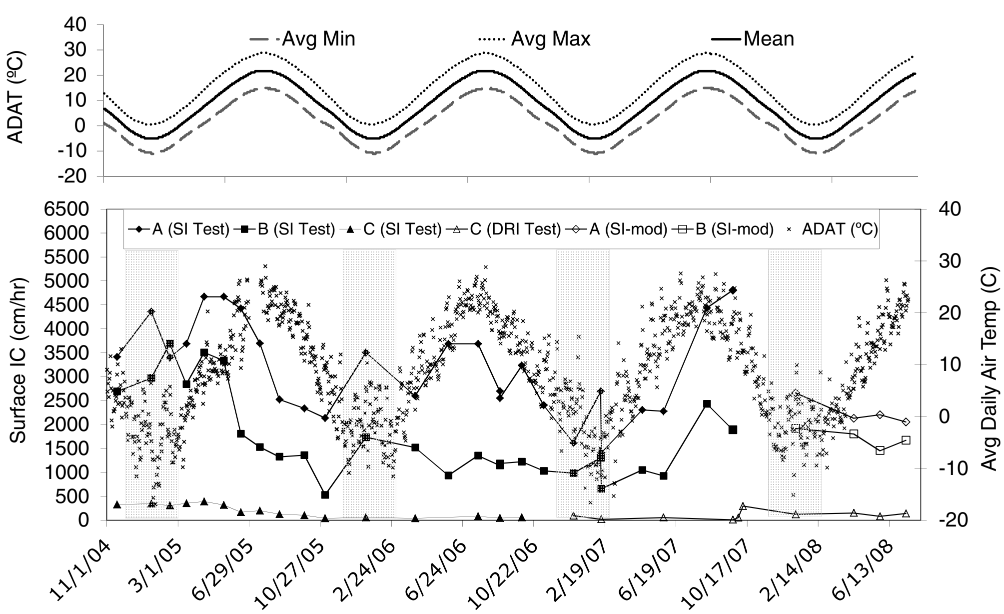

Fig. 1. Time-series plots of porous asphalt surface infiltration capacity (vertical lines indicate winter months) and average daily air temperatures historically and for the monitoring period (2004–2008); SI = surface inundation; DRI = double-ring infiltrometer; ADAT = avg. daily air temp. (pavement cleaning before Sep. 23, 2007, IC measurements)

Table 1. Seasonal Statistical Comparison of Porous Asphalt Surface Infiltration Capacity (in./h) Using Student's t-test

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	n	5	5	3	5	5	3	2	2
	$\bar{x} \pm \sigma$	1,537 ± 228	1,390 ± 421	1,080 ± 274	1,248 ± 211	820 ± 215	1,511 ± 538	943 ± 148	838 ± 42
	COV	0.15	0.30	0.25	0.17	0.26	0.36	0.16	0.05
	Significance	No. $P = 0.451$;		No. $P = 0.457$		$P < 0.05$; $S \gg W$		No. $P = 0.733$	
Location B	n	5	5	3	5	5	3	2	2
	$x \pm \sigma$	1235 ± 171	736 ± 331	496 ± 253	459 ± 59	396 ± 91	688 ± 300	732 ± 33	614 ± 59
	COV	0.14	0.45	0.51	0.13	0.23	0.44	0.04	0.10
	Significance	$P < 0.05$; $W \gg S$		No. $P = 0.808$		No. $P = 0.063$		No. $P = 0.569$	
Location C	n	5	5	3	3	2	4	2	2
	$x \pm \sigma$	345 ± 32	183 ± 83	45 ± 11	60 ± 19	23 ± 21	41 ± 51	54 ± 8	44 ± 18
	COV	0.09	0.46	0.23	0.31	0.91	1.24	0.15	0.40
	Significance	$P < 0.05$; $W \gg S$		No. $P = 0.713$		No. $P = 0.666$		No. $P = 0.829$	

Note: W = November–April; S = May–October. In all time periods, measurements were made using surface inundation tests. Exceptions were for Locations A and B for November 2007–July 2008, where a modified surface inundation test was used, and for Location C for November 2006 and later, where a double-ring infiltrometer (DRI) was used.

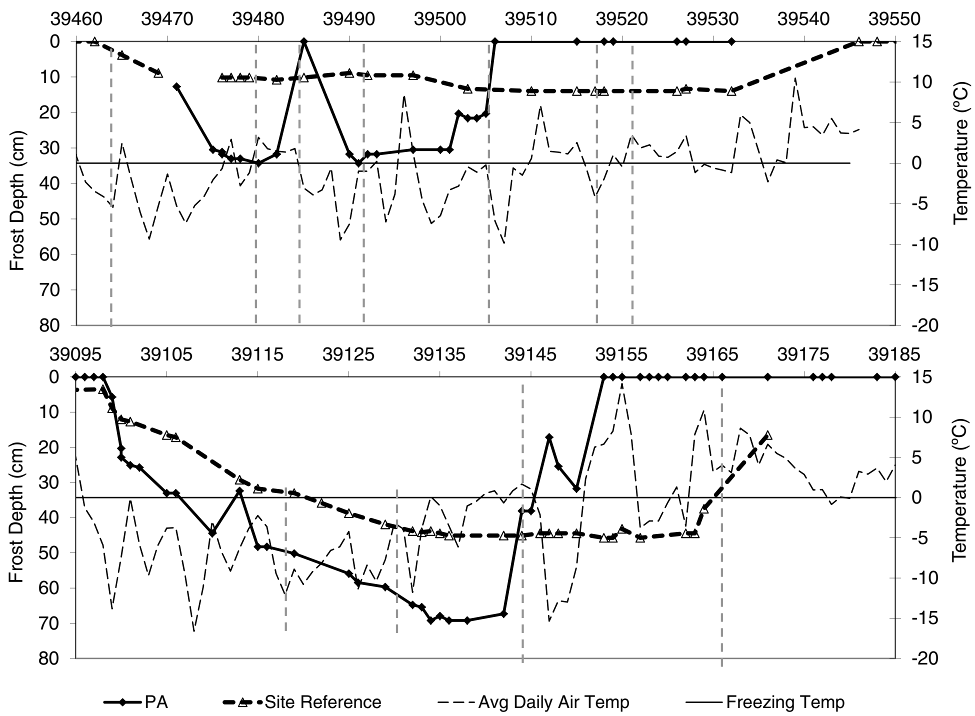

Fig. 2. Frost depth for Winter 2006–2007 (bottom) and 2007–2008 (top); rain events = vertical dashes

The initial decline of IC the summer following installation is supported by Ferguson (2005), who hypothesized that reduction is because of asphalt binder draindown during hot summer months. The PA installation for this location did not include fibers or polymer modifiers, both of which are used to minimize draindown to less than 0.3% (NAPA 2003). Analysis of draindown within the asphalt cores taken at the three locations ranged from 0.3 to 0.45%. Mean in-place draindown was determined by measurement of the asphalt content in the top and bottom halves of the cores to be 4.7 and 5.1%, respectively ($n = 18$). The draindown was apparently limited to the first summer because no equivalent decline in IC was observed for the 2 years following. The initial substantial reduction in summer IC rebounded with the onset of cooler weather. In fact, periods thereafter begin to reflect changes in IC that mirror changes correlated with the cyclical trend of average daily air temperature (ADAT) to some degree.

Several laboratory studies have suggested that the IC of porous asphalt may decline by approximately 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 February 12–13, 2007, demonstrate the effect of air temperature on IC. During this time, the ADAT decreased from −4.4°C to −11.7°C, and the average IC of Locations A and B

Table 2. Hydraulic Performance Summary for 17 Storm Events

		Precipitation					Peak flow reduction				Effluent delay		
Event no.	Date	Storm duration (min)	Prior rainfall[a] (day)	Storm depth (cm)	Peak intensity (cm/5 min)	Storm volume (L)	Peak precip. (cmskm)	Peak Eff Flow (cmskm)	k_p	Precip. centroid (min)	Effluent centroid (min)	Lag time (min)	k_L
1	4/20/05	480	5.9	1.47	0.10	7,665	3.1	0.1	0.04	220	2,690	2,470	12.2
2	5/7/05	965	4.0	1.60	0.03	8,323	0.8	0.2	0.20	410	1,855	1,445	4.5
3	5/21/05	1150	3.0	2.31	0.05	12,025	1.6	0.2	0.15	460	1,780	1,320	3.9
4	8/13/05	765	10.0	1.30	0.20	6,737	6.3	0.0	0.01	360	2,985	2,625	8.3
5	9/15/05	630	10.0	2.26	0.46	11,760	14.2	0.0	0.00	545	1,500	955	2.8
6	10/8/05	1865	8.0	12.7	0.25	66,060	7.9	2.8	0.36	965	1,480	515	1.5
7	11/30/05	805	5.0	1.75	0.08	9,118	2.4	0.3	0.14	535	1,100	565	2.1
8	12/16/05	625	5.5	3.51	0.15	18,232	4.7	0.5	0.11	425	915	490	2.2
9	1/12/06	300	5.8	1.17	0.10	6,079	3.9	0.2	0.06	185	1,700	1,515	9.2
10	3/13/06	1415	2.5	2.34	0.10	12,154	3.2	0.5	0.16	660	1,855	1,195	2.8
11	5/2/06	2130	7.0	7.59	0.15	39,504	4.7	0.5	0.11	1,005	1,915	910	1.9
12	6/1/06	1035	10.7	6.25	1.04	32,502	32.3	1.7	0.05	320	1,100	1,195	3.4
13	11/8/06	465	5.0	0.79	0.05	4,096	1.6	1.4	0.89	190	1,270	1,080	6.7
14	12/23/06	1020	7.5	3.07	0.08	15,987	2.4	0.5	0.23	625	1,935	1,310	3.1
15	1/6/07	760	2.5	1.27	0.08	6,606	2.4	0.3	0.11	645	1,290	645	2.0
16	3/11/07	430	7.0	0.71	0.03	3,699	0.8	0.2	0.20	215	2,715	2,500	12.6
17	4/12/07	590	6.0	0.94	0.03	4,889	0.8	0.3	0.32	235	1,175	940	5.0
Minimum		300	2.5	0.71	0.03	3,699	0.8	0.02	0.002	185	915	490	1.5
25th quartile		590	5.0	1.27	0.05	6,606	1.6	0.2	0.1	235	1,270	910	2.2
Median		765	5.9	1.75	0.10	9,118	3.1	0.3	0.1	425	1,700	1,195	3.4
75th quartile		1,035	7.5	3.07	0.15	15,987	4.7	0.5	0.2	625	1,915	1,445	6.7
Maximum		2,130	10.7	12.7	1.04	66,060	32.3	2.8	0.9	1,005	2,985	2,625	12.6
Average		908	6.2	3.00	0.17	15,614	5.5	0.58	0.2	471	1,721	1,275	5.0
St. dev.		503	2.5	3.13	0.25	16,291	7.7	0.74	0.2	252	605	677	3.6

Note: k_p = peak reduction coefficient, the ratio of peak effluent flow to peak rate of precipitation integrated over watershed area; k_L = lag coefficient, the ratio of the effluent centroid to the precipitation centroid; cmskm = $m^3/s/km^2$.

[a]Prior rainfall calculated as the time in days of antecedent dryness since a minimum 0.1-in. storm event, using the UNH Weather Station gauge. All precipitation falling within 6 h counts as the same storm event.

decreased from 2,000 to 1,030 cm/h in 24 h. The apparent correlation of IC with air temperature continued until April 2008, when the IC rates at Locations A and B stabilized around 2,160 and 1,650 cm/h, respectively. This final trend change is partly because of the modification of the SI testing device (SI-mod). The low-infiltrating area at Location C had low IC since installation because of quality control production problems resulting in a lower percentage void space.

Vacuum maintenance of this PA parking lot occurred only once, on September 22, 2007, and was completed with a combination of an Elgin Whirlwind MV vacuum sweeper and pressure-washing. Pressure-washing was limited to substantially clogged areas with a low-pressure hand wand (3,550 kPa) directed at a low angle to the pavement surface. The lot was routinely plowed and deiced with a sand and salt mixture (~10% sand).

Frost Depth

Depth of frost penetration was observed for the winter seasons of 2006–2007 and 2007–2008 (Fig. 2). Frost depth within the systems is plotted against average daily air temperature and frost depth at a reference location in adjacent soil. Rain events, as occurrences, are plotted as vertical dashed lines. Reliable patterns of freeze and thaw were observed for the two winters and generally reflected a more rapid response to changes in ambient air temperature, in comparison to the reference site located in an adjacent unpaved surface. The same response is not observed in the reference location, likely because of a lack of infiltration of meltwater. The degree of response has not been examined with respect to rain depth or other important factors. Rain events occur throughout the winter and are commonly mixed with snow and ice. The depth of frost penetration was much greater, and the timing of the spring thaw occurred sooner than at the reference location. The frequency and rate of thaw was also greater than the reference site. The porous asphalt thawed completely and refroze repeatedly throughout the winters. The midwinter thaws occurred during episodes of warming and rainfall events in which the infiltration of rainfall and meltwater thawed the frozen filter media. This phenomenon was observed on four occasions during 2008 and one occasion during 2007. The porous pavement thawed completely nearly 30 days earlier than the reference site for both winters. Frost depth trends lagged behind air temperature by a few days, and commonly, the combination effects of ambient air temperature warming followed by rainfall could be observed to thaw the pavement. An example of a rainfall and ambient temperature thaw occurred beginning on March 1, 2007, with warming and rainfall with a frost depth of 69 cm, followed by a number of very cold days and increased frost depth, followed by additional warming and a complete thaw over only 11 days. In contrast, the reference site showed almost no variation at half the depth and remained frozen for almost another 30 days.

Hydrologic Performance and Water Balance

Rainfall and hydrologic performance characteristics of the pavement are presented in Table 2. The water balance was determined for 14 months from April 2005 to June 2006. Peak monthly precipitation volumes were observed in October 2005 (152 m^3) and May 2006 (208 m^3). Minimum monthly precipitation was observed in March 2006 (13.3 m^3). From a storm-water management perspective, it is desirable to have a reduced peak-flow reduction coefficient (k_p), increased lag time, and increased lag coefficient (k_L) relative to unattenuated runoff from impervious surfaces. The PA effluent met these criteria for all storm events considered in this analysis, similar to what might be expected from a shallow flow groundwater signal in small streams. Ideally, storm-water management technologies minimize changes to the hydrologic predevelopment conditions. Fig. 3 depicts rainfall and actual effluent flow in comparison with a rationally derived synthetic flow for a 6.25-cm rainfall event. Fig. 4 illustrates peak-flow performance normalized by the site footprint. Peak flow was reduced significantly in all storm events ($p = 0.009$, at 95% confidence, $n = 17$) with standard pavement flows $\bar{x} = 502\ m^3/s/km^2 \pm 704$ versus flows from the PA lot $\bar{x} = 0.58\ m^3/s/km^2 \pm 0.74$. Even during very large storm events exceeding the 2-year storm (6.35 cm in 24 h), substantial lag time and peak flow reduction were observed. The lag time was increased substantially for all events with an average of 1,275 min.

For the 18-month period (April 1, 2005, to September 30, 2006) that the water balance was determined, a net cumulative recharge was observed for a site located on a hydrologic soil group type C soil. Water balance monitoring began 6 months after site installation. No surface runoff occurred for any storm event, including a 12.7-cm rainfall event. All effluent occurred through subdrains located within the pavement system. Cumulative precipitation increased at a rate greater than cumulative effluent for most of the study period. Cumulative recharge was negative for the first 3 months of the study period, ending in late July 2005. Groundwater was not believed to be a factor in the water balance because water levels in groundwater wells never reached the base elevation of the PA subbase reservoir. By August 2005, the system had a net recharge. By September 30, 2006, precipitation volume totaled 1,220 m^3 and effluent volume totaled 920 m^3, resulting in a net cumulative recharge volume of 299 m^3 (representing a depth of 57.9 cm), which accounted for 25% of cumulative precipitation for the entire study period. Evaporation of groundwater upward through the pavement is unlikely to be significant because of the installation of a capillary barrier (Mays 2001). During months with the greatest precipitation (October 2005, May 2005, and June 2006), precipitation exceeded the effluent volume. Potential sources of error for the water balance include snowmelt onto the pavement footprint and snowplowing outside of the footprint.

Examination of Water Quality

Real-time water quality for specific conductivity (SC), dissolved oxygen (DO), pH, and temperature was analyzed for the 17 storm events. SC was significantly higher in the effluent ($\bar{x} = 1{,}180$ uS/cm) than the influent ($\bar{x} = 415$ uS/cm) (paired t-test $p = 0.0358$, $n = 17$). During storm events, there were predictable patterns observed; influent SC dropped once flow began and then gradually increased back to the prestorm level as flows dissipated. Conversely, effluent specific conductivity increased rapidly once flow began and then gradually decreased to prestorm

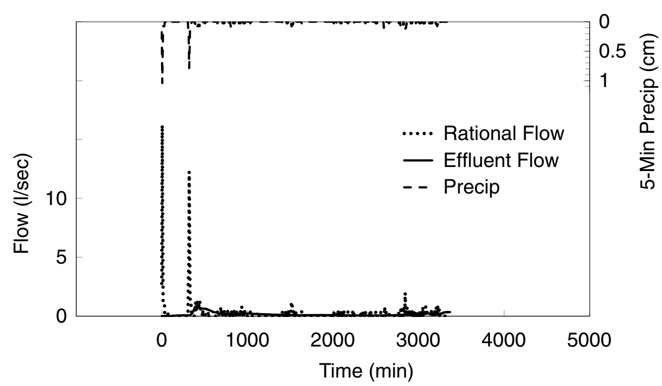

Fig. 3. Hydrologic performance contrasting synthetic rational runoff with effluent flow for 6.25-cm rain event on Jun. 1, 2006

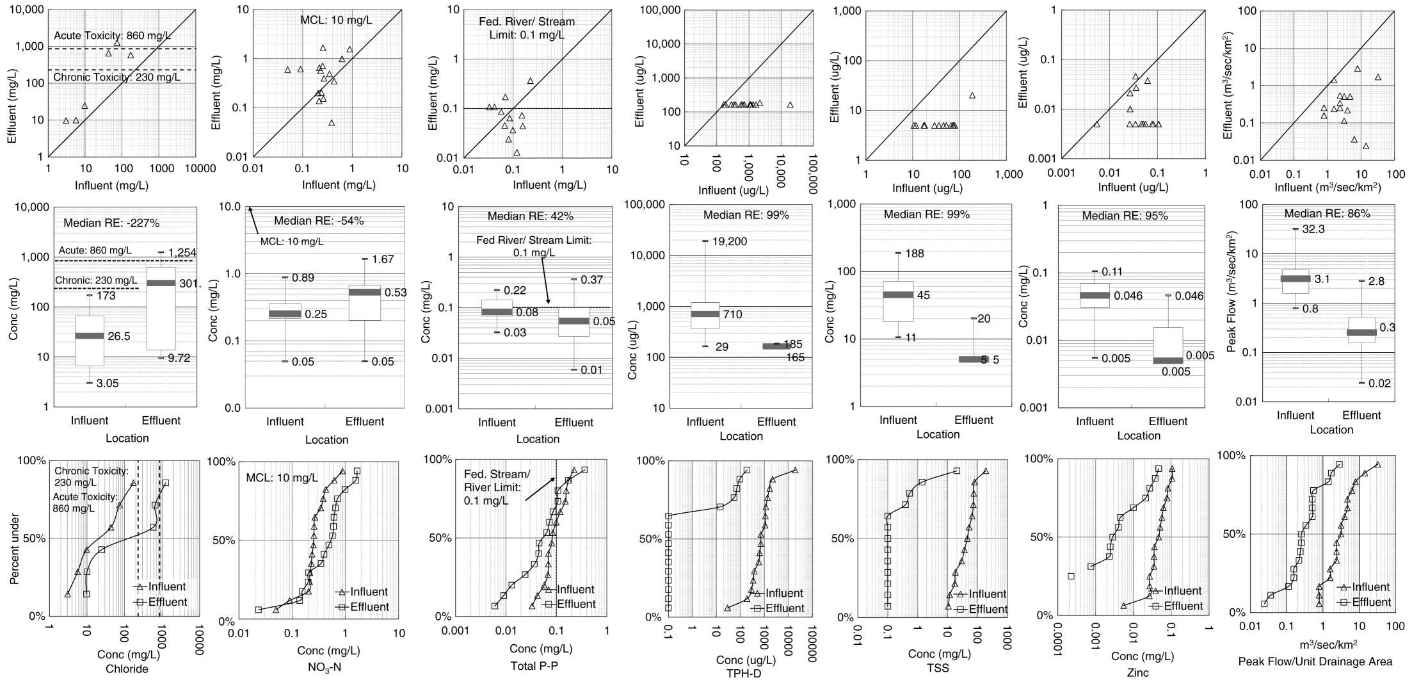

Fig. 4. System performance interquartile distribution and effluent probability plots

levels as flow decreased. DO was not significantly different between influent and effluent ($p = 0.1152$, $n = 17$). Effluent DO was usually slightly lower than influent DO. Effluent pH was significantly greater than influent with a notable buffering effect with a median = 7.1 and 6.1, respectively ($p < 0.0001$). There was no significant difference in median temperatures observed for the influent and effluent, 10.4°C and 9.8°C, respectively ($p = 0.7038$, $n = 17$).

Many EMC values were found to be below detection limits. Values below detection limits are reported and analyzed here as half the detection limit. Fig. 4 presents EMCs interquartile ranges with box and whiskers diagrams and cumulative probability distributions. Treatment for nitrate was significantly poor ($p = 0.0032$, at 95% confidence, $n = 16$) because effluent nitrate ($\bar{x}_{NO3} = 0.31$ mg/L $\pm$ 0.20) was greater than influent ($\bar{x}_{NO3} = 0.58$ mg/L $\pm$ 0.48) for all but two storm events (November 30, 2005, and December 16, 2005), in which little to no treatment was observed. This is to be expected because removal of nitrate typically only occurs with vegetated filtration (Roseen et al. 2006). Additionally, total phosphorous EMC reduction was not significant ($p = 0.649$, at 95% confidence, $n = 14$) with influent $\bar{x}_{TP} = 0.10$ mg/L $\pm$ 0.06 and effluent $\bar{x}_{TP} = 0.08$ mg/L $\pm$ 0.09. Total petroleum hydrocarbons (TPH-D) reduction was significant ($p = 0.069$, at 90% confidence, $n = 16$), with all but one effluent EMC below detection limits (320 ug/L). TPH-D treatment performance during the June 1, 2006 storm event was exceptional with the influent EMC = 19,204 ug/L, and the effluent was not detected. Influent $\bar{x}_{TPH-D} = 1970$ ug/L $\pm$ 4630, and effluent $\bar{x}_{TPH-D} = 166$ ug/L $\pm$ 5.

Treatment reduction for TSS was very significant ($p = 0.002$, at 95% confidence, $n = 13$) with only one effluent event above detection limits (10 mg/L). Influent $\bar{x}_{TSS} = 54$ mg/L $\pm$ 47, and effluent $\bar{x}_{TSS} = 6$ mg/L $\pm$ 4. The October 8, 2005, storm event was exceptionally intense, and storm depth was greater than 12.7 cm over several days. The June 1, 2006, storm event was the most intense storm witnessed to date at the UNHSC, resulting in high mobilization of TSS at the influent (EMC = 188 mg/L) and resulted in an effluent EMC = 20.3 mg/L. The source of TSS during this storm was most likely fine subgrade materials (clays) that passed through the geotextile filter fabric. Turbidity was also observed during an intense 7.6-cm storm on October 11, 2006 (maximum intensity of 2.54 cm/h per 5-min interval). Turbidity in the effluent was not observed at other times. Zinc reduction was also significant ($p = 0.001$, at 95% confidence, $n = 15$). Zinc effluent concentrations were below detection limits 66% of the time (0.01 mg/L). Influent $\bar{x}_{Zn} = 0.052$ mg/L $\pm$ 0.030, and effluent $\bar{x}_{Zn} = 0.013$ mg/L $\pm$ 0.014.

Summary and Conclusions

The porous asphalt pavement system performed impressively as a storm-water management strategy despite cold-climate challenges. The pavement system function remained strong for hydraulics and water quality during the coldest periods of the year. Dissolved anionic contaminants, such as nitrate and chloride, showed no removal, as is typical for nitrate for nonvegetated filtration systems and dissolved chlorides. Phosphorous removal, which is always challenging, was only partial (42% removal efficiency). Cationic and undissolved contaminant removal was nearly complete for TPH, zinc, and TSS. Surface infiltration capacity remained high year-round (2,030 cm/h) despite substantial observed frost penetration (maximum 71 cm). The persistence of infiltration capacity during periods of prolonged frost penetration indicates that the coarse open-graded materials retain significant porosity and remain well-drained throughout the year.

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