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A SIDE-BY-SIDE COMPARISON OF PERVIOUS CONCRETE AND POROUS ASPHALT[1]

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ABSTRACT: This article compares the performance of two permeable pavements, pervious concrete and porous asphalt, that were installed side-by-side in fall 2007. Because the pavements are located directly adjacent to one another, they experience the same vehicle loads, precipitation, and pollution loads. These permeable pavements are part of an infiltration stormwater control measure (SCM). This article focuses on the comparison of water quality parameters, maintenance and durability, and user perception. Eleven different water quality parameters were analyzed at this site for 19 different storm events over a one year period: pH, conductivity, total suspended solids, chlorides, total nitrogen, total phosphorus, total dissolved copper, total dissolved lead, total dissolved cadmium, total dissolved chromium, and total dissolved zinc. Results from the two pavement types were compared using the Mann–Whitney *U*-test. The only parameter that was found to be statistically different between the two pavements was pH. Periodic inspection of the two pavement types indicated that after two years of use both pavements were wearing well. However, there was some evidence of clogging of both pavements and some evidence of surface wear. A survey of users of the lot indicated that the perception of these permeable pavements was favorable.

(KEY TERMS: best management practices; nonpoint source pollution; stormwater management; infiltration; urbanization; permeable pavements.)

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INTRODUCTION AND BACKGROUND

A shift in the methods used to manage stormwater (National Resource Council, 2008) has increased the use of permeable pavements as a means to promote infiltration. The goal of these stormwater control measures (SCMs), which are also called stormwater best management practices (BMPs), is to alleviate the detrimental effects of development by restoring the hydrologic cycle. Permeable pavements include pervious concrete, porous asphalt, permeable pavers, and proprietary products manufactured from recycled materials such as tires and glass. This article focuses on a comparison of two of the most commonly used permeable pavements: pervious concrete and porous asphalt.

Pervious concrete and porous asphalt are similar to their relatively impermeable counterparts. The main difference between permeable and traditional pavements is the screening of aggregate to remove the fines (Pennsylvania Department of

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Environmental Protection, 2006). Although both permeable pavement types were developed in the 1970s, their use has only recently become more widespread (Tennis *et al.*, 2004; Ferguson, 2005). Pervious concrete typically has a porosity between 20 and 30% and an infiltration rate of 7-20 m/h (Tennis *et al.*, 2004). The porosity of porous asphalt generally ranges between 16 and 25% and a typical infiltration rate is 35 m/h (Schaus, 2007). There is a tradeoff between strength and porosity and it is up to the designer to determine which parameter takes precedence (Delatte *et al.*, 2007).

The impermeability of traditional asphalt pavements contributes to the movement of pollutants from the traditional to the permeable pavements (Gilbert and Clausen, 2006). The exported pollutants are dependent upon the pavement material used, the location of the permeable pavement, and the vehicular traffic (if any) found on the site. The sources of roadway and parking lot pollutants come from the pavements themselves, vehicles, litter, and spills onto the roadway surface. Vehicles provide a large percentage of the pollutants through tire wear, fuel losses, lubrication losses, and exhaust emissions. The land environment surrounding the pavements will also convey pollutants to the pavements. These pollutants come in the form of nutrients, pesticides, and deposits from the atmosphere (Barrett *et al.*, 1995; National Resource Council, 2008). The U.S. Environmental Protection Agency (USEPA) (1983) studied urban runoff from locations across the nation, and found that metals such as copper, lead, and zinc were detected in more than 90% of the stormwater samples. Organic chemicals were found in more than 10% of the samples.

Previous research has shown that permeable pavements are effective at reducing the pollutant concentrations found in runoff. For example, the concentrations of nitrogen, copper, and phosphorus were reduced by more than 90% from inlet to outlet at an SCM that utilized pervious concrete in a pedestrian area (Kwiatkowski *et al.*, 2007; Horst *et al.*, 2011). Legret and Colandini (1999) and Rushton (2001) reported a reduction in metals concentration for runoff that infiltrated porous asphalt. Chlorides, of course, present a problem for all SCMs as they are conservative and are flushed through the system. Kadurupokune and Jayasuriya (2009) attribute much of the pollutant reduction to the trapping of sediments, to which the pollutants are attached, in the pore spaces of the permeable pavements. However, pollutants are also likely to sorb to the aggregate in the infiltration beds beneath the pavements and in the natural soils found beneath the infiltration beds (e.g., Pitt *et al.*, 1994; Prakash, 1996; Mikkelsen *et al.*, 1997; Kwiatkowski *et al.*, 2007).

RESEARCH OBJECTIVES

The overarching goal of this research was to holistically compare two permeable pavements, pervious concrete and porous asphalt. To achieve this goal an existing traditionally paved parking area for faculty on Villanova University's campus was demolished and replaced with an infiltration bed that was overlain by the two pavement types. The two pavement types were evaluated by comparing water quality parameters, maintenance requirements, durability, and public perception. Eleven different water quality parameters were analyzed at this site for 19 different storm events over a one year period: pH, conductivity, total suspended solids, chlorides, total nitrogen, total phosphorus, total dissolved copper, total dissolved lead, total dissolved cadmium, total dissolved chromium, and total dissolved zinc. The maintenance requirements and durability were assessed by performing periodic inspections. The faculty using the lot were asked to participate in an on-line survey to ascertain their perceptions of the pavements.

SITE DESCRIPTION

The infiltration SCM that is the focus of this study is part of a research and demonstration park that has been created on Villanova's campus as part of the research efforts of the Villanova Urban Stormwater Partnership (VUSP). Villanova University is located in southeastern Pennsylvania and is about 15 miles west of Philadelphia. The site was selected primarily because it was not slated for development under the university's master plan and there were no known utilities under the lot. A secondary reason was that it was a faculty parking area and, as such, would be in use year round.

The drainage area for the site is divided into two sections, one that drains to the pervious concrete and one that drains to the porous asphalt. The drainage areas are roughly equal and consist of conventional asphalt parking areas that are essentially 100% impervious. All planted areas surrounding the study site are separated from the drainage area by curbs, thus limiting the amount of pore clogging sediment reaching the permeable pavements.

The soil underlying the area was classified according to the Unified Soil Classification System as ML: silt with sand (ASTM D2487). No variation in soil properties was found over the test area. Generally, infiltration SCMs are not built on this type of material because it typically has a low hydraulic conductivity; however, it was not possible to place the SCM elsewhere. It is important to note that despite the low hydraulic conductivity of the material, the site is infiltrating water. The geometric design of the infiltration basins for the given project was governed primarily by site and financial constraints. In the parking lot used for the study, an area between two planted traffic islands provided the best area for the placement of permeable pavements. This location dictated the available surface area, 9.1 m by 30.5 m. Half of this area was allotted for pervious concrete and half for porous asphalt. The depth for each infiltration bed ranges from the minimum of 0.5 m (the minimum recommended depth for permeable pavement infiltration beds) to 1.5 m because of the slope of the site, and the desire to keep the bottom of the beds level. Additionally, because of the slope across the site, the pervious concrete bed bottom is located 0.5 m below the porous asphalt bed bottom. The bed geometry and drainage area was dictated by site and financial constraints, not the volume of water to be detained. However, the amount of runoff that can be stored by the infiltration beds is consistent with most designs in the southeastern Pennsylvania area. The infiltration bed geometry provides a volume of approximately 140 m^3. This volume is filled with AASHTO #2 stone (approximately 102 mm in diameter) which has a porosity of 40%. Thus, the storage volume for water is approximately 56 m^3, which is large enough to store the runoff generated from a 84 mm rain event that falls on the 0.07 hectare site. A bed of this size should capture over 90% of the annual runoff. The storage bed was underlain by a geotextile to separate the stone bed from the underlying original soil.

The storage beds under each pavement type were separated to eliminate the transfer of water and contaminants from one bed to the other (Figure 1). This separation was achieved by placing a Jersey barrier covered with a 2 mm geomembrane down the middle of the infiltration bed to create two equally sized infiltration beds.

The storage beds were overlain by the permeable pavements. The mixture design and thickness of the pavements were developed in consultation with National Asphalt Pavement Association (NAPA) and National Ready Mixed Concrete Association (NRMCA). The pervious concrete was 152 mm thick and consisted of stone aggregate, Portland cement, water, and several modifiers. Stone aggregrate (9.5 mm diameter) comprised 78.8% of the mixture, 16.9% of the mixture was Portland cement, and 4.2% was water. A high range water reducer (0.06%), viscosity modifier admixture (0.05%), and set retarding mixture (0.03%) were also added to the mix to improve workability of the concrete. The thickness of the porous asphalt was 63.5 mm and the mix contained a narrow gradation of stone aggregate (95% of the aggregate was between 12.5 and 2.38 mm in diameter), an asphalt binder, and fibers. Of the total mix, 5.8% was a binder, PG 64-22, that is suitable for daily average high temperatures of 64°C and daily average low temperature of 22°C. Finally, the mixture consisted of 0.20% fibers to make the mixture stiffer and to prevent draindown of the asphalt binder. The as-built porosities of the porous asphalt and pervious concrete were 25 and 27%, respectively, which compares favorably to values typically reported for these pavement types (Tennis *et al.*, 2004; Schaus, 2007).

FIGURE 1. Photograph of the Infiltration Beds During Construction. Note the Jersey barrier and geomembrane used to separate the infiltration beds underlying the two pavement types.

METHODS

Monitoring Equipment

The site was extensively instrumented (Figures 2 and 3). Samples for water quality testing were obtained from first flush samplers and pore water samplers in the natural soils under the stone bed.

GKY FirstFlush Samplers (GKY & Associates, Chantilly, VA) were employed to collect the initial runoff from every storm. Four of these first flush samplers were placed along the uphill edge of the project site, two entering the pervious concrete section and two entering the porous asphalt section.

Six pore water samplers (UMS SPE20; UMS, Munich, Germany) were installed under each

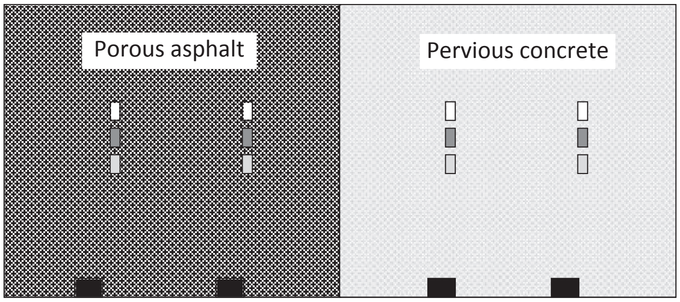

FIGURE 2. Plan View of Site Instrumentation. Includes the GKY FirstFlush samplers (black) and the soil pore water samplers: 15 cm deep (light gray), 30 cm deep (dark gray), and 46 cm deep (white).

pavement to obtain samples from the infiltrated water. Two samplers were placed at three depths below the bottom of the infiltration bed, 15, 30, and 46 cm. The plastic tubes for the samplers were run through conduit to sample containers located near the observation manhole on the pervious concrete side.

A tipping bucket rain gauge, located on the roof of an adjacent building, Mendel Hall, was used to measure the amount of rainfall at the site (http://www.wunderground.com/US/PA/Villanova.html). The rain gauge measured the amount of rainfall every 10 min.

Pre-storm Preparations

Samples were obtained for water quality testing for all rain events that exceeded 6.35 mm of rainfall in an 8-h period. The first flush samplers were prepared prior to any precipitation by placing a clean, acid washed, first flush insert into the sampler. The pore water samplers were prepared for sample collection after a minimum of 4.1 mm of precipitation had fallen. To prepare the pore water samplers, 500 ml Nalge-Nunc heavy-duty vacuum bottles were attached to the filling/venting caps. Using a hand vacuum pump, a vacuum of 70-82 kPa was applied to each bottle. The bottles were then left for 24-36 h to ensure that a sufficient amount of sample had been obtained.

Water Quality Testing

For each stormwater sample that entered the laboratory, approximately 50 ml were allocated for nutrient, chlorides, pH, and conductivity testing. In addition, 300 ml were allocated for suspended metals, total dissolved, and total suspended solids testing, while 20 ml was allocated for dissolved metals testing.

Each of the stormwater samples were analyzed for pH, conductivity, total nitrogen, total phosphorus, total dissolved solids, dissolved cadmium, dissolved chromium, dissolved copper, and dissolved lead. For samples that were below the detection limit (Table 1) for the respective test a value of half of the detection limit was used (Smith, 1991).

There were a total of nine samples that were collected for each storm event. Those samples were two first flush samples for each surface and five soil pore water samples between each surface. In the case where there were two samples collected for the same surface at the same depth, the average was taken. The averaging of the samples provided a representative sample of what was entering the infiltration bed, and to ensure that there were no wide variations a nonparametric test was performed, which showed no statistical difference between samples for any of the water quality parameters tested. The following notation will be used to designate each sample: AFF: asphalt first flush, CFF: concrete first flush, AP15: pore water from 15 cm below porous asphalt, AP30: pore water from 30 cm below porous asphalt, CP15: pore water from 15 cm below pervious concrete, CP30: pore water from 30 cm below pervious concrete, and CP46: pore water from 46 cm below pervious concrete. A sample from AP46 was

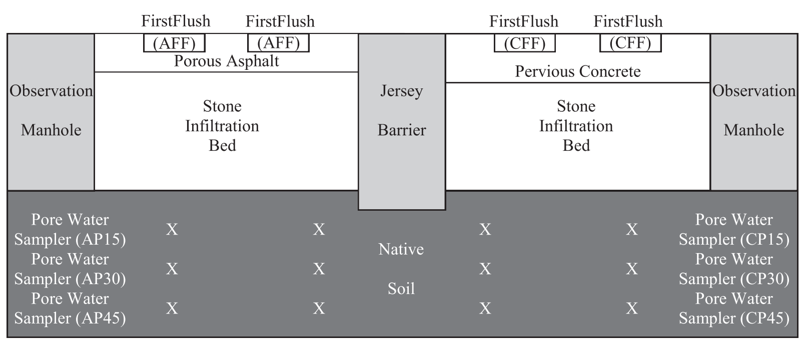

FIGURE 3. Cross-section View of Site Instrumentation. FF indicates first flush sampler, A or C indicates concrete or asphalt, P indicates pore water sampler, and the number indicates depth.

TABLE 1. Minimum Detection Limits.

Test Parameter	Units	Laboratory Method	Minimum Detection Limit
pH		Sension Model 51935-00 Gel-filled pH Electrode*	3.0
Conductivity	μS/cm	Sension Model 51935-00 Gel-filled pH Electrode*	0.0
Total nitrogen	mg/l	Persulfate Digestion Hach # 10071*	1.7
Total phosphorous	mg/l	PhosVer3 with Acid Persulfate Digestion Hach # 8190*	0.06
Dissolved copper	μg/l	Modified Method 7010	2.8
Dissolved lead	μg/l	Modified Method 7010	4.8
Dissolved chromium	μg/l	Modified Method 7010	2.2
Dissolved cadmium	μg/l	Modified Method 7010	0.5
Dissolved zinc	μg/l	Modified Method 7010	4.8
Total dissolved solids	mg/l	Standard Methods	0.0

*Hach Company, Loveland, CO.

attempted, but a water quality sample was never recovered due to equipment malfunction.

Statistical Evaluation

Descriptive statistics, such as the sample count, maximum value, minimum value, mean, and standard deviation for each sample and an average first flush value for both the pervious concrete and porous asphalt surfaces, were calculated using the analytical program SPSS© (IBM, Armonk, NY). Outliers were determined using the box plot outlier test; if a sample had a value that was 1.5 times the range between the 25 and 75 percentile, it was excluded. A total of 10 data points were removed because they failed the outlier test (Table 2).

A nonparametric two independent sample Mann–Whitney *U*-test was performed to compare the samples of the porous asphalt side to the samples from the pervious concrete side to determine if there was a statistical difference between the water quality measurements. The Mann–Whitney *U*-test determines equality of the population means between two samples to determine whether two sampled populations are equivalent in a given location. The observations from both groups were combined and ranked, with the average rank assigned in the case of ties. The number of ties should be small relative to the total number of observations. If the populations were identical in location, the ranks should be randomly mixed between the two samples. The test calculates the number of times that a score from group one precedes a score from group two and the number of times that a score from group two precedes a score from group one. The Mann–Whitney U statistic is the smaller of these two numbers. The Wilcoxon rank sum W statistic, also displayed, is the smaller of the two rank sums. If both samples have the same number of observations, W is the rank sum of the group that is named first in the Two-Independent-Samples Define Groups dialog box. The Mann–Whitney *U*-test also reports the Z statistic or the location of the data if the distribution was normal.

The Mann–Whitney *U*-test then generates a two-tailed significance value. Each two-tailed significance value estimates the probability of obtaining a Z statistic as or more extreme than the one displayed, if there truly is no effect of the treatment. For the purpose of this study, if any two-tailed significance value is below 0.05, the samples are considered statistically different. If any two-tailed significance value is >0.05, the samples are considered statistically similar.

Inspections

Inspections of each pavement type were conducted periodically. The inspector would perform an infiltration test using the procedure described by Delatte *et al.* (2007). This procedure estimated hydraulic conductivity by measuring the time it took a cylinder filled with water to drain through the pavement. Inspectors would also walk around the site with a

TABLE 2. Data Points Removed After Testing for Outliers.

Test	Total Nitrogen (mg/l)	Dissolved Lead	Dissolved Cadmium
Total number of points eliminated	4	4	2
Date/result eliminated (mg/l)	11/15/2007 — 18.5, 11.7	1/10/2008 — 19.2, 11.8	12/2/2007 — 31.6
	12/2/2007 — 15.8	4/3/2008 — 14.01	12/9/2007 — 21.1
	12/9/2007 — 10.4	4/11/2008 — 19.86	

hose and note on a drawing any locations where clogging, sealing, ponding, icing, spalling, or any other features of interest were observed.

Survey

To determine the public opinion regarding the permeable pavements used in this study, a survey was conducted one year after the permeable pavements were installed. A list of people with a parking tag for the lot was obtained from the University. The tag holders were contacted via email and asked to complete an online survey.

RESULTS AND DISCUSSION

Water Quality

Over a one year period (November 11, 2007 to October 25, 2008) 19 storms were analyzed. These storms ranged in duration from 4 to 96 h, with an average storm duration of 33 h. The maximum 10 min intensity ranged from 6 to 73 mm/h, with an average of 29 mm/h. The total volume of rain for the 19 events varied between 7 and 134 mm, with an average of 38 mm.

pH

The number of samples, range of values, and the average and standard deviation for the seven sample locations are shown in Table 3. The samples collected from the first flush samplers were the most acidic out of all of the samples, with values of approximately 6.9. The pH of the samples taken from the soil pore water samples 15 and 30 cm below the storage bed under the porous asphalt surface were close to neutral, with a pH value of 7.02 and 7.07, respectively. The pH from the soil pore water from 15, 30, and 45 cm below the storage bed under the pervious concrete side were basic having values of 7.41, 7.42, and 7.97, respectively. The Mann–Whitney exact significance value for the 15 cm and the 30 cm depths are 0.043 and 0.025 respectively, which is below 0.10, indicating that the pH of the pore water samples collected at 15 and 30 cm below the pavements are statistically different for the two pavement types (Table 3). As expected, when the pH of the samples from the first flush samplers are compared to each other there is no statistical difference.

Total Dissolved Solids, Conductivity, and Chlorides

Only the chlorides data are presented here (Table 4) because, as expected, the data for the total dissolved solids, conductivity, and chlorides are very

TABLE 3. Statistics for the pH.

Sample	*N*	Minimum	Maximum	Mean	Standard Deviation	Asymptotic Significance
AP15	18	6.35	7.82	7.02	0.38	0.043
CP15	8	6.82	8.12	7.41	0.43	
AP30	15	6.16	7.75	7.07	0.48	0.025
CP30	14	4.71	8.30	7.42	0.90	
CP46	17	5.88	9.78	7.97	0.93	NA
AFF	18	5.48	8.50	6.85	0.81	0.817
CFF	17	5.43	7.93	6.86	0.66	

Note: The effective range is from 3.0 to 14.0.

TABLE 4. Statistics for Chlorides.

Sample	*N*	Number of Values Below the Detection Limit	Minimum (mg/l)	Maximum (mg/l)	Mean (mg/l)	Standard Deviation (mg/l)	Asymptotic Significance
AP15	18	0	1.3	2,674	501	603	0.017*
CP15	10	0	8.7	326	169	114	
AP30	16	1	<0.5	911	277	278	0.405
CP30	14	0	16	5,471	854	1,536	
CP46	17	1	<0.5	1,063	310	335	NA
AFF	19	1	<0.5	9,557	858	2,501	0.612
CFF	18	1	<0.5	2,827	278	736	

Note: The effective range is above 0.5 mg/l.
*Difference due to no samples being collected during the winter of 2007 due to an equipment malfunction.

TABLE 5. Statistics for Total Nitrogen.

Sample	*N*	Number of Values Below the Detection Limit	Minimum (mg/l)	Maximum (mg/l)	Mean (mg/l)	Standard Deviation (mg/l)	Asymptotic Significance
AP15	7	0	1.7	5.2	3.5	1.5	0.175
CP15	3	2	<0.8	5.4	2.3	2.7	
AP30	9	2	<0.8	7.1	3.5	2.2	0.264
CP30	9	1	<0.8	4.5	2.6	1.3	
CP46	10	2	<0.8	7.8	2.5	2.1	NA
AFF	14	2	<0.8	5.6	2.3	1.3	0.823
CFF	13	1	<0.8	7.5	2.9	2.2	

Note: The effective range is above 0.8 mg/l.

similar. The maximum value for the pore water collected 15 cm below the concrete side is the lowest. This abnormally low value is a result of no samples being collected during the winter months, when chlorides are the highest, because of an equipment malfunction. Each sample had high variability; the standard deviations for the samples were sometimes larger than the average value. When the samples from the porous asphalt side were compared to their pervious concrete counterparts using the Mann–Whitney *U*-test no significant difference was found (Table 4). There is no significant difference between the first flush samples and the 30 cm deep samples. While the 15 cm samples are statistically different, that is because the pore water sampler at a depth of 15 cm did not yield any samples during the winter of 2008, thus missing the highest chloride values.

Nutrients: Total Nitrogen and Phosphorous

The descriptive statistics for nitrogen indicate that the averages of all of the samples fall within a similar range (Table 5). The asphalt samples have the highest averages with both samples being very close to 3.5 mg/l. When the averages are compared, the nitrogen level in the native soil is equal to or higher than the total nitrogen being introduced to the system from the watershed. This result supports the findings of Kwiatkowski *et al.* (2007) who reported that the native soil had higher total nitrogen values than did the runoff from the surrounding watershed at a pervious concrete site at the same University. When the concrete and asphalt samples are compared using the Mann–Whitney *U*-test, the nitrogen concentrations from samples obtained 15 and 30 cm below the pavements and from the surface from the first flush are statistically similar (Table 5).

Total phosphorus concentrations varied quite substantially, but the average concentrations were very consistent between samples (Table 6). The first flush samples had the widest variation of average concentration between pavement type, with the concrete side having an average concentration of 0.77 mg/l and the asphalt side average was 0.53 mg/l. The soil porewater samples were all between 0.22 and 0.30 mg/l. One explanation for the consistent values between the pore water samples is that the porewater samplers filter the water through a porous cup preventing sediment and soil particles from entering the tubing. Because phosphorus binds easily to soil, the elimination of the soil particles decreases the insoluble phosphorus values. The first flush samples are not filtered so any soil particles that enter the container are included in the total phosphorus value. The results of the Mann–Whitney *U*-test show there

TABLE 6. Statistics for Total Phosphorus.

Sample	*N*	Number of Values Below the Detection Limit	Minimum (mg/l)	Maximum (mg/l)	Mean (mg/l)	Standard Deviation (mg/l)	Asymptotic Significance
AP15	12	2	<0.03	1.03	0.27	0.28	0.421
CP15	5	0	0.07	0.34	0.22	0.13	
AP30	11	2	<0.03	0.82	0.30	0.30	0.435
CP30	11	1	<0.03	0.58	0.24	0.17	
CP46	12	0	0.12	0.58	0.26	0.13	NA
AFF	16	0	0.16	2.40	0.53	0.53	0.823
CFF	15	1	<0.03	2.69	0.77	0.75	

Note: The effective range is above 0.03 mg/l.

TABLE 7. Statistics for Dissolved Copper.

Sample	N	Number of Values Below the Detection Limit	Minimum (μg/l)	Maximum (μg/l)	Mean (μg/l)	Standard Deviation (μg/l)	Asymptotic Significance
AP15	12	7	<1.4	9.23	3.07	2.45	0.200
CP15	6	5	<1.4	3.42	1.74	0.83	
AP30	9	5	<1.4	8.24	3.19	2.55	0.189
CP30	10	3	<1.4	11.65	5.58	3.95	
CP46	10	3	<1.4	12.87	5.61	4.53	NA
AFF	18	2	<1.4	15.65	7.70	3.44	0.235
CFF	18	4	<1.4	22.18	7.07	6.01	

Note: The effective range is above 1.4 μg/l.

is no difference between the total phosphorus concentrations for samples collected at the surface and beneath the two pavement types (Table 6).

Metals: Total Dissolved Copper, Lead, Cadmium, Chromium, and Zinc

The average dissolved copper concentration entering each pavement surface was 7.70 μg/l for the porous asphalt and 7.07 μg/l for the pervious concrete first flush samples (Table 7). The dissolved copper concentrations in the pore water samples were lower than in the first flush. The average copper concentrations in the pore water samples obtained 15 and 30 cm below the porous asphalt were 3.07 and 3.19 μg/l, respectively. On the concrete side, the average copper concentrations from the pore water samplers at 15, 30, and 46 cm were 1.74, 5.58, and 5.61 μg/l, respectively. The average dissolved copper concentration for the two pavement types were compared for statistical difference using the Mann–Whitney *U*-test (Table 7). The results showed no statistical difference between the porous asphalt and pervious concrete for any of the samples.

All of the average values for dissolved lead and chromium fell below the detection limits; thus there is no statistical difference between the two pavements.

TABLE 8. Statistics for Dissolved Cadmium.

Sample	N	Number of Values Below the Detection Limit	Minimum (μg/l)	Maximum (μg/l)	Mean (μg/l)	Standard Deviation (μg/l)	Asymptotic Significance
AP15	13	10	<0.25	2.00	0.44	0.52	0.324
CP15	6	5	<0.25	0.25	0.25	0.00	
AP30	8	4	<0.25	3.30	0.96	1.15	0.824
CP30	9	5	<0.25	5.20	0.93	1.63	
CP46	7	6	<0.25	0.98	0.35	0.28	NA
AFF	18	7	<0.25	5.60	1.04	1.40	0.932
CFF	17	5	<0.25	8.90	0.33	2.16	

Note: The effective range is above 0.25 μg/l.

TABLE 9. Statistics for Dissolved Zinc.

Sample	N	Number of Values Below the Detection Limit	Minimum (μg/l)	Maximum (μg/l)	Mean (μg/l)	Standard Deviation (μg/l)	Asymptotic Significance
AP15	11	2	<2.4	39	17.5	13.0	0.440
CP15	6	2	<2.4	35	12.5	13.1	
AP30	6	1	<2.4	50	23.2	18.6	0.744
CP30	8	2	<2.4	66	20.4	21.4	
CP46	7	2	<2.4	55	19.1	18.3	NA
AFF	16	1	<2.4	1,436	190.6	377.1	0.428
CFF	15	1	<2.4	557	90.4	137.7	

Note: The effective range is above 2.4 μg/l.

TABLE 10. Infiltration Rates of the Permeable Pavements.

	May 2008	August 2008	November 2008	July 2009	August 2009
Concrete — Good Condition	1.1	0.4	0.5	0.5	0.5
Concrete — Poor Condition	0.8	0.0	0.0	0.0	0.0
Asphalt — Good Condition	0.7	0.1	0.1	0.1	0.1
Asphalt — Poor Condition	0.2	0.0	0.0	0.0	0.0

Notes: Values in cm/s as estimated by timing a cylinder of water draining through pavement (Delatte *et al.*, 2007). Good Condition describes pavement area with no clogging. Poor Condition describes pavement area with significant clogging.

Three of the average concentrations for dissolved cadmium fell below the detection limit. For each pavement type, the 30 cm samples and the average first flush samples were above the detection limit with concentrations of 0.96, 0.93, 1.04, and 1.33 μg/l, respectively. No statistical difference was found between the two pavement types (Table 8).

The dissolved zinc concentrations varied greatly from the surface samples to the soil porewater samples (Table 9). The first flush samples had an average concentration of 190.6 and 90.4 μg/l for the porous asphalt and pervious concrete, respectively. The average concentrations of the soil porewater samples were all similar. The Mann–Whitney U-test revealed that

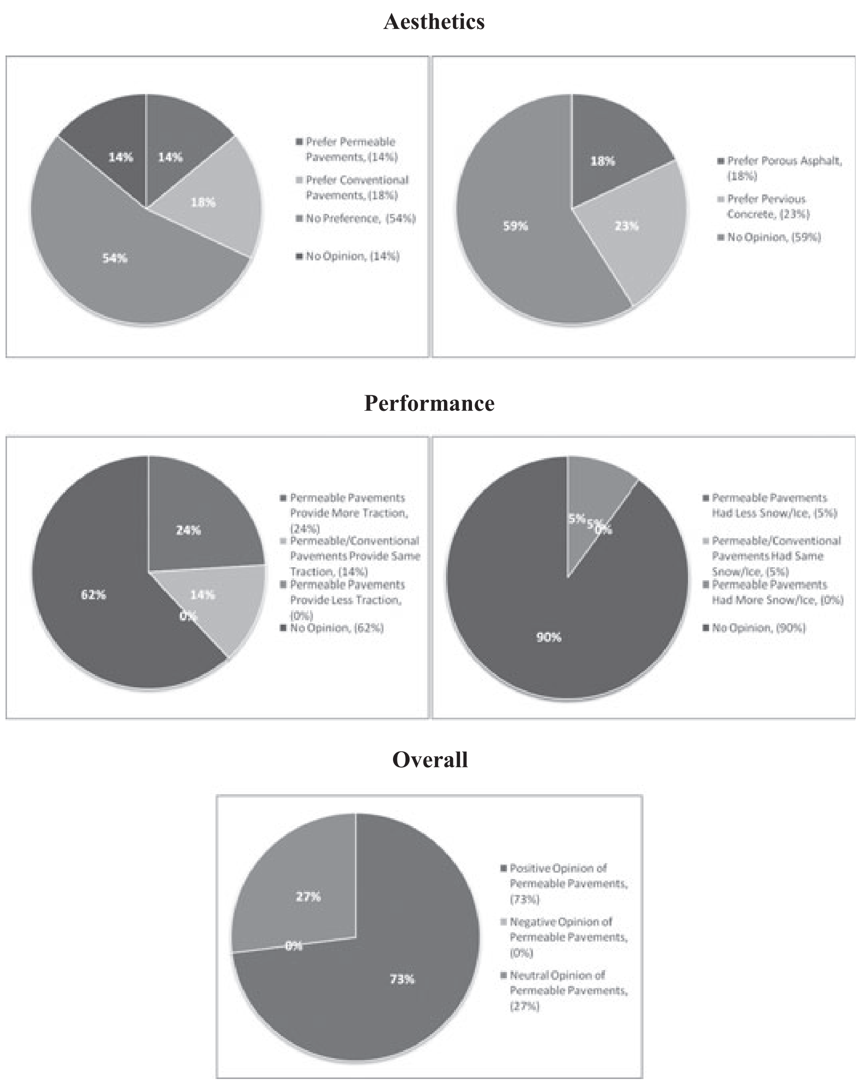

FIGURE 4. Responses to Survey Questions with Regards to Esthetics, Performance, and Overall Opinion.

there was no statistical difference between the pavement types (Table 9).

Maintenance and Durability

Some clogging and oil spots were noted on each pavement type during the site inspections. The infiltration data obtained for each pavement type during the inspections in presented in Table 10. Obviously, clogging has a huge impact on the hydraulic conductivity. Approximately every six months, the site is swept with a vacuum street-sweeper as part of the regular maintenance procedures on campus. An increase in the infiltration rate is observed after the sweeping is completed. Both pavements were wearing well and have not shown significant signs of degradation over the study period.

User Perceptions

Forty-five faculty members held parking tags that would enable them to park on the permeable pavements. Of the 45 faculty members asked to complete the online survey, 22 responded (49% response rate). The questions fell into three categories: esthetics, performance, and the overall opinion of the pavements. The results are summarized in Figure 4.

Esthetics. Survey participants were asked whether they preferred the appearance of conventional asphalt or permeable pavements. Fourteen percent of respondents preferred the look of permeable pavements, 18% preferred the look of conventional asphalt, 54% felt that the pavements looked the same, and 14% had no observation. Additionally, survey participants were asked whether they preferred the appearance of porous asphalt or pervious concrete. Eighteen percent of respondents preferred the look of porous asphalt, 23% preferred the look of pervious concrete, and 59% had no opinion.

Performance. Three questions were asked regarding users experience with the performance of the permeable pavements. Of those surveyed 24% felt that the permeable pavements provided more traction than the conventional asphalt, 14% felt the traction was the same, and 62% had no observation. When asked about the amount of snow and ice on the permeable pavements, 5% respondents felt that there was less snow than on conventional asphalt and 5% stated that the amount of snow and ice was the same as on conventional asphalt. Ninety percent of respondents had no observation. This is likely due to the fact that few snow storms occurred at the site, and those that did occur were nearly a year before the survey was conducted. Finally, survey participants were asked about the roughness of the porous pavements. One hundred percent of those surveyed stated that they had no difficulties associated with the roughness of the pavements.

Overall. The final question of the survey was whether users had a generally positive or negative opinion of the permeable pavement parking lot. Seventy-three percent of respondents had a positive opinion of the parking lot, while 27% had a neutral opinion. No survey participants had a negative opinion of the permeable pavement parking lot. When asked to comment on this, most participants cited the environmental benefits of the project as their reason for having a positive opinion despite no environmental benefits being mentioned in the questions.

CONCLUSIONS

Two permeable pavement types, porous asphalt and pervious concrete, were compared holistically. The two pavements were installed side-by-side in a parking area. From a water quality standpoint, the pavements are nearly identical. The only water quality parameter that was statistically different was pH. This is to be expected as concrete has a lower pH than asphalt. The pavements have not shown significant signs of degradation over the study period and are wearing well. The user perception of the pavements was very positive.

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