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HYDROLOGIC AND WATER QUALITY EVALUATION OF FOUR PERMEABLE PAVEMENTS IN NORTH CAROLINA, USA

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Note: The following is the notation used in this paper: (.) for decimals and (   ) for thousands.

Summary

A permeable pavement parking lot in eastern North Carolina consisting of four types of permeable pavement and standard asphalt was monitored from June 2006 to July 2007 for hydrologic differences in pavement surface runoff volumes, total outflow volumes, peak flow rates, and time to peak, and from January 2007 to July 2007 for water quality concentrations. The four permeable sections were pervious concrete (PC), two types of permeable interlocking concrete pavement (PICP) with small-sized aggregate in the joints and having 12.9% (PICP1) and 8.5% (PICP2) open surface area, and concrete grid pavers (CGP) filled with sand.

All permeable pavements significantly and substantially reduced surface runoff volumes and peak flow rates from those of asphalt ($p<0.01$). Of the permeable pavements, CGP generated the greatest surface runoff volumes ($p<0.01$). The PICP1 and CGP cells generated significantly lower outflow volumes than all other sections evaluated ($p<0.01$), and had the lowest peak flows and the longest time to peak. The response of the PICP1 cell was likely due to an increased base storage volume resulting from an elevated pipe underdrain; whereas, the CGP cell response was attributed to water retention in the sand fill layer.

Overall, different permeable pavement sections performed similarly, but were substantially different from asphalt. The pH of permeable pavement subsurface drainage was higher than that of asphalt runoff ($p<0.01$) with the PC cell having the highest pH values ($p<0.01$). Permeable pavement subsurface drainage had lower NH_4-N ($p<0.01$) and TKN concentrations than asphalt runoff and atmospheric deposition. With the exception of the CGP cell, permeable pavements had higher $NO_{2,3}$-N concentrations than asphalt ($p<0.01$), a probable result of nitrification occurring within the permeable pavement profile. Overall, different permeable pavement sections performed similarly to one another with respect to water quality, but the CGP cell appeared to improve stormwater runoff nitrogen concentrations.

1. INTRODUCTION

Permeable pavements are regarded as an effective tool in managing stormwater. When compared to traditional, impervious asphalt, permeable pavements can reduce runoff quantity, lower peak runoff rates, and delay peak flows due to their high surface infiltration rates [Pratt et al. 1989, Brattebo and Booth 2003, Bean et al. 2007a]. Even in locations where the underlying soil is not ideal for complete infiltration, the installation of underdrain pipes in the permeable pavement base has yielded reductions in outflow volume and peak flow rate, and delayed the time to peak flow [Pratt et al. 1989].

The permeability, evaporation rate, drainage rate, and retention properties of permeable interlocking concrete pavements have been found to be largely dependent on the percent of surface openings and the particle size distribution of the aggregate joint filling and bedding material [Andersen et al. 1999, James and Shahin 1998]. A laboratory study by Andersen et al. [1999], using a 15mm/hr, one hour duration storm, found, on average, that 55% of that simulated rainfall event was retained by a completely dry pavement with a base course depth ranging from 30-70 cm. Pavements that were initially wet retained 30 % of the rainfall, on average. Another study by Pratt et al. [1989] examining permeable pavement stalls lined with an impermeable liner found that parking stalls having various subbase materials displayed subsurface outflow volume reductions from rainfall. This phenomenon was attributed to storage of stormwater on the subbase material surfaces. Rainfall events up to 5 mm produced no subsurface outflow from any pavements evaluated, which were underlain by pea gravel, blast furnace slag, limestone, or granite. The pavements with blast furnace slag were able to retain the greatest amount of runoff, due to the increased surface area of the material.

Pratt et al. [1989] also observed peak flow reductions and delays for permeable pavement fitted with underdrains and an impervious liner. For a rainfall event characterized by 22 mm of rainfall depth and peak rainfall intensity just under 25 mm/hr, permeable pavement peak outflows were roughly 30% of rainfall peak intensities. Permeable pavement subsurface drainage time to peak flows were delayed approximately 5-10 minutes from the peak of rainfall intensity, compared to a 2-3 minute peak flow delay for asphalt runoff. Further, permeable pavement outflows were attenuated to greater extents than what would be expected from traditional asphalt.

A study in Renton, Washington, examined the effectiveness of four different permeable pavements: PICP with open-graded aggregate base, CGP with grass, plastic grid pavers with grass, and plastic grid pavers with aggregate [Brattebo and Booth 2003]. Due to the geographical location of the study, rainfall intensities were lower than those of the Southeast USA, with a maximum 15 minute intensity of 7.4 mm/hr (0.29 in/hr). Most storms had intensities less than 5 mm/hr (0.2 in/hr). Additionally, the in-situ soils underlying the lot were permeable and deep, allowing for rapid exfiltration from the pavement system. The study concluded that with respect to infiltration capabilities and runoff reduction, all permeable pavements performed substantially better than asphalt; however, no substantial differences between permeable pavement types were found.

While substantial research has been performed on metal removal by permeable pavements [Fach and Geiger 2005, Newman et al. 2002], the nutrient removal capabilities of permeable pavements are not well understood. A laboratory water pollution study of various types of concrete grid pavers included analyses on nitrogen and phosphorus removal [Day et al. 1981]. The CGP openings were filled with sod, and underlain with sand and open-graded No. 57 stone limestone aggregate. For 10 simulated rainfall events, the study concluded that there were high phosphorus removal rates, most likely from adsorption to the sand and aggregate. Nitrate-nitrite removal rates were minimal, and high leaching rates to the pavement drainage were observed. In most trials, removal rates of ammonia, organic nitrogen, and total organic carbon were low to minimal.

At a field site in Goldsboro, North Carolina, water quality samples from PICP subsurface drainage were evaluated [Bean et al. 2007b]. Nutrient concentrations from PICP subsurface drainage were compared to those from adjacent asphalt runoff. Total phosphorus (TP), zinc, ammonium-nitrogen (NH4-N), and total Kjeldahl nitrogen (TKN) were all significantly lower in the subsurface drainage. On average, nitrate-nitrogen (NO3-N) in the subsurface drainage was higher than the asphalt runoff.

The objectives of this study were to evaluate and compare hydrologic and water quality differences between permeable pavements and standard asphalt, and differences among various types of permeable pavements for a permeable pavement parking lot sited in clayey soils in Eastern North Carolina. Hydrologic responses of pavement surface runoff, total outflow volume, peak flow, and time to peak were examined. Water quality analyses focused specifically on pH, nutrients, and total suspended solid concentrations and loads. Other than the study conducted in Renton, Washington, USA, this study is unique in literature in that it is a side-by-side comparison of four types of permeable pavements. It is the first study of its kind conducted in a humid, temperate climate zone.

2. SITE DESCRIPTION

A 20-stall employee parking lot was constructed in January 2006 at the City of Kinston Public Service Complex in eastern North Carolina (See Figure 1). The lot was comprised of six 6 m by 18 m pavement sections: two standard asphalt sections each containing two parking stalls and four different permeable pavement sections each containing 4 parking stalls (See Figure 2). The four permeable sections were comprised of the following types of pavement:

- Pervious concrete (PC),
- Permeable interlocking concrete pavers with 12.9% open surface area and openings filled with No. 78 stone (PICP1)
- Concrete grid pavers with 28% surface open areas and opening filled with sand (CGP)
- Permeable interlocking concrete pavers with 8.5% surface open areas and openings filled with No. 78 stone (PICP2).

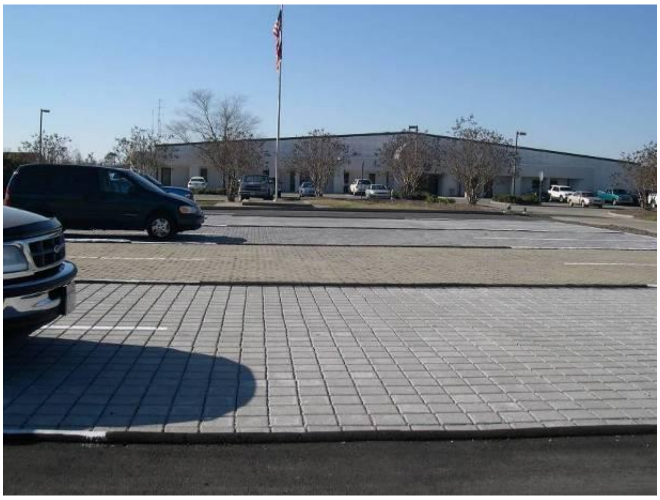

Figure 1. Permeable pavement parking lot at the City of Kinston, NC.

On the ends of both asphalt sections, 3 m x 6 m asphalt entranceways were hydraulically disconnected from the rest of the lot. The lot was surrounded by a concrete curb to prevent any run on from areas surrounding the lot.

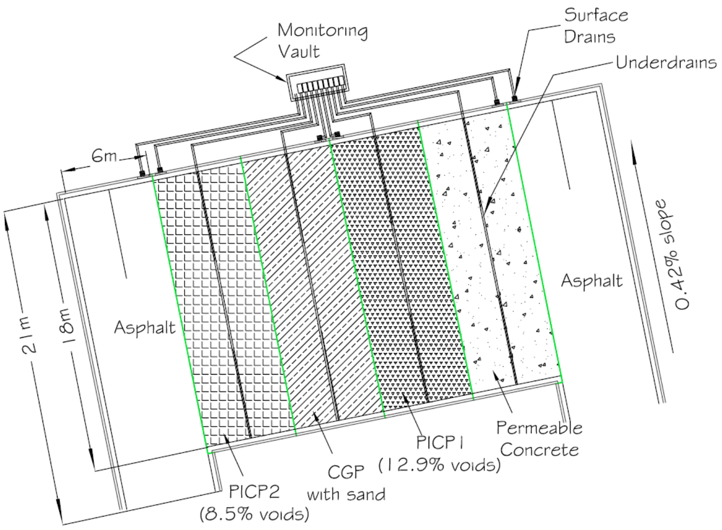

Figure 2. Permeable pavement parking lot design (plan view).

The site investigation found that at a depth of approximately 50 cm, the in-situ soil type changed from sandy loam to sandy clay loam. This depth varied slightly across the lot; however, the change in texture was consistent over the site area. The lower soil horizons had a Unified Soil Classification of CL, SC, and SC-SM [USDA, 2007]. In several locations, iron deposits were observed starting at a depth of 850 mm, probably indicative of a high water table elevation and a confining feature of the lot design. The bottom of the pavement was designed to be above the seasonal high water table.

All permeable sections overlaid a washed ASTM No. 78 stone aggregate bedding layer and a washed ASTM No. 5 stone base course layer, the depths of which varied slightly based on the product specifications of the overlying pavement types. The base course layer was designed to support the expected parking lot traffic loading, estimated as 60 vehicle passes per day. For ease of installation, the excavation depth beneath permeable pavements was kept consistent, so the aggregate storage layer was adjusted for all sections to meet the strength requirements for the section which limited pavement design.

Each pavement section was designed to be hydraulically separate from the other sections. Thirty mil thick (0.75 mm) LLDPE plastic sheeting was trenched between each pavement section to prevent any subsurface flow from one pavement section to the next. The plastic sheet extended from the soil underlying each pavement aggregate base layer to the parking lot surface, where 6.5 cm high asphalt berms were placed to prevent surface flow migration from one pavement section to another.

Due to the low permeability of the in situ soils, perforated corrugated plastic pipe (CPP) underdrains (d=10cm) were installed at the bottom of the each permeable pavement aggregate base course layer to drain water from the system, thereby creating separate “cells.” The aggregate subbase of each permeable pavement section sloped to the corrugated underdrains in the center of each pavement section at a 30:1 side slope. The pavement cells were unlined, to allow for some potential exfiltration of water into the subsoil.

Because design configurations of various permeable pavements differed slightly, the pavements are referred to as cells rather than individual pavement types. Excluding surface runoff, the hydraulic responses of each permeable pavement section were not solely dependent on the pavement type, but rather the entire configuration of the pavement cell (pavement type, structural/storage layer design, and outlet configuration).

The entire parking lot, excluding the entrance ways, was designed with a 0.42% surface and sub-grade slope to provide drainage and allow for monitoring. Surface runoff from each of the six pavement sections drained to a partitioned gutter and then to a monitoring vault, where flow was measured over 30 degree, galvanized steel v-notch weirs. The underdrains from the four permeable sections also flowed to the monitoring vault where four additional weir boxes measured subsurface drainage flow rates.

3. METHODS

Hydrologic measurements were conducted from June 2006 to July 2007. A concrete monitoring vault (4 m x 2 m x 1 m) was installed down slope of the parking lot, approximately 3 m from the edge of the parking lot curb (See Figure 1). The vault was placed such that positive drainage occurred from all monitored sections of the parking lot into the vault. All water measurements and sampling occurred within this vault, from where water then drained via two 250 mm (10 in) culverts to a nearby stream.

The flow rate of the asphalt runoff and permeable pavement subsurface drainage was calculated by continuously measuring the head of water above each 30 degree v-notch weir nappe with separate ISCO® 4230 flow meters. Drainage flow rates were calculated using a laboratory calibrated weir equation for head values less than 0.06 m (Equation 1), and the standard weir equation for flow for head values 0.06 m or greater (See Equation 2) [Grant and Dawson, 2001]. Volumes were calculated from flow rates to determine pollutant loads.

$$\mathbf{Q = 981.76 * H^{2.86}} \quad \text{Where Q = flow rate (l/s), H= head (m)} \qquad \mathbf{(1)}$$

$$\mathbf{Q = 373.2 * H^{2.5}} \quad \text{Where Q = flow rate (l/s) and H= head (m)} \qquad \mathbf{(2)}$$

Water quality measurements were taken from January 2007 to July 2007. Each ISCO® flow meter was connected to a Sigma 900™ or Sigma 900Max ™ automatic sampler that collected composite, flow-weighted samples of either runoff (asphalt) or subsurface drainage (permeable pavement) during a precipitation event. Changes in head level above the weir caused the flow meters to trigger water quality sampling by the automatic samplers.

Precipitation quantity and intensity were measured on site using an automatic ISCO® 674 tipping bucket rain gauge and backup manual rain gauge. Precipitation data from the automatic gauge, which tipped for each 0.25 mm (0.01 in) of precipitation, were recorded by an ISCO® 4230 flow meter. Precipitation samples were collected in a 5 liter oil pan, located on the ground, and analyzed for background atmospheric deposition quality data.

Within 24 hours of a monitored precipitation event, water quality samples were collected from each sampler along with the atmospheric deposition sample from the oil pan. A handheld probe was used to measure pH on-site. Once collected, the samples were chilled in a cooler filled with ice and transported back to NCSU for immediate analysis at the Center for Applied Aquatic Ecology Water Quality Laboratory. Analytical procedures followed U.S. EPA [U.S. EPA 1993] or APHA Standard Methods [APHA et al. 1998] (See Table 1). Excluding pH, which was measured in the field, water quality results only include samples collected and analyzed from January 2007 to July 2007.

Table 1. Laboratory analysis methods.

PARAMETER	PARAMETER	LAB ANALYSIS METHOD
Total Kjeldahl Nitrogen	TKN	EPA Method 351.1 (1993)
Nitrate-Nitrite as Nitrogen	$NO_{2,3}$-N	EPA Method 353.2 (1993) or SM 4500-NO_3 F (1998).
Ammonium as Nitrogen	NH_4-N	EPA Method 350.1 (1993) or SM 4500-NH_3 H (1998)
Total Nitrogen	TN	Calculation =TKN + $NO_{2,3}$N
Organic Nitrogen	ON	Calculation = TKN-NH_4-N
Total Suspended Solids	TSS	SM 2540 D (1998)

3.1 Statistical Analyses

To compare the hydrologic responses of various pavement sections, a one-way analysis between pavements was performed using a multiple linear regression (MLR) procedure for unbalanced designs in which pavements were blocked by storm (α=0.05). Data were square-root transformed to have normal residuals with constant variance. The surface runoff data did not consist of normal residuals with constant variance, and a suitable transformation for the data did not exist. As a result, a nonparametric Wilcoxon signed rank test was used to evaluate differences among pavement types. The effects of independent variables – rainfall depth, rainfall intensity, antecedent dry period (ADP), lot age, and season – were evaluated for each pavement response. A Pearson correlation test procedure was used to identify significant correlations between continuous independent variables, and a multiple linear regression (MLR) forward selection procedure was used to determine which independent variables were significant predictors of surface runoff volume (α=0.05). All statistical analyses were run using SAS® 9.1 software.

4. RESULTS AND DISCUSSION

Fig. 3 illustrates the typical response of a permeable pavement section following a rainfall event. The majority of the stormwater left the permeable pavement cells as subsurface drainage from the underdrains. This is also where permeable pavement peak outflows were observed. Total permeable pavement outflow was defined as the sum of surface runoff and cell subsurface drainage for a particular section. Exfiltrate, which was not monitored, referred to water that entered the soil underlying the permeable sections.

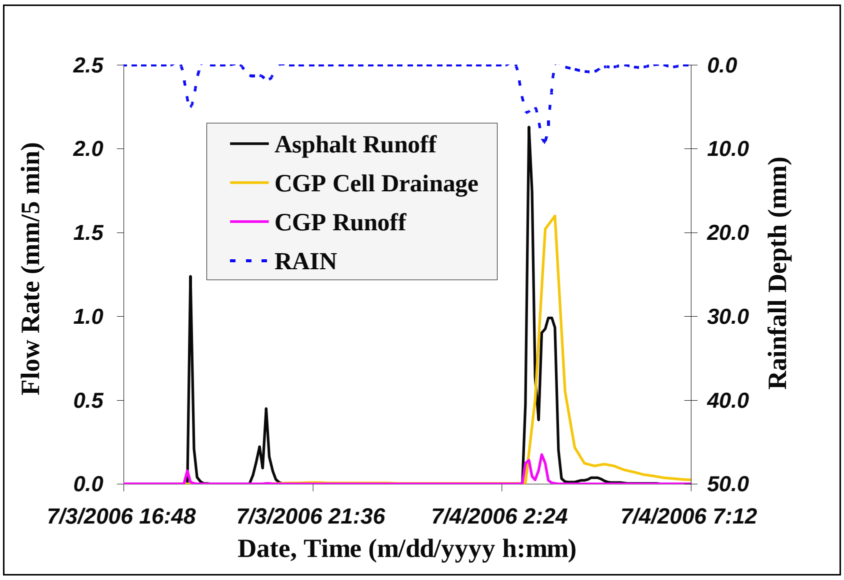

Figure 3. Asphalt runoff and CGP runoff and drainage for 32.8 mm event on 7/3/2006.

4.1 Surface Runoff

Between 40 and 44 events were examined for runoff reduction. When compared to asphalt, all four permeable pavement sections dramatically reduced surface runoff volumes. The marked reductions in permeable pavement surface runoff were similar to results found by Bean *et al*. [2007b] and Brattebo and Booth [2003] on unclogged pavement sites. Mean runoff reductions from rainfall depth were 34.7, 99.9, 99.3, 98.2, and 99.5% for asphalt, PC, PICP1, CGP, and PICP2, respectively (See Table 2). Surface runoff volumes of all pavements were statistically different from one another ($p<0.01$). Expressed in order of highest runoff generation, pavements performed as follows: Asphalt>>CGP>PICP1>PICP2>PC. All pavement surface runoff volumes were positively correlated to rainfall depth and intensity ($p<0.05$). Asphalt, PC and PICP2 were more strongly correlated to rainfall depth, whereas stronger correlations to intensity were observed for PICP1 and CGP. PICP2 runoff was positively correlated to the age of the parking lot, although not significantly ($p=0.059$), reflecting potential clogging of this pavement surface during the study.

Table 2. Percent surface runoff reductions from rainfall depth.

PARAMETER	ASPHALT (N=44)	PC (N=40)	PICP1 (N=41)	CGP (N=40)	PICP2 (N=40)
	PERCENT RUNOFF REDUCTION FROM RAINFALL (%)				
MEAN	34.65	99.86	99.33	98.17	99.51
MEDIAN	29.43	99.94	99.37	98.67	99.68
MIN	-2.73	99.03	97.76	91.11	96.94
MAX	84.80	100.00	100.00	100.00	100.00
STDEV	18.71	0.22	0.58	1.83	0.65

4.2 Total Volumes

The majority of the total outflow for all permeable pavement sections occurred as subsurface drainage. Table 3 details the percentage of outflow volume which occurred as surface runoff for each permeable section. For every measured storm except the 22 November 2006 Storm, surface runoff comprised only 6% of the total outflow volume for CGP, and less than 2% for all other permeable pavements. Two large storms were not accurately monitored due to equipment inundation or malfunction.

Because of the poor infiltration exhibited by the underlying *in-situ* soils, the permeable pavement cells were designed with underdrains to facilitate subsurface drainage in between storm events. As a result, these sections generated greater outflow than would typically be expected in a sandy soil application where in-situ soils were highly permeable.

The PICP1 and CGP cells generated significantly less outflow volumes than the other pavement sections ($p<0.001$) and no statistical difference between these cells was observed. The total outflow volumes of the PC cell, PICP2 cell and asphalt were not statistically different from one another. Average percent volume reductions from rainfall volume were 35.7, 43.9, 66.3, 63.6, and 37.7% for asphalt, PC, PICP1, CGP, and PICP2 cells, respectively.

Table 3. The percentage of surface runoff resulting from total outflow volumes.

STORM EVENT	PC	PICP1	CGP	PICP2
(P=Rainfall Depth)	PERCENTAGE OF SURFACE RUNOFF (%)			
6 mm<P<50 mm[A]	0.2	1.7	6.0	0.7
22 Nov 2006 (P=135 mm)	9.2	30.6	34.8	14.1
A: Storms less tan 6 mm in size were not averaged, dur to the absence of exviltrate generated from PICPI and CGP cells.				

4.3 Water Quality

Table 4 summarizes mean and median concentrations and pollutant loads from the four permeable pavement types, asphalt, and atmospheric deposition. Across the board, the pavements behaved very similarly with respect to each other, with one notable exception being CGP's performance with respect to $NO_{2\text{-}3}$-N (and consequently nitrogen) removal.

Table 4. Mean (and median) pollutant concentrations and loads.

	ATM. DEP.	ASPHALT 1	ASPHALT 2	PC	PICP1	CGP	PICP2
pH	6.7 (6.9)	7.2 (7.2)	7.3 (7.4)	9.2 (9.1)	8.1 (8.0)	7.9 (8.0)	7.9 (7.9)
POLLUTANT CONCENTRATIONS (MG/L)							
TN	1.30 (1.20)	1.24 (1.20)	1.27 (1.16)	1.27 (1.14)	1.73 (1.28)	0.95 (0.83)	1.38 (1.22)
$NO_{2,3}$-N	0.35 (0.32)	0.29 (0.28)	0.31 (0.33)	0.73 (0.63)	1.25 (0.78)	0.46 (0.42)	0.90 (0.83)
NH_4-N	0.59 (0.41)	0.34 (0.22)	0.39 (0.33)	0.05 (0.05)	0.05 (0.04)	0.04 (0.03)	0.05 (0.04)
TKN	0.96 (0.81)	0.95 (0.89)	0.96 (0.81)	0.55 (0.50)	0.48 (0.48)	0.48 (0.47)	0.48 (0.40)
ON	0.29 (0.30)	0.56 (0.46)	0.50 (0.44)	0.52 (0.44)	0.43 (0.37)	0.44 (0.41)	0.43 (0.38)
TSS	9.8 (8.2)	19.4 (18.6)	14.5 (12.3)	15.2 (13.4)	15.2 (12.6)	12.5 (10.4)	13.8 (9.9)
POLLUTANT LOADS (G)							
TN	2.76 (1.90)	1.77 (0.93)	1.74 (0.74)	1.85 (0.93)	1.47 (0.71)	1.57 (0.49)	2.15 (1.41)
$NO_{2,3}$-N	0.74 (0.46)	0.45 (0.23)	0.44 (0.23)	1.04 (0.54)	1.04 (0.48)	0.92 (0.26)	1.35 (0.80)
NH_4-N	1.44 (0.69)	0.54 (0.23)	0.51 (0.21)	0.08 (0.05)	0.04 (0.01)	0.05 (0.03)	0.10 (0.06)
TKN	2.02 (1.16)	1.32 (0.67)	1.30 (0.49)	0.81 (0.39)	0.43 (0.22)	0.64 (0.22)	0.80 (0.41)
ON	0.64 (0.38)	0.81 (0.44)	0.84 (0.25)	0.82 (0.40)	0.39 (0.20)	0.60 (0.20)	0.70 (0.34)
TSS	17.0 (18.1)	27.4 (15.5)	31.9 (8.2)	27.5 (7.8)	17.6 (6.3)	17.2 (5.5)	29.1 (10.1)

4.4 pH

All pavements buffered the pH of the influent acidic rainfall. On average, all permeable pavement drainage had a higher pH than asphalt runoff ($p<0.001$). The PC cell had higher pH values than all other permeable pavement cells ($p<0.001$), probably due to greater contact time with cementitious materials. Atmospheric deposition pH was lower than asphalt and all permeable pavement sections ($p<0.01$). No correlations were observed between atmospheric deposition pH and any pavement pH. Similar buffering capacities of permeable pavements have been observed by James and Shahin [1998] and Pratt et al. [1995].

4.5 Nitrogen

Generally, permeable pavement subsurface drainage tended to have lower NH_4-N and TKN concentrations than asphalt runoff and atmospheric deposition. With the exception of the CGP cell, permeable pavement subsurface drainage had higher $NO_{2,3}$-N concentrations. The CGP cell produced the lowest TN concentrations. Nitrogen loads leaving the PICP1 cell were generally low due to the outflow volume reductions provided by this section. The possible N removal is similar to that found sand filter research [Barrett 2003], not surprising considering the composition of CGP; CGP in essence is a shallow depth sand filter.

4.6 Total Suspended Solids

No significant differences in TSS concentrations were observed among sampling sites. The TSS concentrations from the PC, PICP1, and PICP2 cells were positively correlated to asphalt TSS concentrations ($p < 0.05$), but no other correlations between similar parameters were observed.

5. CONCLUSIONS

The following conclusions can be made from the research presented herein:

1. With respect to runoff reduction and peak flow mitigation, all pavements performed substantially and statistically significantly better than asphalt ($p < 0.001$). Although hydrologic differences among the pavements did exist, they were small in comparison to the overall improvements from asphalt.

2. The majority of outflow resulting from permeable pavements was in the form of subsurface drainage. For storms with rainfall depths less than 50 mm, surface runoff comprised less than 6% of the total outflow volume from the CGP cell, and less than 2% for all other permeable pavement types.

3. One year after lot construction, permeable pavement drainage tended to have lower NH_4-N and TKN concentrations than asphalt runoff and atmospheric deposition. With the exception of CGP cell drainage, permeable pavements had higher $NO_{2,3}$-N concentrations, a probable result of nitrification. The CGP cell had lower $NO_{2,3}$-N concentrations than other permeable pavements ($p<0.01$). CGP also had the lowest mean TN concentrations, although results were not significantly lower than those of asphalt.

4. TP and TSS concentrations were not different among various pavement sections. No liner separated the permeable pavements' subbase from phosphorus laden *in situ* soils, allowing water to interact with *in situ* soils while it drained from the cells. This caused suspected TP leaching from the underlying soils into the underdrains. It is unlikely that TP leached from the pavement materials. Further, it is possible that the disturbance of the underlying soils during site construction resulted in sediments washing from the cells during rainfall events

6. ACKNOWLEDGEMENTS

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