EVALUATION OF VARIOUS TYPES OF PERMEABLE PAVEMENTS WITH RESPECT TO WATER QUALITY IMPROVEMENT AND FLOOD CONTROL

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SUMMARY

In North Carolina and several other U.S. states, all permeable pavements are currently considered to have similar capabilities in reducing runoff, but are not credited with improving water quality. Previous research conducted by the North Carolina State University on one particular permeable block pavement type has shown that when compared to runoff from an adjoining asphalt lot, permeable pavement exfiltrate contained significantly lower concentrations of phosphorous and zinc, as well as reductions in total nitrogen. To further test various permeable pavement designs, a parking lot consisting of four different types of permeable pavements and standard asphalt was constructed in Kinston, NC. The permeable pavement sections consist of permeable interlocking concrete pavers (PICP) with 8.5 % void space, PICP with 12.9 % void space, concrete grid pavers (CGP), and porous concrete (PC), each covering a 1200 sq. ft. area with a 10 in. gravel storage layer. The purpose of this study is to evaluate and compare the effects of each pavement type on water quality and runoff reduction. Conclusions on the difference in reduction between each pavement type have not been determined. Site analyses on every rainfall event will be conducted beginning January, 2006 and will continue for one year. As a result of the Kinston study, it is expected that the state of North Carolina will be able to make an informed judgment on how much pollutant removal credit permeable pavements should receive when implemented as stormwater best management practices. Also, this study can be used to determine whether or not stormwater credit should vary based on pavement type.

Keywords. Permeable pavement, stormwater runoff, water quality, urban development, BMP

1. INTRODUCTION

Urban development has had an adverse effect on both the quantity and quality of surface waters. During rainfall events, impervious areas, such as roadways, driveways, and rooftops, cause water to run off surfaces faster and in greater amounts than from undeveloped pervious areas, such as grasslands and forests. The increase in runoff can cause an increase in overland and streambank erosion, as the water rapidly travels to surface water sources. Surface waters, in turn, experience irregular flow rates and higher sediment loadings. Impervious areas also reduce infiltration, impacting groundwater aquifers. The result is an increase in surface water temperature and pollutant load, which have detrimental effects on aquatic habitats. The most common urban stormwater pollutants include sediment, nutrients, oil and grease, bacteria, and heavy metals (USEPA, 2003).

Two common nutrients found in stormwater runoff are nitrogen and phosphorous. Atmospheric deposition contributes the majority of nitrogen found in urban areas. Fertilizers and sediment transport are the major sources of phosphorous. Other sources of these nutrients include animal and human wastes (NCDENR, 1999). Nutrients deposited on impervious surfaces are more likely to wash off and directly enter surface waters than nutrient deposition in more natural areas (NCDENR, 1999). High concentrations of these nutrients in surface waters can result in eutrophication, which can cause cyanobacterial blooms, oxygen depletion, and death of marine animals in local receiving water bodies. High amounts of nitrite (NO_3-N) in drinking water also pose a health risk to human and animals, especially to infants.

The Environmental Protection Agency recently declared urban storm water runoff the greatest threat to water quality in coastal estuaries, and the third greatest cause of impairment to lakes (USEPA, 2004). A 2000 National Water Inventory declared that 13 percent of impaired rivers, 18 percent of impaired lakes, and 32 percent of impaired estuaries are affected by urban and suburban stormwater runoff (USEPA, 2000). As urban areas expand, the problems associated with urban runoff and water quality continue to grow. Because of their ability to allow water to infiltrate into the surface, permeable pavements can be an effective means of approaching a solution to these problems.

1.1 Permeable Pavements

Permeable pavements are alternatives to the traditional impervious asphalt and concrete pavements. Pervious pore spaces in the permeable pavement surface allow for water to infiltrate into the pavement during rainfall events. Water passes through several layers of pervious material where it is temporarily stored. In areas underlain with highly permeable soils, the captured water slowly infiltrates into the sub-soil. In areas containing soils of lower permeability, water can leave the pavement though an underdrain system. The water that passes through and leaves the pavement is referred to as exfiltrate.

Because of their ability to allow water to quickly infiltrate through the surface, permeable pavements allow for reductions in runoff quantity and peak runoff rates (Pratt *et al.*, 1989; Hunt *et al.*, 2002; Bratteo and Booth, 2003; Bean *et al.*, 2005). Even in areas where the underlying soil is not ideal for permeable pavements, the installation of underdrains has still been shown to reflect these reductions (Pratt *et al.*, 1989). As a result, permeable pavements have been regarded as an effective tool in helping with stormwater control (Watanabe, 1995; Wada *et al*,. 1987). The evaporation rates, drainage rates, and retention properties on permeable pavements are largely dependent on the particle size distribution of the bedding material (Anderson *et al.*, 1999).

Permeable pavements also affect the water quality of stormwater runoff. Permeable pavements have been shown to cause a significant decrease in several heavy metal concentrations as well as suspended solids (Pratt *et al.*, 1989; Pratt *et al.*, 1995; James and Shahin, 1998; Brattebo and Booth, 2003). Removal rates are dependent upon the material used for the pavers and sub-base material, as well as the surface void space (Fach and Geiger, 2005; Pratt *et a*l., 1989). Metal pollutant concentrations within pavements themselves decrease rapidly with depth. Most heavy metals are captured in the top layers of the void space fill media (Dierkes *et al*., 2002). This implies that through regular maintenance, where this top layer is removed and then replaced, there remains a high capability for the pavement to remove heavy metal pollution over long periods of time.

A field study by Bean *et al.* (2004) compared exfiltrate from permeable interlocking concrete pavers (PICP) to asphalt runoff and found that the concentrations of zinc, total kjeldahl nitrogen, and total phosphorous were significantly lower in the PICP exfiltrate. TSS and TN levels were lower in the exfiltrate at all sites; however, the results were not significant. The study failed to make conclusions about differences in nutrient removal between permeable pavement types (Bean et al, 2004). A similar laboratory study by James and Shahin (1998) compared the quantity and quality of runoff from PCIP and rectangular concrete pavers to runoff from an asphalt block. The study determined that water infiltrating through permeable pavements tended to cause an increase in NO_3-N and a decrease in TKN, while having little effect on phosphorous concentrations. For the three pavement types evaluated, the runoff volume from PCIP was the lowest. PCIP runoff also contained the lowest concentrations of heavy metal, oils, grease, and bacteria (James and Shahin, 1998).

Bean and Hunt. (2005) showed that surface clogging of permeable pavements, once a large item of concern, may have been a somewhat exaggerated matter. This led to changes in the North Carolina state credit system for permeable pavements. In 2005, the state of North Carolina finally accepted permeable pavements as a BMP for stormwater control. Permeable pavements are now considered an effective BMP for reducing stormwater runoff volume and peak flow (NCDENR, 2005). In the coastal plain regions of North Carolina, where the underlying soils are relatively sandy, permeable pavements receive a percent impervious reduction credit. For pavements containing at least 6 inches of underlying gravel storage, the total surface area is considered to be 60% managed grass and 40% impervious area. For pavements with at least 4 inches of gravel storage, the total surface area is considered 40% managed grass and 60% impervious area (NCDENR, 2005).

Under the current state stormwater credit system, permeable pavements receive no direct credit for pollutant removal. Further research is needed to verify that permeable pavements are able to efficiently remove pollutants and thus should be awarded credit for water quality improvement. Additionally, no distinction is made among the types of permeable pavement. Research is needed to determine if different types of permeable pavement function in different ways.

2. RESEARCH OBJECTIVES

There are three primary objectives of the proposed study:

(1) Evaluate and compare differences in water quality and runoff reduction between permeable pavements and standard asphalt
(2) Compare differences in water quality among four different types of permeable pavements
(3) Compare differences in runoff reduction among four difference types of permeable pavements

In particular, the study focuses on the concentrations of nitrogen, phosphorous, and total suspended solids (TSS) in the water runoff. As a result of this study, the state of North Carolina will be able to make an informed judgment on how much pollutant removal credit permeable pavements should receive when implemented as stormwater best management practices. Also, this study can be used to determine whether or not stormwater credit should vary based on pavement type.

3. PARKING LOT DESIGN, KINSTON, NC

A 20-stall employee parking lot consisting of four different types of permeable pavements and standard asphalt was constructed at the City of Kinston Public Service Complex in Kinston, NC (Figure 1). Area soil maps identified three predominant soils in the near vicinity of the parking area: Lumbee sandy loam, Johns sandy loam, and Johnston soils. All three soils are characterized as poorly drained, level soils with low shrink-swell potential. Prior to lot construction, an on-site soil evaluation confirmed the presence and characteristics of these soils.

Figure 1. Permeable pavement parking lot in Kinston

The area of each permeable section is 111.5 sq. m., consisting of four parking stalls. Two standard asphalt sections are located to the outside of the permeable pavement sections. Each asphalt section is 111.5 sq. m (1200 sq. ft.) and consists of two parking stalls. On the ends of both asphalt sections, two 3 by 6 meter (10 x 20 ft) sections of asphalt serve as the entrance ways to the parking lot.

The four permeable pavement sections consist of porous concrete (PC), two sections of permeable interlocking concrete pavers (PICP) with pea gravel fill, and concrete grid pavers (CGP) with sand fill; all of which have been observed industry applications in North Carolina. Of the two PICP sections, one contains ConPave ™ Octabrick concrete pavers with a 12.9% void space, and the other SF-Kooperation ™ Rima concrete Stone with an 8.5% void space. Images of each pavement type are show below in Figure 2.

Figure 2. Permeable pavement sections consisting of (from left to right) porous concrete, Octabrick concrete pavers, concrete grid pavers, and Rima concrete stone

All permeable sections have a gravel storage layer, consisting of washed #78 stone and #5 stone, the proportions of which vary based on the product specifications for the overlying pavement types. The gravel layer serves to support the expected parking lot traffic loading, estimated to be 60 vehicle passes per day. The standard Flexible Pavement Method as defined by the American Association of State Highway and Transportation Officials (AASHTO) was used to determine the structural design requirements for PICP and CGP, based on a 10-year design life and an Equivalent Single Axle Loading (ESAL) of 380. The soil support value was assumed to average a conservative value of 4 for the underlying soils. The environmental factor was set at 1.0, assuming moderate drainage and frequent base layer saturation. The following strength coefficients were used to determine layer thickness: paver with sand/gravel fill (0.20), gravel bedding layer (0.07), and gravel subbase (0.14). For ease of installation, the excavation depth beneath permeable pavements was kept consistent, so the gravel storage layer was adjusted to meet the strength requirements for the limiting pavement design. Figure 3 shows the detailed lot cross section for each pavement type.

Assuming no exfiltration, conservative hydraulic analyses indicate that every permeable pavement section would be capable of storing at least 8.9 cm (3.5 in) of rainfall (35% porosity for a 10-inch gravel layer). The two-year, 24-hour rainfall event for Kinston, NC, is approximately 9.65 cm (3.8 in).

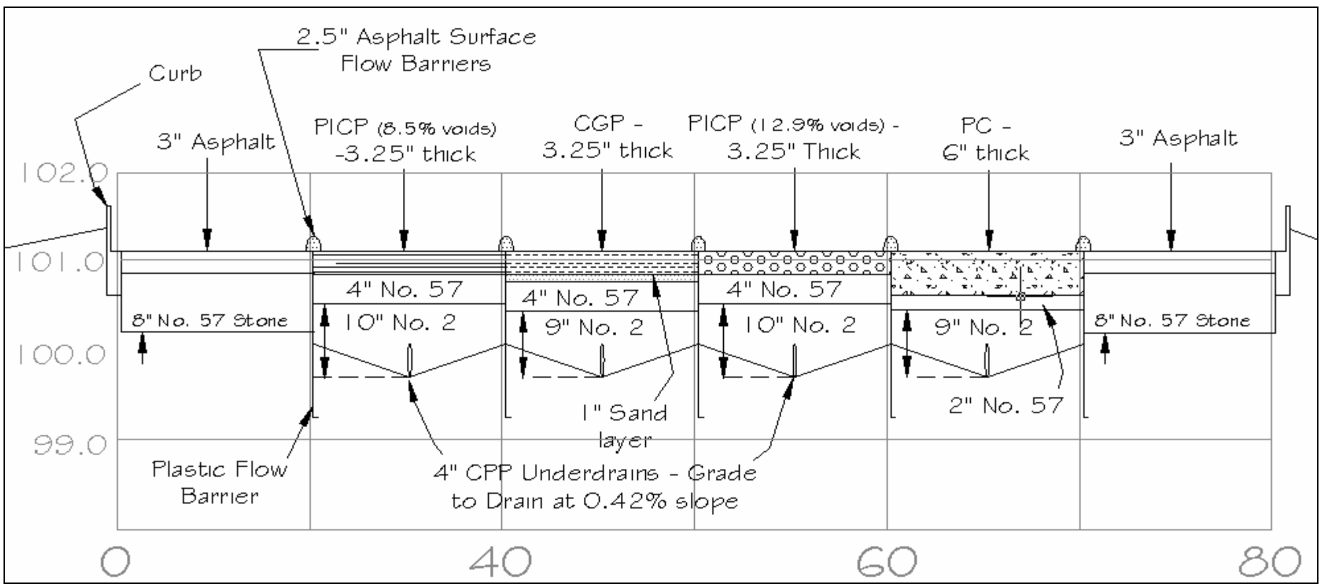

Figure 3. Parking lot cross section (measurements in ft and " = inches; 1 inch=25. 4 mm)

Due to the poor drainage nature of the site soils, underdrains were installed to drain permeable pavement exfiltrate. Beneath each permeable section, at the bottom of the subsurface storage layer, one perforated 10 cm diameter section of corrugated plastic pipe runs the length of the parking lot. The subsurface of each permeable pavement slopes to these corrugated underdrains to allow water entering the pavements to flow out of the system.

Each pavement region is hydraulically separate from the other regions. Rainfall that falls onto or passes through one pavement section will not pass onto an adjacent section. Thirty mil LLPDE plastic sheeting was placed between each pavement section to prevent any subsurface flow from one pavement to the next. The plastic sheet extends from the soil underlying each pavement gravel layer to the parking lot surface, where asphalt speed bumps were placed to prevent surface flow from one pavement section to another.

In order to provide drainage and allow for monitoring, the entire parking lot, excluding the entrance ways, was designed with a 0.42% surface and sub-grade slope. Surface runoff from each of the six sections drains to a partitioned gutter and then to a monitoring vault, where flow is measured and quantified using 30 degree v-notch weir boxes. Subsurface flow from the four permeable sections drains via the underdrains to the monitoring vault where four additional weir boxes measure exfiltrate flow rates. Flow rates for each section can be calculated by measuring the head of water above the weir v-notch opening. Calibration for the ten weirs yielded the following equation relating flow rate to head above the weir opening:

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

$$(Q = 0.0009 * H^{2.86} \quad \text{Where Q= flow rate (cfs), H= head (in))}$$

Head elevation measurements are taken at 5 minute intervals using ten separate pulley-float system data loggers.

A 3.96 x 1.83 x 0.91 m (13 x 6 x 3 ft) concrete monitoring vault is located down slope of the parking lot, approximately 3 meters (10 ft) from the edge of the parking lot curb. The vault has been placed so that positive drainage occurs from all monitored sections of the parking lot into this vault. All water measurements and sampling occur within this vault, from where the water then drains via two 25.4 (10 in) cm culverts to a nearby stream. Electronic sampling units are housed adjacent to the vault in a monitoring shed (Figure 4).

During each rainfall event, flow weighted water quality samples of the surface runoff from each of the two asphalt regions are collected. Additionally, flow weighted exfiltrate samples from each permeable pavement section are also collected. Six total sections are sampled individually using Sigma 900 and Sigma 900Max automatic samplers. Runoff and exfiltrate from rainfall events of 0.25 cm to 5.0 cm (0.1-2.0 in) in size are being collected. ISCO 4230 flow meters continuously measure water elevations in the weir boxes for each of the sections being evaluated for water quality. Changes in head level, indicating flow through the system, trigger water quality sampling via the Sigma 900's and 900Max's to begin. Sampling continues until head levels return to their initial readings.

Rainfall quantities are measured on site in order to determine the total reductions water quantity for each pavement. Automatic ISCO rain gauges and tipping buckets are located at each monitoring site, and manual rain gauges have been installed as backup measuring devices. The ISCO 4230 flow meters record the rainfall quantity and intensity data from the automatic rain gauge. Rainfall samples from the manual rain gauge are collected and analyzed for background rainfall quality data.

Figure 4. Monitoring vault and shed (left) with detail of sampling equipment (right)

The samples collected from the exfiltrate of each permeable pavement, along with both asphalt surface runoff samples and rainfall samples are transported back to NCSU for immediate laboratory analysis at the BAE Environmental Analysis Laboratory. Water quality analyses are currently being done to determine the concentrations of total nitrogen (TN), nitrite-nitrogen (NO_3-N), total kjeldahl nitrogen (TKN), ammonia (NH_4-N), organic nitrogen (ON), total phosphorous (TP), orthophosphate (PO_4), bound phosphate (BP), zinc (Zn), copper (Cu), and total suspended solids (TSS) in each sample. For a given rainfall event, the water quality data for each pavement type is compared and evaluated. Further, the flow rate data from each pavement section is being analyzed to quantify the runoff reductions provided by each of the various pavements.

The Kinston parking lot was completed in February 2006. Site monitoring and sampling began in March 2006 and will continue for the duration of one year. Preliminary results are discussed below.

4. RESULTS

4.1 Water Quantity

All permeable pavement sections have shown dramatic reductions in surface runoff volumes. During most storm events, very little to no surface runoff has been observed on the porous concrete and PICP sections. It is important to note that rain falling on the uncovered gutter flows directly to the surface drains of each permeable section, thereby contributing to a small portion of the runoff data. Graphed below (Figure 5) is a runoff versus exfiltrate curve for the PICP with 8.5% void space during a 2.24 cm (0.88 in) rainfall event.

Figure 5 is typical of the runoff versus exfiltrate curves for the porous concrete and both PICP sections. Comparatively, a larger amount of surface runoff for the grid pavers filled with sand has been observed. The same 2.24 cm rainfall event yielded the hydrograph show in Figure 6. Overall, there is a greater volume of runoff from this section, as well a higher runoff peak flow rate.

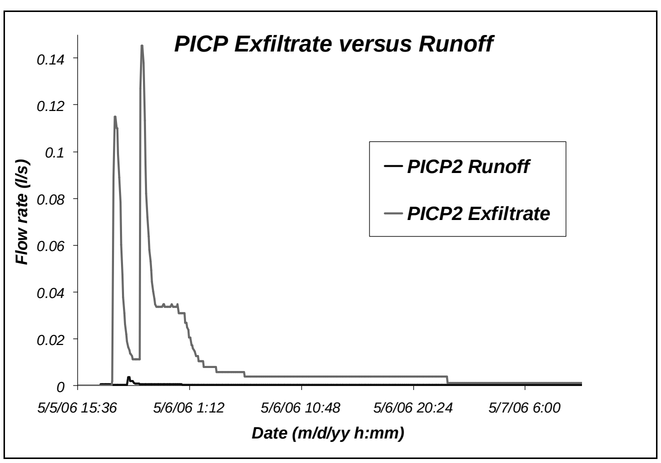

Figure 5. Exfiltrate versus runoff hydrograph for PICP with 8.5% voids

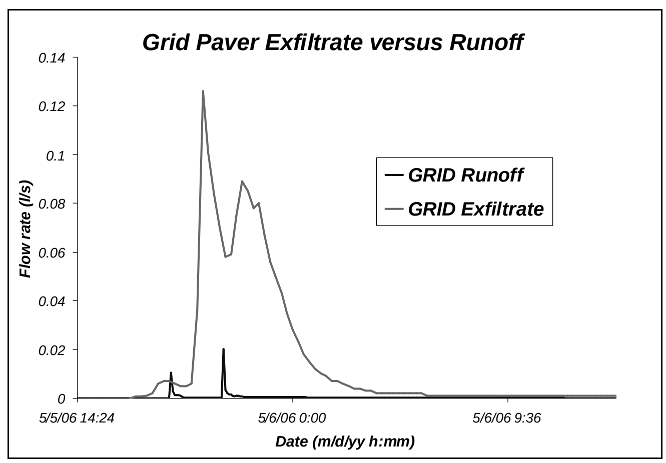

Figure 6. Exfiltrate versus runoff hydrograph for grid pavers

Data have also been indicative of significant exfiltrate peak flow reductions when the maximum flow rates from the permeable pavement exfiltrate flows are compared to the peak runoff flows from the asphalt surface. Table 1 details peak flow rates from each section during several storm events. Percent reductions for each permeable section are the amounts that the peak rates were lower than the asphalt surface peak runoff rates.

Table 1. Peak flow rates for asphalt runoff and permeable pavement exfiltrate (1 in. = 25.4 mm)

DATE	RAINFALL (in.)	Asphalt (l/s)	Flow Rate (l/s)	% Reduced	Flow Rate (l/s)	% Reduced	Flow Rate (l/s)	% Reduced	Flow Rate (l/s)	% Reduced
			----------PC--------		--------PICP1--------		-----CGP------		-------PICP2--------	
5-Jun	0.29	0.245	0.019	92.2	0.015	93.9	0.001	99.6	0.034	86.1
21-Jun	0.24	0.343	0.016	95.3	0.002	99.4	0	100.0	0.029	91.6
25-Jun	1.08	0.998	0.314	68.4	0.338	66.0	0.296	70.2	0.453	54.5
3-Jul	0.37	0.656	0.068	89.6	0.037	94.4	0.003	99.5	0.102	84.5
4-Jul	0.92	1.140	0.637	44.2	0.685	39.9	0.612	46.3	0.721	36.8
6-Jul	0.56	0.735	0.074	89.9	0.048	93.5	0.03	95.9	0.105	85.7
15-Jul	0.52	1.725	0.366	78.8	0.235	86.4	0.025	98.6	0.401	76.8
23-Jul	0.58	1.784	0.357	80.0	0.181	89.9	0.049	97.3	0.572	67.9
25-Jul	0.22	0.151	0.002	98.7	0	100.0	0.001	99.3	0.011	92.7
27-Jul	0.22	0.136	0.009	93.4	0	100.0	0	100.0	0.021	84.6
5-Aug	0.52	0.575	0.121	78.9	0.109	81.0	0.18	68.7	0.216	62.4
11-Aug	0.42	0.328	0.114	65.2	0.073	77.7	0.032	90.2	0.149	54.6
21-Aug	0.68	1.043	0.428	59.0	0.29	72.2	0.144	86.2	0.468	55.1
22-Aug	0.49	1.036	0.182	82.4	0.128	87.6	0.139	86.6	0.33	68.1
			AVG	**79.7**		**84.4**		**88.5**		**71.5**

PC – porous concrete exfiltrate
PICP1–12.9% void space PICP exfiltrate
CGP – concrete grid paver exfiltrate
PICP2 –8.5% void space PICP exfiltrate

Figure 7 shows flow data for three of the pavement sections during two rainfall events that occurred roughly 2 hours apart. During the first rainfall interval in which 5.1 mm (0.20 in) of rain fell, a large reduction in the peaks for both permeable sections was observed. The latter rainfall interval, which consisted of 4.3 mm (0.17 in) of rain, resulted in a smaller peak flow reduction for these same permeable pavements, however the peaks were still lower than that from the asphalt runoff. Because of the close proximity of rainfall, the storage volume of the permeable pavements was reduced. Preliminary data suggests that peak flow reduction may depend on the time between rainfall events, as well as rainfall amount and intensity. Differences between the various types of permeable pavements have yet to be analyzed.

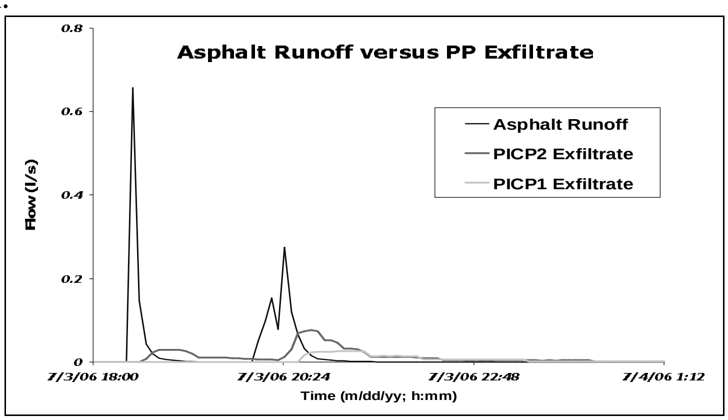

Figure 7. Asphalt runoff versus permeable pavement exfiltrate flow rates

Substantial volume reductions have been observed in the total amount of water leaving the permeable pavement sections as runoff and exfiltrate. Using the measured rainfall amount from each storm, the total volume of water that falls on each pavement section can be estimated. Due to variability in the rainfall, as well as the occurrence of evapotranspiration on each pavement surface, this total volume is a slight overestimate. Calculated in Table 2 are the runoff volumes that pass from each pavement (asphalt surface and permeable surface and exfiltrate) and the percent reduction from the estimated total volume of rain that fell on each pavement surface. Overall, greater reductions are observed for the permeable sections than the asphalt.

Table 2. Runoff volumes and pavement reduction rates as compared to asphalt runoff volumes

DATE	Rainfall	VOLUME RAIN	Runoff Vol (l)	% Reduction
	(in.)	(l)	--------*Asphalt*----------	
5/14/06	0.52	1472.48	771	47.64
5/18/06	0.51	1444.16	1482	-2.62
6/5/06	0.29	821.19	445	45.81
6/8/06	0.17	481.39	203	57.83
6/12/2006	0.72	2038.81	1408	30.94
6/14/06	0.8	2265.35	1598	29.46
6/21/06	0.24	679.60	334	50.85
6/25/06	1.08	3058.22	2992	2.17

Table 2 (continued)

DATE	Exfiltrate Vol (l)	Runoff Vol (l)	% Reduction	Exfiltrate Vol (l)	Runoff Vol (l)	% Reduction	Exfiltrate Vol (l)	Runoff Vol (l)	% Reduction
	----------*Porous Concrete*---------			-----------*Grid Pavers*-----------			--------------*PICP2*---------------		
5/14/06	478	29	65.57	198	100	79.76	579	0	60.68
5/18/06	1033	10	27.78	435	51	66.35	921	10	35.53
6/5/06	334	0	59.33	1	16	97.93	226	0	72.48
6/8/06	192	0	60.12	240	3	49.52	205	0	57.41
6/12/2006	1277	27	36.04	391	124	74.74	1100	5	45.80
6/14/06	1974	25	11.76	1185	115	42.61	1783	6	21.03
6/21/06	158	0	76.75	0	7	98.97	243	0	64.24
6/25/06	1631	3	46.57	1200	52	59.06	2023	9	33.56

4.2 Water Quality

Upon completion of this study, a detailed analysis of water quality will have been conducted. To date, composite samples from ten complete storms have been collected. A summary of the mean water quality parameters is given in Table 3. As of September 2006, results are inconclusive. Complete analyses will be preformed as more samples are obtained.

Table 3. Mean water quality data for rainfall and pavement sections

PAVEMENT	TN	TKN	NO3-N	TP	TSS	pH
Asphalt (n=17)	1.96 ± 1.41	1.58 ± 1.10	0.47 ± 0.36	0.52 ± 0.36	56.40 ±78.88	7.05 ± 0.45
PC (n=15)	2.90 ± 2.08	2.39 ± 2.08	0.51 ± 0.16	0.81 ± 0.58	175.07 ± 80.11	9.81 ± 0.94
PICP1 (n= 11)	2.80 ± 1.53	0.73 ± 0.39	2.07 ± 1.25	0.49 ± 0.24	48.64 ± 21.29	7.99 ± 0.42
CGP (n=15)	2.43 ± 1.08	0.98 ± 0.60	1.45 ± 0.69	0.55 ± 0.23	56.93 ± 36.77	8.01 ± 0.18
PICP2 (n=16)	2.07 ± 1.02	0.59 ± 0.32	1.48 ± 0.78	0.58 ± 0.45	41.75 ± 23.39	7.81 ± 0.29
Rainfall (n=18)	1.19 ± 0.64	0.90 ± 0.58	0.29 ± 0.15	0.62 ±0.65	25.72 ± 24.07	6.54 ± 0.93

units = mg/L

PC – porous concrete exfiltrate
PICP1–12.9% void space PICP exfiltrate
CGP – concrete grid paver exfiltrate
PICP2 –8.5% void space PICP exfiltrate

5. CONCLUSIONS

Preliminary results from the permeable pavement parking lot in Kinston, NC, can be summarized as follows:

1. All permeable pavement sections appear to cause substantial reductions in surface runoff volume. These reductions may be dependant on type of pavement or pavement fill.
2. The peak flow rates of permeable pavement exfiltrates are much lower than the peak flow rates of asphalt runoff. Differences in this reduction between permeable pavements will be analyzed in the near future.
3. Permeable pavements cause a greater reduction in the total water volume leaving the pavement sections during rainfall events. Again, differences in this reduction between various permeable pavements will be analyzed in the near future.
4. Water quality sampling is ongoing; however more data are needed before analyses can be done.

A final report for this project will be completed by May, 2007. Updates and further information on the monitoring project are available at www.bae.ncsu.edu/stormwater.

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