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THE PERFORMANCE OF PERMEABLE INTERLOCKING CONCRETE PAVER STORMWATER MANAGEMENT SYSTEMS AS PART OF SUSTAINABLE MASONRY CONSTRUCTION

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ABSTRACT

With the growing prevalence of sustainable, or 'green', building metrics, the use of permeable interlocking concrete pavers (PICP) within Canada and the United States markets has grown significantly since the 1980's. PICPs can be easily incorporated into otherwise impermeable surfaces, such as parking lots, to allow for the treatment and management of stormwater close to its source within an urban environment. Infiltrating stormwater through a PICP system alters the size and rate of stormwater flows, reducing demand on existing infrastructure, while simultaneously improving the overall quality of water heading to receiving systems. The benefits of PICPs are increasingly recognized by regional and local government agencies and have recently been demonstrated at a pilot parking lot at the Toronto and Region Conservation Authority's (TRCA) Kortright Centre for Conservation. This paper reports on a 2-year monitoring program conducted by TRCA and the University of Guelph that evaluated the performance of AquaPave® and Eco-Optiloc® pavers in relation to Hydromedia® Pervious Concrete pavement and traditional asphalt systems. The permeable pavements functioned well, even through the winter, eliminating direct runoff and reducing the stormwater outflow by 43%. The PICP and Pervious Concrete were effective in improving stormwater quality by capturing or transforming pollutants such as: suspended solids, heavy metals, nutrients and polyaromatic hydrocarbons. In conclusion, permeable interlocking concrete pavers represent an emerging masonry materials market in Canada that can be readily integrated with the aesthetics of masonry building construction while also serving as a stormwater management system beneficial to the environment.

KEYWORDS: masonry materials, permeable interlocking concrete pavers, sustainability, stormwater management

INTRODUCTION

Recent examples of economic hardship at the federal, provincial and municipal levels of government have led to the adoption of more aggressive tactics of generating revenue to finance infrastructure improvements and maintenance. The components of a stormwater management system provide different services for treating and managing stormwater. The most basic, and common, of these systems are traditional conveyance systems, such as curbs, gutters, catch basins and pipes, which transport runoff out of the urban environment to protect residents from high water levels.

Urban centres introduce new and different land uses to a watershed which change the flow paths and movement of water. Most significant is the introduction of roads, roof tops and parking lots which are impermeable surfaces. Precipitation, which prior to urban development could be intercepted and evapotranspired by vegetation or infiltrated into the earth, now exits a catchment as runoff. During construction of new developments the urban environment's ability to infiltrate water is further reduced by practices which compact soils and homogenize uneven terrain. As a result, the hydrology of a catchment before and after urban development differs greatly. The most obvious change is an increase in runoff volume (Walsh et al., 2005a). More subtly, the frequency of flows is altered since small precipitation events, which under pre-development conditions did not generate runoff, now generate runoff flows (Walsh et al., 2005a; Pitt, 1999). Moreover, peak flow rates increase and event durations decrease because water is conveyed more efficiently through the catchment (Walsh et al., 2005a). Overall, existing systems are very effective hydraulically but the speed at which water is conveyed through the catchment area can be excessive and detrimental to natural conditions.

If the negative environmental and ecological impacts created by urban development are to be mitigated, the high volume and unnatural frequency of runoff events must be reduced to better reflect natural conditions. Traditional conveyance storm sewer systems are engineered to carry very large volumes of storm water because impervious surfaces tend to direct rain water at very rapid speeds. This puts an economic stress on municipal infrastructure budgets, which are largely funded by property taxes and one-time development fees, since long-term costs and maintenance fees may not have been adequately assessed when urban development began. As a result there are persisting mechanical stressors on the conveyance systems themselves, which must carry increasingly larger volumes of water for which they may not have been originally intended for. Finally, there are added environmental stressors on local watersheds, due to the damaging effects of water rushing at high velocities as well as the tendency for pollutants to be swept up with outgoing water.

One potential solution is the use of porous materials, such open-jointed masonry pavers, also known as permeable interlocking concrete pavement (PICP) that allow for rain water to be directly infiltrated into the ground. PICPs can be designed to address flooding or safety issues associated with heavy rainfall, while simultaneously limiting environmental and economic impacts incurred by more traditional conveyance storm water management systems. There is an immediate need for experimental work towards the development and commercial application of PICPs and other porous materials within Canadian environments to address increasing costs of traditional conveyance infrastructure. In this paper an extensive and ongoing experimental program examining the performance, maintenance and behavior of PICPs is presented. In the next section a summary of the hazards that stormwater management pose within urban and natural environments will be presented.

ENVIRONMENTAL IMPACTS

Urbanizing natural watersheds will lead to hydrological changes in stream environments, such as changes in flow or erosion, as well as extensive consequences to the stream ecology, such as upsetting natural flora and fauna. Hydrologic flow regimes necessary for biological processes, such as fish spawning, may cease to exist after urbanization has begun within a watershed (Walsh et al., 2005b; Richter et al., 2003; Poff et al., 1997). The increase in the peak flow rate and the frequency of peak flows carried by storm sewer systems to natural streams and rivers can increase erosion thereby changing a stream's morphology (Poff et al., 1997). Without a continuous supply of sediment, bed and bank material that is mobilized is not replaced with new material coming from the upstream catchment. Consequences of erosion may include stream widening and deepening, and an eventual loss of connection along the channel and between the stream and adjacent riparian corridor. Finally, urban development can also change the stream flow characteristics during dry periods. Base flows which are supplied by groundwater can be reduced because large impermeable areas limit the rate of groundwater recharge throughout the watershed. In severe situations streams can dry up and the stream's longitudinal connectivity can be lost. Even if a stream continues to flow, overall water levels are often lower and stream temperatures warmer, disrupting nutrient cycles and preventing access of aquatic species to refuge areas. Therefore, stormwater should be slowed down such that its peak flow is not increased and that it is delivered to natural waterways is extended over a longer period of time.

The integrity of the aquatic environment is further compromised by the quality, or pollution, of stormwater entering the natural system. Human activities in urban centres introduce a wide range of harmful and unnatural pollutants. For example, a typical parking lot may possess a number of different sources of pollution detrimental to natural waterways, which may include engine oil, anti-freeze liquids or deicing salt. The types of pollutants caused by urbanization may include: suspended solids, nutrients, heavy metals, hydrocarbons, salts, bacteria and pathogens. These pollutants accumulate on impermeable surfaces during dry periods and are washed off with runoff during a precipitation event and carried out to receiving waters (Pitt et al., 1996). During summer months, runoff travels over pavements and rooftops which also introduce thermal energy to the stormwater. In the most extreme cases warmed stormwater and depleted groundwater inputs can produce thermally toxic conditions for organisms within the aquatic environment. Therefore, for many land uses, stormwater treatment systems such PICPs can reduce the amount of harmful pollutants travelling onward to natural environments.

Urbanization may also have the effect of reducing the amount of water that is captured within the ground. Rapid stormwater flows will essentially rush out to rivers and streams over very small time periods, rather than slowly moving down from the surface through the ground, eventually lowering the water table. This, in turn, will impact the amount and the quality of groundwater sources when they are relied upon for human drinking water or irrigation. Furthermore, groundwater quality can be compromised when dissolved pollutants migrate into an aquifer. In northern climates the practice of salting roadways for winter maintenance has several impacts to groundwater quality and the salination of aquifers in North America has been well documented (Daley et al., 2009; Meriano et al., 2009; Kelly, 2008; Williams et al., 1997). The cation-exchange reactions induced by sodium ions mobilize organic and inorganic particles within the soil and direct them deeper into the soil column, releasing them into a groundwater system. These exchanges change several soil characteristics including permeability, aeration, electrical conductivity, and osmotic potential (Environment Canada, 2001; Marsalek, 2003; Ramakrishna and Viraraghavan, 2005). In the following section, the use of PICPs and pervious concrete as an alternative stormwater management system will be discussed.

PERMEABLE PAVEMENT STORMWATER MANAGEMENT SYSTEMS

Permeable pavements, including PICPs or poured products such as pervious concrete, direct precipitation directly into the pavement, or fill media, which allows water to flow into the groundwater system or to a surface water drainage network or a combination of both. Infiltration of stormwater can help sustain recharge rates and maintain groundwater levels. In some instances permeable pavements may be designed to act as an area of enhanced recharge. Recharge rates through the permeable pavement are purposefully designed to be higher than the pre-development recharge rate in order to ensure that the pavement remains free of ponded water during precipitation events. Permeable pavements can also be designed to store and detain water, rather than just having it all infiltrate into the ground, and thus reduce peak flow rates. This has substantial environmental and economic benefits by decreasing the required size of conveyance and end-of-pipe infrastructure to process peak stormwater flows. In areas where urbanization has already occurred and traditional stormwater conveyance measures are already in place, permeable pavement will reduce the hydraulic loading on existing infrastructure which can increase its longevity and delay expensive replacement or rehabilitation projects. In cold climates the ability to infiltrate melted snow and ice can lower the cost of snow clearing and reduce the need for salting and sanding of paved surfaces.

Permeable pavements offer several other advantages in addition to reducing runoff volumes and peak flow rates. Infiltration through the pavement allows for in-situ filtration of stormwater which can significantly improve water quality. Thermal enrichment is limited because stormwater is exposed to less solar radiation and has a shorter flow path over warm surfaces. Permeable pavements can be constructed to allow air and water exchange within the sub-surface to support large, healthy trees (Ferguson, 2005). Lastly, allowing water to drain directly through the permeable media prevents water from collecting and ponding on the surface improving friction between pavement and vehicles and safety during precipitation events for pedestrians and drivers. Less ponding water also improves visibility for drivers because there is less spray and misting during a rain event (Ferguson, 2005). However, there is presently a dearth of information related to quantifying the net environmental effects, the required maintenance and general performance of these types of storm water management systems within the context of Canadian cities and cold weather climates. To address the immediate need for this information on behalf of city stakeholders and municipal governments, the Toronto Region Conservation Authority and the University of Guelph have partnered together for the construction and monitoring of a permeable parking lot test facility. A description of the test program as well as preliminary results will be presented in the following sections.

EXPERIMENTAL PROGRAM

A pilot permeable pavement (PP) parking lot was constructed during the fall of 2009 and spring of 2010 at the Kortright Centre for Conservation in Vaughan, Ontario and outfitted for long-term monitoring. The facility consists of four separate pavement *cells* which each represent an effective surface area size of approximately 230 m^2 corresponding to a capacity for 8-10 parked vehicles as indicated in Fig. 1. Each cell is hydraulically separated from adjacent cells and constructed of a different material, Cells 1-3 are constructed with different types of PPs designed to infiltrate rainwater, while Cell 4 is a control cell constructed of impervious asphalt (ASH) and possessing a traditional catch basin. Cell 1 is constructed with Hydromedia® Pervious Concrete (PC) supplied by Lafarge, a pour-in-place material, Cell 2 is constructed with open-jointed Eco-

Optiloc® pavers and Cell 3 is constructed with open-jointed AquaPave® (AP) pavers as indicated in Fig. 1 and depicted by the photos in Fig. 2, respectively. The permeability of the masonry paver system is derived from the space between the pavers rather than the paver material itself.

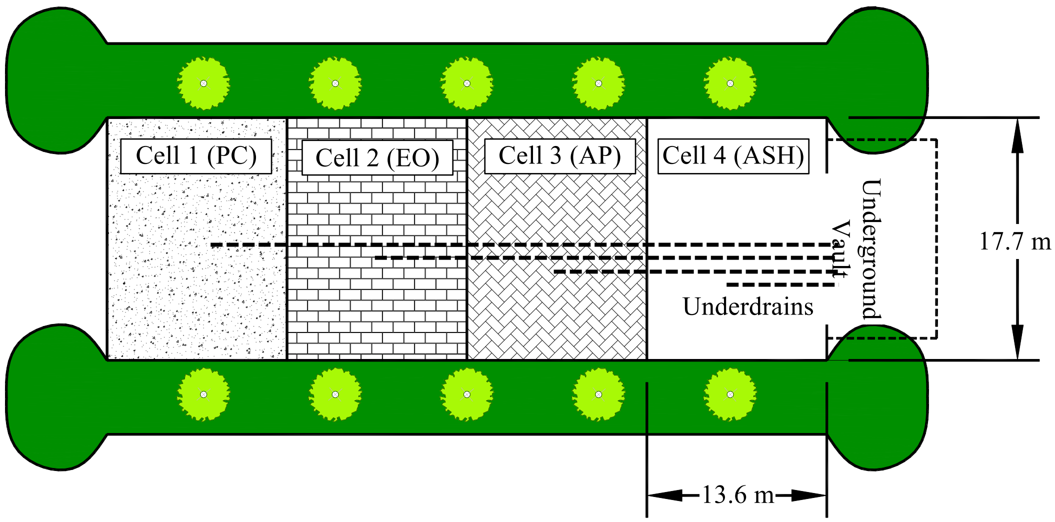

Figure 1: Experimental Site Parking Lot Layout

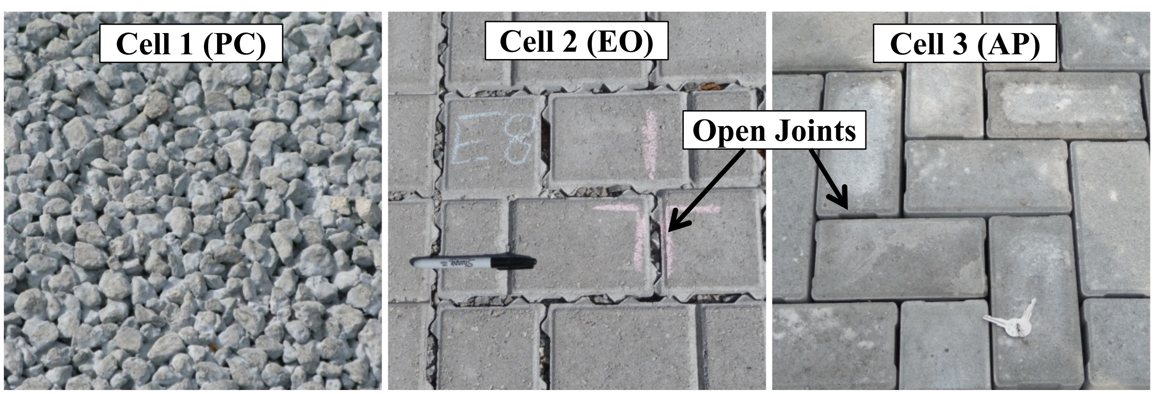

Figure 2: Photos of Selected Porous Materials: Cell 1 - Pervious Concrete (PC) Hydromedia, Cell 2 – PICP Eco-Optiloc (EO), and Cell 3 PICP AquaPave (AP)

To permit sampling of water infiltrated by the PPs, a drainage pipe was installed under Cells 1-3 as indicated by the cross-section schematic in Fig. 3. Aggregate reservoirs are constructed with layers of 19 mm and 60 mm diameter clear stone providing a combined depth of at least 50 cm. The EO pavement uses 1 - 9 mm diameter high performance bedding (HPB) as joint and bedding material while the AP pavement has HPB as bedding and Engineered Joint Stabilizer (diameter ~ 2 - 3 mm) as joint material. The AP pavement also includes an Inbitex® geotextile placed between the bedding and aggregate layers.

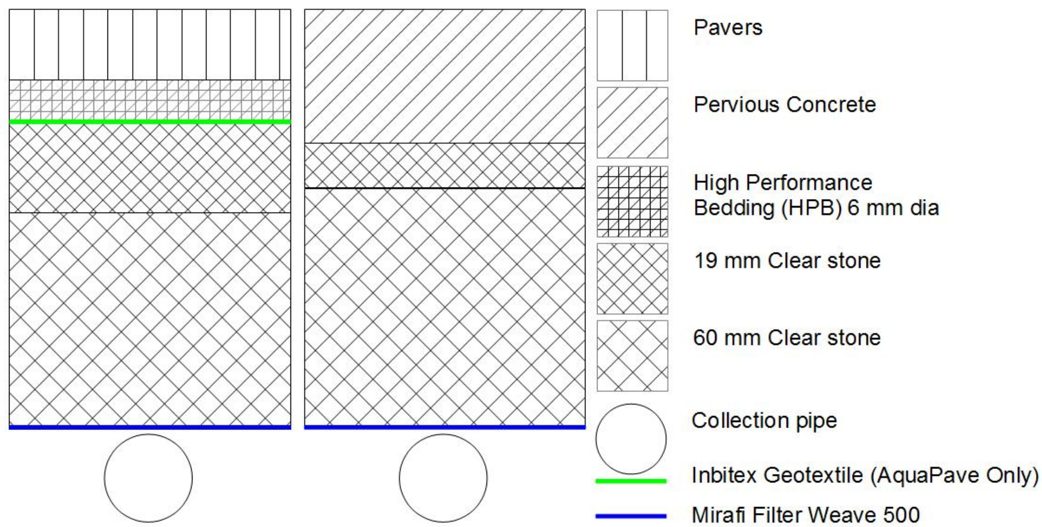

Figure 3: Profile of Porous Paver and Pervious Concrete Cells in Experimental Site

MOVEMENT AND MEASUREMENT OF STORMWATER

Rainfall that falls onto the three PP cells (referred to as stormwater) infiltrates through the pavement materials and aggregate layers. The soils below the parking lot are silty clay till with a low capacity to infiltrate water. As such, a small portion of the stormwater remains trapped in the PPs as residual moisture and may eventually evaporate while some of the stormwater will infiltrate into the soil below the PP cells ultimately migrating into a subsurface or groundwater system. Excess stormwater (i.e. water which does not evaporate or infiltrate) is drained at the base of each PP cell by a 100 mm diameter Big O perforated tubing (referred to as the underdrains) and conveyed separately in sealed pipes to an underground sampling vault as indicated in Fig 1. Stormwater which exits by way of the underdrains is referred to as *outflow* or *effluent*. The ASH cell is drained via a catch basin and piped to the sampling vault, the stormwater collected from the ASH pavement is referred to as the control *runoff*. Underdrains for each cell are fitted with flow restrictors to control the rate of drawdown after storm events and prolong the period over which infiltration can occur.

The flow of stormwater was measured by a Geneq V2A-tipping counters as indicated in Fig. 4a. These tipping buckets recorded the number of times a 3 L bucket 'tipped' in a minute. The total volume of water and peak flow rate was measured for 127 discrete precipitation and snow events. Water levels within the PP systems were monitored by five wells equipped with Onset Hobo U20 and Diver DI 240 water level loggers. The quality of stormwater was assessed by collecting flow-proportioned water samples during precipitation events. Samples were collected by automatic ISCO samplers as indicated in Fig. 4b and submitted to the Ontario Ministry of the Environment (OMOE) Laboratory in Etobicoke, ON for analysis of pollutant event mean concentrations (EMC). In total, 64 runoff events and 43 outflow events were sampled and analyzed. Stormwater was tested for pollutants including total suspended solids (TSS), nutrients (e.g. total nitrogen, TN and total phosphorus, TP) and heavy metals (e.g. Cu and Zn).

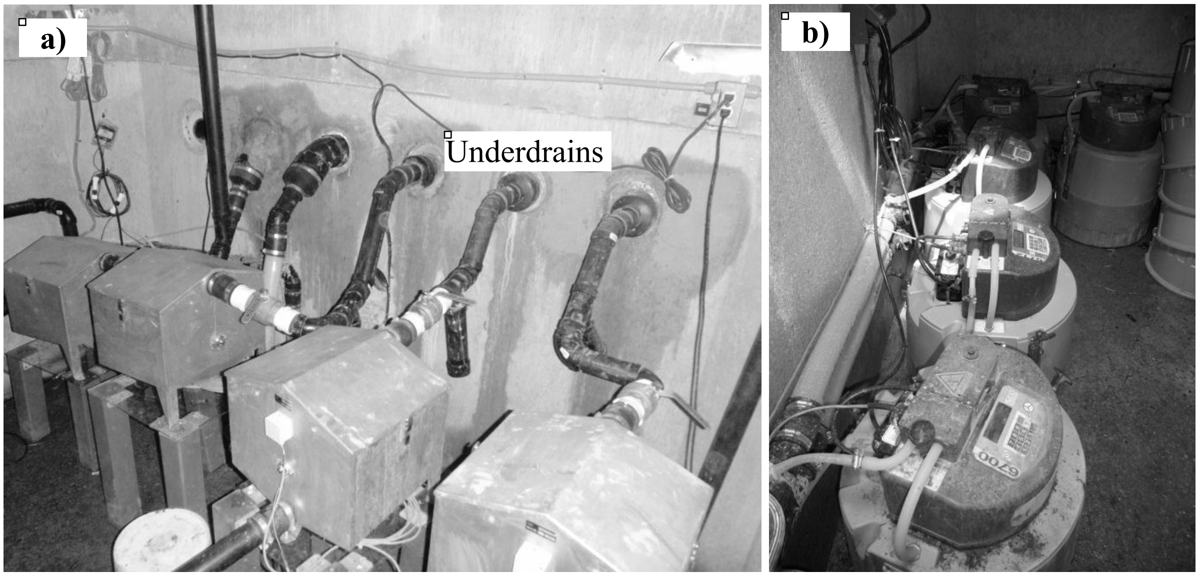

Figure 4: Monitoring Equipment in Underground Vault: a) Tipping Buckets to Measure Flows from the 4 Cells and b) Water Quality Samplers

The performance of the PP systems is assessed for quantity control using volume as described by Eqs. 1 and 2 as well as peak flow determined using reduction metrics from Eq. 3 and for quality control using removal efficiency metrics in Eq. 4.

Total Unit Volume: $$V_{unit} = \frac{V_T}{Area} \tag{1}$$

Percent volume reduction (*VR*): $$VR = \frac{V_{unit}^{ASH} - V_{unit}^{PP}}{V_{unit}^{ASH}} \times 100 \tag{2}$$

Percent peak flow reduction (*QR*): $$QR = \frac{Q_P^{ASH} - Q_P^{PP}}{Q_{PASH}} \times 100 \tag{3}$$

Percent removal efficiency (*RE*): $$RE = 1 - \frac{EMC_{PP}}{EMC_{ASH}} \tag{4}$$

PERMEABLE PAVEMENTS FOR FLOOD AND EROSION CONTROL

Between September 2010 and June 2012, 164 rain and snow events totaling 1,483 mm of precipitation were recorded at the Kortright test site. Throughout the study, 127 flow events were observed from the ASH control pavement cell. Of these, 59 were 'runoff only' flow events in which the ASH pavement produced runoff while the PP underdrains remained dry. During warm months, small precipitation events with less than 7 mm of rainfall did not initiate outflow from the PP underdrains. The infiltrated stormwater was completely captured through wetting of the aggregate, infiltration to native soils and evaporation. During the winter, mid-day runoff of melt water was regularly produced from ASH pavement while the PP underdrains remained unresponsive. Overall, the PPs reduced the volume stormwater outflow by 43%, capturing over 132 kL (m^3) of water.

Observed monthly stormwater volumes are shown in Table 1. During the winter months the PPs (both PICPs and PC) continued to function hydraulically and convey stormwater through the pavement to the underdrains. The PPs were not affected by frost heave because the pavement remained unsaturated at all times. It should be noted that direct runoff has not been observed from any of the PP cells during this study; however, based on staff observations, AP has been more susceptible to temporary ponding than EO or PC. Ponding of slushy melt water was infrequently noted during both winters on AP and the narrow joints of this pavement may also be more susceptible to icing. The sporadic winter maintenance at Kortright may have contributed to the ponding and it might not have been observed had regular plowing and salting occurred. Ponded stormwater ultimately infiltrated into the pavement for all of these incidents.

Table 1: Monthly Stormwater Volumes and Reductions

Month	Volume (L)			Volume Reduction (%)	
	ASH	PICPs	PC	PICPs	PC
Sep 2010	12,912	7,658	7,860	*41*	*39*
Oct 2010	17,631	8,115	9,825	*54*	*44*
Nov 2010	14,454	5,210	6,927	*64*	*52*
Dec 2010	6,672	4,454	5,562	*33*	*17*
Jan 2011	2,307	2,628	2,595	*-14*	*-12*
Feb 2011	7,905	1,346	516	*83*	*93*
Mar 2011	21,927	18,666	35,127	*15*	*-60*
Apr 2011	21,219	12,308	20,145	*42*	*5*
May 2011	26,547	14,819	21,006	*44*	*21*
Jun 2011	7,092	3,116	8,370	-	-
Jul 2011	7,572	3,963	2,940	*48*	*61*
Aug 2011	20,398	14,690	13,941	*28*	*32*
Sep 2011	19,352	9,818	9,291	*49*	*52*
Oct 2011	22,500	12,377	13,953	*45*	*38*
Nov 2011	20,709	1,008	1,566	*95*	*92*
Dec 2011	12,153	3,311	4,539	*73*	*63*
Jan 2012	12,900	6,335	6,126	*51*	*53*
Feb 2012	4,125	4,160	4,230	*-1*	*-3*
Mar 2012	4,692	3,704	5,691	*21*	*-21*
Apr 2012	8,316	407	912	*95*	*89*
May 2012	8,307	1,658	3,240	*80*	*61*
Jun 2012	15,717	7,259	7,167	*54*	*54*

Infiltration of stormwater through the PPs was a slower and longer process than direct runoff of the ASH pavement. Subsequently, the rate of flow out of the PP systems was significantly smaller than the rate of flow off the ASH. Event peak flows were reduced on average by 91% and peak flow reductions were observed in both summer and winter seasons. While there was essentially no detention of stormwater on the ASH pavement outflow from the PPs was delayed and gradual. Temporary detention of stormwater meant that outflow from the PPs occurred later than runoff. Median lag times, the time between the hydrograph centroid ASH runoff and PP outflows was 12 hours during spring/summer/fall and 19 hours during winter indicating the PP systems required more time to drain than the ASH pavement all year. The median length of spring/summer/fall runoff events was 15 hours while outflow from the PPs lasted for 34 hours.

During the winter median length of runoff was 33 hours while outflow from the PPs lasted for 62 hours. This degree of detention is acceptable in the Greater Toronto Region as traditional temporary storage facilities such as ponds typically have detention or drawdown times of up to 72 hours.

PERMEABLE PAVEMENTS FOR STORMWATER QUALITY CONTROL

The PP systems reduced the concentration of total suspended solids (TSS), nutrients (e.g. total nitrogen, TN and total phosphorus, TP) and heavy metals (e.g. Cu and Zn). Figure 5 presents boxplots, grouped by pavement type, for event mean concentration (EMC) data and Tables 2 and 3 present median EMC and removal efficiencies. PP effluent was more likely to have pollutant concentrations which meet provincial or federal water quality objectives than runoff stormwater. Table 4 presents recommended maximum concentration and exceedance percentages for TP, Cu and Zn. The PC and PICP provided similar improvements to stormwater quality but differences in performance were noted throughout the study. For example, both AP and EO effluent were more likely to meet provincial water quality objectives for Cu and TP than PC effluent.

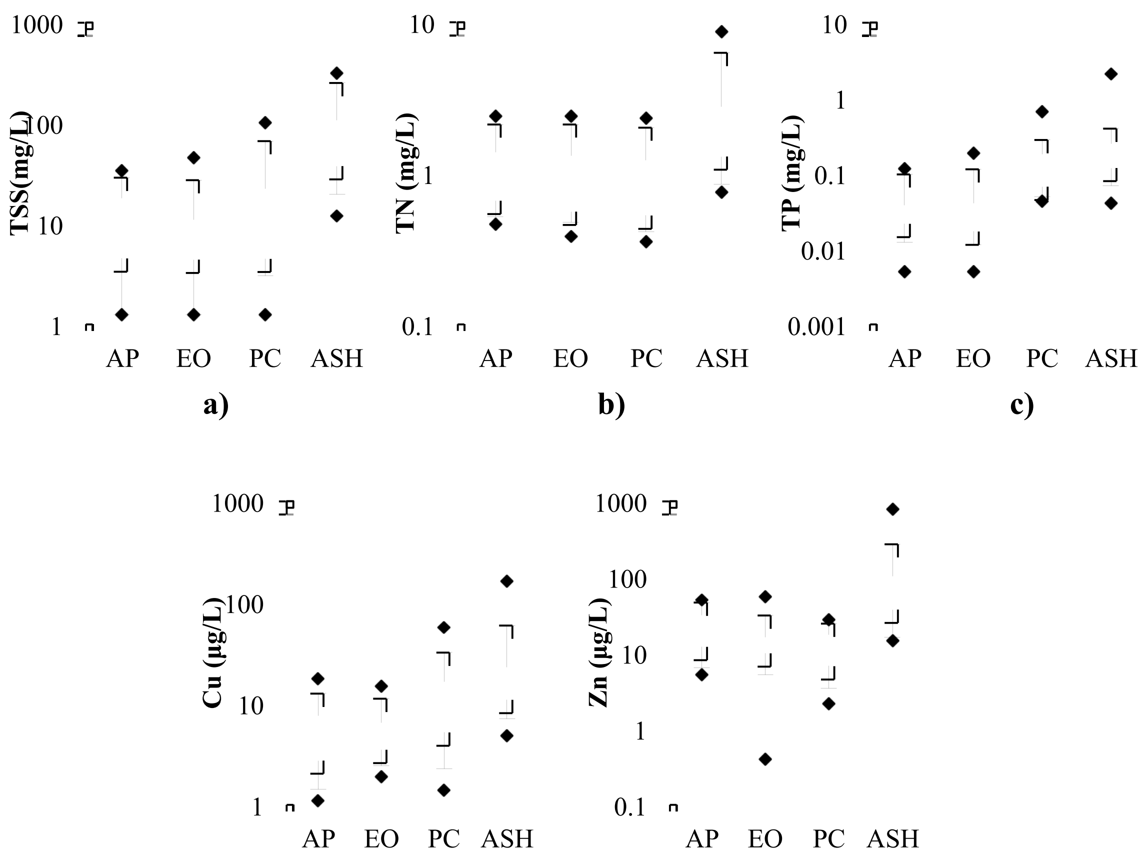

Figure 5: EMC Box Plots Indicating Pollutant Levels for the Different Test Cells: a) Total Suspended Solids (TSS), b) Total Nitrogen (TN), c) Total Phosphorus (TP), d) Heavy Metals (Cu) and e) Heavy Metal (Zn)

The PP systems continued to provide a high level of treatment during the winter. The PPs filtered stormwater to similar residual EMC regardless of the season. Winter was more heavily polluted by suspended solids because vehicular traffic into the parking lot brought in large amounts of dirt and sand. Consequently, in terms of removal efficiency, the PP provided higher removal rates during the winter than other seasons because the PP effluent quality remained unchanged while runoff quality worsened as indicated in Table 3.

Table 2: Spring-Summer-Fall Median EMC and Removal Efficiencies (RE)

Pollutant	EMC				RE (%)		
	ASH	AP	EO	PC	AP	EO	PC
TSS	44	9.2	5.7	6.5	83	87	81
TP	0.17	0.026	0.025	0.12	81	82	9
TN	1.3	1.1	1.0	0.80	35	45	43
Cu	14	6.3	5.6	6.9	62	61	50
Zn	43	16	12	13	80	82	62

Table 3: Winter Median EMC and Removal Efficiencies (RE)

Pollutant	EMC				RE (%)		
	ASH	AP	EO	PC	AP	EO	PC
TSS	93	9.0	8.7	10	90	92	89
TP	0.19	0.030	0.027	0.12	84	85	51
TN	2.4	0.98	0.83	0.86	52	64	69
Cu	17	3.3	4.8	8.8	79	73	58
Zn	69	24	14	10	84	85	51

In addition to removing suspended solids and heavy metals, the PICP cells were shown to reduce nutrient concentrations. Excessive nutrient levels are an increasing problem of urbanization for receiving waters and can damage the health of an aquatic ecosystem by leading to uncontrolled vegetated growth (i.e. eutrophication). The underdrained PP systems can filter out nutrients which are either absorbed by particles suspended in stormwater or in a non-dissolved state thus limiting the availability of nutrients downstream. All of the PP systems provided some nitrogen and phosphorus removal but the PICPs provided a greater amount of TP EMC reduction than the PC as indicated in Table 4.

Table 4: Water Quality Guideline and Exceedance Percentages

Pollutant	Maximum recommended concentration	% of stormwater samples which were greater than water quality guidelines			
		ASH	AP	EO	PC
TP	0.03 mg/L	100	35	49	100
Cu	5 µg/L	80	51	56	78
Zn	20 µg/L	89	47	20	20
**Guideline: Interim Ontario Provincial Water Quality Objective*					

CONCLUSIONS

Requirements for sustainable building construction are projected to grow more stringent in the future with respect to water use and stormwater management. Despite their existence for several decades, permeable interlocking concrete pavers (PICP) and other similar practices which reduce stormwater demands on infrastructure remain in a niche construction category without wide acceptance. However, as indicated in this research project, PICPs can offer significant advantages over traditional stormwater management systems including improved water quality and a reduction in peak flow volumes. In addition, the use of PICP materials can be readily integrated into most construction as a direct substitute for traditional asphalt systems. PICPs are less likely to suffer from any form of frost heave due to their large pore space, can reduce salting requirements in the winter and will have a longer lifespan than traditional asphalt.

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REFERENCES

Daley, M., Potter, J., & McDowell, W. (2009). Salinization of urbanizing New Hampshire streams and groundwater: effects on road salt and hydrologic variability. *Journal of North America Benthological Society , 28* (4), 929-940.

Kelly, W. (2008). Long-term trends in chloride concentrations in shallow aquifers near Chicago. *Ground Water , 46* (5), 772-781.

Meriano, M., Eyles, N., & Howard, K. (2009). Hydrogeological impacts of road salt from Canada's busiest highway on a Lake Ontario watershed (Frenchman's Bay) and lagoon, City of Pickering. *Journal of Contaminant Hydrology , 107*, 66-81.

Pitt, R. (1996). Small storm hydrology and why it is important for the design of stormwater control practices. *Advances in Modeling the Management of Stormwater Infiltration, 7*.

Pitt, R., Clark, S., Parmer, K., & Field, R. (1996). *Groundwater Contamination from Stormwater Infiltration.* Chelsea: Ann Arbor Press, Inc.

Poff, L., Allan, D., Bain, M., Karr, J., Pretegaard, K., Richter, B. & et al. (1997). The natural flow regime: A paradigm for river conservation and restoration. *BioScience, 4*(11), 769-784.

Richter, B., Mathews, R., Hanison, D., & Wiginton, R. (2003). Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Application, 1*, 206-224.

Walsh, C., Fletcher, T., & Ladson, A. (2005). Stream restoration in urban catchments through redesign stormwater systems: looking to the catchment to save the stream. *J. N. Am. Benthol. Soc., 21*(3), 690-705.

Walsh, C., Roy, A., Feminella, J., Cottingham, P., Groffman, P., & Morgan, R. (2005). The urban stream syndrom: current knowledhe and the search for a cure. *The North American Benthological Society, 24*(3), 706-723.

Williams, D., Williams, N., & Cao, Y. (1999). Road salt contamination in a major metropolitan area and development of a biological index to monitor its impact. *Water Research , 34* (1), 127-138.