Performance Evaluation of Permeable Pavements

TECHNICAL BRIEF

Low Impact Development Series

Permeable pavement is a general term used to describe pavements that allow stormwater to drain thorough the surface and into a stone reservoir below the surface where it is temporarily detained or infiltrated into the native soil. Common types include porous asphalt, pervious concrete and permeable interlocking concrete pavers. Since permeable pavements replace conventional asphalt, they are ideal for older built-up areas that lack stormwater management and have little or no space for conventional stormwater facilities. They can also be cost effective in new development areas where lower runoff from infiltration can reduce or eliminate the need conventional infrastructure

This study evaluated the hydrologic, water quality and functional performance of three different permeable pavements (PP) installed on a parking lot at the TRCA's Living City Campus in Vaughan, Ontario. The performance of the PPs was compared to that of a conventional asphalt pavement. Fine textured native soils below the pavements had low permeability with up to 30% clay content. Over a 22 month period, the PPs generated 43% less runoff than the asphalt pavement. Small rain events less than 7 mm were fully infiltrated and evaporated. Sampling of water quality during 56 events showed that PPs significantly improved the quality and reduced the pollutant loading of effluent waters

Most permeable pavements allow water to drain through the surface at a rate that is over 5 times greater than the largest rain storms observed in the Greater Toronto Area. Therefore, surface runoff from new permeable pavements is extremely rare.

Surface permeability declined substantially after 22 months as fine sediment and dirt accumulated in the surface pores, but the PPs maintained sufficient capacity to infiltrate all rainfall from observed storms. Maintenance performed with a vacuum truck provided partial restoration of the two PICPs, and of an older and severely clogged PICP on a nearby parking lot. Pervious concrete permeability did not improve after cleaning, although the pavement retained high infiltration capacity. Overall, the study showed that PPs are an effective stormwater treatment practice for maintaining or restoring infiltration functions on parking lots and roads, even in areas with low permeability soils.

INTRODUCTION

Roads and parking lots increase the imperviousness of land surfaces, resulting in increased volumes and rates of stormwater runoff, and the accumulation and wash-off of contaminants. Conventional stormwater management approaches have focused on conveying the runoff to receiving waters. These approaches have helped to attenuate peak flows and improve water quality, but have not been successful in achieving the level of management necessary to maintain baseflow characteristics in streams, prevent stream erosion and avoid degradation of water quality and aquatic habitat.

Low Impact Development (LID) has emerged as an alternative to conventional stormwater management. LID includes both planning techniques such as alternative development layout, narrower roads, impervious area disconnection and engineering techniques such as rainwater harvesting, bioretention and permeable pavement. When distributed, LID measures intercept rainfall and facilitate its use, return it to the atmosphere as evapotranspiration, infiltrate it into the ground, and/or detain and slowly release it in an effort to reproduce the rates and processes of the pre-development hydrologic regime.

The overall objective of this study was to advance knowledge about the performance of permeable pavements under Ontario climatic and geologic conditions. More specifically, the study was to quantify and compare the performance of various permeable pavements installed on low permeability soils, and evaluate the effectiveness of alternative cleaning practices. Key factors affecting design and their impact on long term performance are also identified and assessed.

STUDY SITE

The parking lot for this project is located at TRCA's Living City Campus at Kortright in Vaughan, roughly 8 km north of Toronto. The research facility consists of four 230–233 m^2 pavement cells (Figure 1). Two cells are constructed with permeable interlocking concrete pavers (AquaPave® and Eco-Optiloc®, hereafter referred to as AP and EO), one cell is constructed with Hydromedia™ Pervious Concrete (PC) and one cell is constructed with traditional asphalt. The PC is estimated to have up to 30% open space. The EO pavement has wide joints between the pavers with roughly 12% open space and 1-9 mm jointing material. The AP has narrow joints with only 2-4% open space, and joint filler ranging from 1 to 3 mm in size. Each permeable pavement cell is drained by a perforated pipe placed 500 mm below the surface at the interface between the open graded granular sub-base layer and the native soil. The asphalt cell is surface drained via a catchbasin in the center of the plot.

Infiltrated water collected from the 3 cells as well as runoff collected in the catchbasin is conveyed separately in sealed pipes to a downstream monitoring vault where automated samplers and flow meters are housed. A Mirafi Filter Weave® 500 geotextile was placed below the open graded base as a separation layer (Figure 2). 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 pavement cells are hydraulically separated by concrete curbs which extend down to the native soil to ensure the separation of runoff and infiltrated stormwater for each pavement type. Concrete pipe collars at cell boundaries prevent water movement along granular trenches surrounding pipes.

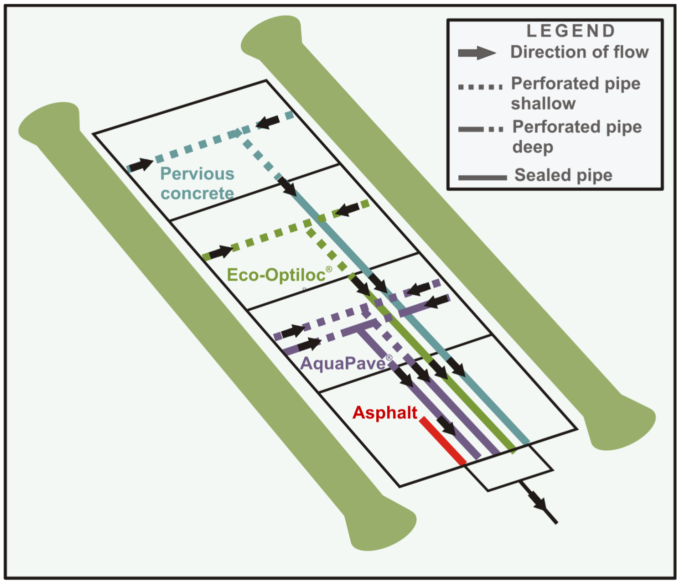

Figure 1. Schematic of Kortright permeable pavement research facility

Beneath the AquaPave cell, a second perforated pipe is placed on a 1.0 x 20 m impermeable liner below 1 meter of native soil. Using two collection pipes at different depths facilitates study of the effect that infiltration through native soils has on water quality and provides a basis for evaluating potential risks to groundwater in situations where the seasonally high water table is 0.5 m below the base of the permeable pavement.

Geotechnical investigations showed native soil conditions below the existing pavement structure to consist primarily of silt to silty clay soils underlain by clayey silt till material at 1.8 to 2.4 m. The saturated hydraulic conductivity of silty clay till materials typically ranges between 10^{-6} and 10^{-4} cm/s, which is equivalent to an infiltration rate of 12 to 50 mm/h based on conversion factors provided by Ontario Ministry of Municipal Affairs and Housing (1997). Wells at Kortright show the water table across the property to be several meters below the surface.

APPROACH

The first phase of this study was conducted over a 22 month period from September 2010 to June 2012. A second phase of monitoring was initiated in October 2012 and was scheduled to end in December 2014. Inside the control vault the quantity and quality of surface and subsurface flows were continuously monitored. Water quantity data were collected with tipping flow buckets while water quality samples were collected with automated samplers. Wells in each cell were equipped with water level sensors to continuously record water levels within the permeable pavement and granular base. The temperature of outflows from the asphalt and AquaPave plots were monitored using temperature sensors. A meteorological station located on site provided continuous precipitation and air temperature data.

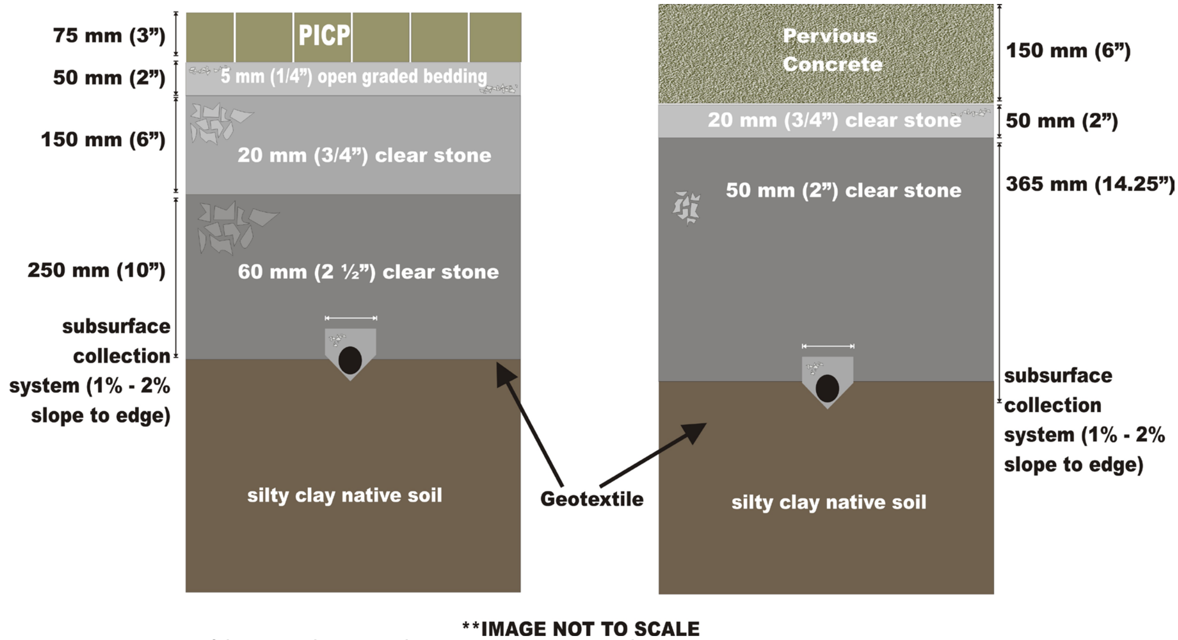

Figure 2. Cross section of the permeable interlocking concrete pavement and previous concrete.

Surface infiltration rates of the permeable pavements (18 measurements per pavement) were conducted annually using ASTM C 1701, *Standard Test Method for Surface Infiltration Rate for Pervious Concrete* to assess changes in surface infiltration over time.

Ball valves attached to the collection pipes restrict the flow of water out of the parking lot allowing water to infiltrate more effectively. Flows from the asphalt plot were restricted to ensure that stormflows did not exceed the tipping bucket's upper measurement limit of 60 L per minute. In November 2011 and April/May 2012 the ball valves were closed to assess infiltration rates into the native soils and evaluate the impact that detention time had on outflow volumes.

Water quality samples were proportioned according to flow by measuring out a volume of water from each discrete sample bottle proportional to the volume of flow since the previous sample. The resulting flow volume proportioned composite samples for each event were subsequently prepared and delivered to the Ontario Ministry of the Environment (OMOE) Laboratory in Etobicoke for analysis following OMOE lab preparation and submission protocols. The major variable groups analyzed included nutrients, metals, hydrocarbons and general chemistry (e.g: pH, hardness, chloride). See the full STEP report (Drake *et al.*, 2012) and Drake *et al.*, 2014a,b for details on data analytical methods.

In order to assess the impact maintenance practices and in-situ conditions have on pavement performance, experiments were conducted on the Kortright parking lot, the Earth Rangers parking lot and other older parking lots within the Greater Toronto Area (GTA). Pavements at the Living City Campus were cleaned with an Elgin Whirlwind Vacuum truck. Surface infiltration rates were measured before and after using ASTM C 1701 to quantify effectiveness of cleaning. In-situ conditions were characterized according to drainage patterns, traffic use, age, and adjacent vegetation to evaluate impacts to pavement performance.

The elevation of the permeable pavements and asphalt surfaces was surveyed once a year to assess how well the pavements hold up to freeze-thaw conditions and traffic loading. Additional observations of ponding during snow melt events and the prevalence of vegetation in the joints was also recorded.

FINDINGS

Overall, the three permeable pavements evaluated in this study reduced the volume of stormwater outflow by 43% and completely infiltrated and evaporated all rainfall from events up to 7 mm in depth. Effective infiltration occurred despite the presence of low permeability silty/clay native soils beneath the pavements. Ongoing monitoring of the site since 2012 has shown that these runoff reduction rates continue to be sus-

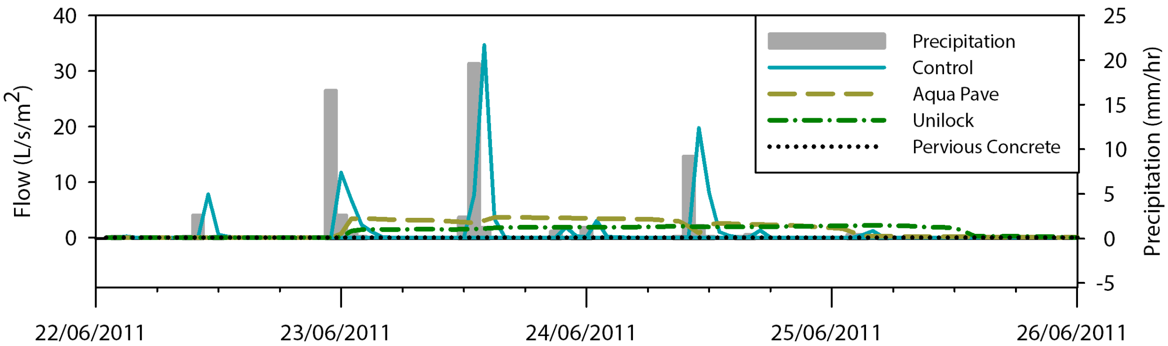

Figure 3. Hydrograph and hyetograph of consecutive June, 2011 rain events for all studied pavement types.

Rainfall runoff that was filtered through the pavements and granular base was considerably cleaner than runoff from the asphalt pavement. Pollutants with significantly lower concentrations in permeable pavement outflows included suspended solids, extractable solvents (oil & grease), ammonia-ammonium nitrogen (NH_3, NH_4+), nitrite, total kjeldahl nitrogen (TKN), total phosphorus, copper, iron, manganese and zinc (Figure 4). The permeable pavements also generated a net reduction in total pollutant mass for all of these constituents in addition to dissolved solids, chloride, sodium, phosphate, and nitrate. The large reduction in pollutant mass is largely attributed to the effective reduction in runoff volumes discussed previously.

tained even after several years of operation. Variations in volume reductions among the permeable pavements was attributed to differences in cell designs and native soil infiltration rates, as well as minor leaks between the plots. Reduction of stormwater volume is a critical function of permeable pavements that helps prevent adverse impacts of impervious surfaces on downstream infrastructure and the health of aquatic systems.

In addition to reducing outflow volumes, the PPs delayed and reduced peak flows. Flow rates were effectively attenuated throughout all seasons, including the winter, over the duration of the study. On average, PP peak flows were 91% smaller than peak runoff flows from the asphalt pavement (Figure 3). A median 14 hour attenuation (or 2.9 lag ratio) of outflow was observed from the PPs. The slower and more controlled outflow closely mimics natural interflow and reduces the risk of flooding and erosion in downstream receiving waters.

Increasing detention times in the pavement base substantially increased the volume of water infiltrated. During normal operation, the flow control valves on the permeable pavement outlets released water slowly over a period of 24 to 36 hours. To assess the effect of detention time on runoff reductions, the flow valves were closed and re-opened for time periods of between 32 and 75 hours, except during one period in the late fall of 2011 when valves were closed for 360 hours (15 days). The closed valve test results (Table 1) show an average runoff volume reduction rate of 82%, ranging from 72 to 99% during individual tests. This was much greater than the 43% runoff reduction rate observed during normal operation. Differences in volume reduction rates during closed valve tests may be in part explained by differences in antecedent moisture conditions and rainfall characteristics.

Seasonal fluctuations in pollutant concentrations were more pronounced in runoff than in PP outflow. In the winter the concentration of pollutants associated with road salting were considerably higher in runoff than in PP outflow. The reduction in concentration is attributed to the detention and dilution of winter stormwater provided by the PP systems. Water quality data collected below native soils indicated that sodium and chloride will migrate onwards to groundwater systems, although further investigation is needed to determine how the presence of these constituents may affect the mobility of other stormwater contaminants, such as metals.

The PICP and PC pavements introduced different constituents into stormwater outflow as a result of leaching of materials within the pavement system. In the case of PC this

Table 1.Closed valve test results

Event Date	Rain (mm)	Closed Valve Time (hrs)	Outflow volume (L/m^2)		Volume Reduction (%)
			Asphalt	Permeable Pavements	
15/11/2011	5.2	46	4.8	1.1	77
23/11/2011	15.4	32	13.2	3.7	72
28/11/2011[1]	82.8	360	84.7	7.55	91
21/04/2012	9	58	8.3	0.06	99
23/04/2012	17	75	14.3	2.4	83
30/04/2012	10.7	43	10.2	1.9	81
03/05/2012	25.4	94	24.1	6.4	73
08/05/2012	6.2	32	6.1	1.1	82

Notes: [1] Results represent four consecutive events beginning on the indicated date. Valves were briefly opened and reclosed during the test.

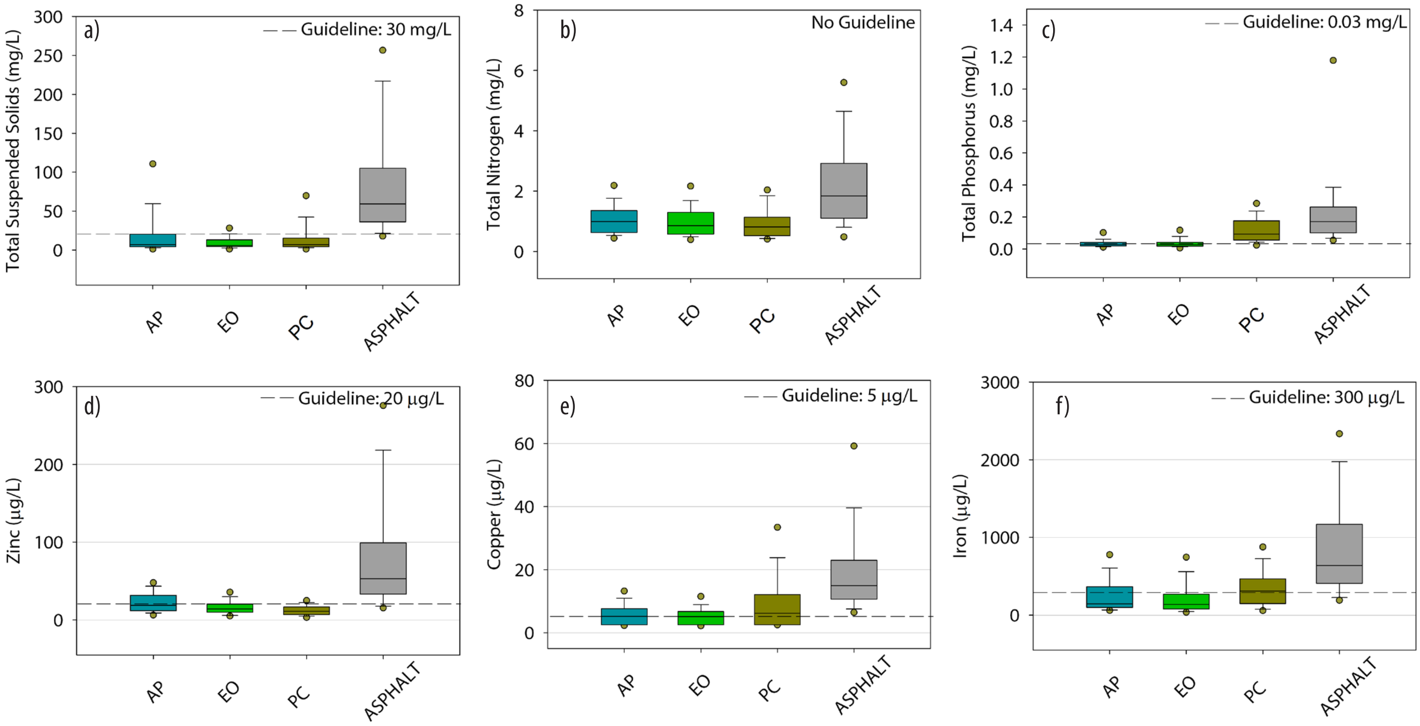

Figure 4. Box plots of outflow water quality for a) Total Suspended Solids; b) Total Nitrogen; c) Total Phosphorus; d) Zinc; e) Copper; f) Iron. AP: Aqua Pave; EO: Eco-Optiloc Unilock; PC: Pervious Concrete.

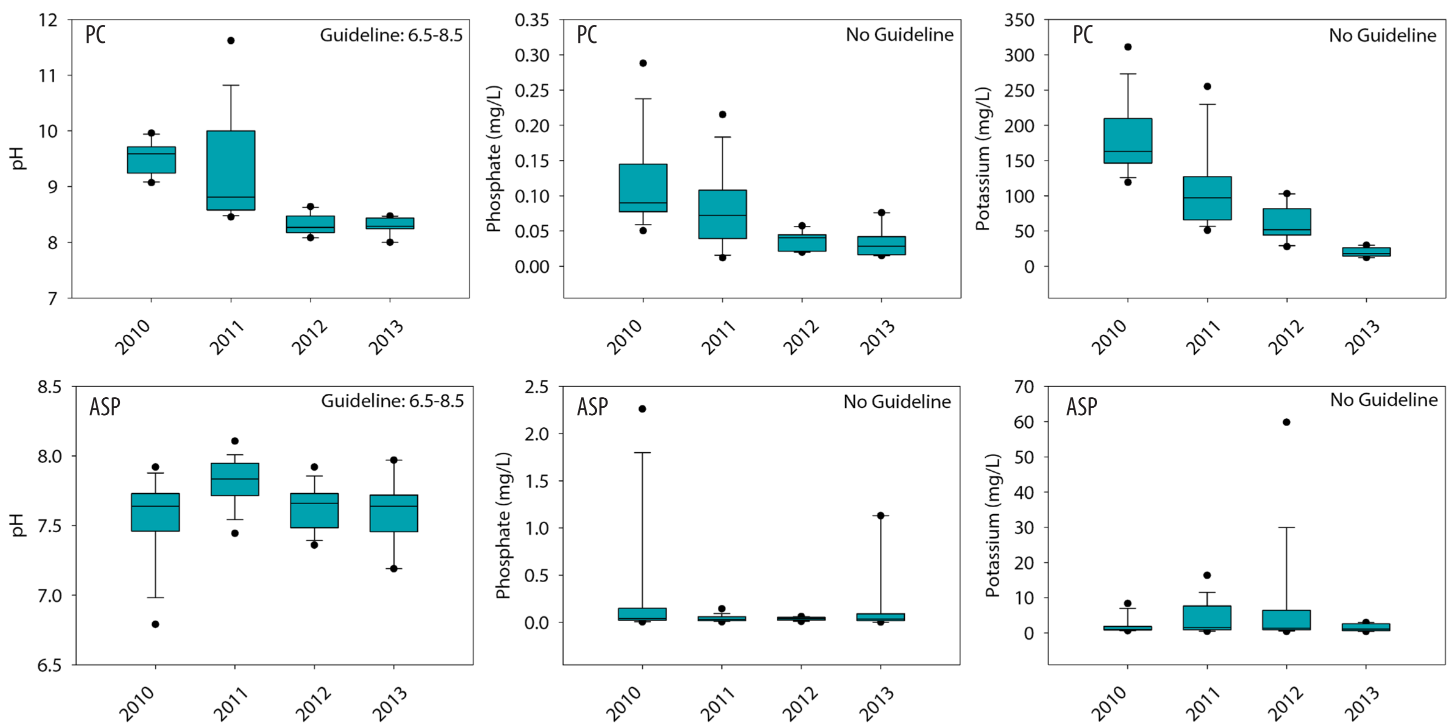

Figure 5. Water quality trends for pH, Phosphate, and Potassium in outflows from the pervious concrete (top row) and asphalt pavements (bottom row). Note difference in y-axis magnitude.

led to a gradual improvement in water quality over the course of the study, as mobile pollutants were ultimately flushed from the pavement. Throughout the first year of monitoring the PC effluent contained elevated levels of phosphate and released highly alkaline stormwater, which are undesirable characteristics for aquatic ecosystems. Concentrations declined significantly after two years (Figure 6). Further investigation is needed to explore the implications of pollutant leaching on stormwater quality from large newly constructed PP installations.

The quality of outflows draining from the pavement base and from a pipe located 1 m below the native soils was similar. The research facility includes underdrains at the interface between the base and native soils, as well as one additional underdrain below 0.5 to 1 m of native soil. The purpose of the second underdrain was to evaluate the quality of water that would infiltrate through the native soil and into the groundwater, and assess whether the quality of infiltrated water changes over time. Figure 6 presents results for selected water quality concentrations of outflows from the upper and lower underdrains (labelled as high and low respectively). To date, there has been little difference in water quality between the two underdrains. Trend analysis shows that total suspended solids concentrations in the lower underdrain have decreased over time, likely due to flushing of sediment that was inadvertently deposited in the perforated pipe during construction of the facility. There was no evidence of increasing metal or phosphate concentrations over the four years.

The permeable pavements helped to mitigate the impact of high surface runoff temperatures on downstream aquatic life. During hot summer days when asphalt runoff temperatures peaked at 26 ° C, the permeable pavement outflows were approximately 3 ° C lower. Flow volumes were also much lower, and of longer duration, which helped to 'smooth' out the thermograph, and reduce thermal loads to receiving waters. The temperature of stormwater runoff is critical importance because fish and other aquatic organisms are very sensitive to even small changes in stream temperature.

Surface infiltration measurements revealed substantial reductions in permeability over a 23 month period, although even at reduced permeability levels, all of the pavements continued to maintain sufficient capacity to rapidly infiltrate all rainfall from observed storms. Between June 2010 and May 2012, permeability reductions of the narrow jointed PICP pavement (AP), wide jointed PICP (EO) and PC were 87%, 70% and 43%, respectively (Figure 7a). These results indicate that PPs with large surface openings may sustain critical infiltration capacity longer without maintenance than PPs with small surface openings. The PC pavement continued to have extremely high infiltration capacity even after two years, with median infiltration rates of 1,072 cm/hr at the end of the 23 month period. By contrast, the median surface infiltration rate of the narrow jointed PICP was only 20 cm/hr after the same time period.

Vacuum cleaning of the permeable pavements provided partial restoration of surface permeability for the PICPs. No benefit was observed from vacuum sweeping for the PC, although the pavement retained a high infiltration capacity. After maintenance of the PICP pavements, there was a statistically significant increase ($p<0.05$) in infiltration rates on the AP and EO pavements from 20 and 94 cm/h prior to cleaning, to 26 and 187 cm/h after cleaning, respectively (Figure 7b). Median infiltration rates on the PC pavement declined slightly after cleaning, but the change was not statistically significant. On the more severely clogged PICP at the Earth Rangers Centre, median infiltration rates increased from 2.5 to 50 cm/hr, demonstrating the effectiveness of this technique for restorative maintenance. In both cases, however,

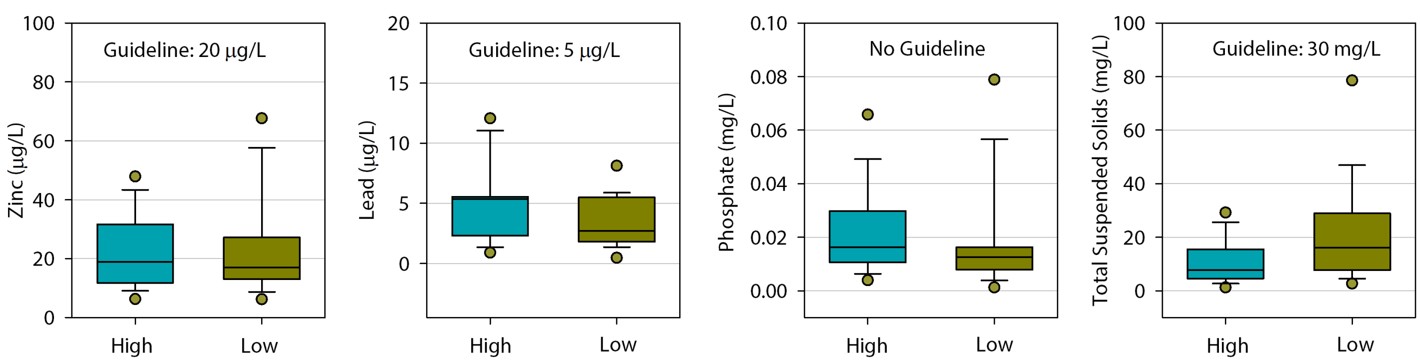

Figure 6. Box plots for selected pollutants in the AP underdrains at the interface between the pavement base and native soil (high), and below 0.5 to 1 m of native soil (low) for all sampled events during the 2010 - 2013 period.

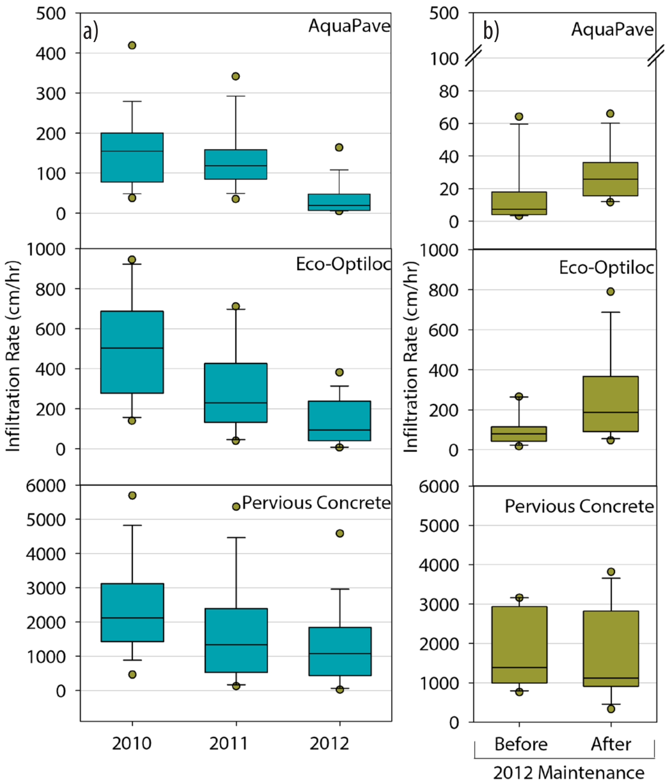

Figure 7. a) Box plots for surface infiltration rates for all three permeable pavements from 2010 to 2012; b) Infiltration rates before and after the 2012 maintenance.

vacuum cleaning did not provide consistent removal of embedded fines within pavement pores or joints. Combining vacuum cleaning with other techniques to loosen the embedded fines would likely help improve overall effectiveness of the cleaning activities.

Winter data showed that the PP systems function well even during freezing temperatures. Elevation surveys indicated that freezing temperatures did not cause surface heaving or slumping. Runoff continued to infiltrate throughout the winter (Drake et al., 2014b). A substantial spring thaw was observed in March 2011, during which the PP delayed the outflow of melt water by three days and greatly reduced peak flows. Increases in outflow volume relative to the conventional asphalt were occasionally observed during the winter and spring due to the delayed release of stormwater stored within the aggregate reservoir.

The initial construction and 50 year life cycle costs of permeable interlocking pavements were estimated to be $100 and $124 per square meter, respectively. These costs were estimated based on life cycle costing tool developed by STEP for the Greater Toronto Area (TRCA, 2013). The life cycle cost includes routine maintenance activities and major rehabilitation costs incurred over a 50 year evaluation period, assuming a discount rate of 5%. Life cycle costs are expressed as 'net present values', which represents the value of the future stream of costs (i.e. cell maintenance, rehabilitation, assumed to be 52%) discounted to the present value via a 'discount rate' which reflects the investor's time value of money. By comparison, the capital and life cycle cost of conventional asphalt was estimated to be $46 and $93 per square meter, respectively. The life cycle cost assumes that the pavement will last for 25 years, and is well maintained, including seal coating every 3 years at a cost of $3.6 per square meter.

Comparisons of the cost of permeable pavements with that of conventional treatment through an oil grit separator showed comparable construction and life cycle costs, but permeable pavements were found to be much less expensive when the treatment benefits of the two practices were considered. These cost comparisons were developed as part of a separate STEP project on the life cycle cost of LID practices (Uda *et al*, 2013). PICP and OGS practice costs were determined for the same land use and drainage area, assuming that the permeable pavement area consisted of an asphalt section draining onto a PICP section of equal size. The initial construction costs of permeable pavement were found to be slightly more expensive, but the life cycle costs were marginally lower. However, when the costs were denominated in terms of the water quality benefits of the practices, the pavement system construction and life cycle costs were 28 and 46% lower, respectively (Figure 8).

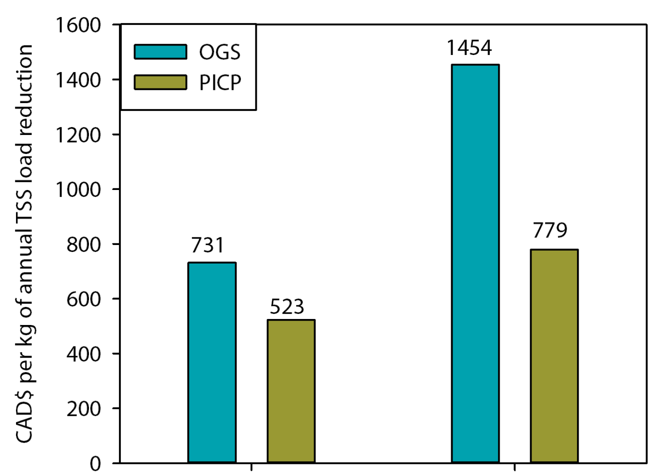

Figure 8 Capital and life cycles of permeable pavement and conventional OGS treatment. It is assumed that the drainage area is 2000 m^2 and an average TSS event mean concentration of 200 mg/L.

RECOMMENDATIONS

Results of this study indicate that PPs can be effective measures for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas, even in areas with low permeability soils. The permeable pavements reduced runoff volumes by 43% relative to conventional asphalt and effluents were generally much cleaner. Maintenance practices were partially effective in improving surface infiltration, even on severely clogged pavements. The following recommendations on pavement design and further research are based on study findings and observations.

- Controlling outflows from partial infiltration PP systems using upturned pipes and/or flow control valves is recommended to increase stormwater volume reductions through infiltration.
- Leaching of pollutants from pavement and aggregate materials was observed from PC. For large PC installations, additional treatment may be required if outflows drain to ecologically sensitive streams. Further testing of the performance and leaching potential of different types of PC is recommended.
- PPs were observed to reduce the loads and concentrations of several stormwater contaminants. Additional investigations are needed to define the specific conditions (e.g. magnitude of load reductions, ecological sensitivity of receiving waters, maintenance guarantees) under which partial infiltration PP systems should be eligible for pollutant removal credits in Ontario jurisdictions.
- Vacuum cleaning of permeable interlocking concrete pavements was found to only partially restore surface permeability after 2 years of operation. Further tests of different techniques for loosening or dislodging compacted material in PP joints or pores prior to cleaning are needed to improve the effectiveness of regenerative air and vacuum sweeping trucks.
- Based on maintenance practices evaluated in this study, annual vacuum cleaning of permeable interlocking concrete pavements is recommended to increase the operational life of these pavements. The PC pavement maintained high surface permeability over the 2 year study period, suggesting that these pavements may require less frequent maintenance.
- Further research on the long-term (> 5 years) performance of PP systems is needed to assess how the hydrologic, water quality and functional characteristics of the pavements may change over time.
- In this study, the 2011/2012 winter was unseasonably warm with low amounts of snowfall. Additional monitoring of winter performance and behaviour is recommended.
- In 2011/2012 operational staff found that the PPs did not require salting as frequently as the asphalt pavement. Further research is needed to evaluate how and whether PPs can maintain safe conditions with lower salt use than conventional pavements.
- Elevation surveys of the pavements showed no significant movement across the four pavement cells. Further testing of pavement movement under increased traffic frequencies and loading scenarios are needed to verify the range of functional conditions under which these pavements are suitable alternatives to asphalt.

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For more information on STEP's other Low Impact Development initiatives, or to access the full report for this study, entitled Performance Evaluation of Permeable Pavements, visit us online at www.sustainabletechnologies.ca

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Toronto and Region Conservation *for* The Living City