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Article

Winter Performance of Inter-Locking Pavers—Stormwater Quantity and Quality

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Abstract: This study examined the effectiveness of open-joint inter-locking pavers in a permeable pavement in cold (winter) conditions. A field-scale inter-locking paver cell (UNI Eco-Optiloc®) was built to evaluate the hydraulic performance and water quality improvements experienced during freeze-thaw and frozen conditions in Calgary, Alberta, Canada. Hydraulic performance was assessed using stormwater runoff reduction (peaks and volumes) and surface infiltration capacity. Water quality performance for removal of total suspended solids (TSS), total nitrogen (TN), total phosphorous (TP) and three heavy metals: copper, lead and zinc, was assessed. Results from the study demonstrated that the inter-locking pavers were effective in attenuating stormwater runoff peak volumes. The surface infiltration capacity decreased significantly due to the deposition of sanding and de-icing materials on the pavement surface during winter operation. Infiltrated stormwater was stored and treated within the pavement structure, which showed removal rates of 91% for TSS, 78% for TP, 6% for TN, 68% for zinc, 69% for copper and 55% for lead.

Keywords: infiltration; permeable pavement; on-site treatment; pollutant removal; runoff reduction; stormwater management; water quality

1. Introduction

The increase in impervious surface that accompanies urbanization often leads to significant and adverse impacts to the urban water environment in the form of increased runoff and impaired water quality. The reduction of infiltration also hinders groundwater recharge and lowers stream base flow. Runoff from impervious areas without on-site treatment increases pollutant loads to receiving streams and thus degrades stream water quality [1]. In the case of urban expansion, traditional stormwater infrastructure such as stormwater retention ponds could lead to ineffective land use if greater numbers and larger sizes are required. Furthermore, such conventional stormwater infrastructure may be incapable of removing pollutants from the stormwater to a satisfactory level before it is released into the receiving water [2,3].

Permeable pavement is one popular low impact development (LID) technology as it allows stormwater runoff to percolate to an underlying reservoir base and at the same time treat stormwater runoff quality on site. During a storm event, stormwater infiltrates through the pavement surface and is then temporarily stored in the pavement structure before it is either further infiltrated to underlying soils or removed by a subsurface drain [4]. As a result, runoff volume can be significantly reduced. At the same time, pollutants in stormwater are trapped and filtered within structure and hence, water quality is improved through on-site treatment [3]. The most widely used permeable pavements today include porous asphalt, porous concrete and concrete paving blocks (or inter-locking pavers). Such pavement systems can be used in pedestrian and vehicular traffic areas such as pathways, driveways, parking lots and access roads [5].

Several research studies have been performed to examine the hydraulic performance of open-joint inter-locking pavers. Fassman and Blackbourn conducted research on a newly built inter-locking paver cell (UNI Eco-Stone®) in Auckland, New Zealand and found that peak runoff was significantly decreased by 89% with an average lag time of 3.2 h. The initial infiltration capacity was 1200 mm/h [6]. Research involving inter-locking pavers in 14 different locations in the USA concluded that pavers were effective in reducing runoff but that continued effectiveness would require removing fine sediments from the surface as part of a maintenance procedure to unclog the surface during operation [7]. In their research, the surface infiltration rate was about 20,000 mm/h without the presence of fine sediments and about 80 mm/h when fine sediments were present. A study on inter-locking pavers in the summer in Calgary, Canada showed that the peak flow was reduced by 40% [3]. In that study, the initial surface infiltration rate was about 3200 mm/h and the rate dropped to 1,800 mm/h after the pavement was put into performance [3]. A field study by the University of Connecticut showed that the reduction in runoff by the inter-locking pavers was 72% as compared to traditional pavement, and the infiltration rate was measured at 200 mm/h [8]. Other studies have shown similar results to these warm weather studies for reducing storm runoff when using inter-locking pavers [9]. But a laboratory based study for hydraulic performance indicated that *winter sanding and de-icing materials* had a negative impact on surface infiltration capacity of inter-locking pavers [10].

Stormwater runoff from urban areas can be polluted by a variety of substances including suspended solids, nitrogen, phosphorus and heavy metals [11,12]. Among the heavy metals, lead (Pb), copper (Cu) and zinc (Zn) showed the highest concentrations in stormwater runoff [13]. The removal of total suspended solids (TSS), Cu, Zn and Pb by the inter-locking pavers has been demonstrated to be very effective [14]. Recent research conducted in Auckland, New Zealand showed that 57% of TSS, 49% of Cu and 85% of Zn were removed from the stormwater runoff by inter-locking pavers [6]. A field based research on six-year-old inter-locking pavers in Renton, Washington, USA demonstrated removal rates of 89% for Cu and 69% for Zn and concluded that the pavers were effective in the treatment of heavy metals even after long periods of time [1]. The study also found that the removal rate of Zn was higher than that of newly built pavement. Continuous water quality monitoring from two inter-locking paver cells (UNI Eco-Stone®) in Waterford, Connecticut, USA demonstrated that the concentrations of TSS, total nitrogen (TN), Cu, Pb and Zn were largely reduced by the on-site treatment of pavement but the concentration of total phosphorous (TP) however, remained at the same level [8]. A study in Reze, France found that the inter-locking pavers could significantly improve the water quality by removing 57% to 85% of Pb, Cu and Zn [15]. A field based study was conducted in Calgary, Alberta, Canada to examine the TSS removal of UNI Eco-Stone® and the result found a removal of 90% to 96% in the summer [16].

Permeable pavements have commonly been installed in locations with mild climates where temperatures are above 0 °C. Thus, as the literature shows, research into both the hydraulic and water quality performance of inter-locking pavers has mostly taken place in mild climate or under warm climatic conditions. However, little research has been conducted to evaluate the performance of permeable pavements and their suitability in cold regions when sanding and de-icing materials must be applied to the pavement surface. Thus, the ability to attenuate storm runoff and peak discharge in sub-zero weather has yet to be clearly understood. Similarly, previous research has targeted the removal of TSS and heavy metals. More research is needed to further investigate water quality performance of inter-locking pavers with respect to nutrients such as TN and TP particularly under cold climatic conditions. In addition, the effect of sanding and de-icing materials on the permeable pavement performance is also required to assess the applicability of permeable pavements for cold regions.

The City of Calgary is intending to apply open-joint inter-locking pavers as a potential permeable pavement in various sites throughout the City. Calgary experiences a dry continental climate with long and cold winters, but also short and warm periods routinely. Winter in Calgary is usually cold with temperatures under 0° C, but Chinook winds (warming trends during winter) quickly bring temperatures above freezing for a few days and often occur in the leeward mountain regions (such as Calgary) and several times every year. Thus, there are several freeze-thaw periods during the wintertime in Calgary. The objectives of this research are to investigate the performance of open-joint inter-locking pavers for mitigating both water quantity and quality in Calgary's winter conditions. The permeable pavement is a system with a surface course of inter-locking pavers and a base structure beneath. The testing done in this research is conducted on this system.

2. Materials and Methods

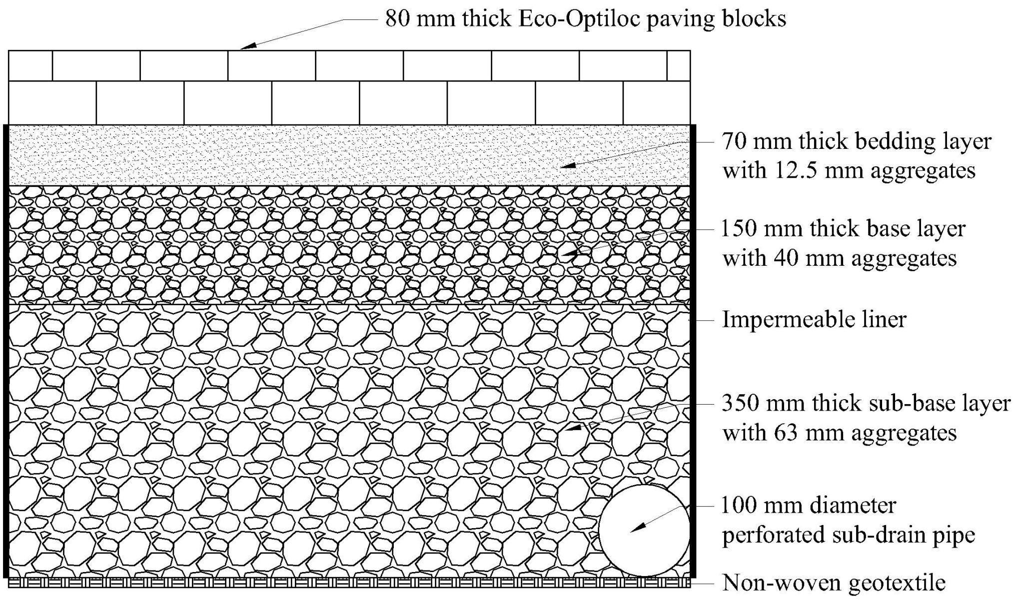
2.1. Study Site

The methodology employed in this research involves generating intensive rain events to simulate the extreme scenarios of rainfall for Calgary over the freeze-up period and during Chinook thaws in the wintertime. Water quality performance was assessed with a focus on TSS, TP, TN, Cu, Pb and Zn.

The study site is located at the intersection of Hochwald Avenue and Quesnay Wood Drive in the south west of Calgary, Alberta, which is referred to as Currie Barracks. The site receives moderate traffic from both light vehicles and occasionally heavy-duty vehicles. The inter-locking paver cell (Eco-Optiloc®) was completed in September, 2011 and has been in use for research since then. The pavement cell is 6.0 m long by 6.0 m wide (36 m^2 for drainage area) with a mild slope towards the intersection. The cell consists of 80 mm thick Eco-Optiloc® paving blocks as the road surface layer with a void ratio of about 12%. The 70 mm bedding layer consists of 12.5 mm aggregates. The base layer is 150 mm thick with larger aggregate size (40 mm). The sub-base is 350 mm thick and has the largest size of aggregates (63 mm) to form adequate void space (about 35%). The aggregates were washed before they were leveled out onto the base during construction. However, visual inspection proved that some fines were still present in the aggregates and thus, the aggregates were washed again before the field tests. Clean water was applied to both the surface and the clean-out pipes in order to soak the aggregates in the base structure and wash out the fines.

A 100 mm perforated sub-drain pipe (made by IPEX Inc., Edmonton, AB, Canada) is placed at the bottom of the pavement cell and leads to a manhole east of the cell with a 2% slope (Manning's n = 0.01). A non-woven geotextile is placed between the sub-base and sub-grade to prevent pollutant migration to the sub-grade soil (Figure 1). The sub-grade soil was found to be fairly impermeable (measured infiltration rate of 0.58 mm/h) and hence, infiltration into the sub-grade for groundwater recharge is negligible.

Figure 1. Cross-section view for the inter-locking paver cell.



2.2. Field Experiments

Field tests for the inter-locking paver cell were conducted on 19 October, 27 October, 10 November, and 14 December, 2011. Four surface infiltration tests were conducted on 17 October and 20 December in 2011, and 25 January and 15 March in 2012.

Stormwater used for the field runoff tests was hauled from a nearby stormwater retention pond to the water storage tanks on site before being applied to the pavement cell. Actual sediment collected from Calgary roads was added to the stormwater to match an average TSS concentration of about

500 mg/L for typical storm runoff in Calgary [17]. The volume of stormwater and storm duration were 4500 L and 20 min, respectively, in order to simulate a one-in-100 year storm event of 20 min duration with a rainfall intensity of about 80 mm/h. In these experiments, the one-in-100 year storm events were simulated because roads are considered part of the major drainage system and should be designed for the 1:100 year storm event, according to the City of Calgary stormwater management manual [17]. During each field runoff test, stormwater was pumped from the water storage tank and then precipitated onto the inter-locking paver cell through a rainfall applicator. The rainfall applicator consisted of a 6 m long Acrylonitrile butadiene styrene (ABS) pipe (2 inch in diameter) with headers on both sides and outlet holes along the pipe in order to evenly disperse stormwater across the width of the pavement. A wooden beam was sealed at the downstream end of the pavement cell to prevent stormwater from running off the pavement surface. Outflow rate from the sub-drain system was continuously monitored in the manhole using a Sigma 950 flow meter. A Sigma 900 flow meter was used to measure the outflow from the water storage tank to ensure that the outflow rate was about 3.7 L/s (equivalent to about 80 mm/h of rainfall applied to the pavement) [3]. The lag time was measured as the time from the beginning of the experiment to the time when outflow was initially observed from the sub-drain pipe in the manhole. The ponding time, which is the duration timed when the pavement surface was submerged under stormwater from the end of pumping, was also recorded. At the same time, water samples were manually collected from the sub-drain pipe in the manhole at a 5-min time interval. Water samples were then delivered to the Civil Engineering Wastewater Laboratory of the University of Calgary for assaying TSS using a standard method and chemical parameters, TP, TN, Pb, Cu and Zn using Hach procedures 8190, 10071, 8033, 8143, and 8009, respectively. The Hach procedures stated above are equivalent to standard methods cited by the American Public Health Association (APHA) for TN, TP, Pb and Zn.

Surface infiltration rate measurements for the inter-locking paver cell were made using single-ring infiltrometers. Galvanized steel rings with dimensions of 30 cm in diameter and 25 cm in height were fixed on the cell surface. A total of six locations were tested on the pavement surface to capture the spatial distribution in infiltration rate over the pavement surface. The rings were sealed on the pavement surface using 1-hour fast curing silicon and plumber's putty. The initial water level in the rings and the time completely draining water into the pavement were recorded. These measurements were repeated at each location until the recorded drainage time became approximately stable.

Climatological variables including daily average air temperature and precipitation were obtained from the weather station at the Calgary International Airport. In addition, two temperature sensors were placed in the pavement: One in the sub-grade and the other between the bedding layer and the base layer. Examination of the temperatures observed from the sensors and the weather station found very little difference between the three sets of data. In particular, when the air temperatures were below zero, so too were the pavement temperatures. Hence, discussion is generated using the environment temperature to represent the temperature of the test dates.

2.3. Analytical Methods

In the field runoff tests the outflow rate was monitored by the Sigma 950 flow meter and the peak flow rate reduction was obtained by:

$$Peak\ Rate\ Reduction = \frac{Q_{inflow} - Q_{outflow\_peak}}{Q_{inflow}} \times 100\% \quad (1)$$

where Q_{inflow} is the inflow rate, which is ensured to be approximately constant in each test from the water storage tank (L/s); and $Q_{outflow\_peak}$ is the peak outflow rate observed from the sub-drain pipe in the manhole (L/s).

The average removal rate of TSS is calculated as:

$$R_{TSS} = \frac{M_{in} - C_{TSS\_out} V_{out}}{M_{in}} \times 100\% \quad (2)$$

where R_{TSS} is the average removal rate of TSS (%); is the sediment load in inflow (g); C_{TSS_out} is the average concentration of TSS from the outflow (g/L); V_{out} is the total volume of stormwater observed from the sub-drain pipe in the manhole (L). The average removal rates of the other pollutants (TP, TN, Pb, Cu and Zn) are also calculated using a similar equation (Equation 2).

The surface infiltration rate for each location is calculated as:

$$F = \frac{h}{T} \quad (3)$$

where F is the surface infiltration rate (mm/h); h is the initial water depth in the infiltrometer (mm); T is the time needed for full infiltration of water in the infiltrometer (h).

The average surface infiltration rate for each surface infiltration test is calculated as:

$$\bar{F} = \frac{\sum_{i=1}^{n} F_i}{n} \quad (4)$$

where $\bar{F}$ is the average surface infiltration rate (mm/h); n is the number of total measurements. The calculated average infiltration rate was taken as the overall infiltration rate over the pavement surface.

The nonparametric Kruskal-Wallis test and multiple comparison tests were employed to compare medians of more than two samples. The analysis is conducted at a significance level of 0.05 using the MATLAB statistical toolbox.

3. Results and Discussion

3.1. Hydraulic Performance

The outflow rates recorded at the manhole *versus* the average applied inflow rates in the four field runoff tests are shown in Figure 2. The time series of both daily average temperature and daily precipitation (rain and snow) during the testing period from October 2011 to December 2011 are also shown in Figure 3. The vertical lines represent the dates of the field runoff tests. The time to manhole, time to peak, and the ponding time on the pavement surface are shown in Table 1. The first test (run in 19 October 2011) was run under mild temperatures (10 °C). The results indicated that the peak rate reduction from the inflow was about 21%. Stormwater runoff was absorbed into the pavement very quickly and no ponding on the pavement surface was observed during this test. The outflow peak discharge was higher than those of the three tests that followed. These results can be ascribed to the newly built pavement's high initial surface infiltration rate (average 7548 mm/h) and the large void ratio (about 35%) within the pavement structure that allows stormwater to travel through the pavement.

The three tests, which were run in 27 October, 10 November, and 14 December, 2011, were run in winter conditions when temperatures were about 4 °C, 2 °C and −3 °C, respectively. The third and fourth tests were conducted in freeze-thaw periods when the temperature fluctuated around 0 °C, which is a typical weather pattern during winter in Calgary. The last three simulated runoff tests showed that there was a moderate level of peak flow rate attenuation ranging from 30% to 50% during the winter. The results of the second test conducted in early winter were similar to those in the first test in terms of time to manhole, time to peak, ponding time and the outflow hydrograph.

Sanding materials were first applied to the road surface before the third test. In the third and fourth tests the detention time within the pavement structure and the lag time to the manhole were longer when compared to those observed in mild temperature conditions. Visible ponding on the pavement surface was observed after the tests, although the ponding depth was very low and insignificant. Low outflow rates were also observed from the manhole in the beginning for both the third and fourth field runoff tests. The ponding and the lowered outflow rate in the beginning were caused by the decreased surface infiltration of the inter-locking pavers due to the deposition of sanding materials on the surface layer, as discussed later. In addition, void space within the pavement structure was reduced as water and moisture retained within the pavement structure was frozen and thus, occupied the void space that would normally drain the stormwater. Continuous vehicular traffic on the pavement surface also played a role on the reduction of void space in the pavement structure after the pavement began operating. In this situation, more time was needed for the stormwater to travel through the pavement structure. Compared to the first two field runoff tests, stormwater was retained for a longer period in the pavement structure in these two runoff tests, which consequently resulted in a longer time to manhole and time to peak. In addition, more time was required to completely drain the stormwater from the pavement structure and hence, a longer falling limb in the outflow hydrograph was detected for both the third and fourth tests.

Based on these test results, the inter-locking pavers appear to be capable of hydraulically handling the simulated one-in-100 year storm event during freeze-thaw periods in wintertime, although their performance is inferior to that under mild temperatures in terms of stormwater ponding. Overall, the pavers can be effective in reducing stormwater ponding in urban settings under both mild and cold conditions. In this field study, the effect of sanding materials and winter conditions (cold temperatures) on the pavers' hydraulic performance could not be investigated separately; the application of sanding materials in the winter is, however, expected to largely affect the hydraulic performance of the inter-locking pavers. Further investigation of their separate roles in a laboratory setting is recommended.

Table 1. Time to manhole, time to peak and ponding time in simulated runoff tests.

Test date	Time to manhole (s)	Time to peak (min)	Ponding time (min)
2011-10-19	50	14	0
2011-10-27	56	18	0
2011-11-10	110	26	15
2011-12-14	106	28	18

Figure 2. Outflow hydrograph from simulated runoff tests for inter-locking pavers.

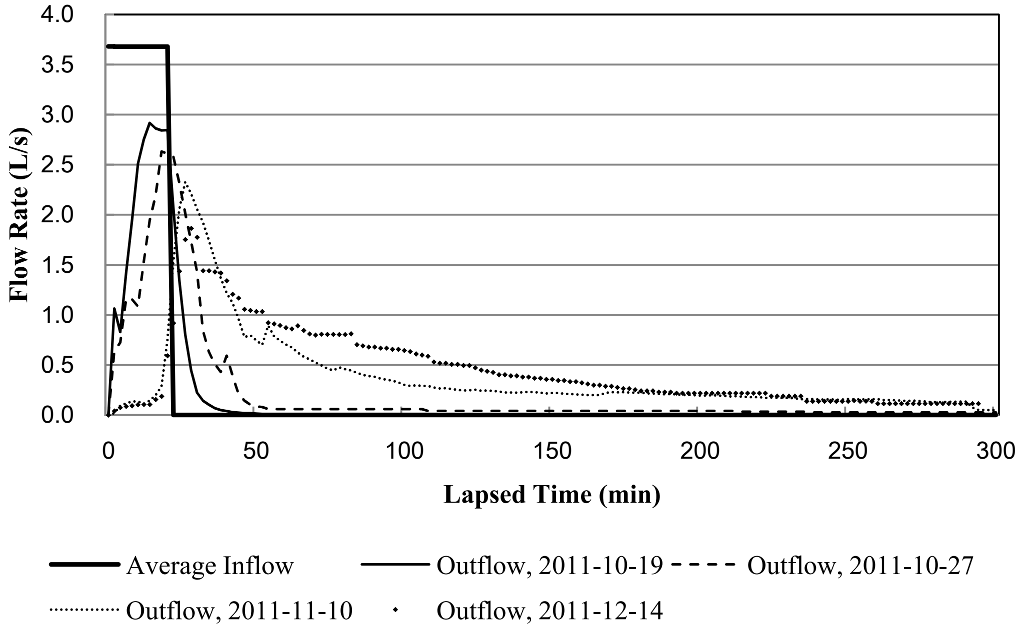
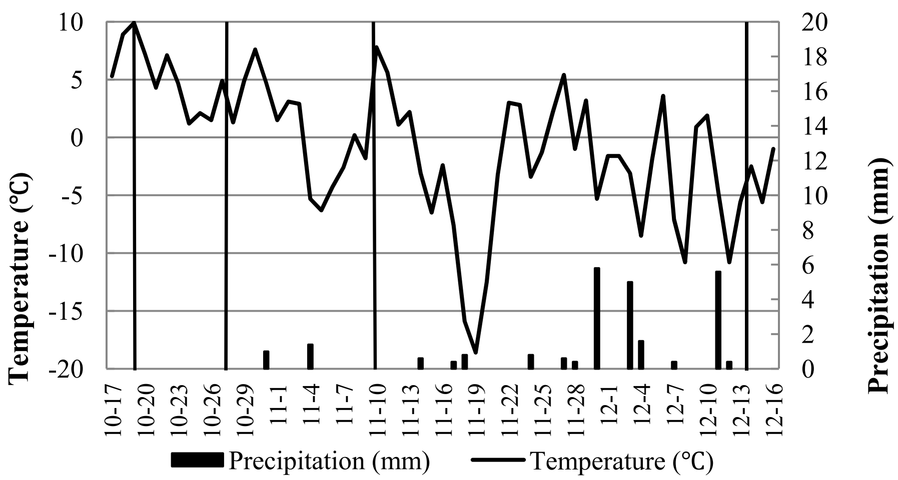


Figure 3. Temperature and precipitation during the test period. Vertical lines indicate the date of the runoff test.



3.2. Surface Infiltration

The calculated average (over six locations on the pavement cell) surface infiltration rates in the four surface infiltration tests are presented in Figure 4. The first surface infiltration test was carried out shortly after the pavement was built and, hence, the result represents the initial surface infiltration rate. As shown in Figure 4, the initial average surface infiltration rate was 7548 mm/h, which was much higher than those obtained from the other three tests. The average infiltration rates calculated from the last three tests were over one order of magnitude lower than the initial average surface infiltration rate. It is difficult to draw conclusions with a data set consisting of only four averages but this is a consequence of the restriction of testing during Chinook Conditions. Testing had to occur during these intermittent thaw periods in order to have the surface amenable to testing. These conditions are infrequent and during this observation period, there were only three Chinooks occurring at times that the authors were able to mobilize stormwater for the tests. However, by examining the meteorology, pavement conditions and behavior during each test, conclusions can be drawn on mechanisms for describing pavement behavior (as discussed below).

In addition, an obvious heterogeneous distribution of surface infiltration rate was observed for the last three tests during the winter; in particular the difference between the middle and side sections of the pavement cell. Among the six locations for infiltration tests, lower infiltration rates were generally observed on the sides of the pavement cell, while higher infiltration rates were found near the middle of the pavement surface. The infiltration rates of the traffic load sections fell between the middle section and side section. The significant difference in sample medians of infiltration rates among the middle, tire track, and side sections of the pavement cell was identified with a nonparametric Kruskal–Wallis test for the last three surface infiltration tests. The highest median was tested in the middle section of the pavement cell, while the lowest median was found at the side section in multiple-comparison test. The multiple-comparison test also showed that the median in the tire track section was significantly different from the side section but not the middle section. The data collected from the first test was not included in the analysis, since significantly high initial infiltration rates were observed from all three sections as compared to the other three tests. The pooled data of infiltration rates in the last three infiltration tests were also plotted in a box plot (Figure 5). The difference between the middle and side sections of the pavement cell is due to the fact that fine and particulate sediments are easily transported to the pavement surface by wind and precipitation from the ambient environment and then deposited on the surface of both sides. In particular the sanding materials commonly accumulate on the sides of roads in the winter. Aside from the unevenly distributed traffic loads on the pavement cell, another factor may be contributing to the non-homogeneous distribution of infiltration rates. Compared to the sides and tire track sections of the pavement, the middle portion was less influenced by sediments or traffic loads and hence, the filtration rate could be kept at relatively high values. Most roads in Canada, however, are designed with a mild crown that carries water to the sides of the road.

Figure 4. Average surface infiltration rate from four single-ring infiltrometer tests.

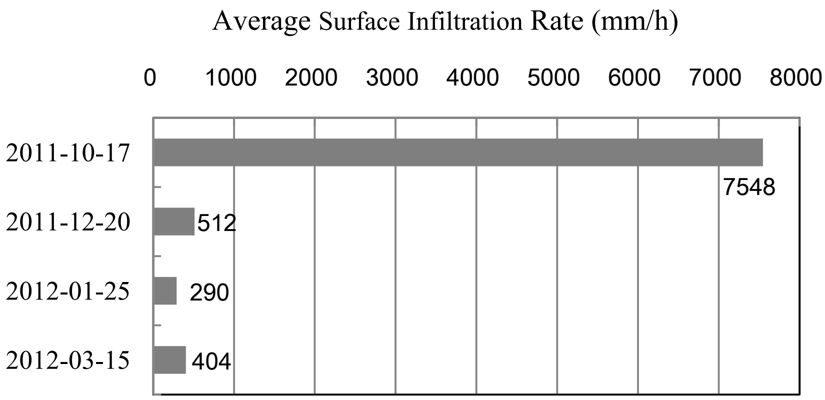
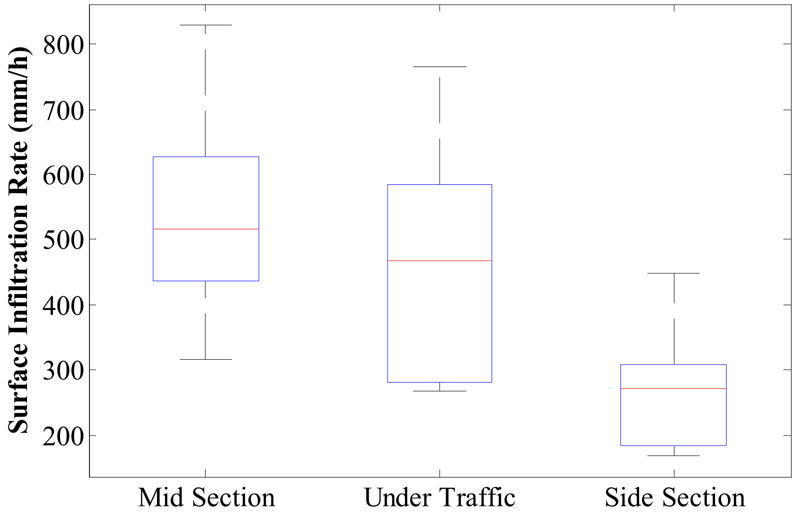


Figure 5. Measured infiltration rates of the middle, under traffic (tire tracks) and side sections of the pavement cell during the winter period.



The temperature dropped below 0 °C and sanding materials were first applied to the pavement surface before the second infiltration test. The average surface infiltration rate was 512 mm/h in the second infiltration test. The infiltration rate was substantially higher in the first infiltration test before the application of sanding materials. This suggests that sanding materials on the pavement surface can quickly cause major clogging in the surface layer and subsequently reduce the surface void space and consequently lead to a dramatic reduction in surface infiltration capacity. The highest infiltration rate was still observed in the middle part of the pavement cell at a rate of about 800mm/h. Some measurements near the edge of the pavement were lower than those in the middle section, which was qualitatively similar to the results in the third and fourth infiltration tests.

The third and fourth surface infiltration tests were run under Chinook conditions as the temperature climbed up to around 0 °C after an initial period of “freezing”. Results from the third infiltration test showed an average surface infiltration of 290 mm/h, which is the lowest among these four infiltration tests. Measurements in the fourth test on 15 March 2012 indicated that the infiltration rate, which was slightly over 400 mm/h, was higher than that in the third infiltration test (290 mm/h). The reason for the observed slight “restoration” of infiltration capacity between these two freeze-thaw periods may be attributed to the different climatic conditions prior to these two tests. Temperature was extremely low in the two weeks prior to the third test on 25 January 2012. From 10 January 2012 to 24 January 2012, the temperature in Calgary dropped to as low as −29 °C. Although the temperature climbed up to 0 °C shortly after the Chinook, the water in the voids of the pavement surface was likely still to be frozen. As a result, the void ratio under the pavement surface might be still very low in this freeze-thaw period and surface infiltration capacity was, thus, very low. However, the fourth test was performed after a short freezing period with a temperature of around −5° C. Under this circumstance, any water that was in liquid form prior to this short freezing period would likely have drained away creating relatively dry void spaces with little water available to actually freeze-up and block flow. Thus, this potentially could “restore” the surface’s infiltrating capacity to some degree. This possibly explains why the surface infiltration rate was higher in this test compared to the third infiltration test without any maintenance (e.g., sanding materials removal).

The surface infiltration tests demonstrated that the surface infiltration capacity can be rapidly reduced in the winter after sanding materials are applied on the pavement surface. The average surface infiltration rate can be as low as 290 mm/h in the winter. However, the runoff tests showed that satisfactory hydraulic performance of inter-locking pavers was possible in handling a one-in-100 year storm event with a rainfall intensity of 80 mm/h—this is an extreme case in Calgary in freeze-thaw periods during the winter time. However, future investigations of the hydraulic performance of the pavers under extreme climatic conditions (like the third infiltration test) are needed. As aforementioned, both sanding materials and cold temperatures could degrade the hydraulic performance of the pavers in winter. These factors would also contribute to the decrease of surface infiltration rates.

3.3. Water Quality

Stormwater samples collected from both inflow and outflow from the sub-drain pipe of the pavement structure in the manhole were taken in the four simulated runoff tests. Removal efficiency for pollutants including TSS, TP, TN, Zn, Cu and Pb were examined to represent the on-site water quality treatment of the inter-locking pavers. The results of average pollutant concentrations in outflows and removal rates for the above pollutants are shown in Table 2.

A TSS removal of 92.4% was achieved under mild climatic condition on 19 October 2011. The other three runoff tests conducted in the time period from 27 October 2011 to 14 December 2011 were run under winter conditions. Hence, water samples from these three tests could represent the water quality performance of the inter-locking paver cell in the wintertime. Average TSS removal rates in these three tests were 93.6%, 89% and 87.8%, respectively, which all remained at a high level, and the rate obtained from the second runoff test was even slightly higher than that from the first test under mild temperatures. This indicated that the inter-locking paver is very effective in removing TSS from the storm runoff regardless of the differing hydraulic performance of the paver under mild and cold temperatures. This is mainly because the solids were physically trapped in the void spaces between the aggregates where stormwater passes through the pavement structure and thus, the temperature may not largely influence this process.

Similar to TSS removal, TP removal observed in low temperatures was almost the same as that in mild temperatures. The results from these tests showed that over 75% of TP was removed from the storm runoff; however, the removal of TN was very low in both mild and low temperatures. The difference between TP and TN removal rates is likely due to the different removal mechanisms. The removal of TP by the pavement is speculated to be governed by chemical processes. When phosphate contacts the aggregates in the pavement structure in the process of infiltration, precipitates of calcium phosphate are formed and, hence, the phosphate portion of the total phosphorus is reduced. Biological processes dominate the removal of TN and the growth of bio-film in the processes is very sensitive to the surrounding temperature [18]. The environment of the pavement structure may not be suitable for bio-film growth. Thus, it is not surprising that the inter-locking pavers are not effective in removing TN.

The removal of heavy metals is moderate and their removal rates are all above 50% in all the runoff tests as shown in Table 2. The mean removal rates of Zn, Cu and Pb during the winter period are about 68%, 69% and 55%, respectively. In addition, there is no obvious difference in the removal rates of heavy metals, as well as TSS, TP and TN, between mild and low temperature conditions. The removal rates under cold temperature conditions appear to be similar to the values obtained under mild temperature conditions. Furthermore, the removal rate of heavy metals from permeable pavement depends on the state of the heavy metals in the stormwater. Previous studies on permeable pavement have shown that heavy metals are mainly trapped on the pavement surface in free element form but heavy metals in ion form are trapped in the base [13]. Thus, the composition of different forms of heavy metals will affect the overall removal rate, since the pavement surface and the pavement base are expected to produce different removal rates.

Table 2. Average pollutant concentrations of outflow and removal rates.

Test date	TSS (mg/L)	TP (mg/L)	TN (mg/L)	Zn (μg/L)	Cu (μg/L)	Pb (μg/L)
2011-10-19 (8 samples)	38 (92.4%)	0.08 (81.3%)	2.8 (3.4%)	30 (50%)	2 (66.7%)	7 (58.8%)
2011-10-27 (10 samples)	32 (93.6%)	0.1 (75.6%)	2.2 (4.3%)	30 (57.1%)	1.5 (70%)	6 (68.4%)
2011-11-10 (10 samples)	55 (89%)	0.07 (80.3%)	2 (7.1%)	20 (60%)	1 (80%)	6 (57.1%)
2011-12-14 (10 samples)	61 (87.8%)	0.09 (75%)	2.5 (7.4%)	10 (75%)	2.5 (58.3%)	7 (53.3%)

4. Conclusions

This study examined both the hydraulic and water quality performance of open-joint inter-locking pavers installed in the City of Calgary, Canada with the aim of evaluating the applicability of this type of permeable pavement for Calgary's winter climate conditions, which are subject to warming Chinooks. A comparison of the pavement performance under mild temperatures and Calgary's typical winter conditions was also made. The investigation of water quantity included surface storm runoff attenuation and surface infiltration. The results of the simulated one-in-100 year runoff tests conducted from October 2011 to December 2011 demonstrated that the inter-locking pavers were able to attenuate the peak discharge to some degree and effectively reduced the surface runoff. The surface infiltration tests were conducted from October 2011 to March 2012. The results indicated that the initial surface infiltration rate was as high as 7548 mm/h but that the dramatic degradation of surface infiltration observed as conditions got colder were likely due to both sanding materials and cold temperatures. However, the reduced surface infiltration rate was still adequate for snow melt and storm runoff during freeze-thaw periods in winter without resulting in obvious surface stormwater ponding. Furthermore, equivalent removal rates of various pollutants under both mild temperatures and winter climatic conditions suggested a satisfactory water quality performance of the pavement. On average 90.7% of TSS, 78% of TP, 5.6% of TN, 55% of Zn, 68% of Cu, and 65% of Pb, were removed from the stormwater in these tested events during the winter. The open-joint inter-locking pavers may also be capable of providing sufficient on-site water quality treatment for various pollutants with the exception of TN. Further investigation of the separate effects of sanding materials and cold temperature conditions however is required to improve the understanding of this type of permeable pavement. The literature shows that the placement of permeable geotextiles at different levels of the sub-base can enhance microbial activity and increase the removal of nitrogen compounds [10]. Research into the position and type of geotextiles used and their effect on increasing removal rates is recommended.

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