Verification of Pervious Concrete Drainage Characteristics using Instrumentation

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Abstract

Pervious concrete pavement is a Low Impact Development pavement alternative. A pervious concrete pavement structure generally involves a pervious concrete surface and a base reservoir layer on a permeable subgrade. The design of a pervious concrete pavement structure in freeze-thaw climates, such as Canada, assumes that water drains quickly through the surface layer and accumulates in the reservoir layer. The accumulated water in the reservoir layer then infiltrates into the subgrade, maintaining the natural hydrological cycle. It is also feasible to provide alternate drainage from the reservoir layer by including a pipe network.

In a Canada-wide study of the performance of pervious concrete pavement by the University of Waterloo, Cement Association of Canada and industry members field sites were constructed and laboratory testing was completed. Subsurface instrumentation was included in some of the pavement structures. Moisture gauges, commonly used for agricultural applications, were placed at various depths throughout the pavement structure of field sites. The permeability of the pervious concrete pavement was measured on the surface throughout the more than two year evaluation period. The data collected from the instrumentation was used to verify the assumed drainage characteristics of pervious concrete pavement. On-site and Environment Canada weather data was combined with the moisture gauge data to track the movement of moisture through the pervious concrete pavement structures. Within this research a method was developed to analyze and interpret the moisture gauge data. The analysis of the collected instrumentation data verified the assumed, effective, drainage characteristics of pervious concrete pavement.

This paper discusses one of the field sites that was instrumented during construction. The data analysis process developed in this research is presented in the paper. The analyzed data will be used to verify the assumed drainage characteristics of pervious concrete pavement. The data and findings presented in the paper provide information not previously available regarding the subsurface drainage of pervious concrete pavement. The results of this research can be used in refining pervious concrete pavement designs in the future.

Introduction

Pervious concrete pavement is a Low Impact Development pavement alternative. A pervious concrete pavement structure generally involves a pervious concrete surface and a base reservoir layer on a permeable subgrade. The design of a pervious concrete pavement structure in freeze-thaw climates, such as Canada, assumes that water drains quickly through the surface layer and accumulates in the reservoir layer. The accumulated water in the reservoir layer then infiltrates into the subgrade, maintaining the natural hydrological cycle. It is also feasible to provide alternate drainage from the reservoir layer by including a pipe network.

A pervious concrete pavement structure is designed with the intention that moisture moves quickly through the pervious concrete layer. Moisture then moves through the granular storage base layer. The moisture accumulates in the bottom of the granular storage base layer until it naturally infiltrates into the existing subgrade.

Drainage of moisture from the surface of a pervious concrete pavement can be observed visually and quantified using equipment such as a Gilson Field Permeameter or following ASTM C1701 / C1701M - 09 Standard Test Method for Infiltration Rate of In Place Pervious Concrete (1), (2). Quantifying and assessing drainage of moisture below the surface in a pervious concrete pavement structure is not straight forward. In this research, instrumentation was included in three of the field sites to attempt to monitor the movement of moisture below the surface. The analysis of the data collected from the instrumentation is expected to describe the subsurface behaviour of drainage of moisture through the pavement structure.

Field Site

The field site presented in this paper is a pervious concrete employee parking lot at a concrete ready mix plant in Barrie, Ontario. The traffic in the parking lot is personal vehicles that are only parked on the pervious concrete. The site includes three different sections, each with a constant pavement structure but differing pervious concrete mix: A; B; and C. The mix design for each section has one variable the aggregate (size and type). The sections were the following:

- Section A – 14 mm limestone;
- Section B – 20 mm gravel; and
- Section C – 20 mm gravel and limestone.

The pavement structure of the entire pervious concrete field site was 175 mm of pervious concrete over 350 mm of clear stone reservoir base. The reservoir base was over the existing silty sand subgrade material.

The pervious concrete was placed using an ABG asphalt paver. The placement with the paver was followed by one pass of a vibratory plate compactor. This technique produced a consistent surface. No joints were formed or saw cut into the pervious concrete surface.

The surface condition of the site was monitored for 40 months following construction. The pervious concrete remained in good condition throughout this time period. Ravelling developed along the construction joints which was a result of the construction technique. Very minimal ravelling developed away from the construction joint locations. Aggregates also fractured in areas of the pavement surface. This was a material deficiency. Surface abrasion was observed following the winter season. Snow removal is anticipated to be the cause of the surface abrasion (3).

The pavement surrounding the pervious concrete is a combination of sand and gravel. A portion of the surrounding sand and gravel is tracked on to the pervious concrete pavement during regular use. On the north side of the parking lot there is a small berm that is covered in grass. Some soil and vegetation from the berm may be washed on to the pervious concrete pavement during rain events.

During the winter the pervious concrete and remainder of the plant is plowed with a front end loader. The snow that is plowed is piled on the pervious concrete and with this comes a large amount of sand and gravel. Some sand is applied to the pervious concrete surface during winter storms, as required. The pervious concrete parking lot is higher on the west side and slopes down to the east.

Instrumentation Data

Moisture Gauges

Watermark moisture gauges were included during the construction of the field site. The moisture gauges in this field site are intended for use in agricultural applications (4). They were selected for use in this project as they can record measurements when not entirely surrounded by soil. This is important as both pervious concrete and clear stone have several voids which could lead to air being adjacent to the moisture gauges in some locations. The moisture gauges were attached to sensor trees and placed in the pavement structures during the construction phase. Figure 1 shows a sensor tree that includes three Watermark moisture gauges.

The sensor trees were constructed and placed within the pavement structure such that the moisture gauges were at different heights, ranging from the pervious concrete surface to within the natural subgrade. The intent of the moisture gauges on the sensor trees is to understand the behavior of moisture after leaving the surface. As is noted in this work, the drainage rate from the surface can be easily monitored using a permeameter, however the movement after this point is unknown. By placing the moisture gauges throughout the depth of the pavement structure, it is anticipated that moisture movement can be followed.

At the field site twelve moisture gauges were used on three sensor trees. The sensor trees were constructed on site and the dimensions of the three trees are consistent. The sensor trees were then placed in the pavement structure when the subgrade layer was exposed. One sensor tree is located in each of the three sections of the site, A, B and C. Figure 2 shows the dimensions of the sensor trees that were installed at the field site.

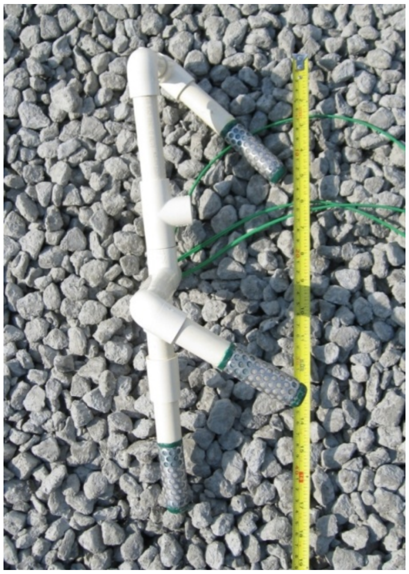

Figure 1: Sensor Tree including three moisture gauges

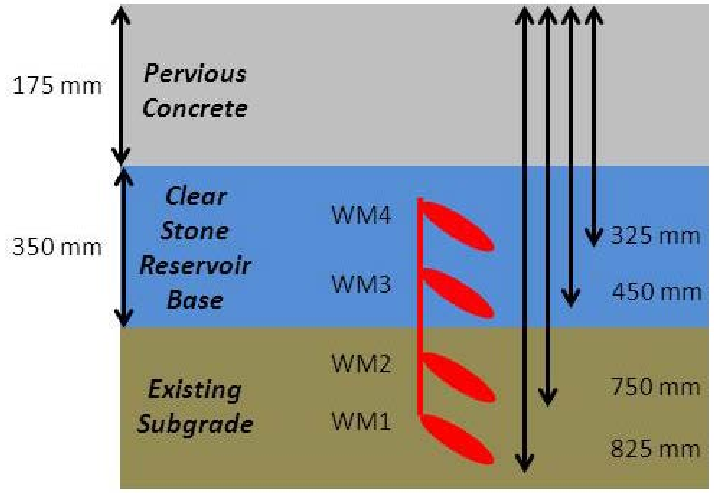

Figure 2: Sensor Tree at Field Site

As Figure 2 shows, there are four moisture gauges in each sensor tree at the field site. In Figure 2 the moisture gauges are labeled as they are in each of the three areas, A, B and C. The letter describing the area of the site (A, B or C) is added to the beginning of the moisture gauge label, such as AWM4 in area A. The reference name for each moisture gauge refers to the mix it is in, A, B or C and then the depth of the moisture gauge, with moisture gauge "1" being the deepest and "4" being closest to the surface. The sensor trees are at the same depths within each mix and are located in the same area of each mix. The site slopes and the sensor trees are all at the same portion of the slope, therefore anticipating that horizontal movement due to the slope would be consistent. Figure 3 shows a summary of the sensor trees at the field site.

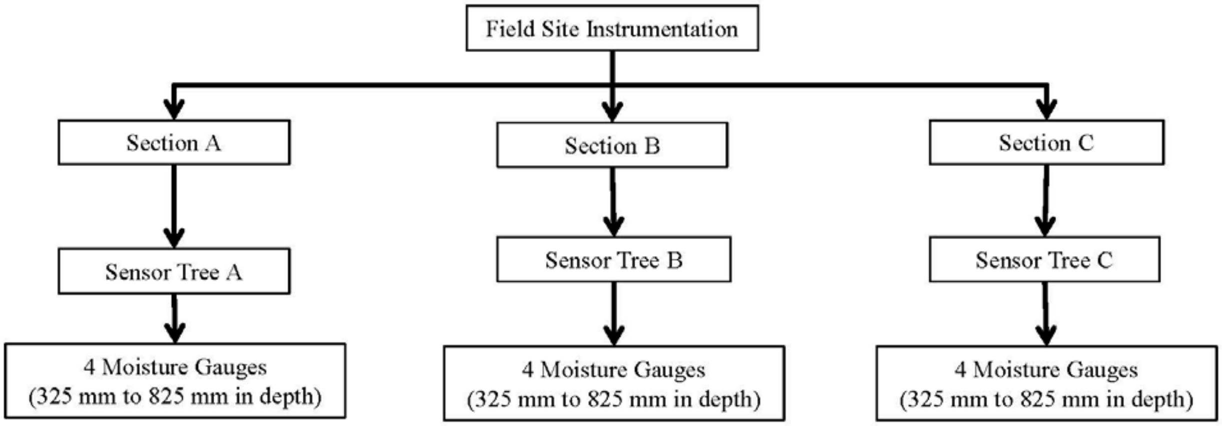

Figure 3: Sensors at Field Site

Temperature Sensors

Temperature probes, model 109B, supplied by Campbell Scientific, were included in the subgrade of the field site. The inclusion of this instrumentation was a necessity in order to interpret data recorded by the moisture gauges. Figure 4 shows a temperature probe during installation at the construction of the field site.

Figure 4: Temperature Probes Being Installed

Weather Station

The field site included a weather station that recorded air temperature and the quantity of rainfall. An example of a weather station is shown in Figure 4.

Figure 5: Weather Station at a Field Site

The weather stations included a PVC tipping bucket rain gauge and a HOBO Pendant Event and Temperature Logger. The logger records rain events in the tipping bucket as well as temperature readings of the air. The temperature readings are taken from within the white housing shown in Figure 4, which is a solar radiation shield. The weather stations provide information regarding the weather activities occurring at each field site. It was intended that the data collected from the weather station would be used to compliment and better understand other data, such as instrumentation data collected in this project.

Environment Canada weather stations are located throughout Canada and fortunately provide public data, including various weather elements at several collection rates (5). Data from one weather station, Egbert was included in the analysis of the instrumentation data at this field site. The data retrieved from the Egbert weather station in Ontario was also supported by the radar images available for the King City station (6; 7).

Analysis Methodology

As noted earlier, the field site included a weather station that measures rainfall and temperature. The tipping bucket measures rainfall accumulation in 0.25 mm quantities. The temperature sensors were programmed to measure air temperature hourly. Both the temperature data and rainfall quantities are recorded on a HOBO event logger.

The weather station does not record snowfall accumulation. With this in mind it was anticipated that weather data from the winter seasons would have to be collected from another source. The weather station was brought indoors in the winter season. Following recommendations from the Department of Environment and Resources Studies Environment Canada liaison at the University of Waterloo, data was downloaded from the Egbert weather station (8). This weather station was recommended based on its location and elevation. Daily data was downloaded for dates when the weather station was not on site.

The weather station data was used to identify dates that should be explored in the moisture gauge data. The weather data was divided into four groups annually, to generally represent the seasons. The months throughout the year were divided in the following way:

- Winter - December, January, February;
- Spring – March, April, May;
- Summer – June, July, August; and
- Fall – September, October, November.

The rain is recorded in the tipping bucket in 0.25 mm intervals. The daily rain accumulation was determined from the tipping bucket data. A continual summation was used to identify the largest quantity of rain over five days in each season. The rain event was then examined in the data. Ideally a rain event from each season would be used that was large in quantity and had minimal to no rain before and after the rain event for several days. It was anticipated that with a scenario such as this it would be easiest to follow moisture through the pavement structure. Some rain events were identified that met this description. However, in many cases this was not possible. The rain events that occurred in each season were evaluated and at least one was selected for analysis.

Maximum quantities of precipitation over five days were identified from the Egbert weather station data (6). Radar data from the King City, ON location was then used to confirm that precipitation events had occurred in the area of the field site on the highlighted dates (7).

A program was developed within this research to record moisture measurements of the material surrounding each Watermark moisture gauge. The moisture gauges are sent an excitation voltage from the CR1000 datalogger (CR1000) and after a pause of three milliseconds the voltage is measured. The measured voltage divided by the excitation voltage is recorded by the CR1000. These readings are converted to resistance and then adjusted to 21°C using Equation 1, results were adjusted to 21 °C for comparison purposes.

$$R_{21} = \frac{R_m}{1 - [0.018(T_m - 21)]} \qquad \text{Equation 1}$$

Where,
R_{21} is the resistance adjusted to 21°C.
R_m is the resistance reading determined from the raw data collected by the CR1000, in kOhms.
T_m is the temperature of the soil surrounding the moisture gauge in °C.

The resistance at 21°C, R_{21}, is then converted to Soil Water Potential (SWP) in centibars (cb) using Equation 2.

$$SWP = 7.407\ x\ R_{21} - 3.704 \qquad \text{Equation 2}$$

Where,
SWP is the soil water potential measured in centibars (cb).

The unit of centibars is equivalent to kPa and therefore equal to kN/m^2. The data in cb represents water tension or SWP and in agricultural applications describes the availability of water for a plant root. When there is minimal available water the centibar values are higher. When water is readily available, the cb values are lower. The moisture gauges are calibrated for 0 to 200 cb as this range is typical in agricultural applications. Although the moisture gauges are calibrated to a range up to 200 cb, Irrometer Co. Inc., the producers and suppliers of Watermark moisture gauges predict that results beyond 200 cb are reasonably accurate and can be used in analysis (4).

Temperature sensors were included at the field site to provide subsurface data for use in analyzing the moisture gauge data. The temperature sensors are also connected to the CR1000 at the site and measurements are taken by the temperature sensors and moisture gauges at the same time. The temperature sensors must be surrounded by material in order to take an accurate reading. For this reason the temperature sensors were located close to the top of the existing subgrade at the field site.

Both the temperature sensors and moisture gauges collect data hourly. This data was averaged over 24 hours to provide a daily value. The centibar readings from the pervious concrete pavement structures are interpreted by comparing the slope between readings. Figure 6 presents an example of SWP data generated from moisture gauges over seven days.

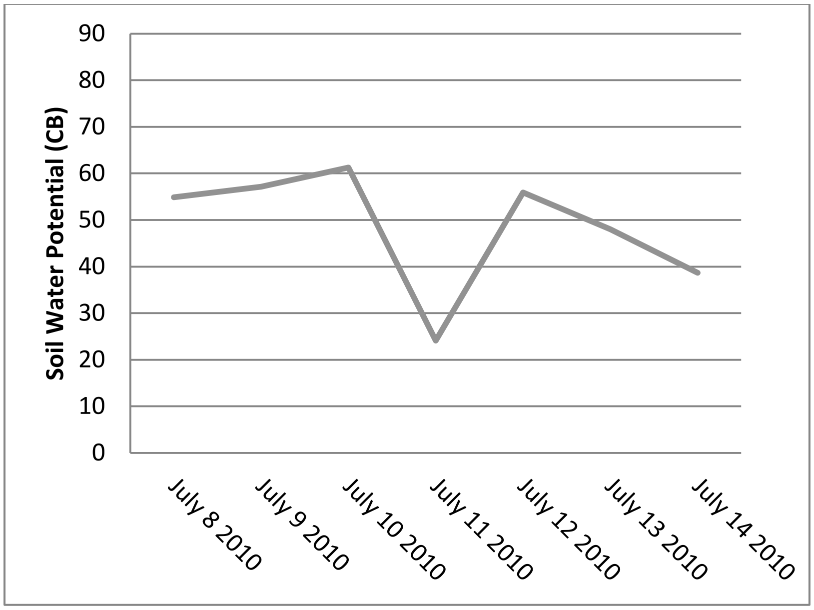

Figure 6: Example of Moisture Gauge Data

Figure 6 shows that the slope changes at July 10 2010, July 11 2010 and July 12 2010 in the plot. Prior to July 10 2010 the slope was positive, it then changed to negative, then positive and finally back to negative. Lower centibar values indicate that more water is present. The negative slope is caused by increased amounts of water moving into the instrumented area as compared to the amount of water draining away. The slope between July 11 2010 and July 12 2010 is positive, therefore water is draining away from the instrumentation at a higher rate than it is coming into the area. Thus, the pavement layer is drying out. In Figure 6 the soil is drying on July 8, 9 and 10 2010. On July 11, the soil becomes wet and starts to dry out until July 12 2010. On July 13 it becomes wet again. Coarser aggregate materials have higher SWP values when saturated as compared to finer grained materials. Saturation values of the pervious concrete and clear stone base layer should be greater than the values observed when the existing subgrade is saturated. The information that is of the most interest from the moisture gauge data is: whether water is travelling through the pavement structure; how quickly it is moving into each area of the pavement structure; and how quickly it drains away from the particular portion of the pavement structure. When the material surrounding the moisture gauge is frozen it is anticipated that a spike in readings would occur.

The results were compiled and analyzed primarily in tabular form. Within the results of each moisture gauge for a particular storm event, the minimum value was highlighted. If no minimum was observed, then there are no highlighted values. The minimum value corresponds to the July 11 2010 data shown in Figure 7-1, the point at which more moisture begins to drain away from the instrumented material than toward the material. In the tabular presentation of the results, it is possible to identify at which point moisture begins to move into the instrumented material as well. This occurs at the point in which the results start decreasing in value.

Instrumentation Functionality Verification

One of the initial large rain events at the field site after construction was plotted for each sensor tree. The plots demonstrate the movement of water through the pavement structure. Figure 7 to Figure 9 show the response of the instrumentation in each of the three mixes during a rain event of 41 mm over five days in Fall 2008. The plot shows the instrumentation readings and rain from November 6, 2008 to November 20, 2008. The site was constructed October 15, 2008 and opened to traffic October 27, 2008.

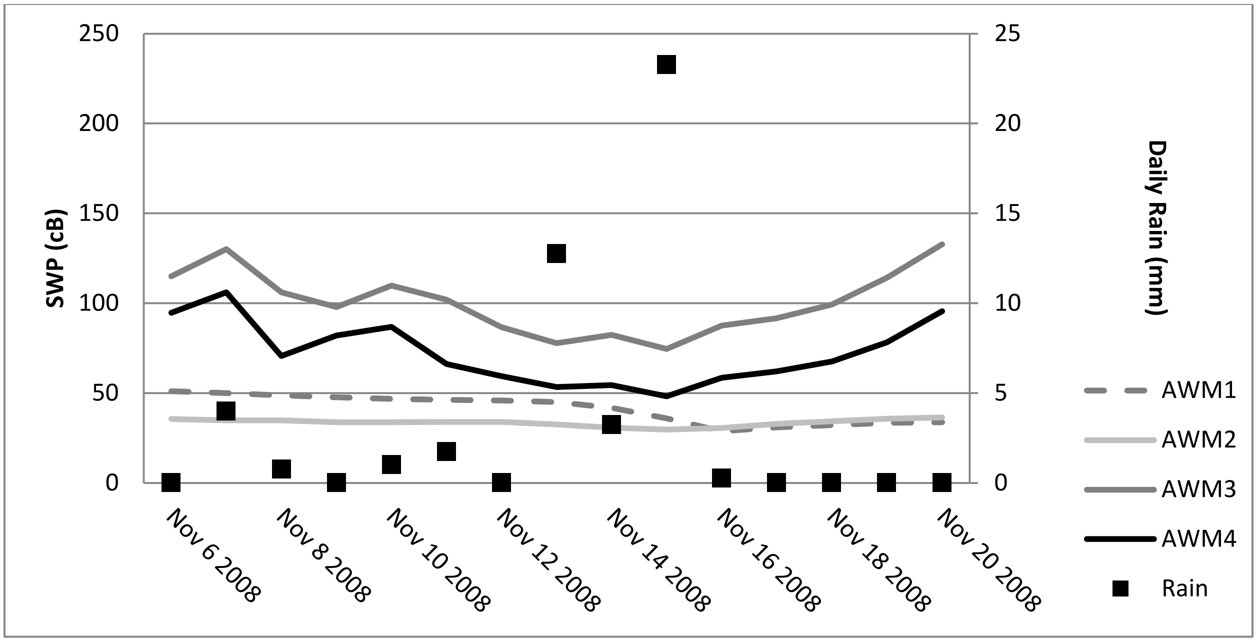

Figure 7: Rain Event Site A Fall 2008

Sections A and B show similar behavior in Figure 7 and Figure 8. The upper two moisture gauges, WM3 and WM4, are dryer and showing more fluctuation while the two moisture gauges in the subgrade, WM1 and WM2, are more consistent and wetter. In A the two largest rainfalls, 13 mm on November 13, 2008 and 23 mm on November 15, 2008 are identifiable by moisture gauges AWM3 and AWM4. On the same day that the rain events occurred, moisture was present at the instrumented areas and it was drained by the next day, November 14, 2008 and November 16, 2008, where positive slopes are notable in both cases. The deepest moisture gauge, AWM1, shows a continual, small negative slope from November 6, 2008 to November 17, 2008. Following November 17, 2008 a slight positive slope is present, however. The higher moisture gauge in the subgrade, AWM2, shows less fluctuation at this scale. However, slight changes in slope are visible with the rain events.

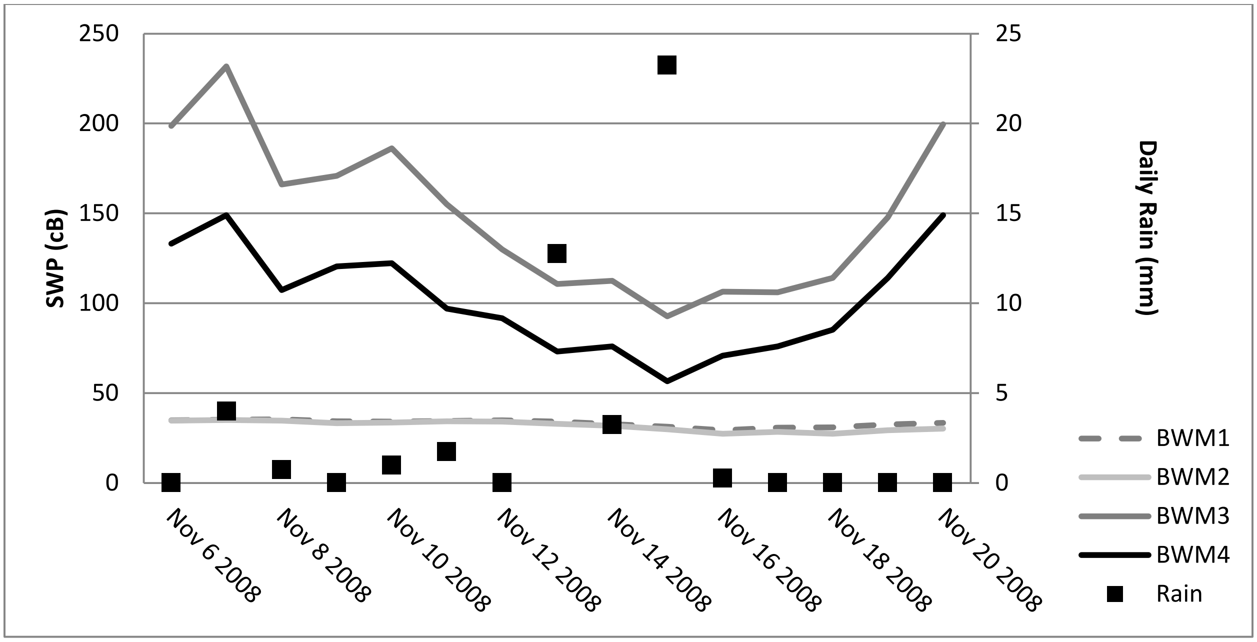

Figure 8: Rain Event Site B Fall 2008

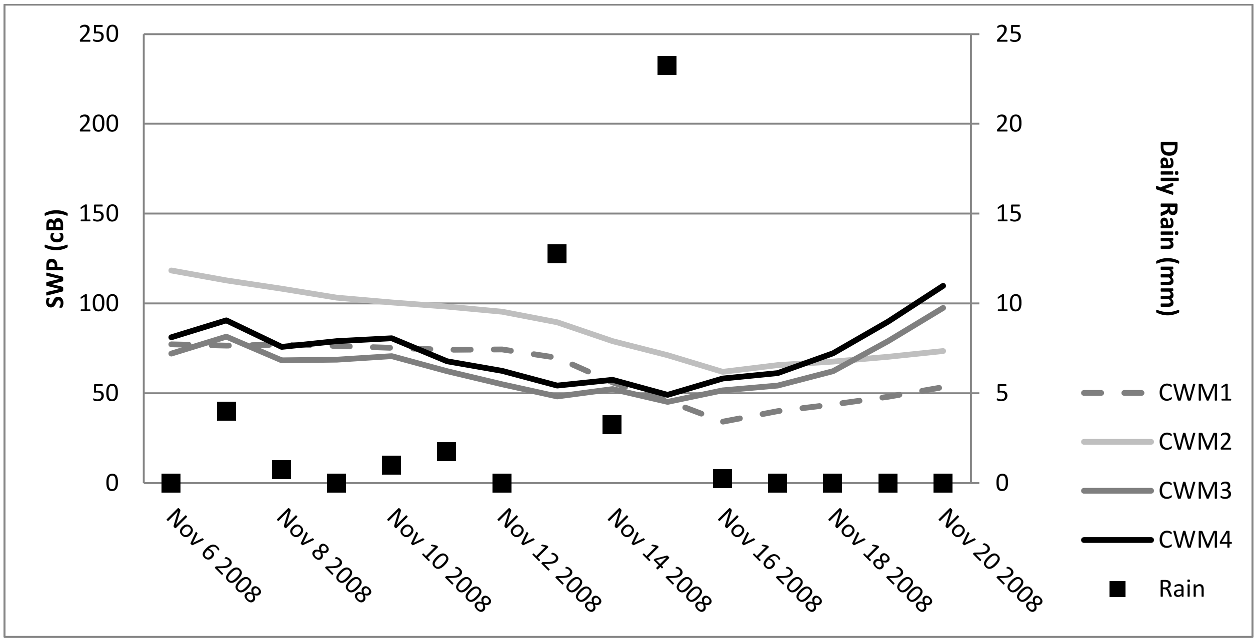

Figure 9: Rain Event Site C Fall 2008

In comparison to A, the two highest moisture gauges in B, BWM4 and BWM3, show a larger reaction to the rain events. Therefore the water is anticipated to be moving faster through the area and also is draining through the pervious concrete layer faster as well. The same trend is seen in BWM3 and BWM4 as AWM3 and AWM4. The changes in SWP are larger in the case of both moisture gauges in section B. The deeper moisture gauges in section B, BWM1 and BWM2, show more consistent readings similar to those in AWM1 and AWM2.

All four moisture gauges in Sensor Tree C showed moisture from the rain event entering the instrumented areas and draining away from them. The deeper moisture gauges, CWM2 and CWM1 showed more fluctuation with the rain event than the comparable moisture gauge in the other two sensor trees. In comparison, the two high moisture gauges showed less change with the rain event than the other two sensor trees. Overall, a substantial, visible change in SWP in the instrumented area was clear in all moisture gauges at the field site.

On October 27, 2008, permeability measurements were taken across the field site. The permeability values of the entire site are shown in Figure 10. The points on the plot represent the individual locations within a section which were each tested three times and averaged. The solid lines represent the average permeability for a particular mix.

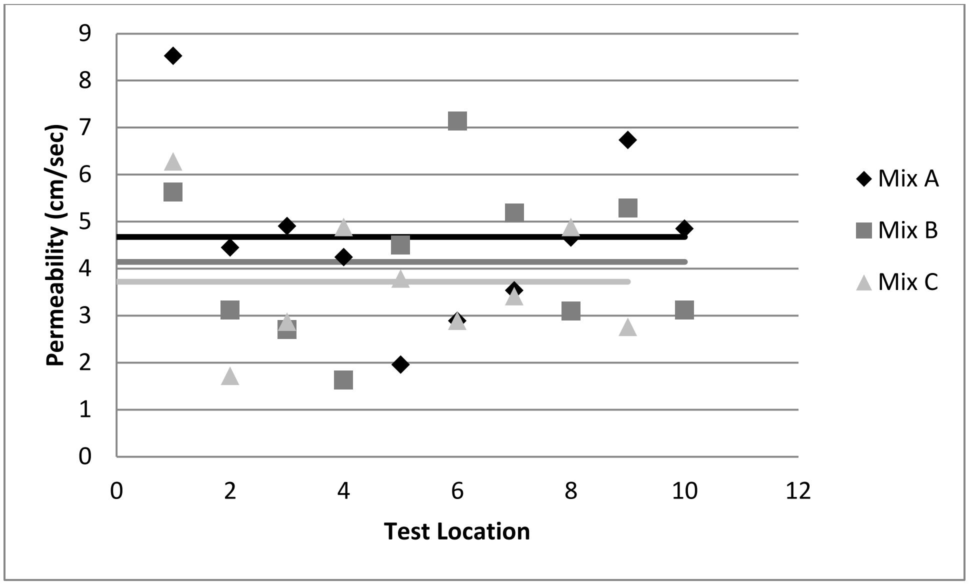

Figure 10: Permeability of Field Site October 2008

As Figure 10 shows, the permeability of each mix was very high following construction. The horizontal line shows the average permeability rate of that mix. The maximum rainfall intensity for a storm in this area is less than 0.01 cm/sec (9). The results of Section C show the lowest average permeability of the three. The lower permeability may lead to the moisture moving to the instrumented area in a continual slower volume rather than a large volume over a shorter period of time. Section B does not have a higher permeability on average than A. However, B does contain a larger aggregate than A. The size of aggregate used in a pervious concrete mix has been found to determine the size of voids created in the pervious concrete layer (10). The difference between the SWP change in the two upper moisture gauges in Sections A and B could be due to the mix designs. The use of smaller aggregate has been identified to create many small voids whereas when larger aggregates are used there are fewer voids but they are larger in size (10).

From Figure 7 to Figure 9 it can be verified that all moisture gauges at the field site were functioning following construction.

Field Site Maintenance in Spring 2010

Maintenance was performed to clean the surface of the pervious concrete at the field site on May 10, 2010. The maintenance involved sweeping loose debris off the surface and then washing the surface with a power washing truck. This permeability renewal maintenance method is discussed further in Henderson, 2012 (3) .

It was anticipated that the volume of water used to wash the pervious concrete would be noticeable in the instrumentation data. A change in SWP from the surface washing was evident in all three mixes and is shown in Figure 11 to Figure 13.

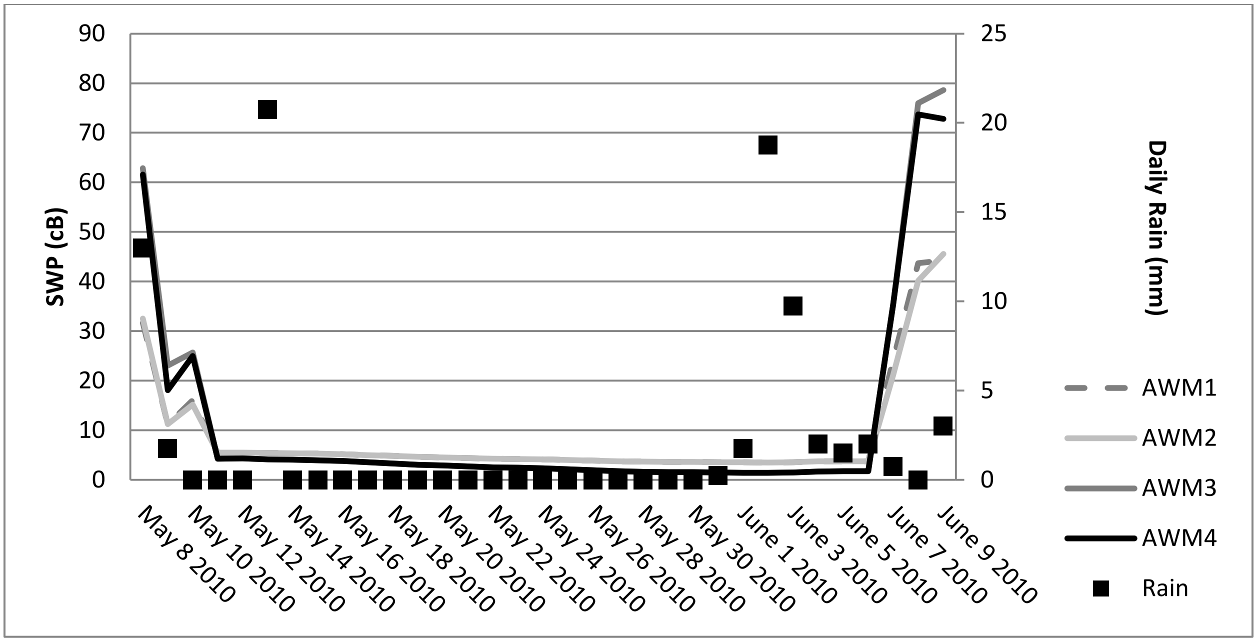

Figure 11: Site A Following Maintenance May 2010

The surface was washed at the beginning of May 2010 and Figure 11 to Figure 13 demonstrate, the water from this event was still present in the base and subgrade of the pavement structure until early June. Additionally, the three figures show that very little rain fell during this time and the water present in the pavement structure was a result of the surface washing. In all three mixes, by June 7, 2010, almost a month after the instrumented layers had become saturated, the base and subgrade were draining at a higher rate than water was moving into these materials.

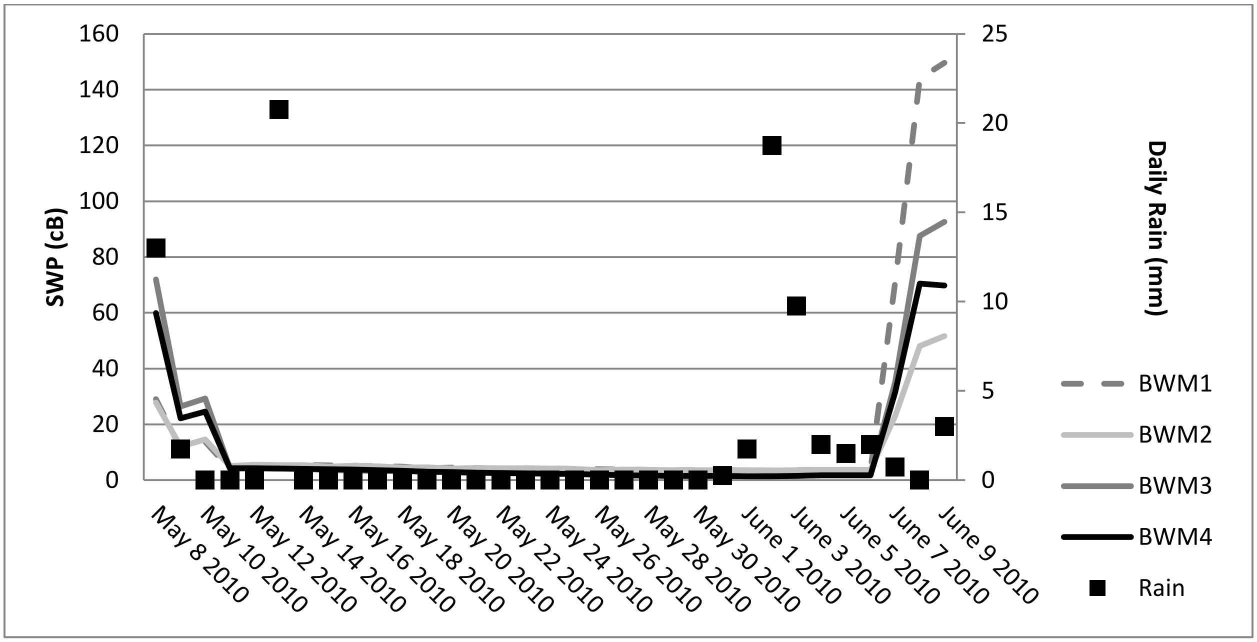

Figure 12: Site B Following Maintenance May 2010

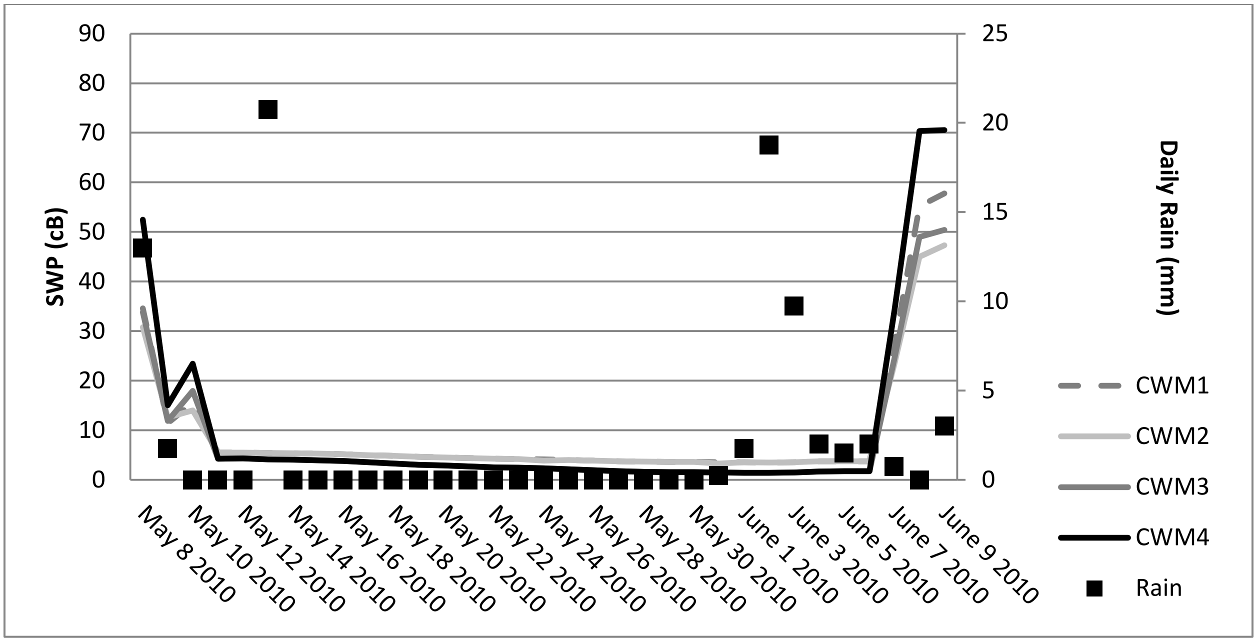

Figure 13: Site C Following Maintenance May 2010

In all three mixes the same trend occurred, in that SWP increased in the highest moisture gauge, "4", to around the same level, 70 cb, on June 8, 2010, suggesting that the water level in the pavement structure was lowering in general. In Section B the behaviour of BWM1 indicates the subgrade around it draining water faster than the same material in the pavement structures of the two adjacent mixes. Moisture gauge BWM3 also shows faster drainage than the comparable moisture gauge "3" in each of the other two mixes.

Given that the sensor readings were consistent for almost four continuous weeks without any rain events, it is anticipated that the portions of the pavement structure that are instrumented: clear stone base; and the subgrade, were saturated during this time. From this event, values representing saturation of the representative materials were determined. The SWP that describes material being saturated is material specific and understood to be unique between similar materials at each field site. Saturation of the clear stone layer, moisture gauges 3 and 4, was 1.6 cb and saturation of the instrumentation in the subgrade was 3.7 cb. It was not suspected that the water would remain in the pavement structure for such a long period of time. The data indicates that the pavement structure became saturated during the permeability renewal maintenance. Although the permeability renewal maintenance method was identified to be a viable alternative in Henderson, 2012 it is evident that the amount of water used in this method should be considered (3).

Seasonal Data and Analysis

A large rain event was identified from the onsite weather station data or Egbert Environment Canada weather station for each season between Fall 2008 and Winter 2011. Each of the rain events and the associated moisture gauge data are provided in detail Henderson, 2012 (3) . Table 1 shows a summary of the moisture movement through the pavement structure for each rain event. The rain events are summarized in Table 2.

The movement of moisture through the pavement structure over time was assessed in Table 1. Table 1 also compares the movement of moisture through the different sections at the field site. When interpreting the results presented in Table 1 it is important to include the rain event information provided in Table 2. For all rain events a large amount of rainfall occurred on day 0. However, more rain may have occurred on any of the following days over approximately the next week.

In the Fall of 2009 the rain event included 40 mm of rain, occurring on days 0 and 2 primarily.

The Sensor Tree A results from the Fall of 2009 indicate that the moisture from the rain event moved through the entire pavement structure on the same day as the rain event occurred, day 0. In the clear stone base layers the moisture drained away from the instrumentation on the same day as the rain event, day 0. Moisture was again present on day 2 of the rain event in the two clear stone base layer moisture gauges. The two deeper moisture gauges showed moisture present on day 0, as previously noted and that moisture continued to drain into the area until day 2 in the area of AWM2 and day 3 in AWM1. The moisture gauge data was observed until day 7.

Table 1: Moisture Movement at the Field Site

Moisture Gauge Location in Pavement Structure (Depth from Surface)	**Date**	**Time from Rain Event to Instrumented Area (Days)**					
		Entering Area			**Draining Area**		
		A	B	C	A	B	C
Clear Stone Base (325 mm) WM4	Fall 2008	0 2	0 2	0 2	1 3-7	1 3-7	1 3-7
	Winter 2009	0-1	0-2	0-1	2-6	3-6	2-6
	Spring 2009	0 3 5 7-8	0 3 5 7-8	0 3-4 6	1-2 4 6 9	1-2 4 6 9	1-2 5 7-9
	Summer 2009	0 2 6 9	0-2 6 8	0 2 6	1 3-5 7-8	3-5 7 9	1 3-4 7-9
	Fall 2009	0 4 6 9	4-6 9	0-1 4-5 7 9	1-3 5 7-8	7-8	2-3 6 8
	Winter 2010	0-1	1 5	0-1	2-5	2-4	2-5
	Spring 2010	2 4 7 8	4 7-8	0 2 4 7-8	3 5-6 9	5-6 9	1 3 5-6 9
	Summer 2010	0 2 4 6-8	0 4 6-9	0 2 4 6-10	1 3 5 9	1-3 5 10-11	1 3 5 11
	Summer 2010	2 4-7 9	2 4-7 9	2 4-7 9	3 8	3 8	3 8
	Fall 2010	0-1 6-7	1 6-7 12	0-1 7	2-5 8-13	2-5 8-11 13	2-6 8-13
	Winter 2011	4-9	11-12	7	10-12	No drying occurred	8-12
Clear Stone Base (450 mm) WM3	Fall 2008	0 2	0 2 4	0 2	1 3-7	1 3 5-7	1 3-7
	Winter 2009	0-1	0-1	0-1	2-6	2-6	2-6
	Spring 2009	0-1 3-5	0 3 8	0 3-4 6	2 6-9	1-2 4-7 9	1-2 5 7-9
	Summer 2009	0-2 6	0-2 6 9	0-2 5-6	3-4 7-9	3-5 7-8	3-4 7-9
	Fall 2009	0-1 4-7 9	0 4 6 9	0-1 4-5 7	2-3 8	1-3 5 7-8	2-3 6 8-9
	Winter 2010	1	1	1	2-5	2-5	2-5
	Spring 2010	2 5 7-8	4 7-8	1-2 4 6-8	3-4 6 9	5-6 9	3 5 9
	Summer 2010	0 4 8-12	0 2 4 6 8-10	0 2 4 6 8-9	1-3 5-7 13-14	1 3 5 7 11	1 3 5 7 10-11
	Summer 2010	2 5-7 9	2 4-7 9	2 4-7 9	3-4 8	3 8	3 8
	Fall 2010	0-1 7 9	1 7 13	1 3 7 9	2-6 8 10-13	2-6 8-12	2 4-6 8 10-13
	Winter 2011	9-11	7	7	12	8-12	8-12
Subgrade (750 mm) WM2	Fall 2008	0-2	0-3 5	0-3	3-7	4 6-7	4-7
	Winter 2009	0-1	0-5	0-1	2-9	6-9	2-9
	Spring 2009	0-1 5-6	0-6	0-1 5	2-4 7-9	7-9	2-4 6-9
	Summer 2009	0-1 3 6	0-4 6	0-1 3 7	2 4-5 7-9	5 7-9	2 4-6 8-9
	Fall 2009	0-1 6-7	0 4-5 7 9	1-5 7-8	2-5 8-9	1-3 6 8	6 9
	Winter 2010	1-2	1	1-2	3-5	2-5	3-5
	Spring 2010	2 5 7-8	5 7-8	2-3 5 7-8	3-4 6 9	6 9	4 6 9
	Summer 2010	0-2 4-5 7-8 11 13	0 4-5 7 10-12	0-1 4-5 11-13	3 6 9-10 12 14	1-3 6 8-9 13-14	2-3 6-10 14-15
	Summer 2010	2 4-7 9	2 4-7 9	4-7 9	3 8	3 8	3 8
	Fall 2010	1 5 7 9	1 6-7 10 12	1-2 7 8 11	2-4 6 10-13	2-5 9 11 13	3-6 9-10 12-13
	Winter 2011	DRY	11-12	DRY	DRY	No drying occurred	DRY
Subgrade (825 mm) WM1	Fall 2008	0-3	0-3	0-3	4-7	4-7	4-7
	Winter 2009	0-1	0-6	0-1	2-9	7-9	2-9
	Spring 2009	0-1 6-7	0-6 8	0-1 5	2-5 8-9	7 9	2-4 6-9
	Summer 2009	0-1 3-4 7	1-3 6	0-1 3-4	2 5-6 8-9	4-5 7-9	2 5-9
	Fall 2009	0-2 6 8	0-1 3-5 7-9	1-3 6 8	3-5 7 9	2 6	4-5 7 9
	Winter 2010	1-2	1	1-2	3-5	2-5	3-5
	Spring 2010	2-3 5 7-8	5 7-8	2-3 5 7-8	4 6 9	6 9	4 6 9
	Summer 2010	3 5-6 10-14	0-1 4-5 10-11	0-1 4-5 11-13	2 4 7-9 15	2-3 6-9 12-15	2-3 6-10 14-15
	Summer 2010	0-2 4-7 9	2 4-7 9	4-7 9	3 8	3 8	3 8
	Fall 2010	1-2 5 7-8	0-1 5 7-8 10 13	1-2 7-8	3-4 6 9-13	2-4 6 9 11-12	3-6 9-13
	Winter 2011	10 12	8 11-12	DRY	11	9-10	DRY

Table 2: Field Site Rain Events

Season	**Winter**			**Spring**			**Summer**			**Fall**		
Year	**Date**	**Day**	**Rainfall (mm)**	**Date**	**Day**	**Rainfall (mm)**	**Date**	**Day**	**Rainfall (mm)**	**Date**	**Day**	**Rainfall (mm)**
2008										Nov 13 2008	0	13
										Nov 14 2008	1	3
										Nov 15 2008	2	23
										Nov 16 2008	3	0
										Total Rainfall (mm)		29
2009	Feb 11 2009	0	20	April 3 2009	0	32	July 23 2009	0	37	Sept 28 2009	0	27
	Feb 12 2009	1	15	April 4 2009	1	2	July 24 2009	1	3	Sept 29 2009	1	9
	Total Rainfall (mm)		35	April 5 2009	2	0	July 25 2009	2	16	*Total Rainfall (mm)*		36
				April 6 2009	3	18	July 26 2009	3	16			
				Total Rainfall (mm)		52	July 27 2009	4	1			
							July 28 2009	5	10			
							July 29 2009	6	3			
							Total Rainfall (mm)		86			
2010	Dec 2 2009	0	9	May 1 2010	0	10	June 12 2010	0	16	Sept 21 2010	0	6
	Dec 3 2009	1	3	May 2 2010	1	14	June 13 2010	1	0	Sept 22 2010	1	15
	Total Rainfall (mm)		12	May 3 2010	2	12	June 16 2010	4	12	Sept 25 2010	4	2
				May 4 2010	3	3	*Total Rainfall (mm)*		28	Sept 26 2010	5	0
				May 5 2010	4	12				Sept 27 2010	6	7
				May 6 2010	5	0	July 9 2010	0	32	Sept 28 2010	7	23
				May 7 2010	6	14	July 10 2010	1	0	*Total Rainfall (mm)*		53
				May 8 2010	7	13	July 11 2010	2	6			
				Total Rainfall (mm)		78	July 12 2010	3	1			
							July 13 2010	4	16			
							Total Rainfall (mm)		55			
2011	Dec 5 2010	0	22									
	Dec 6 2010	1	2									
	Dec 7 2010	2	11									
	Dec 8 2010	3	6									
	Total Rainfall (mm)		41									

The moisture gauges in Sensor Tree B during the Fall of 2009 rain event show moisture moving through the entire pavement structure on the same day as the rain event, day 0. Moisture drained away from the two instrumented areas in the clear stone base layer on the same day that the rain event occurred. Moisture again moved into and away from these two areas on the second day of rain in the rain event, day 2. Moisture drained into the deeper clear stone base instrumented area (BWM3) on day 4 as well. The two moisture gauges in the subgrade material showed moisture moving into the area on the same day as the rain event and continuing to drain into the area until day 3 of the rain event. Moisture gauge BWM2 also showed moisture moving into the instrumented area on day 5, possibly the moisture from BWM3 on day 4. All four moisture gauges showed continual drainage of moisture away from the instrumented area until the end of the observation, day 7.

In Sensor Tree C, moisture moved into and away from the clear stone material instrumented by CWM3 and CWM4 on the same day as the rain event occurred, day 0 and day 2. Moisture moved continually toward the instrumented areas in the subgrade material during days 0 to 3 of the rain event. All four moisture gauges indicated that moisture was draining away from the instrumented material throughout the remainder of the observation period, day 7.

The Fall 2009 rain event that was described in the above discussion occurred shortly after the construction of Site 4 and presents the initial drainage characteristics of the three pavement structures at the site. All three sections, 4A, 4B and 4C show similar drainage abilities, with moisture travelling throughout the depth of the pavement structure on the same day that the rain event occurred, day 0. Two days after the end of the rain event, day 4, the deepest instrumented material, 825 mm from the surface, subgrade, was demonstrating that the surrounding material was draining and no further moisture was moving into this area from the rain event.

The rain event in the Fall of 2010 included 53 mm of rain, dispersed between days 0 and 1 and 6 and 7 primarily. The larger quantities of rain occurred on days 1 and 7. It is unknown what quantity of rain generally moves throughout the depth of a pervious concrete pavement structure. It is assumed that small quantities of rain would not travel through the entire depth of the pavement structure as some would evaporate and some would eventually remain in a location where there is not an interconnected void, either in the pervious concrete layer or the clear stone base material. Assuming that a sufficient number of routes exist through the pavement structure, it is not anticipated that a small quantity of water becoming trapped in non-connected void areas is an issue.

In the area instrumented by Sensor Tree A, the moisture gauges in the clear stone base, AWM4 and AWM3 both indicated the presence of moisture on the same days as the rain events occurring, days 0, 1, 6 and 7. The higher moisture gauge in the subgrade material, AWM2 shows that only the moisture from the heavier rain falls drained to this area and it moves into the area on the same day as it occurred. Additionally moisture drains into this area and away from it on day 5 and 9 as well, 4 and 2 days after the heavier rainfalls respectively. The deepest moisture gauge AWM1 shows moisture draining into the area continually on days 1 to 2 and 7 to 8. Therefore on the same day as the heavier rain event and continuing for one following day. Again moisture moved into and away from the deepest instrumented area on day 5 as well. The behaviour of the material in the instrumented areas was observed until day 13. Each moisture gauge demonstrates a clear time span of three to five days between the two periods of rain when moisture in continually draining away from the areas. Therefore both rain events had completely drained through a depth in the pavement structure of 825 mm two to three days after occurring.

In the area of Sensor Tree B, the moisture gauges in the clear stone base layer both identified the presence of moisture on the same day as the rain event, days 1 and 7. Moisture is also present on days 12 and 13 in the areas of moisture gauges BWM4 and BWM3 respectively. No rain occurred at this time. It is possible that this is moisture draining through layers of the pervious concrete pavement structure from another source. Moisture gauge BWM2, the higher of the two in the subgrade material shows moisture on the same days as the rain events and then draining away. Moisture is again present on day 10 and 12, likely due to an outside source. The deepest moisture gauge, BWM1, shows the presence of moisture on the same day as the rain event and during the second rain event, day 7, the moisture continues to drain into the instrumented area for an additional day, until day 8. In all instrumented locations, drying of the material began the day after the rain event, day 2. The material at each level in the pavement structure was continually drying until the next rain event occurred, on day 6. Following the rain on days 6 and 7 the drying behaviour is not as defined due to the presence on moisture from another source.

The material instrumented by Sensor Tree C, shows the presence of the rain event on the same day as it occurred in each location, days 1 and 7. In the area of CWM4, the moisture moved into and away from the material generally on the same day. In the location of CWM3 the moisture also moved into and away from the material on the same day as the rain event occurred. However, moisture also moved into and away from the material on days 3 and 9 as well. It is anticipated that on both these days this was moisture that had drained through the entire pavement structure prior to this location at a slower rate. Perhaps some of the drainage routes that are available have become slower or others have become obstructed. Both of the moisture gauges in the subgrade material, CWM2 and CWM1 show the moisture moving into the associated material on the day of the rain event and the following day. Moisture also moves into and away from CWM2 on day 11. This could be the moisture that was present at CWM3 on day 9. The moisture is not identified at CWM1 at any time and there is anticipated to be a small quantity. A draining period is present at each moisture gauge two to three days after the occurrence of the rain event.

The pavement structure at Site 4 has a consistent thickness throughout. Each of the three pervious concrete mix designs at Site 4 are the same, the difference is only in the size and type of aggregate that was used. In the Fall of 2009 moisture from one rain event, occurring on days 0 and 2 moved through the entire pavement structure surrounding Sensor Tree A by day 3. Following day 3, all material was identified as drying. In the Fall of 2010, the same performance was occurring in the material surrounding Sensor Tree A. All moisture from a rain event on days 0 and 1 had moved throughout the pavement structure by day 2 or 3. In the Fall of 2009, moisture moved through the entire pavement structure around Sensor Tree B by day 3. There was some moisture present in the material surrounding AWM3 and AWM2 on days 4 and 5 which did demonstrate moving to AWM1. In the Fall of 2010 a rain event moved through the entire pavement structure at Sensor Tree B by day 2, after rain occurring on days 0 and 1. At Sensor Tree B the performance identified in the Fall of 2009 was still present in Fall of 2010. Finally, in the Fall of 2009 rain events moved through the pavement structure instrumented with

Sensor Tree C one day after the rain event, day 3. In the Fall of 2010, the rain event moved through the pavement structure in Section 4C fully by two days after the end of the rain event, day 3.

The results presented for the field site indicate that each pavement structure is providing similar moisture behaviour. This finding is anticipated as the pavement structures are identical other than the pervious concrete layer. As was identified earlier in Figure 10 the permeability rates of the three pervious concrete mixes at the site are similar. Given that the pavement structures are consistent and the surface performance of the three mixes has been observed to be similar it is anticipated that the subsurface behaviour of the three sections would also be similar.

The data collected and reviewed from the moisture gauges at the other field sites in addition to this one indicated that the permeability rate of the pervious concrete surface layer is critical as to whether moisture will drain vertically through the pervious concrete pavement structure (3). Vertical drainage from the pavement surface to the subgrade is observed in the data from this field site. The data from a field site with minimal surface drainage did not demonstrate vertical movement of moisture through the entire pavement structure. At the third instrumented field site there was less surface permeability than at the site presented in this paper however, it was deemed to be sufficient for the local rain events. Moisture was identified in the instrumented portion of the pervious concrete layer after a rain event at this site. In the Fall of 2009, immediately following construction, moisture drained into the instrumented portion of the pervious concrete layer on the same day or following day as the rain event occurring at this site. By the Spring of 2011 moisture reached the instrumented portion of the pervious concrete pavement two to four days after the rain event. This delay reflects the decreased permeability rate of the pervious concrete pavement surface at this site. It is possible to track moisture moving through the reservoir base layer and into the subgrade during rain events at this site. The drainage of the reservoir base layer continues to be very functional and effective (3).

The three field sites that were instrumented, each showed clearly different performance in terms on subsurface drainage. Comparisons regarding the total time required for a rain event to drain through the pervious concrete pavement structure are not relevant as only the field site presented in this paper clearly demonstrated this ability and continued to demonstrate this. However, even within this field site there were fluctuations between seasons and years regarding the number of days for a rain event to move through the depths of the pavement structure. Some of the reasons for changes in time between rain events and water reaching the instrumentation are the following:

- Previous recent rain events and associated moisture still being present in some areas of the pavement structure;
- No rain events recently and area is dry and thus all drainage routes are available so water drains easily and efficiently;
- Horizontal, downhill flow from surrounding area: pervious concrete; vegetated berm; and roller compacter concrete and;
- Debris in voids at surface of pervious concrete, slowing down initial drainage of water;

The moisture gauges installed in the three field sites during construction provided a unique descriptive tool regarding the subsurface behaviour of pervious concrete pavement. The three field sites that were instrumented all proved to have adequate pavement structures for drainage purposes below the pervious concrete layer. It was not possible to fully examine the true drainage capabilities of these layers without the pervious concrete layers providing vertical drainage capabilities. The conclusions that could be drawn for the field site presented in this paper were that the unbound clear stone base layer was effective in providing vertical drainage. The silty sand subgrade material was permeable and therefore the instrumentation did not demonstrate continual saturation of the clear stone base layer. The drainage through the pavement structure did not appear to have any locations leading to delays or water being held for a substantial period of time. This performance of the base layer and subgrade is ideal and superior to the anticipated average pervious concrete pavement scenario.

Conclusions

The field site demonstrated that it was possible to successfully instrument a pervious concrete pavement structure with moisture and temperature sensors. The verification of the functionality of all the instrumentation was successful at the field site. Through the verification of the moisture gauge functionality other observations were also concluded. Permeability renewal maintenance proved to have the potential to saturate the pervious concrete pavement structure for a four week period. As is discussed below, the storage capabilities of the clear stone base layer were only tested following permeability renewal maintenance involving washing of the surface. This maintenance was performed using street grade equipment. The volume of water used in this maintenance lead to the pervious concrete pavement structure from a depth of 325 mm to 825 mm being saturated for four weeks. The water may have been higher in the pavement structure but the moisture gauge closest to the surface was at a depth of 325 mm.

The subsurface drainage that was quantified by the instrumentation confirmed observations from the surface of the pavement and exceeded other expectations. The subsurface analysis quantified and confirmed that moisture was not able to drain completely vertically through the pavement structures at the two field sites not presented in this paper. In comparison, the subsurface drainage at the field site presented in this paper surpassed the assumed behaviour of pervious concrete pavement structures. The pavement structure in general was highly permeable and this was identified as moisture was not found to be holding in the bottom of the storage base layer at any time or for any period of time. The successful overall drainage performance of this field site demonstrates the effective use of pervious concrete pavement in southern Canada.

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