

Water Quality Treatment Efficacy Model of Porous Concrete Pavement

J. He^{*1}, J. Huang¹, C. Valeo², A. Chu¹

¹Department of Civil Engineering, Schulich School of Engineering, University of Calgary, Calgary, Alberta, Canada

²Department of Mechanical Engineering, University of Victoria, Victoria, British Columbia, Canada

^{*1}jianhe@ucalgary.ca; ¹jiahuang@ucalgary.ca; ²valeo@uvic.ca; ¹achu@ucalgary.ca

Abstract-Permeable pavement is a low impact development technology that has been suggested for improvement of urban stormwater management. Performance of permeable pavement has been extensively evaluated by field observations so far. However, modeling tools, which can aid in the design of permeable pavement, are still lacking, particularly in relation to water quality. Therefore, this paper aimed to develop effective modeling approaches to simulate porous concrete pavement, a common type of permeable pavement. To fulfill this objective, both field and laboratory investigations were conducted. An empirical model was developed using laboratory results and field observations, and a conceptual model was formulated based on the physical processes of pollutant removal by porous media. This paper focused on two water quality parameters: total suspended solids and total phosphorus. Both modeling approaches produced fairly good results, which suggest the potential use of both models in practice.

Keywords-Conceptual Model; Empirical Model; Low Impact Development; Porous Concrete Pavement; Water Quality

I. INTRODUCTION

Urbanization not only results in an increase in stormwater runoff due to reduced pervious surface area, but has also been suggested to deteriorate the water quality in receiving water bodies [1, 2, 3, 4]. Thus, one of the primary objectives of urban stormwater management is to abate the adverse effects of urbanization through various structural and non-structural technologies. Among these technologies, low impact development techniques (LIDs), which use on-site natural features to protect water quality through land-use planning, have demonstrated promise, particularly in urban settings. Among a variety of LIDs, permeable pavement, which normally consists of a porous surface layer and one or more sub-surface gravel layers, has been shown to be effective against increasing stormwater runoff and the degradation of urban stormwater quality [5]. The physical structure of permeable pavement allows stormwater, which quickly infiltrates the surface layer of pavement, to be treated on-site. Therefore, permeable pavements can mitigate the impacts of urban stormwater posed by urbanization [6].

Porous concrete (PC), along with porous asphalt and permeable inter-locking pavers, is a commonly used permeable pavement worldwide in driveways, parking lots and access roads [7]. Sansalone et al. [8] investigated a PC in Ohio, U.S.A. and concluded that PC is effective in reducing surface runoff and attenuating peak flows. Another study by Collins et al. [9] conducted in coastal North Carolina, U.S.A., determined that PC has the capability to mitigate storm runoff and peak flow ranging from 60% to 75%. Overall, previous studies have demonstrated the benefit of PC in urban stormwater quantity management. The hydrologic efficacy of PC might be a function of climatic condition or geographical location besides magnitude of storm, surface porosity, pavement age and maintenance [10, 11].

Regarding pollutant removal efficacy, permeable pavement has been consistently shown to be capable of removing 80-95% of total suspended solids (TSS) from stormwater [6, 12, 13, 14]. Unlike TSS removal, the removal rate of total phosphorus (TP) has varied widely in previous studies. Several studies [15, 16, 17] observed that the removal rate of TP is greater than 70%, whereas other works [14, 18] documented low TP removal rates ranging from 40% to 60%. Gilbert and Clusen [19], however, claimed that permeable pavement barely removes TP from stormwater runoff. In addition, water quality performance of PC is also a function of its engineering structure (i.e., the thickness of gravel layers and gravel size), in addition to climatic and geographic conditions. Few studies have been conducted to assess the effects of gravel size and the depth of gravel layers on pollutant removal. Hatt et al. [20] demonstrated a link between the capability of removing TSS and TP and the depth of the gravel layer consisting of 10.5 mm gravels, which are typically used in the bedding layer of permeable pavements.

Simple and intuitive modeling tools are always preferable in engineering design because of their easy application. However, a large number of previous studies have focused on either field observations or laboratory investigations, while the informational bridge between field and laboratory observations appears to be lacking. To transfer the knowledge obtained from the lab-scale pavements to the field-scale pavements, an empirical modeling approach can be used to predict pollutant removal rates as functions of pavement structure.

Cost often constrains the empirical modeling approach aforementioned, as both the laboratory and field investigations must be comparable in their design. Due to this, numerical or conceptual modeling approaches, which often require our understanding of governing physical processes and the use of complex mathematical formula to represent the physical phenomena, might be alternatives to empirical modeling. In addition, this approach can apply to a wide range of conditions, while empirical models are often limited to specific conditions under which experiments and field observations are conducted.

In theory, the hydrologic performance of permeable pavement can be modeled as porous media; for example, Tan et al. [21] and Montes and Haselbach [22] used the Kozeny-Carman equation. Kuang et al. [23] proposed that the Kozeny-Carman equation can successfully simulate hydraulic conductivity with proper calibration by comparing various pore-structure equations. Similarly, pollutant removal mechanisms of permeable pavement and filters are comparable; therefore, the theory that was developed for filters is also applicable to permeable pavement. Several studies have applied the theory developed for sand filtration to stormwater management. Siriwardene et al. [24] modified the model created by Yao [25] for sand filtration to simulate the sediment transport in gravel layers installed in a stormwater pond and sediment basin.

Due to rapid urbanization in Calgary, Alberta, Canada, the city has faced increasing pressure to improve urban stormwater management. Permeable pavement has been considered as a potentially effective measure to reduce surface runoff and simultaneously treat stormwater runoff on-site. To investigate the efficiency of PC under Calgary's climate and to facilitate the development of engineering design tools and guidelines for permeable pavement, both field and laboratory investigations were conducted. This paper also aimed to develop models to simulate PC performance on water quality in the removal of TSS and/or TP using empirical and conceptual modeling approaches.

II. STUDY AREA AND METHODS

A. Study Site and Field-scale Study

The city of Calgary is the most populated municipality in Alberta, Canada, with over one million inhabitants. The city is situated in a semiarid region and in the transition zone between the Canadian Rockies foothills and the Canadian Prairies. Calgary experiences a dry humid continental climate, with warm summers and cold winters. During winter months, dry westerly Chinook winds routinely blow into the city from the mountains causing the temperature to raise quickly and result in snowmelt. Calgary receives an average of 418.1 mm of annual precipitation; the normal annual rainfall amount at the Calgary International Airport (1971 to 2000) is 320.6 mm. Rainfall events generally occur from May to September, while the average daily temperature is roughly 10 °C or higher during those months.

Calgary has been challenged to reduce pollutant loading into the natural receiving water bodies, in order to maintain good water quality. Among various pollutants, phosphorous has been ascribed to low dissolved oxygen concentration in the Bow River, as high concentrations of phosphorous result in eutrophication. The city of Calgary, which is the most populated community along the river, has contributed large amount of phosphorus into the river from both point and non-point source pollution. In past decades, the city has made significant efforts to reduce phosphorus loading from wastewater treatment plants by enhancing wastewater treatment techniques. Most recently, attention has shifted to the management of urban stormwater runoff, a non-point source pollution, to further reduce phosphorus loading from the city. This paper focused on permeable pavement as a promising technology to remove TP and TSS, common pollutants in urban stormwater.

A field-scale PC cell, which is 6.0 m long and 6.0 m wide with a 1% slope towards the east, was constructed in September of 2011 on Hochwald Avenue in the southwest of Calgary (Figure 1(a)). Its surface layer was replaced in October of 2012. The PC normally receives moderate light vehicle traffic year-round, with occasional heavy duty vehicles. As illustrated in Figure 1(b), the PC consists of two layers: a surface layer of 150 mm porous concrete, and a 500 mm bedding layer of 63 mm gravel. A 100 mm perforated under drain pipe (made by IPEX Inc., Edmonton, Alberta, Canada) is placed at the bottom of the pavement cell and leads to a manhole located east of the field-scale cell with a 2% slope (Manning's $n = 0.01$). In this study, the under drain pipe was considered to be a component of the PC. The under drain pipe may have an effect on hydraulic performance; however, the investigation of the effect of under drain pipes was beyond the scope of this paper. Water samples were manually collected from the manhole where the outflow leads to the under drain pipe; water quantity was monitored using a flow meter. A non-woven geo-textile was used to prevent pollutants from migrating to the underlying soil, which is fairly impermeable. In each field test, a 100-year storm event of 20 minutes in duration and an intensity of 80 mm/hr was simulated. The storm event was selected considering that permeable pavements are part of the major drainage system, which have the expected capacity to drain stormwater runoff from 100-year storm events [26]. Water withdrawn from a nearby stormwater pond was mixed with sediment collected from Calgary's streets to prepare the synthetic urban stormwater of approximately 500 mg/L TSS. The assay of TSS was conducted using the standard method; the Hach procedure 8190 was used to analyze TP. Several hydrologic parameters in addition to pavement temperature (T_p) were measured in each experimental run. The hydrologic parameters include peak reduction (p_r), which is the ratio of the difference between the peak outflow and inflow to the inflow; time to peak (t_p); and discharge time (t_d), which is the time interval for infiltrated storm runoff to drain out of the pavement. A total of 13 surface infiltration rate (SIR) tests were performed between October 2012 and December 2013. In each SIR test, 12 single-ring infiltrometers were evenly distributed on the pavement surface. Each ring was filled to the top with water, and the time needed for all water to infiltrate the PC was recorded. SIR was estimated by averaging the measurements of the 12 infiltrometers.

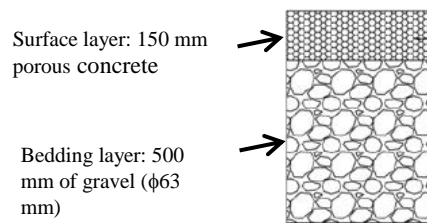
B. Laboratory Experiment

Lab-cells of the bedding and surface layers, measuring 450 mm by 450 mm, were held in a wood frame as shown in Figure 2. To prevent potential water leakage, the wood frame of 3/4 inch plywood was painted with a waterproof coating and the

connections on all four sides were sealed with silicone. Stainless steel netting was placed at the bottom of the cell to maintain the structural integrity of the testing materials, and a tray was placed at the bottom of each wood frame to collect outflow. Water samples were manually collected from the tray. The size of bedding gravel might be related to pollutant removal; however, the investigation of the relationship between gravel size and pollutant removal is beyond the scope of this paper. As 63 mm gravel was used in the field-scale PC, the same gravel size was used in the laboratory experiment. Considering that the bedding layer is more significant than the surface layer in terms of the hydraulic and water quality performance of permeable pavements, the performance of the bedding layers of various thicknesses ranging from 100 to 500 mm at every 100 mm, was investigated in this paper. In addition, the surface layer of 150 mm porous concrete was also studied. Similar to the field study, a rainfall applicator was used to generate evenly distributed 100-year return period storm events over the lab-cells in each laboratory experiment. The water used in the laboratory experiments was prepared by mixing sediments collected from Calgary’s streets with tap water; TSS concentration was also approximately 500 mg/L.



(a) Plan views of the study site.



(b) Structure of PC.

Fig. 1. Field-scale study site (shown by the arrow in the rectangle in (a)); and structure of porous concrete pavement.



Rainfall applicator
Wood frame holding gravel or surface layer

Fig. 2. Lab-scale experimental setup.

C. Analysis and Modeling

The removal rate of pollutant R (%), is calculated by:

$$R = \frac{C_I V_I - C_O V_O}{C_I V_I} \cdot 100\% \quad (1)$$

where C is the concentration of pollutant (mg/L); V is the volume of stormwater (L); and the subscripts I and O denote inflow and outflow, respectively. In addition, regression analysis was employed to develop empirical models to relate pollutant removal rates to the thickness of the gravel layer.

The modified Kozeny-Carman equation was employed to simulate the infiltrated flow through the permeable pavement structure [21, 23] by assuming that the infiltrated water only flows in the vertical direction:

$$\frac{\partial v}{\partial L} = \frac{1}{180} \frac{m^3}{(1-m)^2} \cdot (\varphi d)^2 \cdot \frac{g}{\mu L} \quad (2)$$

where v is the flow velocity in the vertical direction (m/s); m is the porosity (of surface or bedding gravel layer); φ represents the sphericity of the gravel in the bedding gravel layer and ranges from 0 to 1 depending on the shape of gravel (0.1 to 0.2 was used in the paper due to the irregular shape of the gravel); d represents the gravel diameter (63mm); g is the gravitational acceleration (m/s^2); μ is the kinematic viscosity of the fluid (m^2/s); and L is the thickness of the pavement (m).

The outflow rate from the sub-drainage is calculated by:

$$Q_{out} = \delta A \sqrt{2gH} \quad (3)$$

where δ is the transient loss coefficient (typically between 0.4 and 0.8); and A is the cross-sectional area of the under drain pipe.

Yao et al. (1971) developed a sediment removal model for a sand filter in the water and wastewater treatment processes. Due to the similarity of media used in both sand filters and permeable pavements, the following equation (Eq.4) used to model sand filters can also be used to simulate the process of sediment removal by permeable pavements:

$$\frac{\partial C}{\partial L} = -\frac{3(1-m)}{2d} \alpha \eta C \quad (4)$$

where C is the concentration of pollutant (mg/L); α denotes the contact efficiency (the number of contacts which succeed in producing adhesion divided by the number of collisions which occur between suspended particles and gravel media); and η is the ratio of particles striking the gravel media by interception, sedimentation or diffusion, to total particles flowing towards the gravel media. Tufenkji & Elimelech [27] determined that η is related to the size of gravel, flow velocity, pavement temperature and particle size distribution (PSD) of inflow TSS. Thus the equation (3) can be rewritten as:

$$\frac{\partial C}{\partial L} = -\frac{3(1-m)}{2d} \alpha C \cdot \left[0.9 \left(\frac{kT}{\mu d_p dv} \right)^{2/3} + \frac{3}{2} \left(\frac{d_p}{d} \right)^2 + \frac{(\rho_p - \rho) g d_p^2}{18 \mu v} \right] \quad (5)$$

where k is the Boltzmann constant (1.3805×10^{-23} J/K); T is the absolute temperature of stormwater (K); d_p is the particle diameter (m); ρ_p is the density of particles ($1,100 \text{ kg/m}^3$); and ρ is the density of fluid (kg/m^3).

In the conceptual model, the porosity of the surface layer was assumed to be a linear function of the logarithm of surface infiltration, while the porosity of the bedding layer was determined by model calibration. The assumption of the surface layer porosity was also justified in the model calibration. Equations 2-5 were solved using the finite difference approximation method. MATLAB was used to program the conceptual model.

III. ANALYSIS AND MODELLING RESULTS

A. Field Experiment Results

Figure 3 shows the time series of SIR. Gradual degradation of SIR was observed from the initial test in October 2012 until May 2013, when pressure washing was applied to recover pavement surface infiltration. SIR began to decline immediately following the pressure wash until the end of 2013.

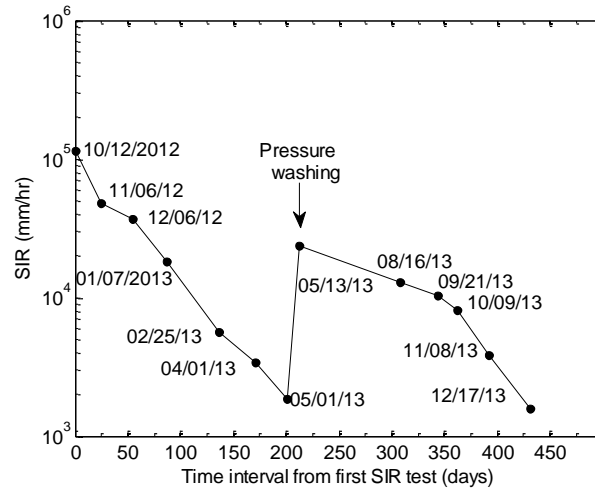


Fig. 3. Time series of average SIR in field experiments.

A total of six field tests were conducted during the study time period. The inflow concentrations of TSS and TP were in the range of 491-539 mg/L with a mean of 508 mg/L, and 0.24-0.43 mg/L with a mean of 0.35 mg/L, respectively. It was found that 85-90% of inflows were captured at the outlet of the pavement in the mass balance analysis. The water loss of approximately 5-10%, was potentially due to water retention in the pavement, as well as to water leakage out of the pavement. Correlation coefficients between SIR and hydraulic variables p_r , t_p and t_d were calculated; the correlation coefficients are -0.74 ($p=0.09$), -0.86 ($p=0.03$), and -0.79 ($p=0.06$), respectively.

The removal rates of TSS and TP calculated from each field test are shown in Table 1; the removal rates are nearly constant. TSS removal rates are all above 90% with an average rate of 91.9% and a standard deviation of 1.54%; TP removal rates range from 76% to 84% with an average of 79.9% and a standard deviation of 2.68%. The calculated correlation coefficients between TSS removal rate and SIR, and between TP removal rate and SIR are not significant, as the p -values are 0.52 and 0.49, respectively.

TABLE 1. REMOVAL RATES OF TSS AND TP CALCULATED IN SIX FIELD TESTS.

Event No.	Date	TSS removal rate (%)	TP removal rate (%)
1	19/10/2012	90.6	81.1
2	28/03/2013	91.5	75.7
3	24/09/2013	94.6	83.8
4	10/10/2012	90.8	80.5
5	13/11/2013	91.0	79.4
6	28/11/2013	92.7	78.9

B. Laboratory Experiment Results

The box plot in Figure 4 shows the removal rates of TSS and TP by PC surface layer. In general, the removal rate of TSS is higher than that of TP. The removal rates of TSS range from 16% to 27%, with an average of 20%; TP removal rates vary from 2% to 12%, with an average of 8%. When comparing the pollutant removal rates of the surface layer and the bedding gravel layers, both TSS and TP removal rates in the surface layer are much lower than those of the bedding gravel layer.

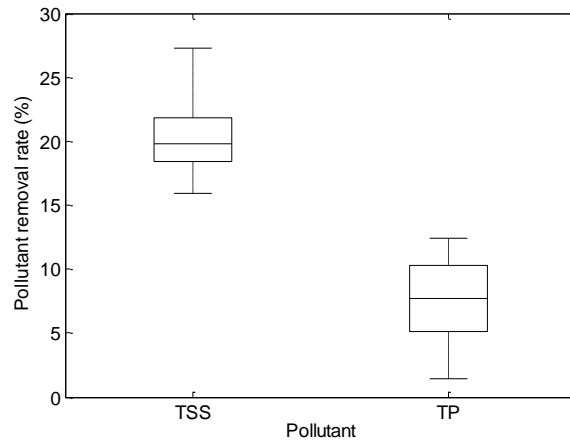


Fig. 4. Removal rates of TSS and TP of PC surface layer in laboratory experiments.

Figure 5 demonstrates the dependency of the removal rates of TSS and TP on the thickness of the bedding gravel layer. The linear regressions of the removal rates based on the thickness of the gravel layer are also illustrated in Figure 5. Figure 6 displays the strong linear relationship between TSS and TP removal rates of the bedding gravel layer. As illustrated in Figure 7, TSS removal rates of both field-scale and lab-scale PCs are higher than TP removal rates, and TSS and TP removal rates are approximately equivalent between field-scale and lab-scale PCs, both of which have a surface layer of 150 mm thick and a 500 mm layer of bedding gravel.

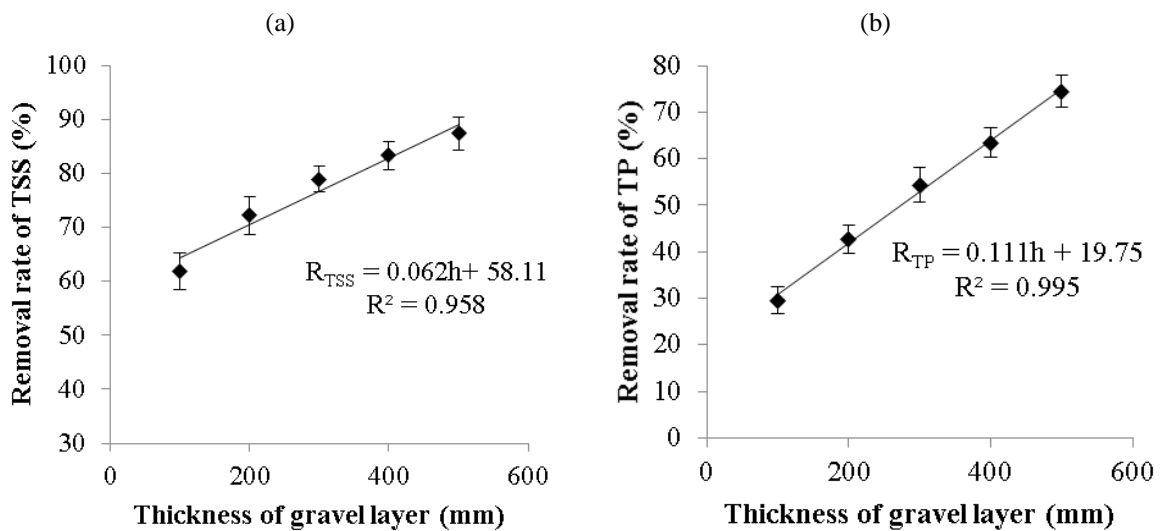


Fig. 5. Relationships between: (a) TSS removal rate and thickness of bedding layer; and (b) TP removal rate and thickness of the bedding gravel layer. In the regression equations, h denotes the thickness of the gravel layer.

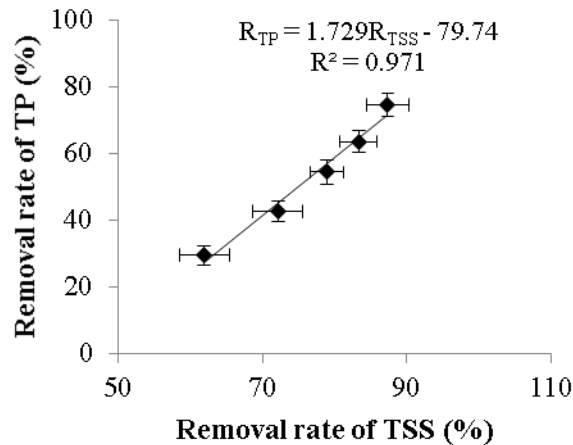


Fig. 6. Relationship between TSS and TP removal rates.

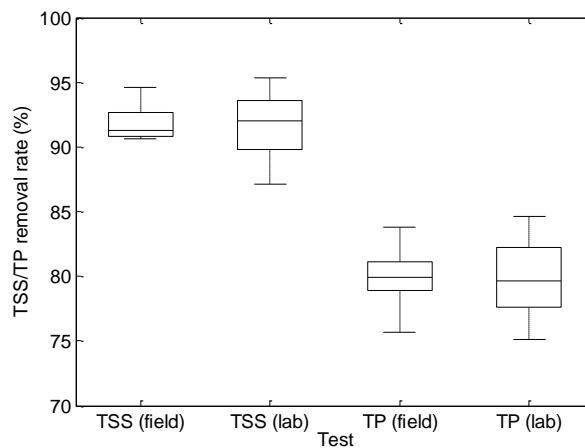


Fig. 7. Comparison of TSS and TP removal rates of field-scale and lab-scale PCs.

C. Empirical Modelling Results

An empirical model was developed to simulate the pollutant removal efficacy of field-scale PC using results obtained from lab-scale experiments, including both the surface and bedding gravel layers. According to pollutant mass balance, the empirical model of the field-scale PC proposed in this paper can be expressed as:

$$R = [1 - b(1 - R_S)(1 - R_B)] \cdot 100\% \quad (6)$$

where R_S is the pollutant removal rate of the surface layer; and R_B is the pollutant removal rate of the bedding gravel layer. The flow mass balance coefficient b , which denotes the water loss during the infiltration process, is also taken into consideration. The independent variables in the empirical model, R_S and R_B , were obtained from the laboratory experiment results, while b was determined based on the mass balance analysis in the field study ($b=0.9$). As illustrated in the laboratory test results, the pollutant removal rates appear to be dependent on the thickness of the bedding gravel layer; thus, the developed regression equations of pollutant removal rates based on the thickness of the bedding layer (Figure 5) were used to estimate R_B in the equation, given a thickness of the layer. Based on the laboratory experiment results of the surface layer, the average removal rates of TSS and TP (8% and 20%, respectively) were used to simulate TSS and TP removal rates in field-scale PC. The observed average removal rates of TSS and TP in the field experiments are 91.9% and 79.9%, respectively; the modeled TSS and TP removal rates by the field-scale PC (150 mm surface layer and 500 mm gravel layer) using Equation 6 are 92.9% and 82.2%, respectively. The prediction errors are 0.3% and 2.9% for TSS and TP, respectively.

D. Conceptual Modelling Results

The field observations were used to calibrate and validate the proposed conceptual model. Among the six test events (Table 1), Events 1, 2, 4 and 6 were used for model calibration, while Events 3 and 5 were used for model validation. The simulated and observed hydrographs in Event 1 are displayed in Figure 8(a) as an example. The prediction errors of Q_p , t_p , and total flow volume, which are the ratios of differences between simulated and observed values to the observed values, are: -0.15%, 6.25%,

and -2.08%, respectively. The simulated TSS removal rates in these four calibration events are 93.9%, 93.5%, 95.6%, and 95.9%, respectively; the respective prediction errors are 3.64%, 2.19%, 5.29% and 3.45%

The porosity curves of both the surface layer (m_s) and the bedding layer (m_b), which are functions of time, were developed using regression analysis in model calibration. As illustrated in Figure 3, pressure washing was applied to recover SIR in May 2013. The effectiveness of pressure washing was proved by the fact that SIR was significantly improved afterwards; thus, the porosity curves for the surface layer were developed separately for before and after pressure washing (Equations 7-8). Pressure washing was not speculated to affect the infiltration rate of the bedding layer. The porosity of the bedding layer was continuously decreased with time throughout study time period (Equation 9). The three curves are expressed as follows:

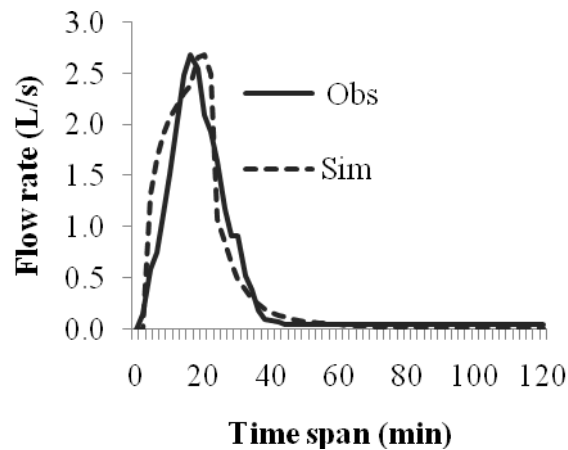
$$m_{S_before} = 25.38e^{-0.08t} \quad (7)$$

$$m_{S_after} = 22.90e^{-0.03(t-7)} \quad (8)$$

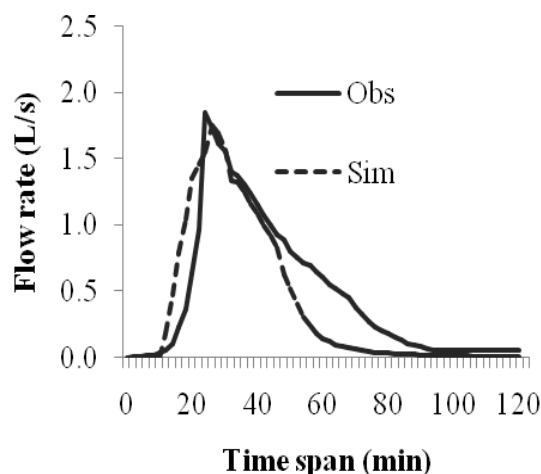
$$m_b = 31.35e^{-0.04t} \quad (9)$$

where t is the time (month), which is the number of months between Event 1 and any other events.

The calibrated regression curves for the porosity of the surface and bedding layers (Equations 7-9) were applied to estimate the porosity of each layer in Events 3 and 5 for model validation. Figure 8(b) illustrates the observed and simulated hydrographs in model validation (Event 5). Table 2 summarizes the model validation results of hydraulic and water quality performance. The absolute values of the prediction errors are all less than 10% in these two validation events.



(a) Model calibration in Event 1.



(b) Model validation in Event 5.

Fig. 8. Observed (Obs) and simulated (Sim) hydrographs in model calibration and validation.

TABLE 2. MODEL VALIDATION RESULTS (EVENTS 3 AND 5).

Event No.	Parameter	Q_p (L/s)	t_p (min)	Total volume (L)	TSS removal rate (%)
3	Observed	2.283	20	3520	94.6
	Simulated	2.285	19	3510	95.8
	Error (%)	0.09	-5.00	-0.28	1.27
5	Observed	1.849	24	3400	91.0
	Simulated	1.752	26	3091	96.3
	Error (%)	-5.25	8.33	-9.09	5.82

IV. DISCUSSIONS AND CONCLUSION

SIR of PC demonstrates gradual degradation with time. Pressure washing appears to be an efficient way to recover pavement surface infiltration, as it increased SIR from 1,837 mm/hr to 23,790 mm/hr after application. SIRs measured during the study period were all above the required minimum level of infiltration of 80 mm/hr, the average rainfall intensity of the 100-year event. The reduction of SIR did not consequently lead to surface ponding during the study period. However, if SIR continues to decrease to below 80 mm/hr, surface ponding on the pavement would be expected. Therefore, it would be feasible to determine the time interval for pavement maintenance based on the time required for SIR to decrease below 80 mm/hr.

Additionally, the gradual change in SIR affects the PC hydraulic performance. The decrease of SIR would lead to increases of the three hydraulic variables (p_r , t_p and t_d), delay the discharge of stormwater out of permeable pavements, and consequently attenuate the flow peak with stormwater temporarily stored within the pavements. This would reduce the pressure on the downstream drainage systems; however, very low SIR would cause surface ponding. Therefore, the trade-off between the reduction of pressure on the downstream drainage system and the ability to quickly discharge surface runoff through the pavement surface should be taken into consideration when designing and conduction maintenance on permeable pavements. Although SIR does influence the hydraulic performance of PC, the impact of SIR on pollutant removal rate appears to be negligible; correlation coefficients between SIR and TSS removal rates and between SIR and TP removal rates were not significant in the field experimental study. Both TSS and TP removal rates were approximately constant in all field experiments.

The results from laboratory experiments demonstrated the effect of the thickness of the bedding gravel layer on both TSS and TP removal rates. Both TSS and TP removal rates appear to linearly increase with an increase in the thickness of the bedding layer. In addition, TSS and TP removal rates of the surface layer are much lower than those of the bedding gravel layer (100-500 mm thickness). The difference between the TSS and TP removal of the surface and gravel layers might be ascribed to their different physical structure, as the surface layer is designed to enhance water infiltration without causing surface ponding under extreme events (such as the 100-year event). The strong dependency between TSS and TP removal rates suggest that their removal might be largely governed by the same physical mechanisms; thus, TP removal can be modeled as a certain percentage of TSS removal. The result is not surprising due to the fact that TP might largely exist in particulate form. The quantitative relationship between TSS and TP removal might also be site-specific.

Approximately equivalent TSS and TP removal rates were observed in the field-scale and lab-scale PCs (Figure 7), when the structure of the lab-scale PC is same as that of the field-scale PC. In this study, both the field-scale and the lab-scale PCs consist of a 150 mm surface layer and a 500 mm bedding gravel layer. The results imply that the empirical model developed based upon the results of the laboratory experimental study might be applicable in the modeling of TSS and TP removal of field-scale PC. This is further supported by the good performance of the developed empirical model in predicting TSS and TP removal rates of field-scale PC. It was also found that the degradation of SIR does not affect TSS and TP removal, when surface ponding does not occur; however, it leads to the attenuation of outflow peak and a delay in discharge downstream, but no decrease in total volume discharged.

In addition, the developed conceptual model can effectively simulate the PC hydraulic and water quality performance. The model is capable of capturing the effect of SIR on PC hydraulic performance quite well, as demonstrated in the results from both model calibration and validation, represented as functions of time. When comparing the conceptual and empirical modeling approaches, it can be concluded that both modeling approaches perform equivalently well in terms of modeling TSS and TP removal rates. However, as demonstrated in the modeling approaches, the development of an empirical model might largely depend on the physical characteristics of the pavement structure, including the thickness of the layers and material used.

Thus, both laboratory and field studies are needed. In addition, in the developed conceptual model, the functions of porosity for the surface and bedding layers in which time is the independent variable were developed based on field observations, and are thus site-specific. Additionally, the models were developed using data collected from both the laboratory and field studies given design storms of the 100-year event. SIR was high enough to deter surface ponding in all experiments. Further research on PC performance under a variety of storm events and further degradation of SIR (e.g., below the average rainfall intensity of design storm) would further deepen our understanding of PC and therefore its role in urban stormwater management.

ACKNOWLEDGMENT

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada, the City of Calgary and Urban System Ltd. for the financial support of this research. Additionally, the authors thank Phillip Jerome, Heather Feil and Ian Huybregts for assistance with site construction and field experiments. Further thanks are extended to Lafarge and Harald von Langsdorff from UNI-GROUP U.S.A. for material donations, and Canada Lands Company and Arcturus Realty Corporation for land use.

REFERENCES

- [1] Ellis, J.B., Revitt, D.M. & Lundy, L., "An impact assessment methodology for urban surface runoff quality following best practice treatment," *Science of the Total Environment* 416: 172-79, 2012.
- [2] Finkenbine, J., Atwater, J. & Mavinic, D., "Stream health after urbanization," *Journal of American Water Resources Association* 36(5): 1149-60, 2000.
- [3] Kayhanian, M., McKenzie, E., Leatherbarrow, J. & Young, T., "Characteristics of road sediment fractionated particles captured from paved surfaces, surface run-off and detention basins," *Science of the Total Environment* 439: 172-86, 2012.
- [4] Tuccillo, M.E., "Size fractionation of metals in runoff from residential and highway storm sewers," *Science of the Total Environment* 355: 288-300, 2006.
- [5] Balades, J., Legret, M. & Madiec, H., "Permeable pavements: pollution management tools," *Water Science & Technology* 32(1): 49-56, 1995.
- [6] Pratt, C., "A review of source control of urban stormwater runoff," *Water and Environment Journal* 9(2): 132-139, 1995.
- [7] Watanabe, S., "Study on storm water control by permeable pavement and infiltration pipes," *Water Science & Technology* 32(1): 25-32, 1995.
- [8] Sansalone, J., Kuang, X. & Ranieri, V., "Permeable pavement as a hydraulic and filtration interface for urban drainage," *Journal of Irrigation and Drainage Engineering* 134(5): 666-674, 2008.
- [9] Collins, K.A., Hunt, W.F. & Hathaway, J.M., "Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina," *Journal of Hydrologic Engineering* 13(12): 1146-1157, 2008.
- [10] Scholz, M. & Grabowiecki, P., "Review of permeable pavement systems," *Building and Environment* 42(11): 3830-3836, 2007.
- [11] Chai, L., Kayhanian, M., Givens, B., Harvey, J.T. & Jones, D., "Hydraulic performance of fully permeable highway shoulder for storm water runoff management," *Journal of Environmental Engineering* 138(7): 711-722, 2012.
- [12] Brown, C., Chu, A., van Duin, B. & Valeo, C., "Characteristics of sediment removal in two types of permeable pavement," *Water Quality Research Journal of Canada* 44(1): 59-70, 2009.
- [13] Pagotto, C., Legret, M. & Le Cloirec, P., "Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement," *Water Research* 34(18): 4446-4454, 2000.
- [14] Bean, E.Z., Hunt, W.F. & Bidelsbach, D.A., "Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts," *Journal of Irrigation and Drainage Engineering* 133(6): 583-92, 2007.
- [15] Ball, J. & Rankin, K., "The hydrological performance of a permeable pavement," *Urban Water Journal* 7(2): 79-90, 2010.
- [16] Eck, B.J., Winston, R.J., Hunt, W.F. & Barrett, M.E., "Water quality of drainage from permeable friction course," *Journal of Environmental Engineering* 138(2): 174-81, 2011.
- [17] Tota-Maharaj, K. & Scholz, M., "Efficiency of permeable pavement systems for the removal of urban runoff pollutants under varying environmental conditions," *Environmental Progress & Sustainable Energy* 29(3): 358-69, 2010.
- [18] Rushton, B.T., "Low-impact parking lot design reduces runoff and pollutant loads," *Journal of Water Resources Planning and Management* 127(3): 172-179, 2001.
- [19] Gilbert, J.K. & Clausen, J.C., "Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut," *Water Research* 40(4): 826-32, 2006.
- [20] Hatt, B.E., Fletcher, T.D. & Deletic, A., "Treatment performance of gravel filter media: implications for design and application of stormwater infiltration systems," *Water Research* 41(12): 2513-2524, 2007.
- [21] Tan, S., Fwa, T. & Han, C., "Clogging evaluation of permeable bases," *Journal of Transportation Engineering* 129(3): 309-315, 2003.
- [22] Montes, F. & Haselbach, L., "Measuring hydraulic conductivity in pervious concrete," *Environmental Engineering Science* 23(6): 960-969, 2006.
- [23] Kuang, X., Sansalone, J., Ying, G. & Ranieri, V., "Pore-structure models of hydraulic conductivity for permeable pavement," *Journal of Hydrology* 399(3): 148-157, 2011.
- [24] Siriwardene, N.R., Deletic, A. & Fletcher, T.D., "Modeling of sediment transport through stormwater gravel filters over their lifespan," *Environmental Science & Technology* 41(23): 8099-8103, 2007.
- [25] Yao, K.M., Habibian, M.T. & O'Melia, C.R., "Water and waste water filtration: concepts and applications," *Environmental Science & Technology* 5(11): 1105-1112, 1971.
- [26] The City of Calgary. 2011. *Stormwater management and design manual*. Calgary, Canada.
- [27] Tufenkji, N. & Elimelech, M., "Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media," *Environmental Science & Technology* 38(2): 529-536, 2004.