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INVESTIGATION ON HYDROLOGIC PERFORMANCE OF PERVIOUS CONCRETE PAVEMENT BY FINITE ELEMENT ANALYSIS

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Abstract – *Pervious concrete pavement has been used widely as an effective practice for water management in low-impact development techniques. The hydrologic performance of pervious concrete pavement depends significantly on the rainfall intensity and the designed slope. This study assessed the hydrologic performance of pervious concrete pavement by evaluating the time for surface ponding via finite element analysis. A series of simulations were carried out to explore the relationship between hydrologic performance and pervious concrete pavement by the Hydrus 2D program. The research's results showed that as the slope increased, the time of surface ponding also increased. The data indicated that the slope variable had a low impact on the water level in pervious concrete pavement under a constant rainfall intensity. Observation of the effect of rainfall intensity showed that when the rainfall intensity increased twofold, the time for surface ponding dropped about two times. Furthermore, when surface ponding appeared, pervious concrete pavement at higher rainfall intensity had lower water content. The rainfall intensity also significantly affects the hydrologic performance of the pervious concrete pavement. This study only assessed the hydrologic performance by using the time for surface ponding via finite element analysis. Further experimental studies should be conducted to examine the relationship of other factors to the hydrologic performance of pervious concrete pavement.*

Keywords: finite element analysis, hydrologic performance, pervious concrete pavement.

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I. INTRODUCTION

Nowadays, permeable pavement systems have been used widely throughout the world. They have provided remarkable benefits in stormwater management for regions during urbanization [1–3]. Generally, permeable pavement systems are classified into different types: porous asphalt, pervious concrete (PC), permeable friction course, and permeable interlocking concrete pavement [4]. PC pavement refers to a type of permeable pavement system which is constructed with PC for the surface, an open-grade aggregate for the permeable base (or reservoir), and an incompressible layer for the subgrade. Since all the layers of the PC pavement are designed to have high porosity, water is allowed to infiltrate through its body and drain out vertically or/and laterally. As a result, PC pavement has a high potential for reducing peak flow, outflow volume, and pollutants during rainfall [5–7]. The hydrologic performance of a PC pavement depends on many factors, which are classified into three main components. The first component is the properties of the PC pavement material, which include porosity and permeability. Second is the geometric design of the pavement, such as the longitudinal slope, cross slope, length, width and thickness. And the final component refers to environmental factors like rainfall intensity and freeze/thaw cycle. In the environment component, rainfall intensity is the critical factor that should be considered carefully [8, 9].

Many previous studies have considered the effect of these components on the hydrologic performance of PC pavement [8–10]. Crookes et al. [11] conducted a study evaluating the hydrologic and quality control performance of pervious concrete pavement in Ontario. In the study, PC pavement used in an in-field parking lot was studies. The hydrologic performance of the PC pavement was measured by the infiltration capacity, which was measured according to the manual in ASTM C1701 standard [12], whereas the quality control performance of the PC pavement was evaluated by an experiment in Niagara Analytical Laboratories Inc. [13]. The results showed that, for the hydrologic performance, PC pavement exhibited a more naturalized hydrologic response than the conventional pavement. It also reduced the outflow volume and extended the lag time for peak flow. For the water quality performance, the PC pavement reduced the majority of pollutants in the rainfall. Based on the results, they suggested using the PC pavement to control the rainwater in urban areas and to conduct further studies about the hydrologic performance of PC pavement due to clogging.

In another study, Brown et al. [14] experimented on the PC pavement and porous asphalt pavement to evaluate their hydrologic performance using in Low Impact Development technique. The two permeable pavement systems were used in parking lots to accommodate rainfall in the area. The authors concluded that the two permeable pavement systems could reduce the outflow volume by 69%. In the case of using permeable pavement for water pollution filtration, both systems had yielded positive results by reducing 49% of total nitrogen, 51% of total phosphorus, and 89% of total suspended solids. The authors recommended combining the Bioretention cells with the two permeable pavement systems to improve stormwater management.

According to research by Collins et al. [15], they also observed the hydrologic performance of the PC pavement by studying four permeable pavement systems in parking lots, including PC pavement, two types of permeable interlocking concrete pavement, and concrete grid paver pavement. The hydrologic performance of the four pavements was measured by surface runoff volume, outflow volume, peak flow rate, and lag time to peak. The results showed that all permeable pavement systems illustrated similar effects on reducing the surface runoff volume and peak flow rate. The authors recommended that to increase the benefits of permeable pavement systems in stormwater management, construction designers should consider using an appropriate underdrain according to the conditions like soil, climate and weather to satisfy the requirements of each specific area.

In 2015, Teodosio et al. [16] finished a study using the finite element method (FEM) to observe the hydrologic performance of PC pavement. In the study, a PC pavement was simulated to observe infiltration during heavy rains. The results showed that as the rainfall intensity increased, the time taken for water flow above PC pavement decreased. The analysis for the PC pavement with underdrain indicated that, when using the underdrain in the PC pavement, the effect of evaporation on the water flow in the PC pavement could be negligible. It was recommended that further analyses should mention observing the hydrologic performance of PC pavement. In low impact development technique, the hydrologic performance of the PC pavement could be evaluated by the time of peak flow, which is the time that surface ponding is initiated [17, 18]. In a similar study, Park et al. [19] observed the time for surface ponding for PC pavement with a rainfall simulator. The authors conducted rainfall simulation tests with rainfall intensities ranging from 50 mm/h to 150 mm/h. The results showed that the time for surface ponding dropped from 16 to 21 minutes for PC pavement, and 10 minutes for the impermeable pavement, regardless of rainfall intensity. The result of the simulation tests proved that PC pavement was more efficient in rainwater management than impermeable pavement

Based on the review of previous studies, although the hydrologic performance of PC pavement could be assessed by the time for surface ponding and experimental measurement or FEM could be used, there were not many studies on the hydrologic performance of PC pavement. Furthermore, extensive research into the effect of slope and rainfall intensity on the hydrologic performance of PC pavement has been modest. This study was carried out to assess the hydrologic performance of PC pavement in terms of considering the slope and rainfall intensity. To explore the collected data and verify previous hypotheses, PC pavements with different slope values were simulated with various rainfall intensity values. The hydrologic performance of the PC pavement was evaluated based on the finite element analysis program Hydrus 2D.

II. WATER FLOW IN A PERVIOUS CONCRETE PAVEMENT

According to the definitions in ASCE 2015 [20], water from rainfall infiltrates into the PC pavement body and moves to the base layer, which works as a reservoir layer. From the base/reservoir layer, water can drain out the PC pavement vertically through the uncompacted subgrade or/and laterally through the reservoir layer. This study researched PC pavement that comprised of PC and the base layer with lateral drainage. The lateral movement of water from rainfall in the PC pavement is described in Figure 1.

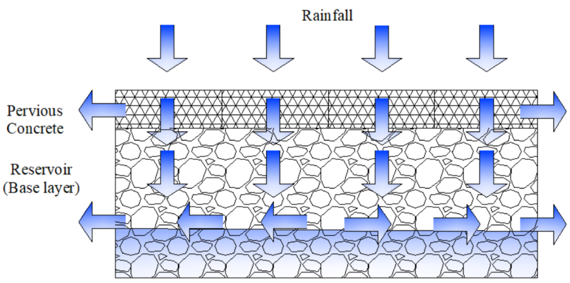


Fig. 1: Lateral movement of water from rainfall in the PC pavement observed in this study, after ASCE 2015 [20]

III. FINITE ELEMENT ANALYSIS FOR PERVIOUS CONCRETE PAVEMENT

A. *Finite element program*

In this study, a finite element program, Hydrus 2D, was used to model the lateral movement of water in the PC pavement. The analysis assumed that water flows in a two-dimensional channel with an unsaturated flow. The Hydrus 2D program incorporates the Richards equation, which is widely used for unsaturated water flow. The governing of the unsaturated water flow is expressed in Equation 1 [21].

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[k\left(k_{ij}^{A}\frac{\partial h}{\partial x_j} + k_{iz}^{A}\right)\right] - S \qquad (1)$$

To solve Equation 1, the two components of hydraulic properties are utilized. One is the soil water characteristic curve (SWCC), which represents the nonlinear relationship between the volumetric water content and the suction in the soil and is presented in Equation 2 [22, 23].

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \qquad (2)$$

A third equation that was used relates to the unsaturated hydraulic conductivity function, which represents the nonlinear relationship between the unsaturated hydraulic conductivity and water retention in the soil [22], [23]. This relationship in presented in Equation 3 [21, 24].

$$k(h) = k_s S_e^{l}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad (3)$$

B. *Pervious pavement Geometric*

The PC pavement in this study was constructed using PC for the surface and open-graded aggregate material for the reservoir. It was assumed that water from rainfall can infiltrate into the pores, and then drain out laterally through the side. PC pavement with geometric dimension following the typical PC pavement defined in the ASCE manual [20] was used for the simulation. The configurations of PC pavement is presented in Figure 2.

C. *Boundary conditions*

In this study, water was allowed to drain laterally through the side of the PC pavement. There were three main types of boundary conditions applied in the analysis: atmospheric, no flux, and drain conditions. Figure 2 illustrates the application of the boundary conditions in modeling the PC pavement. The surface of the PC pavement, i.e., the AB line where rainfall occurred, was assigned the atmospheric condition. The outlet

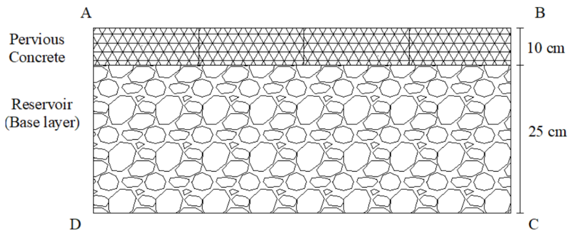


Fig. 2: PC pavement geometric dimension, after ASCE 2015 [20]

of the PC pavement, i.e., the AD line where the water drained out laterally, was assigned the drain condition. Finally, the two sides BC and CD lines where the water could not drain out, were assigned the no-flux-boundary conditions. In this study, it was assumed that before the rain event happened, the PC pavement was in a dry condition, meaning that in the initial conditions of the experiment, the PC pavement was set with no water in the body.

D. Analysis cases

Different slope values were simulated to observe the time for surface ponding. According to the manual in ASCE [20], the effective slope value for the PC pavement should be in the range of 1 to 5%. In this study, PC pavements with the slope of 1%, 3%, and 5% were analyzed at a constant rainfall intensity of 100 mm/h. Later, to observe the effect of rainfall intensity on the hydrologic performance of PC pavement, PC pavement with a slope of 5% was simulated with rainfall intensity of 50 mm/h, 100 mm/h, and 200 mm/h.

E. Material parameters

In this study, the material parameters for the PC pavement were used based on the previous literature. While the hydraulic conductivity and SWCC parameters for the surface PC were used following those in the study "Numerical Study on the Hydrologic Characteristic of Permeable Friction Course Pavement"[25], the ones for the base/reservoir layer were used following those in the study of Kayhanian and Chai [26]. A summary of the material parameters in the finite element analysis is presented in Table 1.

Table 1: Materials parameters for PC pavement, after [25, 26]

PC pavement layer	Hydraulic conductivity, k (cm/min)	SWCC parameter				
		θ_r	θ_s	α	n	m
Surface, PC	60	0.001	0.32	2.23	1.63	0.5
Base/Reservoir, open-graded aggregate	467	0.03	0.4	2.00	2.00	0.5

IV. RESULTS AND DISCUSSION

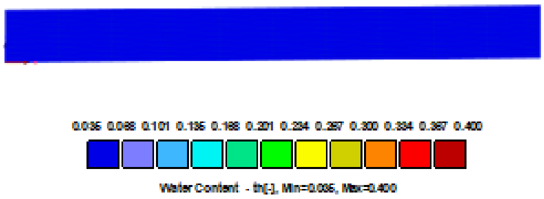
A. Effect of slope on the hydrologic performance

The PC pavement with different slope values was studied by imitating a constant rainfall intensity of 100 mm/h to observe the time for surface ponding. In addition, the results show the water levels in the PC pavement illustrated by water content. The findings of water content at the time for surface ponding in the PC pavement according to slope values are shown in Figure 3 and Figure 4.

Figure 3 illustrates that when surface ponding appeared, the water level in the PC pavement did not change much. Thus, it could be concluded that when the surface ponding happened, PC pavement with different slope values resulted in the same water level in the body.

The results in Figure 4 show that as the slope increased, the time for surface ponding increased. For instance, at the slope of 1%, the time for surface ponding is 72 minutes. At 3% and 5%, the time for surface ponding is 81 minutes and 83 minutes, respectively. This performance is consistent with the results of the two studies conducted by Tan et al. [8] and Kayhanian and Chai [25]. A possible explanation is that the PC pavement with a higher slope resulted in a higher flow rate. Therefore, PC with a higher slope took a long time for surface ponding.

The results of observing the water in the body of PC pavement while varying the time of rainfall is shown in Figure 5. The results demonstrate that the water levels in the PC pavement with different slope values are quite similar. The conclusion was



(a) Water content at a slope of 1% before rainfall

(b) Water content at a slope of 1% after rainfall

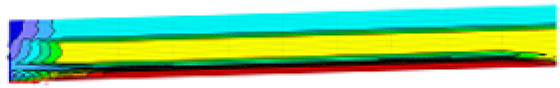
(c) Water content at a slope of 3% before rainfall

(d) Water content at a slope of 3% after rainfall

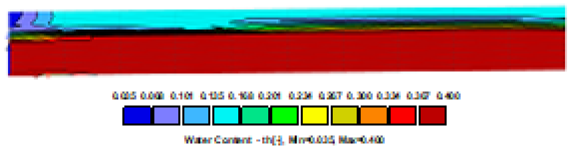
(e) Water content at a slope of 5% before rainfall

(f) Water content at a slope of 5% after rainfall

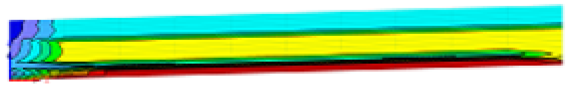
Fig. 3: Water content in PC pavement with different slope values



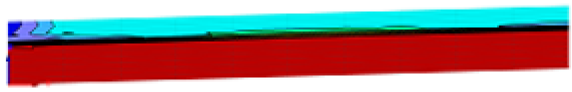
(a) Water content at a slope of 1% after rainfall 20 minutes



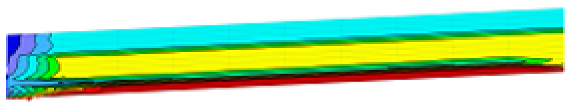
(b) Water content at a slope of 1% after rainfall 60 minutes



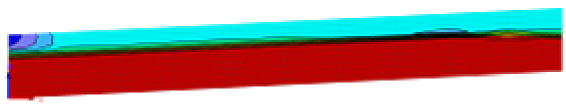
(c) Water content at a slope of 3% after rainfall 20 minutes



(d) Water content at a slope of 3% after rainfall 60 minutes



(e) Water content at a slope of 5% after rainfall 20 minutes



(f) Water content at a slope of 5% after rainfall 60 minutes

Fig. 5: Water content in PC pavement at different time

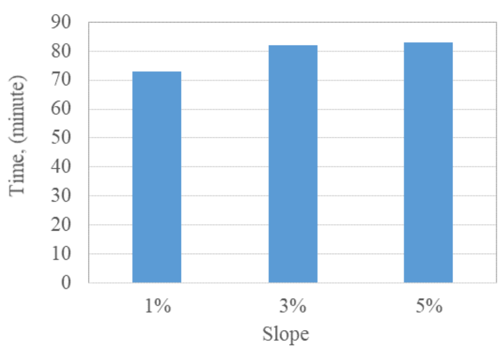


Fig. 4: Time for surface ponding

made that the slope variable had a low impact on the water level in the PC pavement under a constant rainfall intensity.

B. Effect of rainfall intensity

To observe the effect of rainfall intensity on the time for surface ponding, PC pavement with a slope of 5% was simulated with various rainfall intensities of 50 mm/h, 100 mm/h, and 200 mm/h. The result of the water level in the PC pavement when the surface ponding happened can be seen in Figures 6, 7, and 8.

As shown in Figures 6-8, the area of the water content of 0.136 – 0.168 in the PC pavement at

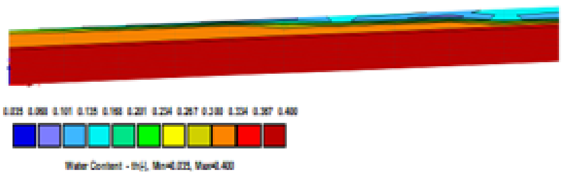


Fig. 6: Water content in the PC pavement with rainfall intensity of 50 mm/h

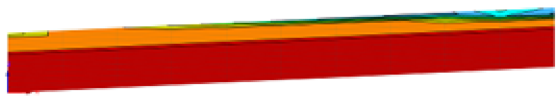


Fig. 7: Water content in the PC pavement with rainfall intensity of 100 mm/h

rainfall intensity of 50 mm/h is larger than that at rainfall intensity of 100 mm/h and 200 mm/h. It is evident that when surface ponding appeared, PC pavement at higher rainfall intensity had lower water content. In other words, PC pavement at higher rainfall intensity had a higher degree of saturation. This is the reason that PC pavement at higher rainfall intensity resulted in a long time for surface ponding. The time required for surface ponding of the PC pavements at different rainfall intensity values is given in Figure 9.

Based on the results, when the rainfall intensity increased twofold, the time for surface dropped about two times. For example, at the rainfall intensity of 50 mm/h, the time for surface ponding was 156 minutes. When the rainfall intensity doubled to 100 mm/h, the surface ponding time decreased to 82 minutes. This suggests that at higher rainfall intensity, more water infiltrates through the PC pavement and PC pavement becomes saturated faster, thus resulting in earlier surface ponding. This indicated that rainfall intensity affects the hydrologic performance of PC pavement.

V. CONCLUSION

PC pavement has been used widely as an effective practice for water management in low-impact development techniques. The hydrologic performance of PC pavement significantly depends on the designed slope and rainfall intensity.

Fig. 8: Water content in the PC pavement with rainfall intensity of 200 mm/h

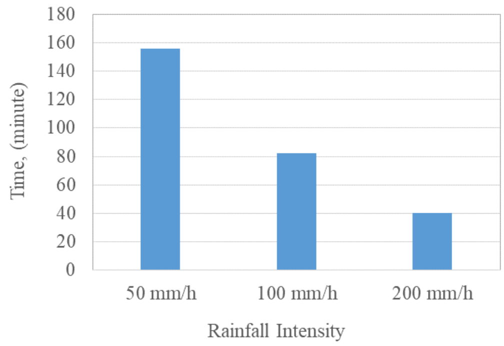


Fig. 9: Time required for surface ponding of PC pavement at different rainfall intensity values

This study assessed the hydrologic performance of PC pavement in terms of evaluating the time of surface ponding by finite element analysis. The following conclusions collected from the analysis process were drawn. First of all, this study proved that as the slope increased, the time for surface ponding increased. A possible explanation is that the PC pavement with a higher slope resulted in a higher flow rate. Therefore, PC with a higher slope took a long time for surface ponding. Besides, it was observed that at the time of surface ponding, the water content in the PC pavement seemed to not change. Thus, it indicates that when the surface ponding happened, PC pavement with different slope values resulted in quite similar water levels in the body.

This research also indicated that the slope variable had a low impact on the water level in the PC pavement under a constant rainfall intensity. Observation of the effect of rainfall intensity on the time for surface ponding showed that when the rainfall intensity increased twofold, the time for surface dropped about two times. It means that the higher rainfall intensity and water infiltration through the PC pavement was, the faster PC pavement became saturated. Another point worth noting is that when surface ponding appeared, PC pavement at higher rainfall intensity had lower water content. In other words, PC pavement at higher rainfall intensity had a higher degree of saturation. Overall, these results indicated that rainfall intensity has a significant effect on the hydrologic performance of the PC pavement.

This study only assessed the hydrologic performance of the PC pavement using time for surface ponding via finite element analysis. Further intensive experimental studies should be carried out to examine the hydrologic performance of PC pavement and the effect of other factors.

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