A FINITE ELEMENT STUDY OF THE EFFECT OF SLOPE AND RAINFALL INTENSITY ON SUBSURFACE OUTFLOW OF PERMEABLE FRICTION COURSE PAVEMENT

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Abstract – *Permeable friction course pavement is designed with high porosity so that water can infiltrate into its pores and drain out laterally through the side. This study observes the subsurface outflow of a permeable friction course pavement via the finite element analysis program SV Flux 2D. A series of analyses were conducted for the permeable friction course pavement with different slope and rainfall intensity values. The results showed that different slope values provided different results for the subsurface outflow. As the slope increased, the subsurface outflow of the permeable friction course pavement increased. It is noticed that the effect of slope on the subsurface outflow decreased when the slope increased from 6% to 8%. In addition, this study also found that as the time of rain events increased, the subsurface outflow pavement was reduced. The investigation of the effect of rainfall intensity on the subsurface outflow of the permeable friction course pavement showed that as the rainfall intensity increased, the subsurface outflow steadily increased. However, it is noted that at the higher rainfall intensity, the pavement became saturated faster and the overflow happened earlier. In the future, further studies focused on the drainage of permeable friction course pavement including subsurface and surface outflow should be carried out.*

Keywords: permeable friction course, rainfall intensity, subsurface outflow.

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I. INTRODUCTION

In recent years, the development of industrialization and urbanization in many regions in Vietnam has provided remarkable negative impacts on water hydrology and environment. Thus, the solutions for these concerns have been needed. Among the solutions, low-impact development (LID) technology is introduced as a potential solution. With the implementation of LID strategies, after urban development, the performance of water hydrology can be maintained as much as possible in comparison with before urban development occurred [1]. One of the typical practices of LID strategies is permeable friction course (PFC) pavement, which is a layer of porous asphalt laid on the surface layer of conventional impermeable asphalt pavement [2]. The PFC pavement is designed with high porosity; therefore, water can infiltrate into the pores in its body. After that, water drains out laterally through the side of the PFC pavement. Consequently, PFC pavement can reduce the surface runoff and pollutants in the rainwater. Hence, it decreases the negative impacts of urbanization and industrialization on water hydrology [3].

According to the design guide of the American Society of Civil Engineering (ASCE) for PFC pavement, the outflow of the PFC pavement is a major design consideration [4]. The outflow of PFC pavement consists of the subsurface and surface outflow. The outflow of PFC pavement depends on many factors that could be categorized into three main factors. The first factor is the property of the PFC pavement material, such as porosity and permeability. The second one is the geometric design of the PFC pavement, such as the longitudinal slope, cross slope, length, width, and thickness. And the final one is the environmental factors, such as rainfall intensity and clogging conditions [5, 6].

The subsurface flow of the PFC pavement and its dependence on the above three factors have been investigated in previous studies based on the finite element method (FEM). Tan et al. [7] used finite element analysis through the SEEP 3D program to evaluate the subsurface outflow of a PFC pavement in terms of different slope values. In their analysis, the permeability value of the PFC pavement was assumed to be 103 mm/s with an anisotropy ratio of 1. The results showed that as the slope increased, the subsurface outflow of PFC pavement increased. It was reported that the subsurface outflow results by FEM depended on the element size. PFC pavement with the finer mesh in the analysis resulted in a larger subsurface outflow. The conclusion was made that the subsurface outflow of the PFC pavement was affected significantly by the slope and the rainfall intensity. In another study by Zhang et al. [8], the subsurface outflow of PFC pavement was assessed by three-dimensional finite element analysis. This study calculated the subsurface outflow for the PFC pavement with various values of longitudinal, transverse slope, and permeability. The results showed that the subsurface outflow of PFC pavement increased dramatically when the permeability and slope increased. However, at a high longitudinal slope, the subsurface outflow of PFC maintained stability. The authors suggested that further research should be carried out to investigate the effect of the porosity and the pore shape on the drainage of PFC pavement. Recently, Chen et al. [9] observed the subsurface outflow of PFC pavement by FEM. In their study, the subsurface outflow of PFC pavement was observed by the runoff coefficient, which is the ratio of outflow volume to testing time. The PFC pavement with different slope values was used to simulate various rainfall intensity values. Based on the results, the study found that the longitudinal slope values had an unremarkable effect on the subsurface outflow of PFC pavement. In contrast, the transverse slope had a significant effect on the subsurface outflow of PFC pavement. The FEM results compared well with the experiment results. The recommendation was made that the method in the study can used to extract the subsurface outflow of the PFC pavement.

Previous studies have shown that the subsurface outflow of PFC pavement depends on many factors, such as geometric dimension and rainfall intensity. To observe the subsurface outflow of PFC pavement, FEM can be utilized effectively. Until now, there have not been many studies conducted on the subsurface outflow of PFC pavement while considering slope and rainfall intensity values. To fill this gap, the current study observed the subsurface outflow of PFC pavement and its dependence on the slope and rainfall intensity values. A series of analyses were conducted for a PFC pavement via a finite element program SV Flux 2D. Based on the results, the subsurface outflow of the PFC pavement was evaluated and compared.

II. LITERATURE REVIEW

The subsurface flow of a PFC pavement is the flow of water inside the body and drains through the side of the pavement without surface ponding (surface flow). At a constant rainfall intensity, the water from rainfall infiltrates into the pores of the PFC pavement body and then drains out laterally through the side without surface ponding. For a while, when the body of PFC pavement is nearly saturated, the water starts to flow above the surface of PFC pavement, which is called surface flow. In this study, the authors focused on the subsurface flow of the PFC pavement under a constant rainfall intensity.

The head of subsurface flow in a PFC pavement body is considered to be laminar or between laminar and turbulent [10, 11]. This value is a function of the rainfall intensity and time of rain event, as well as the permeability and geometric design of the PFC pavement. During the rainfall event, the pores in the PFC pavement are filled with water, and the water head increases gradually. The head of subsurface flow H in a PFC pavement body is illustrated in Figure 1.

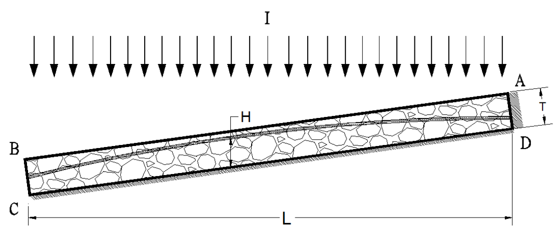

Fig. 1: Subsurface flow in a PFC pavement body [10]

III. RESEARCH METHOD

Subsurface flow analysis

To extract the subsurface flow, a finite element program SV Flux 2D was used. The program can analyze the transient flow of water for the unsaturated seepage in the PFC pavement. The governing equation of two-dimensional water flow is expressed in the program as follows [12]:

$$\frac{\partial}{\partial x}\left[k_x \frac{\partial h}{\partial x} + k_{vd} \frac{\partial u_w}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y \frac{\partial h}{\partial y} + k_{vd} \frac{\partial u_w}{\partial y}\right] = -\gamma_w m_2^w \frac{\partial h}{\partial t}$$

where k_x and k_y are the hydraulic conductivity values in the horizontal and vertical directions, respectively, h is the total water head, k_{vd} is the vapor conductivity, u_w is the pore water pressure, Υ_w is the unit weight of water, $m2^w$ is the coefficient of water storage obtained from the derivative of the soil-water characteristic curve (SWCC), and *t* is the time.

Boundary conditions

To model the PFC pavement with a rain event, three main types of boundary conditions were utilized. They are climate, review, and zero-flux conditions. The implementation of the boundary conditions can be referred to in Figure 1. The AB line, along which rainfall occurred, was assigned the climate boundary condition. The outlet side of the PFC pavement, i.e., the BC line, from where the subsurface outflow happened, was assigned the review boundary condition. Finally, the bottom CD line and the upper AD line were assigned zero-flux boundary conditions to model the impermeable characteristics. The PFC pavement with the boundary conditions in the program is displayed in Figure 2.

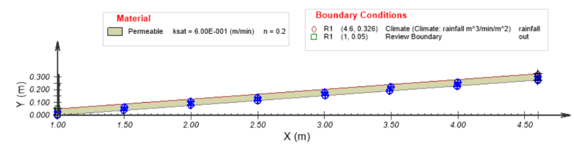

Fig. 2: PFC pavement in the SV Flux 2D program

Analysis cases

The PFC pavement with a length of 3.6 m and thickness of 0.05 m was used during analysis. To observe the effect of slope values on the subsurface outflow of the PFC pavement, a series of analyses with various slopes including 2%, 4%, 6%, and 8%, respectively, and a rainfall intensity of 100 mm/h were conducted. These slope values were chosen based on the manual [13]. Furthermore, the effect of rainfall intensity on the subsurface outflow of the PFC pavement was also evaluated. As reported by Antunes et al. [14], the design rainfall intensity for permeable pavement was about 100 mm/h. Hence, the PFC in this study with a slope of 6% was simulated with different rainfall intensity values as 90 mm/h, 100 mm/h, 110 mm/h, and 120 mm/h. In each case, the subsurface outflow of the PFC pavement side was recorded from the beginning of the rain event until the surface ponding happened, continuously. The analysis was stopped when the surface ponding happens.

Material parameters

The horizontal and vertical permeability values of the PFC pavement used in the analysis followed the study by Yoo et al. [15], which was about 10 mm/s. In the SV Flux 2D program, to perform the nonlinear relationship between the volumetric water content and the suction in PFC pavement, the SWCC was used. In this study, Van Genuchten's equation [16, 17] was used to model

SWCC, as follows:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(a\psi^n\right)\right]^m}$$

where θ is the volumetric water content, θs is the saturated volumetric water content, θr is the residual volumetric water content, Ψ is the soil suction, and *a*, *n*, and *m* are the material (fitting) parameters.

The SWCC parameters of a previous concrete given by Lim et al. [18] were used for that of the PFC pavement in this study. These parameters were determined through an equation of Fredlund et al. [19] by using Fredlund's device [20]. The SWCC parameters and the curve are presented in Table 1 and Figure 3, respectively.

Table 1: SWCC parameters for the PFC pavement in the study [18, 21]

Volumetric water, θ_s (%)	Volumetric water, θ (%)	Soil suction, Ψ (kPa)	Material Parameters	
			a	*n*
20	0.001	0.01	2.23	1.63

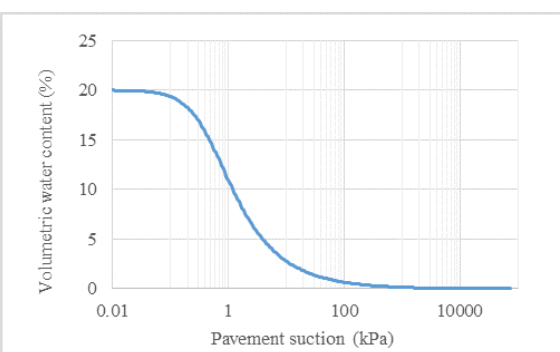

Fig. 3: SWCC curve for PFC pavement [21]

In the SV Flux program, the suction pressure could be applied by using the negative value for the pore water pressure. As shown in Figure 3, PFC pavement is totally dry when the suction pressure as 200 kPa. Hence, the pore water pressure in the PFC pavement was set at –200 kPa before the analysis. During the analysis, data for subsurface outflow were continually recorded. The PFC pavement with initial pore water pressure is presented in Figure 4 below.

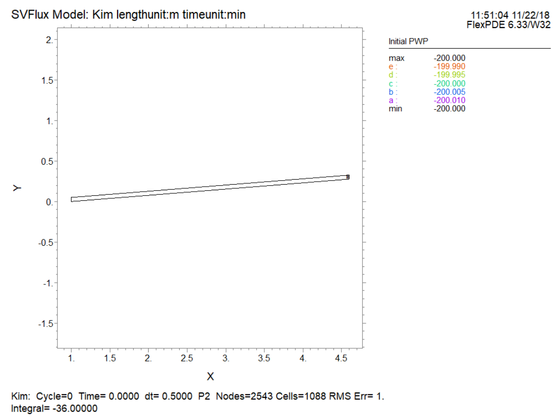

Fig. 4: Initial pore water pressure before analysis in the program

IV. RESULTS AND DISCUSSION

Effects of slope on the subsurface outflow of permeable friction course pavement

To observe the effect of slope on the subsurface outflow of the PFC pavement, a series of analyses were carried out for the PFC pavement having slopes of 2%, 4%, 6%, and 8%. The results of subsurface outflow of PFC pavement according to different slopes are presented in Figure 5 below.

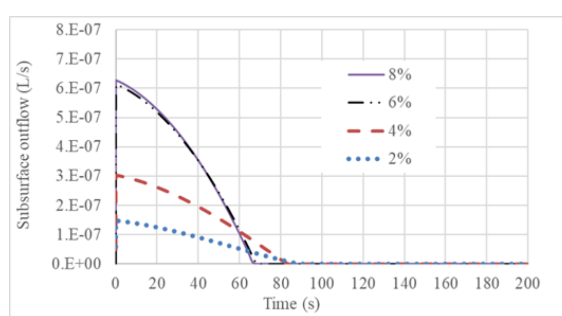

Fig. 5: Subsurface outflow of PFC with different slope values

Based on the results in Figure 5, it can be seen that different slope values provided different subsurface outflow results for the PFC pavement. As the slope increased, the subsurface outflow of the PFC pavement increased. This behavior is consistent with that of other studies conducted by Zhang et al. [8] and Ji et al. [22]. For instance, at the slope of 2%, the maximum outflow is about 1.5 x 10^{-7} (L/s). At the slope of 4%, the maximum outflow doubled to about 3 x 10^{-7} (L/s). The reason is that when the slope increased, the flow rate of PFC pavement increased; therefore, it resulted in a significant increase in subsurface outflow.

It is noticed that the results of subsurface outflow from PFC with slopes of 2%, 4%, and 6% are different from each other. Nevertheless, those from PFC pavement with slopes of 6% and 8% are quite similar. It indicated that at a great slope value such as 6% and 8%, the effect of slope on the subsurface outflow may be insignificant.

Effect of rainfall intensity on the subsurface outflow of permeable friction course pavement

In this study, to investigate the effect of rainfall intensity on the subsurface outflow of the PFC pavement, one having a slope of 6% was simulated with the different rainfall intensity values 90, 100, 110, and 120 mm/h. The results of subsurface outflow at various rainfall intensity values are shown in Figure 6 below.

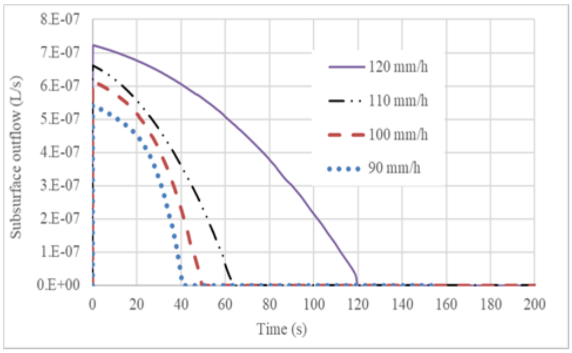

Fig. 6: Subsurface outflow of PFC with different rainfall intensity values

The results in Figure 6 show that as the rainfall intensity increased, the subsurface outflow of the PFC pavement steadily increased. A possible explanation is that at a higher rainfall intensity, water infiltrates into the pores in the PFC pavement body faster; therefore, water starts to drain out faster and results in an increase in the outflow. However, it is noted that at higher rainfall intensity, the PFC pavement becomes saturated earlier. Thus, a designer should consider an appropriate rainfall intensity to effectively use the PFC pavement in the field.

The outflow of PFC pavement with time of rain event showed that at a high rainfall intensity, the rate of reduction in subsurface outflow is low. For example, at a rainfall intensity of 90 mm/h, the outflow took only 40 seconds to go down from 5.5 x 10^{-7} L/s to about 0 L/s. At the rainfall intensity of 120 mm/h, the outflow took about 120 seconds to go down from 7 x 10^{-7} L/s to about 0 L/s. It is noted when the rainfall intensity increased, the reduction rate of subsurface outflow of PFC pavement decreased. This could be attributed to the saturation of the PFC pavement. At the higher rainfall intensity, the saturation of the PFC happened faster. Thus, subsurface outflow is reduced more slowly.

V. CONCLUSIONS

The PFC pavement is designed with high porosity so that water can infiltrate into its pores and drain out laterally through the side. This study observed the subsurface outflow of PFC pavement via the finite element program SV Flux 2D. A series of analyses were conducted for the PFC pavement with different slope and rainfall intensity values. Based on the results, the conclusions of the current study were drawn.

Different slope values provided different results for the subsurface outflow of PFC pavement. As the slope increased, the subsurface outflow of the PFC pavement increased. When the slope is 2%, the maximum outflow is about 1.5 x 10^{-7} (L/s). In addition, at the slope of 4%, the maximum outflow doubled to about 3 x 10^{-7} (L/s). In addition, this study also figured that the effect of slope on the subsurface outflow decreased when the slope increased. The reason is that when the slope increased, the flow rate of

PFC pavement increased; therefore, it resulted in a significant increase in subsurface outflow.

The outflow of PFC pavement with time of rain event showed that at high rainfall intensity, the rate of reduction in subsurface outflow is low. At a rainfall intensity of 90 mm/h, the outflow took only 40 seconds to go down from 5.5 x 10^{-7} L/s to about 0 L/s. However, at the rainfall intensity of 120 mm/h, the outflow took about 120 seconds to go down from 7 x 10^{-7} L/s to about 0 L/s. It is noted that at the higher rainfall intensity, the PFC pavement became saturated faster. Thus, designers should consider rainfall intensity to effectively use the PFC pavement in the field. In the future, further studies focusing on the drainage of PFC pavement including subsurface and surface flow should be carried out.

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