

AN EXPERIMENTAL AND MODELING STUDY OF PERVIOUS PAVEMENT BICYCLE LANES

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ABSTRACT. The installation of pervious pavements is an increasingly popular practice for reducing stormwater runoff in urban areas. Oftentimes, the lack of an appropriate model to design these systems prevents them from being used in areas where stormwater design codes must be satisfied. Specifically, this research presents a working model and design aid for the design of a pervious pavement bicycle lane to improve the current conditions of stormwater management along urban roadways.

It was determined that the slopes encountered along the vertical profile of a roadway would be a limiting criteria for the design of a porous pavement bicycle lane. A numerical model was first developed to solve the St. Venant equations for the flow of runoff above the surface of a porous pavement. The purpose of the surface flow model is to predict the distance that will be required for the runoff from the impervious roadway surface to fully infiltrate into the porous pavement surface. This result is important to ensure that the bicycle lane will have sufficient width to fully intercept the flow and prevent ponding on the road surface.

Experiments were conducted by constructing a full scale bicycle lane cross section inside a plywood tank. The first experiment was conducted to determine the storage capacity of the aggregate and pervious concrete layers and to verify the porosity of the aggregate base layer. Observations indicated minimal losses within the system. The storage capacity of the aggregate base layer was calibrated by simulating a constant rainfall intensity of 11.6 inches per hour. The calibration test of the experimental bicycle lane section yielded a porosity of 0.35, and confirms that a porosity of 0.36 obtained according to ASTM C 29 is representative of the base material and can be used to accurately estimate the storage capacity of the bicycle lane base course. Infiltration test were also performed according to ASTM C 1701 yielding an average infiltration rate of 1191.5 inches per hour.

A second series of experiments was conducted to determine the effects of slope on the required distance for complete infiltration. A sharp crested weir was utilized to spread a maximum flow 0.0267 cubic feet per second across the pavement surface pitched at angles of 0%, 5%, and 10% above the horizontal. This maximum flow rate

is equivalent to a rainfall intensity of 10.0 inches per hour falling on a single lane of roadway, ten feet wide, with a longitudinal slope of 5.0% and a cross slope of 1.0%. The resultant distances required to fully infiltrate the initial flow were then measured and compared with the results obtained through the numerical simulation. The length required for total infiltration ranged from 4.25 to 5.00 inches [0.1079 to 0.1270 meters].

INTRODUCTION

Bicycles have proven to be an efficient and reliable form of transportation in urban setting. However, very few cities in South Carolina or the United States have dedicated bicycle lanes included in their transportation infrastructure network. With as much as 60% of the world's population expected to live in urban settings by the year 2025; the addition of bicycle lanes into the transportation network could significantly impact the sustainability of our urban infrastructure (Sansalone et al. 2008). Furthermore, the use of pervious pavements as a low impact development (LID) technique would both reduce the quantity of stormwater runoff and improve the quality of stormwater entering the states many streams, lakes, and rivers as well as ocean and coastal resources. Many times the benefits of using pervious pavements are ignored and not taken into account when designing other systems such as storm sewers. Other factors including the lack of technical guidelines for installation and maintenance for permeable pavements have resulted in some failures of past installations (Eisenberg 2010). Practicing engineers need both a design aid and research supported methods for designing these improvements before they can be fully implemented throughout the state.

Background and Related Work

Current models for pervious pavement focus on vertical infiltration rates on near level sites and determine storage needs based on peak runoff requirements. This presents a significant problem for applications where pervious pavements are used along roadways where significant slopes can be encountered. Current research is inconclusive whether infiltration rates increase or decrease

as slope angle increases; therefore it will be necessary to determine the effects of slope on infiltration rates for pervious pavement surfaces (Chen and Young 2007) (Essig et al. 2009). An experimental study is being conducted to test the effects of slope on infiltration and flow through the pervious pavement system to better understand the considerations which need to be included in a design aid for pervious bicycle lanes. The pervious pavement, aggregate sub-base, and the existing sub-soil are all elements of the pervious pavement systems that must be considered to evaluate the benefit of using a pervious pavement system.

PROJECT OBJECTIVES

1. Determine the effects of slope on infiltration rates of pervious pavements.
2. Create a numerical model to use for the design of porous pavement bicycle lanes along impervious roadways.
3. Validate the numerical model for surface infiltration through experimental testing of a full scale bicycle lane model.

PROJECT DESCRIPTION

The long term goal of this project is to develop a design aid for use in designing porous pavement bicycle lanes. First, a numerical model must be created which accounts for the flow of stormwater runoff on the surface of a pervious pavement and through the porous media of the base material and the subgrade soil. Second, experiments must be performed to validate the numerical model within the appropriate parameter ranges.

Experimental Design

A model bicycle lane was constructed to test the flow of runoff through the various layers of the pervious matrix. The test rig consists of a plywood box constructed on a steel frame. The interior dimensions are 35.5 inches by 84 inches and a depth of 36 inches. The rig is filled from the bottom with 16 inches of Cecil soil, 8 inches of No. 57 stone base, and 6 inches of pervious concrete mixed with 89M stone.

Water is allowed to flow laterally out of the downstream end of the box. At the downstream end there are a pair of metal trays which collect water flowing from the pavement and aggregate layers respectively. The rig is equipped with three variable area flow meters to regulate the amount of water placed on the pavement surface. A soaker hose is used to simulate rainfall and a weir is used that creates sheet flow to simulate run-on. A panel of manometer tubes is situated along the length of the box



Figure 1: Image of the test rig showing the pavement, weir, manometers for measuring subsurface flow, and the collection trays at the downstream end.

perpendicular to the flow direction to measure the depth of water in the aggregate layer. See figure 1 for an image of the test rig.

Numerical Modeling

The results of these experiments are being used to guide the development, and verify the results, of a numerical model to simulate the use of a pervious pavement bicycle lane system for design purposes. Eventually, the numerical model will account for both the surface flow and sub-surface flow through the pervious matrix using mass conservation and conservation of momentum relationships.

The equations below represent the conservation of volume and the conservation of momentum simplified for a rectangular channel.

The first step in the combined flow model is to determine the steady state surface infiltration rate and the corresponding surface wave. Our goal is to determine the relationship between the pavement slope and the distance required for total infiltration of a constant runoff. The basic equations are conservation of volume

$$y \frac{du}{dx} = -f - u \frac{dy}{dx}$$

and conservation of momentum

$$\left(gy - u^2 \right) \frac{dy}{dx} = gy \left(s_0 - \frac{u^2 n^2}{y^{4/3}} \right) + 2uf$$

where the infiltration rate, f , is given by,

$$f = k \left(1 + \frac{y}{T} \right),$$

a function of the hydraulic conductivity, k , of the pavement, the depth of flow, y , and the thickness of the pavement, T . The remaining variables are distance, x , flow velocity, u , manning's coefficient, n , bed slope, s_0 , and gravitational acceleration, g .

It can be seen that the infiltration rate function, f , can be further simplified when the depth, y , is much smaller than the pavement thickness, T , yielding

$$f \approx k.$$

Hence the conservation of volume,

$$\frac{dq}{dx} = -f = -k \left(1 + \frac{y}{T} \right),$$

yields the distance, x , required for infiltration is given by,

$$x = \frac{q_0}{f} = \frac{q_0}{k},$$

where q_0 is the initial flow rate per unit width.

METHODS

Test Rig Calibration

Before conducting extensive experiments, the test rig must be calibrated to account for any leaks or other minor losses that will affect the correlation between experimental results and predicted outcomes. For the first series of experiments, the top of the soil layer was sealed with a sheet of plastic to simulate a zero soil infiltration condition. These experiments are used to calibrate the numerical model and to examine the storage capacity of the aggregate base layer. The test rig was calibrated by leveling the frame and sealing the open end of the rig. A constant rainfall rate was simulated using the soaker hose and the depth of water in the aggregate layer was recorded at constant time intervals as it was allowed to fill. A plot of depth against time will give a straight line of slope equal to the filling rate (u) which can be related imposed rainfall rate (i) and the layer porosity (ϕ) by

$$u = \frac{i}{\phi}.$$

Surface Flow Experiments

A series of tests were run in which a fixed volume flow rate of water was evenly released across the width of the pavement at the upstream end. The distance from the release point to the point where the flow had fully infiltrated was measured for pavement slopes equal to 0%, 5%, and 10%. Flow across the pervious pavement was non-uniform; therefore, the maximum and minimum flow lengths were recorded. The measured flow lengths were then plotted and compared with the lengths required for



Figure 2: Image of calibration testing. Red food coloring has been used to enhance the resolution of the water level inside manometer tubes. Photos were taken at 30 second intervals to determine the change in depth of water within the aggregate layer over time.

complete infiltration predicted by the surface flow model.

RESULTS

Calibration Test Results

Infiltration tests were performed according to ASTM C 1701 yielding maximum and minimum infiltration rates of 1575.8 and 989.0 inches per hour were obtained from the three test locations. These yield intrinsic permeabilities of 1.1×10^{-8} and 6.9×10^{-9} ft² [1.0×10^{-9} and 6.4×10^{-10} m²] with corresponding Reynolds numbers of 0.36 and 0.18 which indicates that the vertical flow occurs within the Darcy flow regime and thus the Forchheimer term can be ignored in our model (Nield and Bejan 2006). Consequently, the maximum and minimum hydraulic conductivity, K , values are 0.034 and 0.021 feet per second [0.0103 and 0.0064 meters per second]. The porosity, ϕ , of the aggregate layer was determined in accordance with ASTM C 29 and found to be 0.36. Results of the rainfall filling test with a rainfall intensity of 11.6 inches per hour produced an average porosity, ϕ , equal to 0.35.

Surface Flow Test Results

The experimental results obtained from the surface flow test were compared with the predicted values obtained using the numerical model. Results are reported for initial flow rates ranging from 4 to 12 gallons per minute and pavement slopes of 0%, 5%, and 10%. The experimental data is plotted in figure 3 as a bar extending from the minimum to maximum flow distance with a circle

CONCLUSION

A comparison of the numerical model and the results of the surface run-on test indicate that St. Venant equations can be used to reasonably predict the maximum distance required for complete infiltration of runoff. However, it should also be noted that the solution can be further simplified when the depth of flow is much smaller than the thickness of the pavement. For this case, the distance is equal to the ratio of the flow rate per unit width and the hydraulic conductivity. The numerical surface flow model has been shown to accurately predict the maximum infiltration distance within the range of experimental values when computed using the minimum hydraulic conductivity obtained from the results of the in-place infiltration test ASTM C 1701. Further modeling and experimental verification is required to determine if ponding would occur on a bicycle lane surface as the runoff flow rate increases, due to the addition of impervious surface or increased rainfall, or the hydraulic conductivity decreases, due to surface clogging or other factors.

FUTURE WORK

Further experiments will be conducted to examine the subsurface flow in the aggregate with varying subsoil types and infiltration rates. The goal is to examine three representative soil types from the state of South Carolina to determine if porous pavement bicycle lanes could be incorporated as a viable low impact development technique throughout the state. A cost analysis will also be performed to determine if the use of porous pavement bicycle lanes will be economically feasible.

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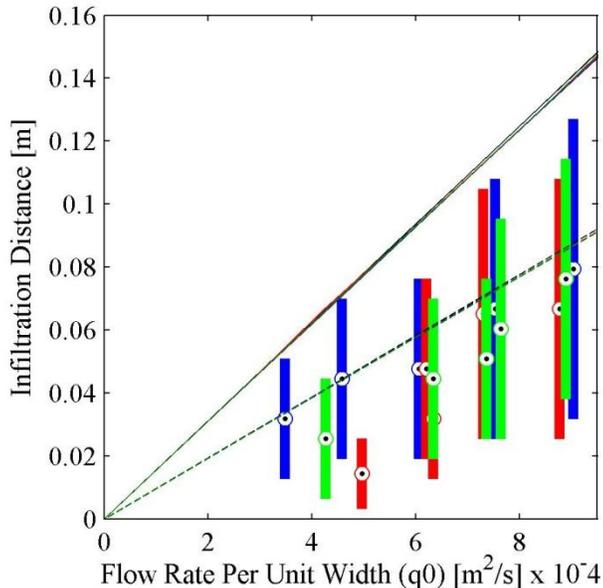


Figure 3: Plot of measured infiltration distance versus flow rate for pavement slopes of 0% (blue), 5% (red), and 10% (green). The solid line represents model results for hydraulic conductivity, K, equal to 0.0064 m/s, and the dashed line represents K equal to 0.0103 m/s.

representing the average. Also in figure 3, results of the numerical model are shown where the solid line model predictions represent the lower limit of hydraulic conductivity while the dashed lines represent the upper limit of hydraulic conductivity.

DISCUSSION

The results of the numerical model for the surface flow test indicate that the distance required for infiltration of surface runoff, sheet flow, allowed to flow across a pervious pavement surface increases flow rate. The length of flow varies on average +/- 1 cm from 0% to 10% slope for each respective flow rate with the maximum length of flow occurring at 0% slope; however, there is no clear pattern that flow length decreases with slope. Instead, infiltration appears to be more effected by the distribution of pore spaces in the pervious concrete surface. Also, all experimental observations lie beneath the model output for the minimum hydraulic conductivity. Therefore, it is reasonable to conclude that the minimum hydraulic conductivity can be used to estimate the maximum distance required for complete infiltration. Finally, the experimental results yield a maximum run-on distance of approximately 13 cm for runoff from one 10 foot lane width.

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