Drainage Hydraulics of Porous Pavement Overlays

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ABSTRACT

Permeable friction course is an innovative technology for highway pavements that allows rainfall to drain within the pavement rather than across it. Unlike other porous pavements, permeable friction course (PFC) is overlain on a base of regular impervious pavement. When it rains, water infiltrates the porous layer and seeps to the side of the road by gravity. By removing water from the road surface, PFC improves safety by decreasing splashing and hydroplaning. Under high rainfall intensities, the capacity of the pavement is exceeded and drainage occurs both within and on top of the pavement. A Permeable Friction Course Drainage Code (PerfCode) has been developed to capture the hydraulics of this coupled, unsteady flow process. This presentation summarizes the model’s development, shows that model results compare favorably to field measurements, and gives a case study in which PFC reduces the duration of sheet flow conditions by 80% compared to conventional pavement.

INTRODUCTION

New roadway materials are changing the wet weather driving experience. One exciting and innovative material is a porous pavement that allows water to drain through the roadway rather than across it. The pavement—called permeable friction course (PFC)—is placed in a 50mm layer on top of conventional, impermeable, pavement. During rain events, water seeps into the porous layer and flows to the side of the road by gravity. By removing water from the road surface, PFC improves safety by reducing splashing and hydroplaning (Berbee et al., 1999). In addition to safety benefits, PFC has also been shown to reduce pollutants commonly observed in highway runoff (Barrett, 2008).

Although usually placed in a 50mm layer, the PFC thickness may be selected so that all of the rainfall for a design event drains within the pavement. Structural and cost concerns prevent the use of an arbitrarily thick porous layer. Additionally, PFC has been shown to clog over time, resulting in lower subsurface drainage capacity (NCHRP, 2009). Therefore, some storms will exceed the installed capacity, forcing drainage to occur both on the pavement surface and within the porous matrix. This paper describes a model for this coupled unsteady drainage process.

A precise description of PFC's response to rainfall events is needed for several reasons including driver safety, water quality, and scientific interest. From a safety perspective, flow over traffic lanes can cause vehicles to hydroplane. Hydroplaning is especially hazardous when right and left tires encounter different water depths—the difference in resistance imposes a torque on the vehicle, potentially causing the driver to lose control. A detailed runoff model for PFC could identify areas of excessive sheet flow depth so that additional drainage can be provided. Such a model also has implications for water quality. Field studies of runoff from PFC have shown that runoff concentrations of pollutants are lower for PFC than conventional pavement, but the mechanisms responsible for lower concentrations have not been identified (Barrett, 2008). Possible mechanisms include reduced wash-off from vehicles, filtration and absorption within the pavement, and even biological activity. Studying these mechanisms in detail requires an accurate hydraulic model. Finally, the proposed model is of general scientific interest because the problem of flow over porous media appears in numerous applications. Civil engineering applications include surface irrigation, watershed modeling, and sediment transport. A better technical understanding of flow in PFC will contribute to a diverse scientific field and promote wider use of the material, thereby improving driver safety and the environment.

Figure 1 shows a photograph of a PFC layer. The PFC overlay is very thin compared to the length and width of the roadway section. A cross section of typical PFC roadway is shown in Figure 2 and a more detailed schematic of the PFC layer is shown in Figure 3.

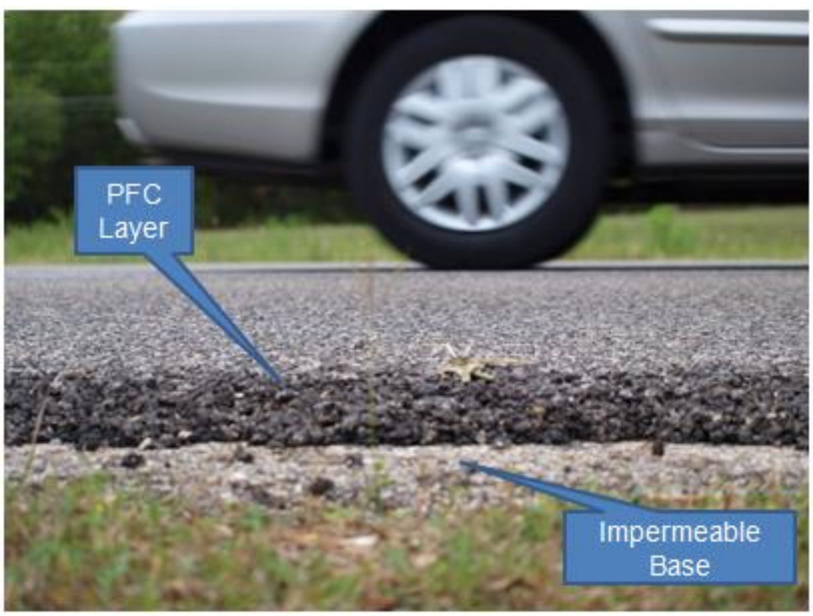

Figure 1. Photograph of PFC layer on Loop 360, Austin, Texas

MODEL DEVELOPMENT

The processes that are represented in this model are precipitation, saturated porous media flow, and overland flow. Infiltration and partially saturated porous media flow are neglected because the hydraulic conductivity of the porous layer is much greater than the rainfall rate. Precipitation is assumed to be a known function of time.

Figure 2 is a sketch of the dimensional variables used to represent physical quantities. The rainfall rate $r(t)$ is assumed to be spatially uniform, but variable in time. The elevation of the bottom of the PFC layer with respect to a datum is $z(x, y)$. The PFC layer has a thickness b, which is taken as constant throughout the domain. The saturated thickness of water in the PFC layer is $h_p(x, y)$ where the subscript refers to the pavement. The specific discharge through the PFC is $\vec{q}$. On the pavement surface, the thickness of sheet flow is $h_s(x, y)$ and the average velocity is $\vec{v}$. The total head of water at any point in the domain is $H(x, y)$.

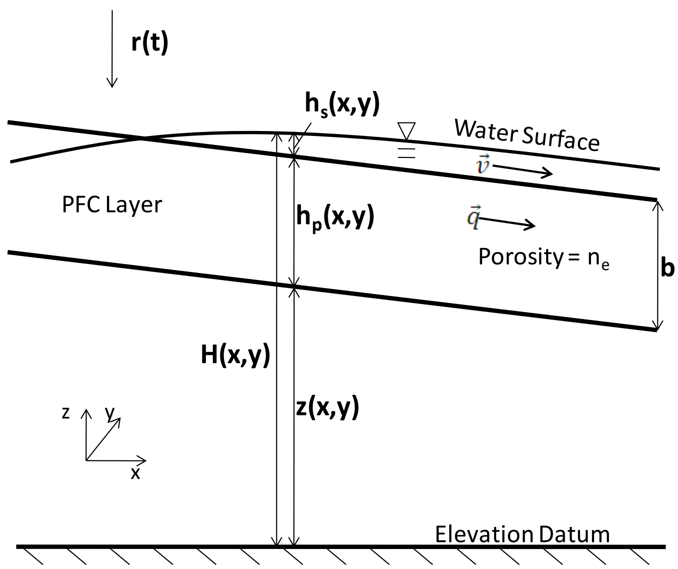

Figure 2. Schematic cross section of permeable friction course roadway

Flow within the PFC layer is treated as an unconfined aquifer of variable saturated thickness using Darcy's law and the Dupuit-Forchheimer assumptions. The governing equation for unsteady flow is then the Boussineq equation (Halek and Svec, 1979) and the porous medium is characterized by the effective porosity n_e and the saturated hydraulic conductivity K.

Sheet flow on the PFC surface is modeled using the diffusion wave approximation to the Saint-Venant equations, which is appropriate for urban slopes (Daluz-Vieira, 1983). A vectorized form of Manning's equation is used to characterize the surface roughness both chosen because of its simplicity and because it gives good agreement with experimental measurements (see also Charbeneau et al., 2009).

Figure 3 shows the governing equation for flow both within and on top of a PFC layer. When the saturated thickness (h_p) is less than the thickness of the PFC layer, the porosity term is active, h_s equals zero and the Boussinesq equation results. When the saturated thickness is equal to or greater than the thickness of the PFC layer, the porosity term is inactive, h_p equals the layer thickness, and the surface flow term is active. Both the Boussinesq equation and diffusion wave model are non-linear so solving the governing equation is a challenge.

Porous media flow by Boussinesq equation

Sheet flow by diffusion wave model

$$\{n_e\}\frac{\partial H}{\partial t} = \nabla \cdot \left(K h_p \nabla H\right) + \nabla \cdot \left(\frac{h_s^{5/3}}{n\sqrt{S_f}} \nabla H\right) + r$$

Porosity applies only when flow is contained in the pavement ($h_p \le b$)

Hydraulic conductivity

Manning's n

Friction slope

Rainfall

Figure 3. Annotated governing equation for surface/subsurface flow in PFC

Boundary conditions of both Dirichlet and Neumann types were formulated for the governing equation. Neumann conditions were applied at no-flow boundaries. Outflow boundaries were handled as Dirichlet boundaries using a new method of characteristics formulation based on kinematic flow. The finite volume method was used to develop a numerical model of the governing equation. The Crank-Nicolson method is used to solve final system equations. Within each timestep the system is linearized using Picard iteration. Within each iteration the penta-diagonal linear system is solved using the Gauss-Seidel method. The Permeable Friction Course Drainage Code (PerfCode), written in the Fortran 90 language, was developed to perform these calculations. The interested reader should consult Eck (2010) for additional details regarding the model development and implementation.

MODEL VALIDATION

The model formulation was validated by demonstrating that results from PerfCode agree with steady state solutions obtained analytically. The section selected for testing is 10m wide and 20m long with a 3% cross slope and 0% longitudinal slope. Other parameters were hydraulic conductivity (1cm/s), porosity (0.2), and rainfall rate (1cm/hr). Simulations for three conditions were performed by varying the PFC thickness: (1) PFC flow only, (2) sheet flow only, and (3) combined PFC and sheet flow. Because the objective of these simulations was a comparison with analytical solutions, the domain and boundary conditions were chosen to make the flow one-dimensional. For each simulation the discharge from the outflow boundary was tracked through time. Results presented here include runoff hydrographs from all three cases (Figure 4).

Outflow hydrographs are plotted on a logarithmic scale on account of the wide range of times required to reach steady state. Several points of interest are noted on the hydrographs.

- The presence of a PFC layer delays the initial discharge from the roadway, in this case by about 1 minute from when rainfall begins.
- PFC delays the peak flow by nearly 10,000 seconds—much longer than most actual storms.
- For the combined case, the transition to sheet flow is evidenced as a sharp increase in the slope of the hydrograph.
- For the PFC flow only, the break in slope around 8000s corresponds to the time when the outflow boundary reaches the maximum depth allowed by the kinematic condition.

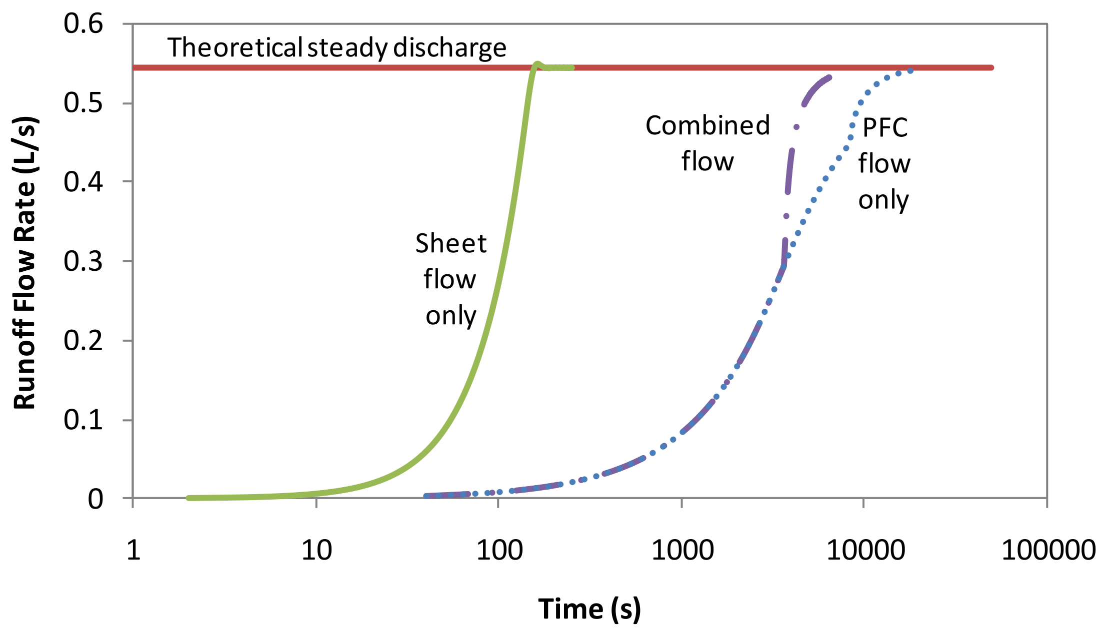

Figure 4: Runoff hydrographs from a linear section

Collectively, the validation results show that the results predicted by PerfCode are consistent with the steady state equations and that the model has good mass balance properties.

COMPARISON WITH FIELD DATA

This section compares model results with field data from a monitoring site constructed on Loop 360 near Austin, Texas. In the autumn of 2006 equipment for automatic sample collection and hydrograph measurement was installed. A drainage system was constructed using 10cm PVC pipe to collect runoff from an 18m length of roadway and direct it to the sampler. A 15cm H-flume was used to measure the flow rate from the drainage pipe. An ISCO 4230 bubbler flow meter measured the water depth in the H-flume and calculated the flow rate. An ISCO 674 tipping bucket rain gage recorded rainfall. Both rainfall and runoff were recorded in five-minute intervals, rainfall as the total depth and runoff as the average flow rate. The model application uses the measured rainfall as a model input and computes the runoff hydrograph for comparison with the measured one.

Figure 5. Photograph of H-flume and drainage pipe at Loop 360 monitoring site

At the location of the monitoring site, Loop 360 is a four-lane divided highway. The monitoring site is situated on the right-hand shoulder of the south-bound traffic lanes. The traffic lanes (7.3m) and right hand shoulder (3m) slope to the driver's right-hand side at cross-slopes of 2% and 4%, respectively. The left shoulder (1.8m) drains to the left at a cross-slope of 4%. The entire section has a longitudinal slope of 2.3%. This geometric information was used to develop input files for the model.

The hydraulic conductivity and porosity for this roadway were measured by Klenzendorf (2010). Values of Manning's n have not been measured for PFC, but a value of 0.015 appears appropriate considering the analysis of Charbeneau et al. (2009).

During the storm of June 3, 2007 the monitoring site received 36mm of rainfall over a 4 hour period. The peak rainfall depths on a five, fifteen and sixty minute intervals were 6.1mm, 6.6mm, and 13.5mm, respectively. About 90% of the rainfall was measured as runoff, a reasonable mass balance for field sampling.

A model time step of 5s was used when the all of the drainage was contained within the pavement, but a step of 0.1s was needed during sheet flow for the model to remain stable. In order to make a fair comparison with the field measurements, the calculated flow rates were averaged over five minute intervals. A weighted average flow rate was used so that a five-minute interval containing two sizes of time step had the proper flow rate. These averaged flow rates showed generally good agreement with the field measurements (Figure 6). The model predicted peak flows of the proper time and magnitude, and the shape of the hydrograph generally matches the field observations.

The model predicted a peak flow of 2.6 L/s, which is 76% of the measured value of 3.4 L/s. The difference between the modeled and measured flow rates (residual) had a mean 0.016L/s, median 0.035 L/s, standard deviation 0.16 L/s and standard error of the mean 0.02 L/s. The largest residuals were associated with high flow rates. This comparison suggests that the model parameters were consistent with field conditions and lends credibility to the associated depth predictions.

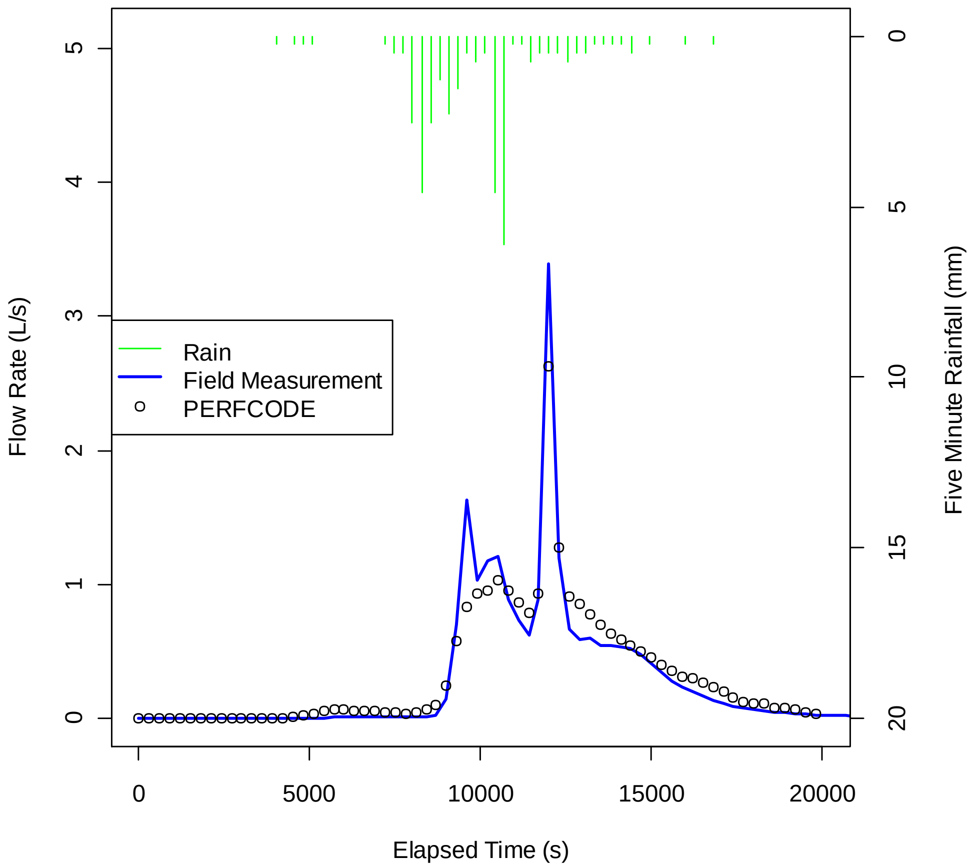

Figure 6. Comparison of modeled and measured hydrographs for June 3, 2007

During this simulation, maximum depth was 5.13cm above the impervious layer, which represents a sheet flow depth of 1.3mm. This maximum occurred near the edge of the right traffic lane (Figure 7). This peak occurred 3 hours and16 minutes after the start of the simulation (11791.9s) and during the peak rainfall intensity of 73 mm/hr.

The simulation results show that sheet flow begins 2.2m from the grade break for the left hand shoulder (Figure 7). Under most conditions, this break in slope acts as a no-flow boundary within the domain; the no flow condition is assumed here for purposes of comparison with the analytical model even though some flow does occur. At the peak rainfall rate for this storm, the analytical model (see Charbeneau and Barrett, 2008) predicts sheet flow at 3.4m from the break for the left shoulder and a maximum sheet flow depth of 1.3mm. This seems a reasonable match, considering that the numerical model is not at steady state, and that boundary condition is approximate.

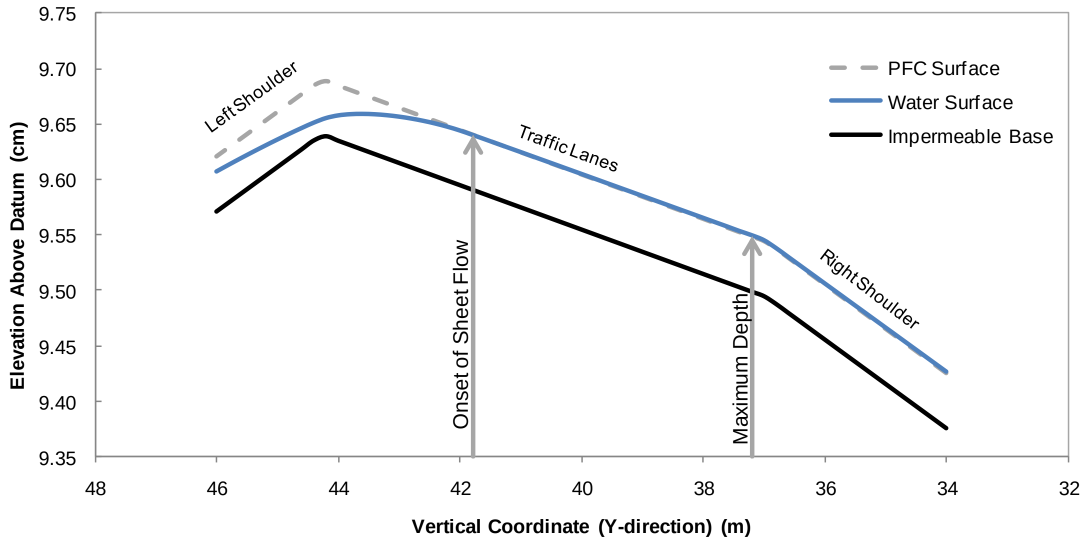

Figure 7. Drainage profile through maximum depth section

One opportunity afforded by PerfCode is to compare results with and without PFC for the same storm event. Such an analysis gives direct insight about how PFC changes the drainage hydraulics as compared to conventional pavement. The same roadway geometry and simulation parameters used for the comparison with field measurements were used in this simulation, except that the thickness of the PFC layer was set to zero so that all drainage occurred as sheet flow.

The simulated hydrograph for Loop 360 without PFC is shown in Figure 8 along with the simulated hydrograph corresponding with a 5cm PFC layer. Both hydrographs have been time averaged over the reporting period for rainfall measurements (5 minutes). Without the PFC layer, rainfall appears as runoff faster especially early in the storm (9,000s) when flow would be contained within the PFC.

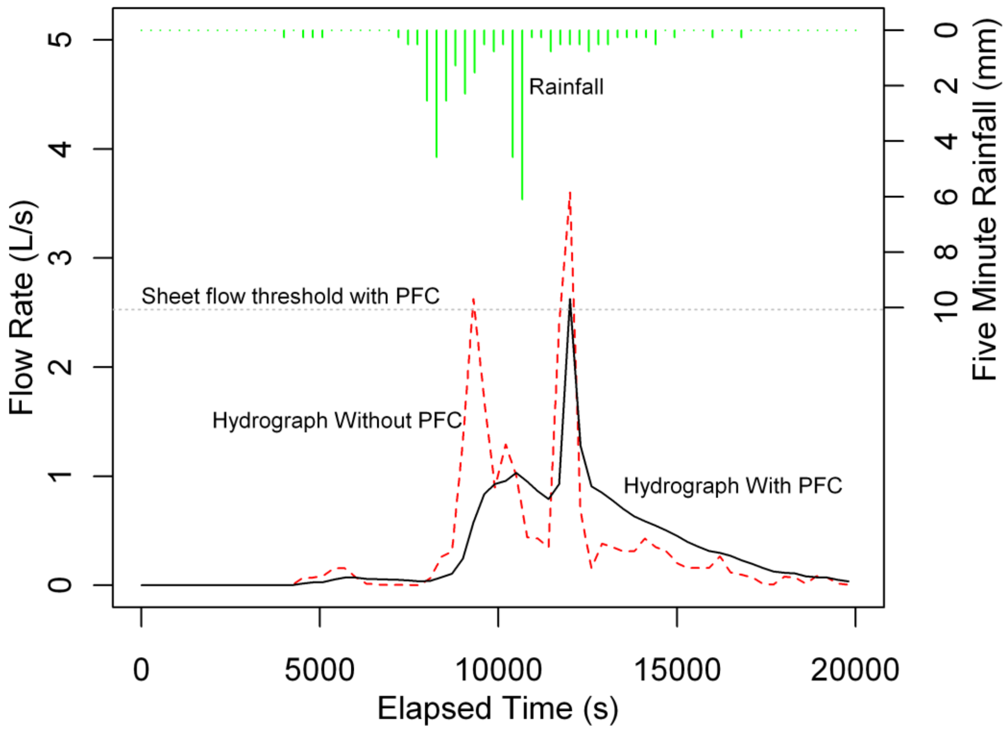

Figure 8. Simulated hydrographs for Loop 360 monitoring site with and without 50mm layer of PFC.

A PFC layer might be expected to delay the runoff hydrograph due to storage within the pavement, but that effect is not observed in this case. The high rainfall intensity overwhelmed the capacity of the PFC layer, causing the peak flow to occur at the same time in both cases.

The presence of a PFC layer reduced the sheet flow thickness during this event. For areas of the road that experienced sheet flow in both cases, the depth of sheet flow was reduced by an average of 0.42mm. In addition to reducing the depth of sheet flow on the highway, PFC also reduced the duration that sheet flow was present. The horizontal line on Figure 8 indicates that sheet flow occurred for only one reporting period (300 seconds) when the PFC layer was present. Without the PFC layer, sheet flow depths in excess of 0.1mm were present for 11,400 seconds.

CONCLUSIONS

The development, validation and application of PerfCode has provided insight into the drainage behavior of PFC highways.

Predictions of runoff hydrographs for PFC roadways are available for the first time. These hydrographs show that PFC delays the initial discharge from the roadway compared to conventional pavement and that flow in a PFC layer requires a long time to reach steady state. For a constant rainfall case, PFC delayed the initial discharge by 60 seconds and required 50 times more rainfall to reach steady state, though these values depend on problem parameters.

One dimensional steady state equations remain a powerful tool for engineering design. For the particular storm investigated here, the 1D steady state equations and PerfCode differed by 1.2m with respect to the location that sheet flow begins. However, the location and magnitude of the maximum sheet flow depth were closely predicted by the 1D steady state equations. The steady state equations (Charbeneau and Barrett, 2008) are suitable for aiding design of PFC thickness on straight roads, but cannot address roadways with spatially variable configuration nor the dynamic response of roadway drainage.

PerfCode is applicable to a variety of practical problems related to PFC highways. Applications include analysis of more complex roadway geometry such as sag vertical curves and superelevation transitions. Future work will examine these areas and the effect of curb and gutter edge treatments on the drainage performance of PFC roadways.

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