# Quantifying the behavior of porous asphalt overlays with respect to drainage hydraulics and runoff water quality

J. Brandon Klenzendorf

Bradley J. Eck

Randall J. Charbeneau

Michael E. Barrett

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## *Abstract*

Porous pavements are gaining popularity in urban settings on highways for water quality benefits, noise reduction, and reduced splash and spray in wet weather. Over time, porous pavements can become clogged with sediment resulting in a decrease in porosity and hydraulic conductivity and loss of drainage benefits. This paper provides an overview of water quality benefits and methodology for measuring hydraulic conductivity specifically for permeable friction course (PFC). PFC is a layer of porous asphalt ranging from 2.5 to 5.0 cm thick placed as an overlay on conventional impervious roadways. Research studies show a reduction in total suspended solids and total metals in runoff from PFC surfaces when compared to runoff from conventional pavements. Monitoring results were mixed for nutrient removal from PFC. Porosity and hydraulic conductivity data collected over multiple years from different roadways in Austin, Texas, are presented. Porosity values of PFC specimens range from 0.12 to 0.23. The non-linear flow relationship observed during hydraulic testing requires analysis of the Forchheimer equation as opposed to the typical Darcy's law. Hydraulic conductivity values range from 0.02 to 3.0 cm/s with significant variability. Furthermore, hydraulic modeling of PFC is useful for design purposes and determines when the layer becomes saturated and surface runoff is expected. Flow through PFC is modeled as an unconfined aquifer with an underlying sloping impervious boundary. The use of porous pavements in an urban environment not only improves driving conditions but also helps reduce the adverse impacts of urbanization on surface water and groundwater quality.

## ***Introduction***

Land development and urbanization commonly result in the replacement of natural land cover with impervious surfaces such as roadways, parking lots, sidewalks, and buildings. Increased impervious areas can impede rainfall from naturally infiltrating into the ground; result in a decrease of evapotransporation; and potentially decrease recharge to groundwater supplies. In addition, urbanization impacts surface water hydrologic processes (i.e., increasing peak flow rates and flow velocities) resulting in an increased potential for stream erosion and flooding. Pollutants associated with urbanization, such as oil and grease from vehicles, nutrients from fertilizers, floatable debris, etc. are washed off of impervious surfaces and enter the surrounding waterways degrading both surface water and groundwater quality (WEF/ASCE, 1998). A variety of stormwater control measures (SCMs) or best management practices (BMPs) can be used to alleviate the negative impacts of urbanization. These practices typically include detention or retention ponds, constructed wetlands, and sand filters (Middleton and Barrett, 2008; Carleton et al., 2000; Urbonas, 1999). Traditional SCMs are designed to retain stormwater runoff and release the water slowly after the storm event has passed. This helps to decrease the peak flow rates and improves water quality through the settling and/or filtering of particles. More recently, various low impact development (LID) practices have gained popularity and interest in order to mitigate the adverse impacts of urbanization. LID methods include the use of green roofs, bioretention, rain gardens, rainwater harvesting, and porous pavement systems (Gregoire and Clausen, 2011; Trowsdale and Simcock, 2011; Davis and McCuen, 2005; Ferguson, 2005; Mendez et al., 2011). LID technologies are generally designed to mimic the natural infiltration of the area to improve water quality and help recharge groundwater resources.

In Texas, the Edwards Aquifer has been identified as a valuable natural resource and specific protections have been enacted to preserve both the quantity and quality of recharge entering the aquifer. In particular, regulations require that new development remove 80 percent of the increase in the load of total suspended solids (TSS) from runoff. A range of management practices including sand filters, vegetated filter strips, and extended detention basins are used to meet the load reduction requirement. Separate from the need to protect the Edwards Aquifer, the Texas Department of Transportation (TxDOT) re-surfaced an existing road over the Edwards Aquifer recharge zone with permeable friction course (PFC) for the noise, traction, and visibility benefits described below. The re-surfaced area included a monitoring site for an ongoing study regarding the performance of vegetated filter strips. After installation of PFC, monitoring results from the same site showed much lower concentrations of many constituents in highway runoff (Barrett et al., 2006).

This paper addresses the quality of runoff and hydraulic properties of the surface course porous pavement referred to as PFC. PFC is a thin layer of porous asphalt placed on top of conventional impervious pavement (Figure 1). Due to the underlying impervious pavement, PFC does not facilitate direct infiltration under the roadway. Measurements of the quality of PFC runoff have been made at several locations in the United States and Europe. This paper synthesizes these results from a variety of locales and climates and provides a summary of expected effluent concentrations of pollutants from PFC. Hydraulic properties of PFC were evaluated at three locations near Austin, Texas. Both porosity and hydraulic conductivity measurements of PFC in the lab and in the field are described. Finally, a description of the drainage behavior is provided through the use of a transient numerical model. Each of these topics is briefly discussed to provide an overview of PFC with additional references provided for more in depth details.

## ***Literature Review***

Porous surface course, such as PFC, consists of a porous asphalt layer ranging from 2.5 to 5.0 cm thick with an effective porosity of roughly 0.20 placed as an overlay on a conventional roadway surface. The void space in the porous asphalt studied in this paper is created by removing the fine aggregate from traditional asphalt mixes and increasing the volume of asphalt binder. The asphalt gradation consists primarily of aggregate sizes greater than 0.5 cm (TxDOT, 2004; TRB, 2009). During a rainfall event, water enters the pore space of the surface course and is removed from the roadway surface. Water then flows laterally along the underlying impervious layer to the roadway shoulder where it resurfaces and flows into a drainage swale running parallel to the road. Porous surface courses are typically used on high traffic roads such as highways.

Decreased surface runoff (i.e., sheet flow on the roadway surface) due to the installation of PFC provides numerous advantages related to improved driving conditions and water quality benefits. Driver safety benefits are a result of better traction and skid resistance, decreased hydroplaning, a reduction of splash and spray from vehicles, increased visibility, and decreased light reflection from water on the road surface (TRB, 2009). Porous surface course has also been shown to reduce noise (Bendtsen and Andersen, 2005) and improve the water quality of runoff by capturing pollutants in the pore space and reducing the amount of pollutants washed off of vehicles (Stotz and Krauth, 1994; Berbee et al., 1999; Pagotto et al., 2000; Barrett et al., 2006; Eck et al., 2011; Winston et al., 2011). PFC is therefore an innovative approach to treating highway runoff because the road surface acts as the treatment device. Using PFC as a water quality measure requires no additional construction materials and no additional right-of-way adjacent to the road. However, PFC is generally considered a sacrificial overlay that is expected to degrade and be replaced at a greater frequency than conventional pavement. PFC typically has a design life of roughly 10 years (TRB, 2009).

One potential shortcoming of porous surface courses is that the pore space can become clogged with sediment over time. Trapped sediment can reduce the drainage potential of PFC (Fwa et al., 1999) that may result in a reduction of the driver safety and water quality benefits. Water quality monitoring can be used to assess whether these benefits persist. However, as an alternative to continuous water quality monitoring, the measurement of hydraulic conductivity can be used as an indicator for when water quality benefits are anticipated to degrade as the PFC becomes clogged. Previous studies have been conducted on methods to measure the hydraulic conductivity of PFC. Tan et al. (1997) describe a falling head test used to measure the one-dimensional hydraulic conductivity of PFC experiencing non-linear flow. Tan et al. (1999) update this methodology to account for three-dimensional flow using a field test. Charbeneau et al. (2011) describe an approximate analytic solution for two-dimensional radial flow. This solution is used to determine the hydraulic conductivity under non-linear flow for constant head tests conducted on PFC core specimens in the laboratory and a falling head test used in the field. Improvements on the Charbeneau et al. (2011) methodology that fully account for non-linear effects through numerical modeling are described below. Charbeneau and Barrett (2008) describe analytical solutions to determine the steady state water depths within PFC for a constant rainfall rate. This model is useful for design purposes in order to determine the required thickness of the PFC layer and has been improved upon using a transient numerical model described below.

A number of studies examine the quality of runoff from roads paved with PFC. Initial measurements were made in Europe by Stotz and Krauth (1994), followed by Berbee et al. (1999) and Pagotto et al. (2000). The first known measurements for PFC runoff in the United States were from Texas (Barrett et al., 2006). Owing to its importance in the Edwards Aquifer region of Texas, the quality of runoff from PFC has received continued attention with results published by Barrett and Shaw (2007), Barrett (2008), and Eck et al. (2011). The Texas Commission on Environmental Quality (TCEQ) governs development and permanent water quality SCMs within the Edwards Aquifer region to prevent groundwater contamination. Based on monitoring studies from Texas, PFC has been approved by TCEQ as a SCM for highways within the Edwards Aquifer recharge zone (TCEQ, 2011). Outside of Texas, water quality levels produced by PFC can be categorized as excellent in the environmentally sensitive Potomac River Basin (Davis and McCuen, 2005). This allows the roadway itself to serve as a water quality treatment system and reduces the need for additional structural SCMs which can be costly and result in additional land procurement.

## ***Water Quality***

The quality of water appearing as runoff from PFC has been measured by the authors near Austin, Texas, and by others in North Carolina, Massachusetts, France, Germany, and the Netherlands (Barrett, 2008; Eck et al., 2011, Stotz and Krauth, 1994; Berbee et al., 1999; Pagotto et al., 2000; Smith and Granato, 2010; Winston et al., 2011). The aim of the present discussion is a new synthesis of water quality results to present the general trends observed from runoff and effluent concentrations from PFC at varying locations and climates.

Table 1 summarizes monitoring results for highways paved with PFC at 13 locations in the United States and Europe. Monitoring campaigns were staged between 1990 and 2009, ranged in length from seven months to five years, and reported different water quality parameters. The present summary focuses on the broad contaminant classes of solids and sediments, nutrients, and metals. Constituent concentrations are tabulated as the median of observed effluent mean concentrations (EMCs) with the exception of two sites (one in Germany and one in France) for which only weighted average concentrations were available. The number of sampled storm events at each site ranged from five to 48, for a total of 215 events across 12 sites; the number of sampled events was not reported for the thirteenth location (in Germany). Average traffic counts ranged from 12,000 to 191,000 vehicles per day. The non-parametric Spearman's rho rank correlation coefficient and its associated p-value were computed to test for a relationship between traffic loading and pollution levels. Spearman's rho was used to test for correlation because it accounts for the magnitude of differences between points as well as the sign (Helsel and Hirsch, 2002).

Concentrations of suspended sediments and solids were most commonly reported as TSS (at nine sites), but also reported as suspended sediment concentration (SSC, at three sites) and filterable solids (FS, at one site). TSS values were available from Texas, North Carolina, the Netherlands, and France, and were of the same order of magnitude; observed TSS median concentrations from PFC ranged from 6.3 to 17 mg/L. For monitoring sites in Massachusetts, SSC was reported instead of TSS. Observed SSC median concentrations ranged from 52 to 710 mg/L. Values of SSC and TSS are not directly comparable. The resulting p-value from the Spearman's rho test indicates that concentrations of TSS or SSC were not statistically correlated to traffic volumes at a significance level of 0.05. This result suggests that relatively low sediment levels are expected regardless of traffic volume.

Summarized parameters for nutrients included total Kjeldahl nitrogen (TKN), nitrate, and total phosphorous (total P). Correlations between traffic volume and nitrogen levels were not performed because nitrogen data grouped by location, making it impossible to isolate the effect of traffic volume from atmospheric deposition. The highest levels of total P occurred in Massachusetts (typically greater than 0.1 mg/L) and the lowest levels were found in Texas (approximately 0.04 mg/L). Levels of total P were not statistically correlated to traffic volumes (p-value = 0.70).

Metals concentrations showed considerable variation between sites, with the lowest levels observed in Texas and the highest levels found in Massachusetts and Germany. Concentrations of total copper (total Cu) were on the order of 10 μg/L in Texas, and ranged from 20 to 70 μg/L in Europe. Two of the Massachusetts sites fell within the European range, and one site had much greater median concentrations of total Cu at 180 μg/L. Concentrations of total zinc (total Zn) were approximately 20 μg/L in Texas, but were greater than 47 μg/L for all other locations. All three Texas sites had median concentrations of total lead (total Pb) below the 1.0 μg/L detection limit. Similar to the sediment concentrations, concentrations of total metals were not statistically correlated to traffic volumes using Spearman's rho (p-values > 0.34) (Helsel and Hirsch, 2002).

Overall, the most polluted location as estimated by the reported parameters was Interstate 93 in Massachusetts, which saw high median concentrations for each class of contaminant and also had high traffic loadings. It should be noted that the pavement at the Interstate 93 location was 13 years old, past the recommended useful life for such pavements (TRB, 2009). As a porous layer ages, the pore space is expected to clog with trapped sediment and thus behave more like conventional pavement.

Six of the PFC monitoring sites were paired with monitoring sites for conventional pavement, enabling a direct comparison of the runoff quality between pavement types for the same rainfall event and traffic conditions. These results are summarized as the relative percent difference in median or weighted average concentrations for selected water quality parameters (Table 2). The test used to evaluate the statistical significance of each difference is also noted in the table. The parametric Students t-test, non-parametric Mann-Whitney test, and non-parametric Wilcoxon signed rank test are used to determine statistical significance between the means or medians of the paired data (Helsel and Hirsch, 2002). At five of the six paired locations, levels of TSS and total metals were significantly lower in runoff from PFC compared to conventional pavement at a significance level of 0.05. Furthermore, the relative differences for TSS are consistent with removal rates expected from practices such as sand filters or bioretention systems (Barrett, 2003; Hunt et al., 2008; Hsieh and Davis, 2005).

Results of removal rates for nutrients at the paired sites were mixed. Levels of total P were significantly lower at all three Texas sites but were not reported for the French or Dutch studies. For nitrogen species, the French study found substantial differences between the pavements, but the Texas sites did not.

Concentrations of total metals from PFC were generally significantly reduced when compared to conventional pavement. The site in Massachusetts did not show a decrease in total metals, but all other sites showed a statistical decrease in total metals at a significance level of 0.05.

The monitoring results from the three sites in Massachusetts stand out from other results in the literature both because of high observed concentrations and because differences in concentration were not observed at the paired monitoring site. These differences may be attributable to the practice of applying sand to improve conditions in the winter as is the usual practice in Massachusetts (Smith and Granato, 2010). Applying sand would be expected to clog the PFC layer and reduce the water quality benefits. Furthermore, the PFC in Massachusetts is past the end of its design life. Therefore, hydraulic conductivity tests are recommended to assess whether the PFC layer is draining properly.

## ***Analysis of Hydraulic Properties***

Measurement of the hydraulic properties of PFC is necessary to assess the drainage capacity of the pavement and the extent of clogging over the pavement design life. The properties investigated in this research were effective porosity and saturated hydraulic conductivity. Both properties are measured on core specimens in the laboratory, and a new field test was developed to measure in-situ hydraulic conductivity. Multiple core specimens were extracted from three roadways around Austin, Texas for four consecutive years (2007 to 2010). Core specimens were obtained by saw cutting the pavement surface using a drilling press attached to a truck and operated by an independent subcontractor. The recovered core consists of the PFC layer together with the underlying impervious asphalt layer. Water is applied to the saw blades in order to reduce any increases in temperature due to cutting friction and minimize potential temperature effects on the asphalt binder material. Core specimens were extracted with a 15.1 cm diameter (in 2007 and 2010) and a 21.8 cm diameter (in 2008 and 2009). The impervious base material was removed from the specimen prior to testing which resulted in a core thickness of 2.5 to 5.0 cm.

The effective porosity of the core specimens was determined using a non-destructive test that measures the differential submerged weight of the core between saturated and unsaturated conditions (Charbeneau et al., 2011). Hydraulic conductivity of PFC core specimens can be measured in the laboratory using a series of constant head tests. The laboratory test setup is shown schematically in Figure 2 (Charbeneau et al., 2011 with permission from ASCE). The core specimen was fastened between two metal plates with rubber gaskets on the upper and lower surface of the specimen which created a no flow boundary on these surfaces. A peristaltic pump created a constant inflow rate through the standpipe with radius $R_s$ = 1.88 cm. An ISCO bubbler flow meter measured the water depth in the standpipe or the change in head through the entire core specimen, $h_s$. The core specimen was submerged in a tank of water which established the head on the radial periphery of the core. Water entered the core vertically through the standpipe, and then turned to exit the core in the radial direction. A stopwatch and glassware were used to measure the volumetric flow rate, $Q$, produced by the pump. The resulting head versus flow rate relationship was non-linear so that Darcy's law is not applicable (Charbeneau et al., 2011).

Non-linear flow arises due to increased inertial forces within the porous media. The transition from linear flow to non-linear flow typically occurs at a Reynolds number value ranging from one to 10 (Bear, 1972). For the case of PFC, non-linear flow arises due to the large pore volumes within the media and large gradients imposed during testing. Non-linear flow is typically characterized by the Forchheimer equation (see Bear, 1972). The Forchheimer equation is presented as:

$$I = aq + bq^2 \qquad (1)$$

where $I$ is the local hydraulic gradient [with units (L/L)], $q$ is the local specific discharge (L/T), and $a$ and $b$ are the linear and non-linear Forchheimer coefficients, respectively. $a$ is equal to the inverse of the hydraulic conductivity and has units (T/L); i.e., $a = 1/K$ where $K$ is the hydraulic conductivity (L/T). $b$ has units of ($T^2/L^2$) and is equal to zero when Darcy's law is applicable. Larger $b$ values result in a greater non-linear effect and give an indication of when the magnitude of the hydraulic gradient will result in significant non-linear effects.

Due to the two-dimensional radial flow pattern imposed during testing, the local hydraulic gradient and specific discharge cannot be directly measured in the lab. Therefore, the measured flow relationship can be modeled using a modified Forchheimer equation for the global conditions of the core specimen:

$$h_s = \alpha Q + \beta Q^2 \qquad (2)$$

where $h_s$ is the standpipe head, $Q$ is the volumetric flow rate, $\alpha$ is the linear modified Forchheimer coefficient [with units ($T/L^2$)], and $\beta$ is the non-linear modified Forchheimer coefficient ($T^2/L^5$). Experimental data can be fit to the modified Forchheimer Equation (2) in order to determine the values of $\alpha$ and $\beta$. However, these coefficients give no indication of the hydraulic conductivity without proper numerical modeling of the original Forchheimer equation.

The approximate analytical solution provided by Charbeneau et al. (2011) is improved upon through numerical modeling of the Forchheimer equation to relate the measured global variables ($h_s$ and $Q$) to the theoretical local variables ($I$ and $q$). Klenzendorf et al. (2010) use a finite-difference numerical model that solves the continuity equation for two-dimensional non-linear flow and relates the measured global modified Forchheimer coefficients ($\alpha$ and $\beta$) to the original Forchheimer coefficients ($a$ and $b$). Inputs to the model are the core dimensions: core thickness, $b_c$; core radius, $R_c$; and standpipe radius, $R_s$. Multiple numerical simulations were conducted to determine a relationship between the linear original and modified Forchheimer coefficients, resulting in the following power-law regression equation (Klenzendorf et al., 2010):

$$a \approx 5.8 R_s \left( \frac{b_c}{R_c} \right)^{0.33} \alpha \tag{3}$$

The ranges of core dimensions used in the numerical simulations were: 1.5 cm $\leq R_s \leq$ 3.0 cm, 2.5 cm $\leq b_c \leq$ 5.0 cm, and 7.5 cm $\leq R_c \leq$ 25.0 cm. Therefore, Equation (3) can be used to estimate the hydraulic conductivity ($K = 1/a$) from the measured value of $\alpha$ and the known core dimensions. The constant of 5.8 in the power-law regression equation is dimensionless which allows for use of any consistent system of units for the input variables.

In order to assess the potential water quality benefits of PFC, a non-destructive field test is desirable for measurement of in-situ hydraulic conductivity. Typically, in-situ hydraulic conductivity measurements are conducted with infiltrometers such as a double-ring infiltrometer or Guelph permeameter which make two general assumptions about the porous medium. The first assumption is that the porous medium is infinite such that there is no underlying impervious boundary and a one-dimensional flow pattern exists. This assumption is violated for the case of PFC since the porous asphalt layer ranges from 2.5 to 5.0 cm thick with an impervious pavement surface underneath forcing two-dimensional flow conditions. The second assumption is that Darcy's law is applicable. This assumption does not apply for PFC using large head values since a non-linear flow relationship has been observed under typical testing conditions. Therefore, the need for a new field test apparatus and methodology which accounts for two-dimensional non-linear flow is necessary to determine the in-situ hydraulic conductivity of PFC. A field test apparatus has been developed for this research using a falling head test and creates similar boundary conditions imposed in the laboratory (Charbeneau et al., 2011). The field test apparatus, shown in Figure 3 (Charbeneau et al., 2011 with permission from ASCE), consists of a solid metal base plate with a radius of $R_c$ = 22.9 cm and a standpipe with radius $R_s$ = 5.1 cm. Silicon vacuum grease was applied to the lower side of the base plate in order to seal the surface voids of the PFC surface and creates a no flow boundary on the surface. The underlying impervious asphalt surface provides the second no flow boundary to match boundary conditions imposed in the lab.

The test methodology consists of applying the vacuum grease to the base plate and pressing the plate on the pavement surface to create a seal. Water is allowed to flow through the standpipe prior to testing in order to saturate the pore space within the PFC layer. The falling head test is conducted by filling the standpipe and starting a stopwatch at the initial water depth. The split function on the stopwatch is used at roughly half the initial water depth, and the stopwatch is stopped when the water depth has reached the bottom of the standpipe. The test is repeated three times using the same water depths and the average of the three time measurements is used for the analysis. This results in three time-depth pairs which can be used to determine the two modified Forchheimer coefficients ($\alpha$ and $\beta$) using the falling head equations described in Charbeneau et al. (2011).

The experimentally measured modified Forchheimer coefficients can be related to the original Forchheimer coefficients through numerical modeling. The test apparatus has a constant standpipe radius, $R_s$, and constant base plate radius, $R_c$. Therefore, multiple model simulations were conducted to develop a regression equation relating $a$ as a function of only $\alpha$ and $b_c$. The actual PFC thickness cannot be measured in the field, so the average thickness from the core specimens can be used for the value of $b_c$. The following power-law regression equation provides an estimate of the in-situ hydraulic conductivity specifically for the test apparatus used in this research (Klenzendorf et al., 2010):

$$a \approx 5 b_c^{0.75} \alpha \tag{4}$$

The range of core thicknesses used in the numerical simulations is: 2.5 cm $\le b_c \le$ 5.0 cm. Equation (4) is only applicable to the test apparatus used in this research study (with $R_c$ = 22.9 cm and $R_s$ = 5.1 cm), and the input variables must have units of cm and seconds as the constant term has dimensions associated with it (i.e., 5 cm$^{0.25}$).

One application of the hydraulic properties of PFC is for use in design of the pavement thickness and for simulation of the drainage process. The drainage process exhibited by PFC highways can be interpreted as a specialized problem in hillslope hydrology. The PFC layer behaves as a thin unconfined sloping aquifer. Due to its large hydraulic conductivity and small thickness, recharge occurs practically instantaneously. Under light rainfall, all drainage occurs within the pavement but under heavy rainfall the capacity of the pavement is exceeded and drainage occurs both within the pavement and as sheet flow on the roadway surface. The Permeable Friction Course Drainage Code (Perfcode) was developed to study this coupled unsteady drainage process (Eck et al., 2010). Perfcode applies the Boussinesq equation for flow within the PFC layer (Halec and Svec, 1979):

$$n_e \frac{\partial H_p}{\partial t} = \nabla \bullet (K H_p \nabla h) + r \tag{5}$$

where $n_e$ is the effective porosity, $H_p$ is the saturated thickness within the pavement, $t$ is time, $K$ is the hydraulic conductivity, $h$ is the head, and $r$ is the rainfall rate.

Sheet flow over the pavement surface is modeled using the diffusion wave approximation to the shallow water equations (Jeong and Charbeneau, 2010):

$$\frac{\partial H_s}{\partial t} = \nabla \bullet \left(\frac{1}{n} \frac{H_s^{5/3}}{\sqrt{S_f}} \nabla h\right) + r \tag{6}$$

where $H_s$ is the sheet flow thickness, $n$ is Manning's roughness coefficient, $S_f$ is the friction slope, and other terms are as defined above.

The governing equation for unsteady PFC drainage is found by adding Equations (5) and (6) as described by Eck et al. (2010). Perfcode solves the resulting form on a structured curvilinear grid. An algebraic system of non-linear equations is developed using the finite-volume method and solved using Picard iteration and the Gauss-Seidel technique (Ferziger and Peric, 2002).

## ***Hydraulic Results***

PFC core specimens were collected from three roadways located in the Austin, Texas area (Loop 360, FM 1431, and RR 620). Loop 360 is a four lane divided highway located west of

Austin over the Edwards Aquifer recharge zone. The PFC overlay was installed in October 2004 and has an average traffic count of approximately 50,000 vehicles per day. FM 1431 is a four lane highway northwest of Austin and outside of the Edwards Aquifer Contributing Zone. The PFC overlay on FM 1431 was installed in February 2004 and has an average traffic count of 18,000 vehicles per day. RR 620 is also a four lane highway north of Austin and located within the Edwards Aquifer Recharge Zone where the PFC was installed in June 2004. RR 620 has an average traffic count of 40,000 vehicles per day. Effective porosity values of the PFC core specimens ranged from 0.12 to 0.23. The average core specimen porosity with plus/minus one standard deviation for each of the three roadways over the past four years is shown in Figure 4. Three core specimens were collected each year from FM 1431 and RR 620, whereas six core specimens were collected from Loop 360 each year (three cores from the travel lane and three cores from the shoulder). Core specimens were not collected on FM 1431 in 2010 due to realignment of the road and abandonment of the previous coring location.

Hydraulic conductivity values of the PFC core specimens ranged from 0.2 to 3.0 cm/s. The average core specimen hydraulic conductivity with plus/minus one standard deviation for each of the three roadways over the past four years is shown in Figure 5. There is large variability in the measured hydraulic conductivity values. PFC is expected to have a decrease in porosity and hydraulic conductivity over time due to the pore space becoming clogged with trapped sediment and ultimately resulting in a decrease in water quality benefits. However, there has not been an observable decrease in the water quality benefits of the pavements from field monitoring results at the corresponding monitoring locations where these core specimens were collected. Therefore, additional research and monitoring is needed in order to determine when water quality benefits begin to degrade and what the resulting porosity and hydraulic conductivity are at the onset of degradation. Currently, the PFC surfaces in Texas are roughly seven years old and are nearing the end of their design life. Maintenance of the surface, such as vacuum washing, has not been conducted at these sites. Similarly, the monitoring conducted at the North Carolina sites described above have shown continued water quality benefits despite the PFC nearing the end of the recommended design life.

In order to assess the in-situ hydraulic conductivity, field tests were conducted at each of the three roadways (Klenzendorf et al., 2010). The average in-situ hydraulic conductivity observed for Loop 360 was roughly 3 cm/s. This hydraulic conductivity value is of the same order of magnitude measured from the core specimens. The measured in-situ hydraulic conductivity for FM 1431 was 0.6 cm/s, which agrees well with the core specimen data. Finally, the measured in-situ hydraulic conductivity for RR 620 was 1.5 cm/s, which is slightly larger than that obtained in laboratory. Further testing may be necessary to verify these results and obtain additional data.

The measured hydraulic properties of PFC were used for Perfcode simulations at the Loop 360 monitoring site near Austin, Texas. This location was ideal for a comparison between model results and field measurements because hydraulic properties of the PFC were available from the tests described above and because rainfall and runoff were also measured at this location. Results for one storm event are discussed here. The interested reader should consult Eck et al. (2010) for a discussion of model validation and results for additional storm events.

On 3 June 2007, the site received 36 mm of rainfall over a four hour period; this corresponds to a return period of less than two years at this location (Asquith and Rousel, 2004). Peak rainfall depths on five, fifteen, and sixty minute intervals were 6.1 mm, 6.6 mm, and 13.5 mm, respectively. Rainfall measurements were used along with PFC properties to simulate the runoff hydrograph for this event (Figure 6). The model predicted a peak discharge of 2.6 L/s, which is

76 percent of the measured peak discharge of 3.4 L/s. The residuals (differences between modeled and measured values) had a mean of 0.016 L/s, median of 0.035 L/s, standard deviation of 0.16 L/s, and standard error of the mean 0.02 L/s. The close agreement between modeled and measured values suggests that the drainage process is well described by Perfcode and properly parameterized by the measured values of porosity and hydraulic conductivity.

## ***Summary and Conclusions***

Porous pavements are used in an urban setting to mitigate adverse impacts of increased impervious cover on surface water and groundwater quality. Specifically, PFC is used as a surface overlay on high speed roadways in Texas and as an approved SCM over the Edwards Aquifer recharge zone. Research studies conducted in the United States and Europe on the water quality benefits of PFC are reviewed and compared with average daily traffic counts. Water quality results are also compared between a PFC surface and conventional pavement. In general, the PFC surface produces significantly lower concentrations of TSS, total Cu, total Pb, and total Zn compared to conventional pavements. Results are mixed for nutrient concentrations. These findings suggest that PFC is efficient at removing sediment and sediment-bound pollutants and can be an effective stormwater treatment method for the protection of surface water and groundwater quality for these pollutants.

In order to assess the effectiveness of the PFC layer as a stormwater treatment method, both porosity and hydraulic conductivity measurements were conducted on PFC core specimens. It is expected that as sediment is trapped within the pore space, the PFC layer will begin to act as conventional pavement and the water quality benefits degrade. Porosity and hydraulic conductivity measurements give an indication of when these benefits will be lost. Core specimens were collected at three different roadways for four consecutive years. Porosity ranged from 0.12 to 0.23. Hydraulic conductivity was determined with constant head tests in the laboratory, and a non-linear flow relationship was observed that required Forchheimer equation analysis. Due to the two-dimensional flow pattern, a modified Forchheimer equation was used. Measured modified Forchheimer coefficients were related to the originally defined Forchheimer coefficients through numerical modeling and used to determine hydraulic conductivity. Core specimen hydraulic conductivity values ranged from 0.2 to 3.0 cm/s.

In addition to laboratory tests on PFC core specimens, a field test apparatus and methodology were developed to determine the in-situ hydraulic conductivity. The field test methodology accounts for non-linear flow as well as the imposed two-dimensional flow pattern. In-situ hydraulic conductivity values closely matched the core specimen hydraulic conductivity, but additional testing is still needed.

Finally, Perfcode, a finite-volume numerical model, provides unique insight into the PFC drainage process. Model inputs are measured porosity, hydraulic conductivity, and rainfall. The results are the variation of water depth within the pavement and on the pavement surface during the event and the runoff hydrograph. The model may be used to study how the width and slope of a PFC highway affect the drainage process and to estimate the peak runoff. Designing with these estimates in mind can help prevent ponding on the roadway surface and improve the driving experience.

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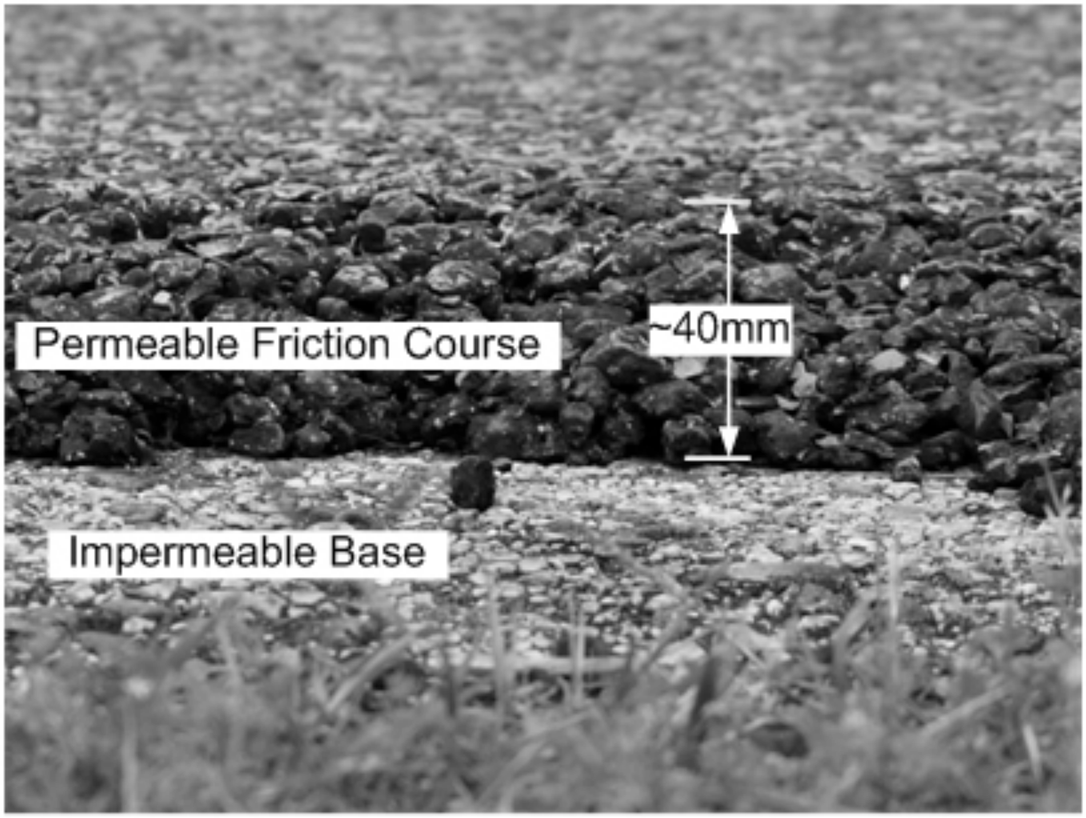


**Figure 1 – Photograph of permeable friction course on Loop 360 near Austin, Texas taken 26 April 2009**

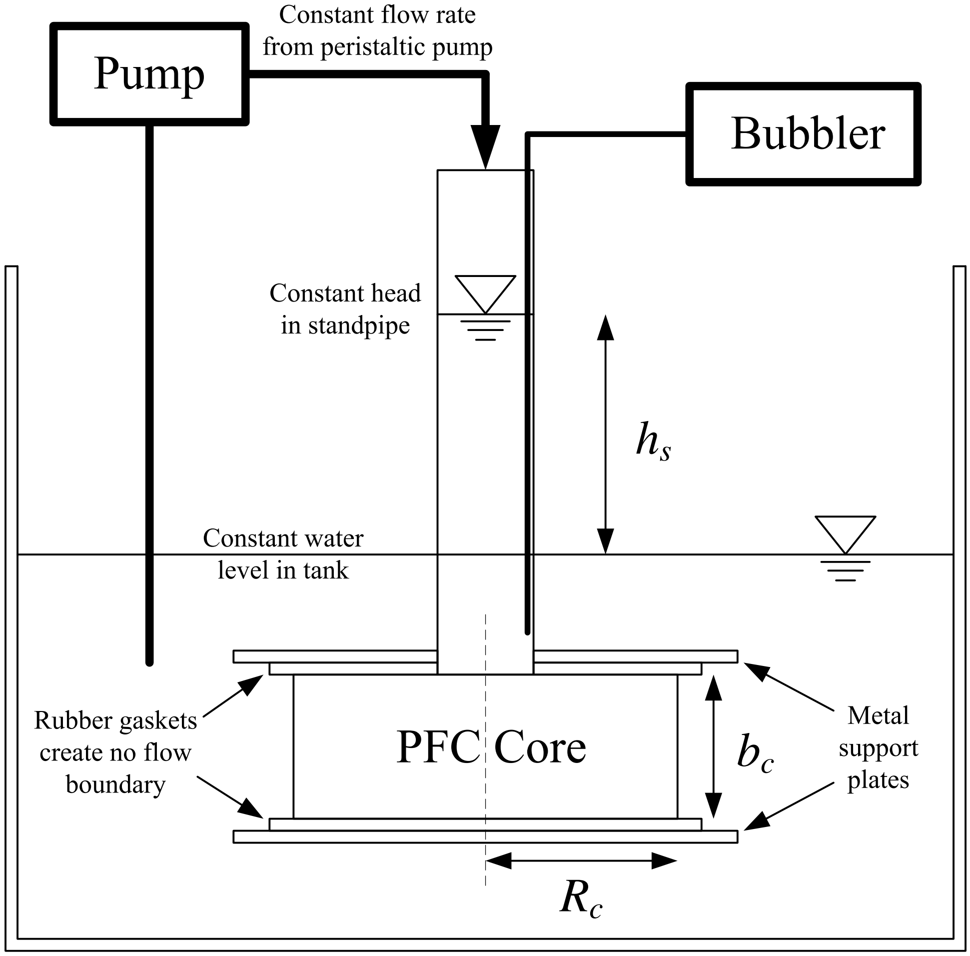


**Figure 2 – Laboratory test setup for measuring hydraulic conductivity of PFC core specimens using constant head tests (from Charbeneau et al., 2011 with permission from ASCE)**

**Figure 3 – Field test apparatus for measuring in-situ hydraulic conductivity using falling head test (from Charbeneau et al., 2011 with permission from ASCE)**

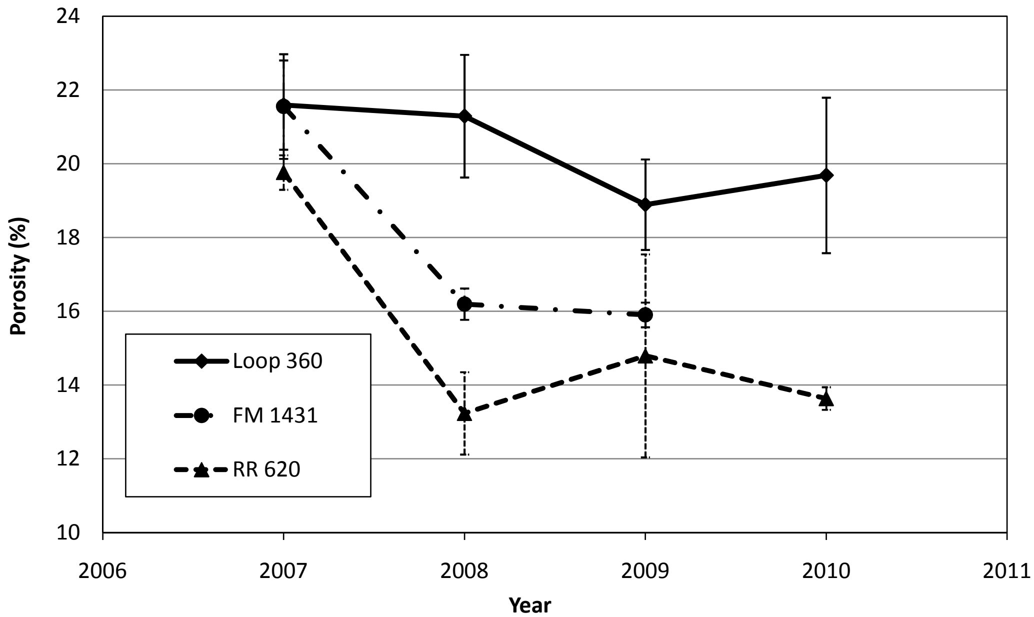


**Figure 4 – Average effective porosity plus/minus one standard deviation of PFC core specimens for three roadways over four years**

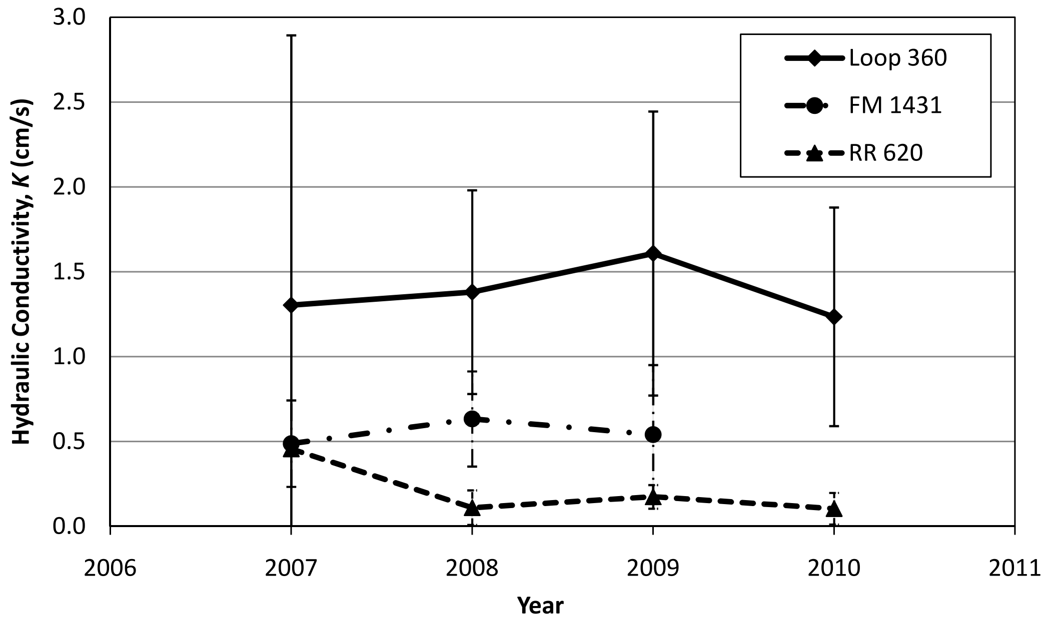


**Figure 5 – Average hydraulic conductivity plus/minus one standard deviation of PFC core specimens for three roadways over four years**

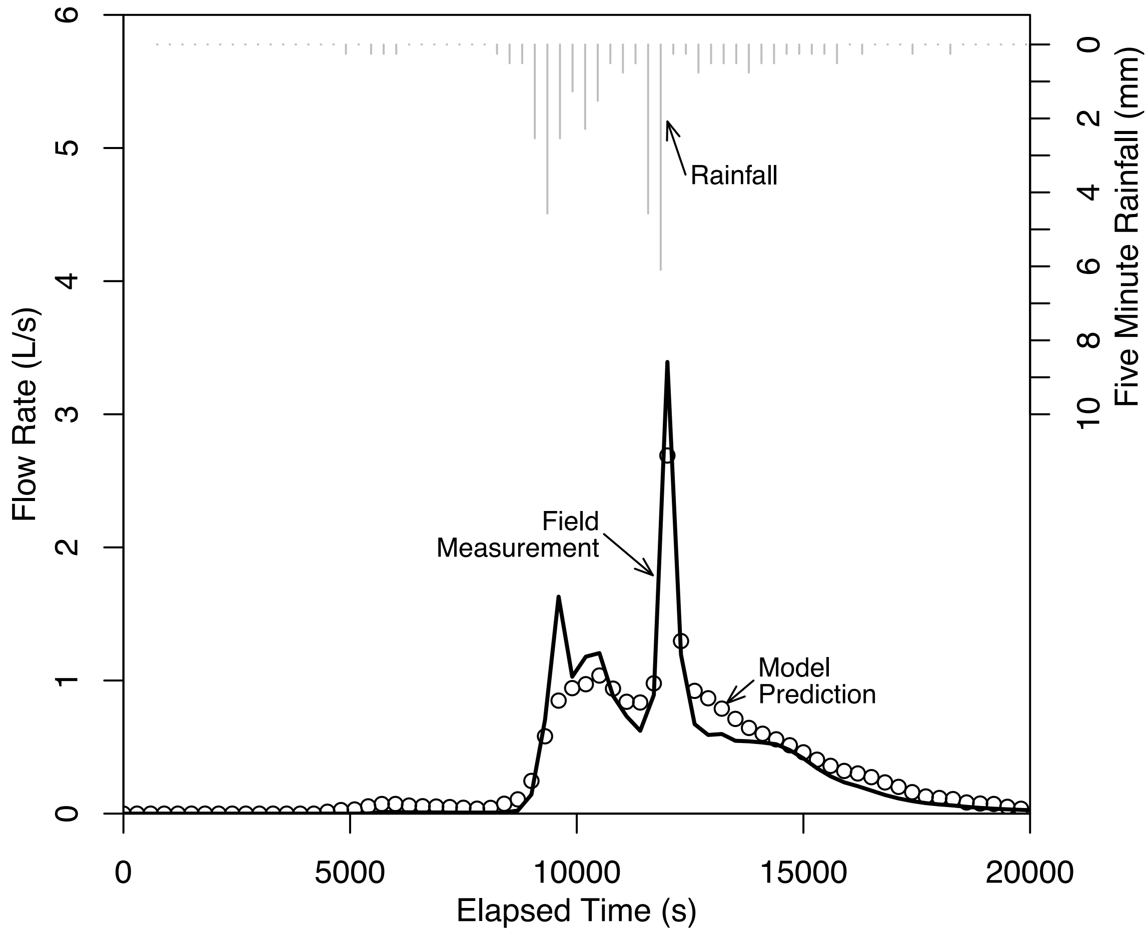


**Figure 6 - Comparison of modeled and measured hydrographs for storm of 3 June 2007 on Loop 360 near Austin, Texas**

**Table 1 – Effluent contaminant concentrations in PFC runoff reported as the median of observed values or the weighted mean**

| Monitoring Location | Data Source | Sampling Start | Study Period (Months) | Number of Samples | Average Daily Traffic Count | TSS mg/L | SSC mg/L | TKN mg/L | Nitrate mg/L | Total P mg/L | Total Cu µg/L | Total Pb µg/L | Total Zn µg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Median Concentrations | | | | | | | |
| A9, Netherlands | 1 | Jul 1994 | 15 | 6 | 83,000 | 17 [a] | -- | -- | -- | -- | 40 | 7.0 | 47 |
| Loop 360, TX (1) | 2 | Nov 2004 | 60 | 48 | 50,000 | 8.0 | -- | 0.79 | 0.28 | 0.04 | 11 | <1.0 | 22 |
| Interstate 95, MA | 3 | Sep 2005 | 24 | 18 | 180,600 | -- | 88 | -- | -- | 0.13 | 52 | 18 | 110 |
| Interstate 190, MA | 3 | Aug 2005 | 7 | 6 | 41,168 | -- | 52 | -- | -- | 0.14 | 19 | 5.3 | 81 |
| Interstate 93, MA | 3 | Apr 2006 | 10 | 5 | 191,000 | -- | 710 | -- | -- | 0.34 | 180 | 76 | 610 |
| Loop 360, TX (2) | 2 | Mar 2007 | 9 | 13 | 50,000 | 12 | -- | 0.50 | 0.21 | 0.04 | 12 | <1.0 | 17 |
| Interstate 40, NC (1) | 4 | Sep 2008 | 21 | 23 | 20,000 | 9.0 | -- | 0.82 | 0.39 | 0.05 | -- | -- | -- |
| Interstate 40, NC (2) | 4 | Sep 2008 | 21 | 23 | 20,000 | 17 | -- | 0.97 | 0.40 | 0.08 | -- | -- | -- |
| Interstate 40, NC (3) | 4 | Sep 2008 | 21 | 20 | 18,000 | 8.0 | -- | 1.0 | 0.76 | 0.08 | -- | -- | -- |
| Interstate 40, NC (4) | 4 | Sep 2008 | 21 | 20 | 17,000 | 8.4 | -- | 1.1 | 1.1 | 0.10 | -- | -- | -- |
| RR 620, TX | 2 | Feb 2009 | 10 | 8 | 40,000 | 6.3 | -- | 0.62 | 0.27 | 0.04 | 7.5 | <1.0 | 18 |
| | | | | | | Weighted Average Concentrations | | | | | | | |
| A6, Germany | 5 | Apr 1990 | 1 | -- | 34,675 | 56 (FS) | | -- | 2.2 [b] | -- | 70 | 96 | 600 |
| A11, France | 6 | Jun 1997 | 1 | 25 | 12,000 | 8.2 | -- | 1.2 | 2.1 | -- | 20 | 8.7 | 77 |
| | | | | | Spearman's Rho: | 0.26 | 0.80 | -- | -- | 0.14 | 0.36 | 0.10 | 0.22 |
| | | | | | p-value: | 0.50 | 0.33 | -- | -- | 0.70 | 0.34 | 0.79 | 0.57 |

[a] Value determined from five samples

[b] Value reported as sum of $NO_3$ and $NO_2$

Data Sources: (1) Berbee et al., 1999; (2) Eck et al., 2011; (3) Smith and Granato, 2009; (4) Winston et al., 2011; (5) Stotz and Krauth, 1994; (6) Pagotto et al., 2000

**Table 2 – Relative percent difference in concentration at sites where paired data was collected from both PFC and conventional pavement**

| Monitoring Location | Data Source | Statistical Test | TSS | SSC | TKN | Nitrate | Total P | Total Cu | Total Pb | Total Zn |
|---|---|---|---|---|---|---|---|---|---|---|
| A9, Netherlands | 1 | N/A | -91[b] | -- | -- | -- | -- | -66[b] | -92 | -90[b] |
| Loop 360, TX (1) | 2 | Mann-Whitney | -93[a] | -- | -25 | 6 | -75[a] | -60[a] | < -90[a] | -87[a] |
| Interstate 95, MA | 3 | Wilcoxon Signed Rank | -- | -28 | -- | -- | -35 | 8.2 | 7.6 | -49 |
| Loop 360, TX (2) | 2 | Wilcoxon Signed Rank | -91[a] | -- | -49 | 31 | -66[a] | -56[a] | < -90[a] | -87[a] |
| RR 620, TX | 2 | Wilcoxon Signed Rank | -96[a] | -- | -63[a] | 46 | -78[a] | -69[a] | < -96[a] | -90[a] |
| A11, France | 6 | Students t-test | -81[a] | -- | -43[a] | -69[a] | -- | -35[a] | -78[a] | -66[a] |

[a] Significant at 95% confidence level

[b] Statistical tests were not reported, but the ranges of observed values did not overlap for this parameter

Note: Negative values indicate lower pollutant concentrations from PFC when compared to conventional pavement

Data Sources: (1) Berbee et al., 1999; (2) Eck et al., 2011; (3) Smith and Granato, 2009; (6) Pagotto et al., 2000