Infiltration and Clogging by Sand and Clay in a Pervious Concrete Pavement System

J. Patrick Coughlin, M.ASCE1; Chelsea D. Campbell2; and David C. Mays, P.E., M.ASCE3

Abstract: From a hydrologic perspective, one limitation of pervious concrete pavement is the risk of clogging, defined as a reduction in hydraulic conductivity that reduces infiltration into the pavement or exfiltration into the subgrade. Accordingly, a laboratory study was performed to measure clogging by sand and clay (sodium montmorillonite) in a saturated pervious concrete pavement system, and the subsequent effect of surface cleaning by pressure washing. Both sand and clay caused measurable clogging that was not reversible by pressure washing. However, even after clogging, the infiltration and exfiltration rates were well above the average intensity of 66 mm/h for the 100-year 1-h design storm for Denver. This result is encouraging, but should be interpreted with caution, because in these experiments the flow-limiting layer was never the pervious concrete, but rather the subgrade, which in this case was a thin layer of sand with a large hydraulic conductivity. Accordingly, this study suggests that pervious concrete would be effective for storm-water detention when provided with an engineered drainage system, but that its performance for storm-water infiltration will be limited by the rate of exfiltration to the subgrade.

CE Database subject headings: Concrete pavements; Infiltration; Sand filters; Clays; Clogging; Hydraulic conductivity.

Author keywords: Concrete pavements; Infiltration; Sand; Clays; Clogging; Hydraulic conductivity.

Introduction

The use of impervious pavement has numerous detrimental effects on watersheds, including increased storm-water runoff, reduced groundwater recharge, and consequently increased contaminant transport. In fact, imperviousness has been identified as the single parameter that can be used to predict the health of riparian ecosystems within a watershed (Schueler et al. 2009). In recognition of the above detrimental effects, the National Research Council (2008) has recently recommended “retrofitting urban areas with features that hold and treat storm water.” Among the best management practices (BMPs) available to accomplish this goal, pervious concrete is popular because it reduces imperviousness, holds storm water, and removes pollutants as storm-water flows through the underlying base course and subgrade (Environmental Protection Agency 1999; Ferguson 2005; Tennis et al. 2004).

Pervious concrete is similar to conventional concrete but is designed without fine aggregate (i.e., sand). The resulting pavement has a porosity in the range of 0.15–0.30 (Haselbach et al. 2006) and a median pore size in the range of 2–4 mm (Sansalone et al. 2008; Sumanasooriya and Neithalath 2009), which renders it highly pervious. From a material science perspective, the limitations of pervious concrete are its strength, durability, and freeze-thaw performance (Colorado Ready Mixed Concrete Association 2009; Yang and Jiang 2003). From a hydrologic perspective, perhaps the most important limitation of pervious concrete is clogging (Bean et al. 2007; Ferguson 2005; Haselbach 2010; Haselbach et al. 2006; Lindsey et al. 1992; Rushton 2001; Sansalone et al. 2008).

For the purpose of this study, the term clogging refers to a reduction in hydraulic conductivity that reduces infiltration into the pavement or exfiltration into the subgrade. The term exfiltration refers to flow from an engineered structure, such as pervious concrete or base course, to the underlying subgrade (Sansalone and Teng 2005; Tyner et al. 2009). Previous studies suggest that retention of sand-sized materials does not result in significant clogging (González-Angullo et al. 2008; Haselbach et al. 2006). In contrast, retention of fines (i.e., silt- and clay-sized materials) is a far greater concern (Haselbach 2010; Lindsey et al. 1992; Siriwardene et al. 2007). The important role of fines has also been noted in studies on granular media filters, in which a small volume of fines, approximately 3% of the pore space, can reduce the hydraulic conductivity by 2–3 orders of magnitude (Mays and Hunt 2005, 2007).

The present study reports clogging by sand and clay in a saturated pervious concrete pavement system and the subsequent effect of surface cleaning by pressure washing. Both sand and clay are used to quantify their relative concern as clogging materials. Saturated conditions represent the limiting case of ponded infiltration, similar to the conditions chosen by Siriwardene et al. (2007), but in contrast to other studies that used unsaturated conditions (González-Angullo et al. 2008; Haselbach 2010; Haselbach et al. 2006). Imposition of saturated conditions also allowed direct calculation of the hydraulic conductivity, in one experiment, for each layer of the pervious concrete system: a surface course of pervious concrete, a base course meeting Colorado Department of Transportation (CDOT) criteria, and a subgrade of sand. The focus on such a pervious concrete system was deliberate because in many cases infiltration is limited not by the pervious concrete itself, but by the underlying materials (Collins et al. 2008; Dreelin et al. 2006;
Haselbach et al. 2006; Tennis et al. 2004; Tyner et al. 2009). Finally, pressure washing was used to evaluate its effectiveness as a maintenance technique for pervious concrete pavement.

Methods

The laboratory apparatus was designed to simulate one-dimensional saturated flow through pervious concrete and two underlying layers (Fig. 1). The apparatus was a polycarbonate box, containing the base course and substitute subgrade, which supported a sample of pervious concrete above its open top. Above the pervious concrete was a short open frame of polycarbonate, of the same cross section as the lower box, used to impose constant head ponded conditions. Below the pervious concrete, the base course was 168 mm thick, within the recommended range of 150 to 300 mm (Tennis et al. 2004). Below the base course, the substitute subgrade was 144 mm thick. Details on the base course and the substitute subgrade are provided subsequently. Six pressure ports were drilled in three pairs on opposite sides of the box, close to layer transitions. Single barb fittings were used to connect these ports to flexible plastic tubes, which were attached to vertical meter sticks and used as piezometers. The substitute subgrade was supported by a stainless steel #100 screen mesh above a bottom void, which drained the apparatus through a needle valve, and also provided saturation water through a hose connection. Silicone caulk was used to seal the outside edges of the pervious concrete samples and to join them to the top frame and the bottom box.

Pervious concrete was provided by a local landscaping supplier, Colorado Hardscapes. They used 3/8-in. (9.5 mm) pea gravel (ASTM C33 #8 to #16 sieves) in a 1:4 water to cementitious material ratio. This is slightly less than the typical range of 0.27 to 0.34 for pervious concrete pavements (Tennis et al. 2004).

No additives were used in the mix. The samples were poured on a bed of gravel, some of which was retained on the pervious concrete, giving the bottom a rougher surface than the top. Accordingly, the pervious concrete samples were mounted top-side-down in the infiltration apparatus, to ensure a uniform interface between the pervious concrete and the underlying base course. In contrast to field-poured pervious concrete, which has a vertical distribution of porosity (Haselbach and Freeman 2006), these samples were not compacted, so the top-side-down mounting will not affect the results because the porosity is constant. All four samples were allowed to cure for more than a month before experimentation was performed. The porosity of each sample was determined by measuring its bulk volume and the volume of water displaced by the dry sample (Table 1).

The base course was provided by CDOT per their standard specifications (CDOT 2005 §703.03). The substitute subgrade was a sand whose gradation is shown in Fig. 2, along with the gradation for the CDOT base course. The sand was selected to represent a best-case scenario of an underlying soil with a high hydraulic conductivity, and was also used as a clogging material. The other clogging material was sodium-rich montmorillonite clay (SWy-2, Source Clays Repository, West Lafayette, Indiana), which was applied without further preparation, and was selected because it is a common clay mineral and the primary constituent of bentonite (van Olphen 1977).

For each of the four pervious concrete samples, infiltration and head loss were recorded for a series of eight runs. These eight runs included one without clogging materials, three with increasing amounts of sand, three with increasing amounts of clay, and one after pressure washing (Table 2). The one exception was sample 2, for which pressure washing was not tested. Before starting each series of eight runs, the apparatus was saturated with tap water (21°C and pH 8.2) through the hose connection to the bottom void. To reduce air bubbles, the system was filled slowly over several minutes. Next, the valve to the hose connection was closed, and a leak check was performed on the static water. Then the open frame above the pervious concrete was gradually filled with tap water until it overflowed. In sample 1, the tap water created a bare

<p>| Table 1. Details on the Pervious Concrete Samples |
|-----------------------------|-----------------|----------------|---------------|</p>
<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness [mm]</th>
<th>Area [mm²]</th>
<th>Porosity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>109 ± 3</td>
<td>23,000 ± 400</td>
<td>0.23 ± 0.02</td>
</tr>
<tr>
<td>2</td>
<td>98 ± 3</td>
<td>23,500 ± 400</td>
<td>0.33 ± 0.03</td>
</tr>
<tr>
<td>3</td>
<td>98 ± 3</td>
<td>21,900 ± 400</td>
<td>0.26 ± 0.01</td>
</tr>
<tr>
<td>4</td>
<td>100 ± 3</td>
<td>24,000 ± 400</td>
<td>0.27 ± 0.03</td>
</tr>
</tbody>
</table>

Fig. 1. Infiltration apparatus, with dimensions in millimeters, and gray fluid in the piezometer tubes; the head loss across the subgrade is designated ΔhSG, and the head loss across all porous media (pervious concrete, base course, and subgrade) is designated ΔhPM.

Fig. 2. Grain size distribution for CDOT base course (solid) and subgrade sand (dashed).

spot on the pavement surface where no clogging materials were visible, so in samples 2–4, a perforated board was used to distribute this tap water uniformly across the top. Next, the needle valve was opened, and the system was left to reach steady-state, defined as constant discharge through the needle valve and constant head in the piezometers. Discharge was determined by triplicate measurements of the volume of water leaving the outlet in 30 s (samples 1–3) or 60 s (sample 4). The sample time was increased for sample 4 because the discharge was smaller than the other samples, presumably because of clogging in the needle valve. The head loss in each layer was measured as the difference in piezometer readings, or by the difference between the piezometer and the free head at the top of the apparatus. One-dimensional flow was confirmed by checking that piezometers on opposite sides of the apparatus had similar readings.

For each of the four pervious concrete samples, the eight runs proceeded as follows: After recording the discharge and taking head measurements with a clean pavement system, clogging materials were added by draining the apparatus to just below the pervious concrete surface, uniformly distributing a known weight of sand or clay through a sieve, and then adding tap water through the perforated board at the top (Table 2). For pervious concrete samples 1, 3, and 4, the pervious concrete surface was pressure washed after run 7 by using a jet velocity of 9 m/s, determined by measuring the maximum elevation of the jet when directed upward. This velocity is smaller than that of a commercial pressure washer, but it nevertheless appeared to be effective in cleaning the pavement surface. The jet angle varied between 15° and 90° above horizontal. After taking one final set of discharge and head measurements, called run 8, the apparatus was then disassembled and rebuilt with a new pervious concrete sample, new base course, and transport of fines from the base course to the top of the apparatus. One-dimensional flow was confirmed by checking that piezometers on opposite sides of the apparatus had similar readings.

Table 2. Clogging Material Added in Each Run

<table>
<thead>
<tr>
<th>Run</th>
<th>m_sand [g]</th>
<th>m_clay [g]</th>
<th>m_sand [kg/m²]</th>
<th>m_clay [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>20 ± 0.1</td>
<td>0</td>
<td>0.87 ± 0.03</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>60 ± 0.1</td>
<td>0</td>
<td>2.6 ± 0.1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>140 ± 0.2</td>
<td>0</td>
<td>6.1 ± 0.2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>140 ± 0.2</td>
<td>2 ± 0.1</td>
<td>6.1 ± 0.2</td>
<td>0.087 ± 0.006</td>
</tr>
<tr>
<td>6</td>
<td>140 ± 0.2</td>
<td>6 ± 0.1</td>
<td>6.1 ± 0.2</td>
<td>0.26 ± 0.01</td>
</tr>
<tr>
<td>7</td>
<td>140 ± 0.2</td>
<td>14 ± 0.2</td>
<td>6.1 ± 0.2</td>
<td>0.61 ± 0.03</td>
</tr>
</tbody>
</table>

Note: The final two columns are normalized by the average cross section of all 4 samples, A = 0.0231 ± 0.0009 m²; the mass of sand and clay were not measured after pressure washing.

For the conditions used in this study, infiltration and exfiltration rates are identical. These results indicate three important observations. First, addition of sand or clay always leads to clogging. The one exception was between runs 5 and 6 of sample 1, which lacked a perforated board to uniformly distribute the tap water above the sample. Second, from a hydrologic perspective, clay is much more damaging than sand. Specifically, clogging per mass of clay is approximately ten times more than clogging per mass of sand, except for the first 1 g of clay added to sample 2, for which the clogging is considerably more than sand. Third, for the three samples that were pressure washed, comparison of the infiltration rates for run 7 (maximum clogging) and run 8 (after pressure washing) indicate that pressure washing is ineffective, at least under the conditions used in this study. This result is notable considering that Fig. 3(d) appears to be clean.

Comparing samples 1–4, there was a steady decline in the initial infiltration rate, f_o, resulting from progressive clogging of the needle valve draining the apparatus. To compare all results, Fig. 4(b) plots the relative infiltration rate f/f_o. The results for all samples are remarkably similar, with fully clogged f between 65–70% of f_o except for sample 2, as discussed previously.

Although determination of hydraulic conductivity (Montes and Haselbach 2006) was not an objective of the current study, the infiltration rate in sample 1 was large enough to produce significant head loss relative to the measurement error, so for this sample it was possible to calculate the hydraulic conductivity, K, from Darcy’s Law

\[ K = \frac{Q \Delta x}{A \Delta h} \]  

where \( \Delta x = \) the layer thickness; and \( \Delta h = \) the head loss (Fig. 5). These results should be interpreted with caution because the errors are large, and because the Reynolds number is approaching the range of 1–10, which is the upper limit for which Darcy’s Law is valid (Fitts 2002). Specifically, for flow in porous media, Reynolds number is

\[ R = \frac{fd_{50}}{\nu} \]  

where \( d_{50} = \) the median grain size; and \( \nu = \) the kinematic viscosity of water. For the limiting case, using the initial infiltration rate of \( f = 1970 \text{ mm/h} = 0.55 \text{ mm/s} \) and the nominal 3/8 in size of the pervious concrete \( d_{50} = 9.5 \text{ mm} \) and \( \nu = 1.0 \times 10^{-6} \text{ m/s} \), the Reynolds number is \( R = 5.2 \). But, having stated these qualifications, Fig. 5 does suggest that the hydraulic conductivity of all layers declines with additional clogging material, presumably because of the roughness of the pervious concrete samples. Errors for calculated results were estimated by using standard error propagation rules (Rice 1995).

Results

A sequence of photographs for sample 3 is shown in Fig. 3, illustrating the clean sample, the sample after clogging with sand, the sample after additional clogging with clay, and the sample after pressure washing. The final photograph, Fig. 3(d), appears “visibly clean and open,” which Ferguson (2005) used to characterize another clogged pervious concrete pavement after pressure washing.

Steady-state infiltration rates, shown in Fig. 4(a), were calculated from

\[ f = \frac{Q}{A} \]  

where \( f = \) infiltration rate, \( Q = \) discharge; \( A = \) cross-sectional area. For the conditions used in this study, infiltration and exfiltration rates are identical. These results indicate three important observations. First, addition of sand or clay always leads to clogging. The one exception was between runs 5 and 6 of sample 1, which lacked a perforated board to uniformly distribute the tap water above the sample. Second, from a hydrologic perspective, clay is much more damaging than sand. Specifically, clogging per mass of clay is approximately ten times more than clogging per mass of sand, except for the first 1 g of clay added to sample 2, for which the clogging is considerably more than sand. Third, for the three samples that were pressure washed, comparison of the infiltration rates for run 7 (maximum clogging) and run 8 (after pressure washing) indicate that pressure washing is ineffective, at least under the conditions used in this study. This result is notable considering that Fig. 3(d) appears to be clean.

Comparing samples 1–4, there was a steady decline in the initial infiltration rate, f_o, resulting from progressive clogging of the needle valve draining the apparatus. To compare all results, Fig. 4(b) plots the relative infiltration rate f/f_o. The results for all samples are remarkably similar, with fully clogged f between 65–70% of f_o except for sample 2, as discussed previously.

Although determination of hydraulic conductivity (Montes and Haselbach 2006) was not an objective of the current study, the infiltration rate in sample 1 was large enough to produce significant head loss relative to the measurement error, so for this sample it was possible to calculate the hydraulic conductivity, K, from Darcy’s Law

\[ K = \frac{Q \Delta x}{A \Delta h} \]  

where \( \Delta x = \) the layer thickness; and \( \Delta h = \) the head loss (Fig. 5). These results should be interpreted with caution because the errors are large, and because the Reynolds number is approaching the range of 1–10, which is the upper limit for which Darcy’s Law is valid (Fitts 2002). Specifically, for flow in porous media, Reynolds number is

\[ R = \frac{fd_{50}}{\nu} \]  

where \( d_{50} = \) the median grain size; and \( \nu = \) the kinematic viscosity of water. For the limiting case, using the initial infiltration rate of \( f = 1970 \text{ mm/h} = 0.55 \text{ mm/s} \) and the nominal 3/8 in size of the pervious concrete \( d_{50} = 9.5 \text{ mm} \) and \( \nu = 1.0 \times 10^{-6} \text{ m/s} \), the Reynolds number is \( R = 5.2 \). But, having stated these qualifications, Fig. 5 does suggest that the hydraulic conductivity of all layers declines with additional clogging material, presumably because of the roughness of the pervious concrete samples. Errors for calculated results were estimated by using standard error propagation rules (Rice 1995).

Results

A sequence of photographs for sample 3 is shown in Fig. 3, illustrating the clean sample, the sample after clogging with sand, the sample after additional clogging with clay, and the sample after pressure washing. The final photograph, Fig. 3(d), appears “visibly
significant in all experiments. To place all results in a consistent framework, consider the fraction of porous media head loss that occurs in the substitute subgrade

$$\varphi = \frac{\Delta h_{SG}}{\Delta h_{PM}}$$

where $\Delta h_{PM} = h_{top} - h_{void}$ is the head loss across the porous media (pervious concrete, base course, and substitute subgrade); $h_{top}$ is the free head at the top of the apparatus; and $h_{void}$ is the head measured in the void (Fig. 1). Across all 4 samples and 8 runs, the substitute subgrade accounted for 61–89% of the porous media head loss.

Fig. 3. Photographs showing the surface of sample 3: (a) initial condition when dry; (b) after adding 140 g of sand; (c) after adding an additional 14 g of clay; (d) after pressure washing.
leaving only 11–39% of the porous media head loss to the pervious concrete and base course (Fig. 6). Even after adding a significant quantity of clay and sand, most of the head loss in the pervious concrete pavement system occurred in the substitute subgrade rather than the paving materials. This is notable, particularly considering that nearly any installation would have a subgrade that is thicker than 144 mm and has a smaller hydraulic conductivity than the sand employed here.

Discussion

The results presented in Figs. 4 and 5 indicate that clay was more damaging than sand from a hydrologic perspective, and that pressure washing had no significant effect on the infiltration rate, in contrast to the visual inspection of the pavement surface shown in Fig. 3(d). The ineffectiveness of pressure washing is analogous to the ineffectiveness of brushing and vacuuming of porous pavements made of paving blocks (Pezzaniti et al. 2009). The ineffectiveness of pressure washing, in fact, is consistent with the head loss data presented in Fig. 6, which indicates that the limiting factor was not the hydraulic conductivity of the pervious concrete (or the base course) but the hydraulic conductivity of the substitute subgrade. The pressure washing is ineffective because the pervious concrete, even when clogged with sand and clay, represents a very small fraction of the overall head loss in this study, although it should be noted that the pervious concrete was shown to be the infiltration-limiting layer in a recently published field study (Chopra et al. 2010). However, in cases where the soil is the infiltration-limiting layer, one can think of the pervious concrete as transparent with respect to infiltration. Indeed, this notion is consistent with the emphasis that previous writers have placed on the hydraulic conductivity of the subgrade (Collins et al. 2008; Dreelin et al. 2006; Haselbach et al. 2006; Tennis et al. 2004; Tyner et al. 2009), and with the fact that porous pavements require particular care to avoid compacting the subgrade during construction (Ferguson 2005).

Despite the clogging shown in Figs. 4 and 5, the overall infiltration rate in these experiments was well above the intensity of the relevant design storm. Specifically, the smallest infiltration rate recorded (after pressure washing sample 4) was 22 ± 03 mm/h, compared to an average intensity of 66 mm/h for the 100-year 1-h design storm in Denver (Urban Drainage and Flood Control District 2004). This result is encouraging, but it should be interpreted with caution, simply because the substitute subgrade was represented in these experiments by a 144-mm layer of sand, which represents a best-case scenario from the perspective of exfiltration. Regular field installations will almost always have thicker subgrades consisting of soils with less hydraulic conductivity than sand, which means the infiltration and exfiltration rates could be orders of magnitude less than the results reported here. On the other hand, if the pervious concrete and base course drained to an engineered collection system, then these results suggest that pervious concrete pavement would be an effective BMP in cases where infiltration is required, but not exfiltration.

For comparison, it is useful to compare and contrast the present results with recent reports on clogging and cleaning of pervious concrete. Chopra et al. (2010) reported that infiltration rates into pervious concrete can be effectively restored by pressure washing, on the basis of laboratory experiments in which the pervious concrete was washed with an open base, rather than mounted on base course. This is a key distinction, because it implies that their clogging materials were physically removed in a manner that would not be possible in a pervious concrete system. Haselbach (2010) reported clogging of pervious concrete by concentrated clay suspensions and subsequent improvements after drying, brushing, and flushing with clay-free water. Haselbach used three clays, including bentonite, whose primary constituent is montmorillonite. A direct comparison is not possible, because Haselbach used an unsaturated single layer of pervious concrete and performed cleaning with a brush, in contrast to the saturated three layer system with cleaning by pressure washing reported here, but a few observations are possible. Haselbach’s limited success in restoring the infiltration of pervious concrete clogged with bentonite is consistent with the results reported in Figs. 4 and 5. For other clays, kaolinite and red clay, Haselbach’s observations are qualitatively different. By using solid concentrations of 170–230 g/L for kaolinite and 10–100 g/L for red clay, Haselbach reported surface clogging, for which brush cleaning restored up to 18% of the infiltration rate after the first clogging cycle, as opposed to the depth clogging observed in this study. It is not possible to determine whether this qualitative difference—between surface and depth clogging—results from using different clays, by using different cleaning techniques, or the difference between a single layer of pervious concrete and a pervious concrete system, but it does emphasize an important general observation: Depth clogging, in which clogging materials accumulate below the pavement surface, is a major concern simply because cleaning is difficult in this circumstance (Bean et al. 2007; Haselbach and Freeman 2006; Hatt et al. 2008) and is analogous to the phenomenon of clogging at the soil interface observed in studies of granular infiltration systems (Siriwardene et al. 2007). Further, depth clogging likely explains why pressure washing provided no significant improvement in infiltration, although the surface appeared clean.

Comparison of the current study with the extensive field analysis of Bean et al. (2007) brings up several questions of how laboratory and field analysis can be incorporated to better understand the mechanisms of failure in pervious concrete and surfaces attributable to clogging. The detailed field analysis by Bean et al. (2007) reports and records infiltration rates for four sites of varied design, pavement materials, dimensions, locations, and uses. In contrast, the current laboratory study, conducted with pervious concrete and an underlying soil system designed to simulate saturated onedimensional flow, showed almost no measurable reduction in hydraulic conductivity in the pervious concrete layer, because essentially all head loss occurred in the base course and substitute subgrade. The current study suggests that surface infiltration is affected by all the underlying soils, geo-membranes, saturated water storage, and their interfaces. Each of these media or interfaces could interact with the varied clogging materials that could be present at each of the sites. On the basis of this understanding,
one can speculate that clogging materials may originate on the surface, but easily transfer through the pervious surface and interact with the different underlying layers. This does not appear to contradict the study of Bean et al. (2007), and perhaps even opens up the opportunity to do further laboratory work that better simulates field conditions. In the meantime, the best message to practitioners is to design a large enough volumetric storage area of gravel or equivalent base course under the pervious surface. In other words, the infiltration capacity of pervious concrete pavement systems appears to be more reliable than their exfiltration capacity.

As a final note, because the pervious concrete had very little effect on the observed infiltration and exfiltration rates, one would speculate that the present results would also provide insight into the hydrologic performance of other porous pavements, such as porous asphalt or paving blocks, in circumstances where the subgrade exfiltration is the flow-limiting element in the pervious pavement system.

Conclusions

The conclusions of this study may be summarized as follows:

- Both sand and clay (montmorillonite) cause clogging, with clay causing approximately ten times more clogging than sand per mass.
- After clogging, the infiltration rate was still above the average intensity of the relevant design storm, but this result may be an artifact of using a thin substitute subgrade with a large hydraulic conductivity.
- Even when clogged with sand and clay, most of the head loss occurred in the substitute subgrade rather than the pervious concrete. Thus, the subgrade exfiltration is the flow-limiting element.
- Pervious concrete would be effective for storm-water retention, when provided with an engineered drainage system, but its performance for storm-water infiltration will be limited by the exfiltration characteristics of the subgrade.
- Pressure washing does not restore infiltration into pervious concrete pavement systems when the subgrade is the exfiltration-limiting element.

Acknowledgments

The writers would like to thank Stephan Durham, Bethany Hynes, Ed Moss, Larry Scherrer, and Mike Schiavone for collegial assistance, the Colorado Department of Transportation for donating the base course and sand, and Colorado Hardscapes for donating the pervious concrete samples. The writers would also like to thank the anonymous referees for their constructive feedback.

References


学霸图书馆

www.xuebalib.com

本文献由“学霸图书馆-文献云下载”收集自网络，仅供学习交流使用。

学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。

图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：

图书馆首页 文献云下载 图书馆入口 外文数据库大全 疑难文献辅助工具