Permeable Friction Course (PFC) for Improving Highway Runoff

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Philadelphia, PA
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Presentation Overview

- PFC Background
- Water Quality Monitoring
- Hydraulic Testing
- Hydraulic Modeling
- Conclusions
Benefits associated with driver safety and water quality
- Approved as BMP/SCM for Edwards Aquifer zone in Texas
- Considered sacrificial layer with design life of ~10 years
- Pore space can become clogged over time
  - Will drainage benefits degrade over time?
Aggregate Gradation

PFC

HMA
Where is PFC Being Used?
Improved Driver Safety

- Reduction in splash/spray
- Improved visibility
- Reduced hydroplaning
- Decreased stopping distance
BMP Assessment

- Four levels to assess performance of BMPs
  - Visual inspection
  - Capacity testing
  - Synthetic runoff testing
  - Stormwater monitoring
Monitoring Sites and Methods

Site 1

Site 2 & Site 3
TSS at Site 2

- TSS (mg/L)
- Date
- PFC
- Conventional
## Effluent Concentrations from PFC

<table>
<thead>
<tr>
<th>Monitoring Location</th>
<th>No. of Samples</th>
<th>TSS (mg/L)</th>
<th>SSC</th>
<th>TKN (mg/L)</th>
<th>Nitrate (mg/L)</th>
<th>Total P (μg/L)</th>
<th>Total Cu (μg/L)</th>
<th>Total Pb (μg/L)</th>
<th>Total Zn (μg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop 360, TX (1)²</td>
<td>48</td>
<td>8.0</td>
<td>--</td>
<td>0.79</td>
<td>0.28</td>
<td>0.04</td>
<td>11</td>
<td>&lt;1.0</td>
<td>22</td>
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<td>Loop 360, TX (2)²</td>
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<td>12</td>
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<td>0.21</td>
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<td>12</td>
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<tr>
<td>RR 620, TX²</td>
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<td>6.3</td>
<td>--</td>
<td>0.62</td>
<td>0.27</td>
<td>0.04</td>
<td>7.5</td>
<td>&lt;1.0</td>
<td>18</td>
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<tr>
<td>A9, Netherlands¹</td>
<td>6</td>
<td>17</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>40</td>
<td>7.0</td>
<td>47</td>
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<tr>
<td>Interstate 95, MA³</td>
<td>18</td>
<td>--</td>
<td>88</td>
<td>--</td>
<td>--</td>
<td>0.13</td>
<td>52</td>
<td>18</td>
<td>110</td>
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<tr>
<td>Interstate 190, MA³</td>
<td>6</td>
<td>--</td>
<td>52</td>
<td>--</td>
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<td>--</td>
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<td>--</td>
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<td>76</td>
<td>610</td>
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<tr>
<td>Interstate 40, NC (1)⁴</td>
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<td>0.39</td>
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<td>17</td>
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<td>0.40</td>
<td>0.08</td>
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<tr>
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<td>8.0</td>
<td>--</td>
<td>1.0</td>
<td>0.76</td>
<td>0.08</td>
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<td>A6, Germany⁵</td>
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<td>56 (FS)</td>
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<td>1.2</td>
<td>2.1</td>
<td>--</td>
<td>20</td>
<td>8.7</td>
<td>77</td>
</tr>
</tbody>
</table>

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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

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- Value determined from five samples
- Value reported as sum of NO₃ and NO₂
### Paired Samples

- Percent reduction from PFC compared to conventional pavement

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<th>Nitrate</th>
<th>Total P</th>
<th>Total Cu</th>
<th>Total Pb</th>
<th>Total Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop 360, TX (1)^2</td>
<td>-93^a</td>
<td>--</td>
<td>-25</td>
<td>6</td>
<td>-75^a</td>
<td>-60^a</td>
<td>&lt; -90^a</td>
<td>-87^a</td>
</tr>
<tr>
<td>Loop 360, TX (2)^2</td>
<td>-91^a</td>
<td>--</td>
<td>-49</td>
<td>31</td>
<td>-66^a</td>
<td>-56^a</td>
<td>&lt; -90^a</td>
<td>-87^a</td>
</tr>
<tr>
<td>RR 620, TX^2</td>
<td>-96^a</td>
<td>--</td>
<td>-63^a</td>
<td>46</td>
<td>-78^a</td>
<td>-69^a</td>
<td>&lt; -96^a</td>
<td>-90^a</td>
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<tr>
<td>A9, Netherlands^1</td>
<td>-91^b</td>
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<td>--</td>
<td>--</td>
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<td>--</td>
<td>-66^b</td>
<td>-92</td>
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<td>Interstate 95, MA^3</td>
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<td>--</td>
<td>--</td>
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<td>8.2</td>
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<td>A11, France^6</td>
<td>-81^a</td>
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<td>-69^a</td>
<td>--</td>
<td>-35^a</td>
<td>-78^a</td>
<td>-66^a</td>
</tr>
</tbody>
</table>

^a Significant at 95% confidence level
^b Statistical tests were not reported, but the ranges of observed values did not overlap for this parameter

1 Berbee et al., 1999; 2 Eck et al., 2011; 3 Smith and Granato, 2009; 6 Pagotto et al., 2000
BMP Assessment

- Four levels to assess performance of BMPs
  - Visual inspection
  - Capacity testing
  - Synthetic runoff testing
  - Stormwater monitoring
PFC Core Specimens

- Laboratory measurement on core specimens
  - Three roadways: Loop 360, FM 1431, and RR 620
  - Four years: 2007 to 2010
- Lab measurement of effective porosity
- Lab measurement of hydraulic conductivity
- Develop field test to measure in-situ hydraulic conductivity
Porosity Results

- Average porosity ± one standard deviation

![Graph showing porosity results over years for different loops: Loop 360, FM 1431, RR 620. Porosity values decrease over time with error bars indicating variability.](image)
- Series of constant head tests
- No-flow and known head boundary conditions
- Two-dimensional, nonlinear cylindrical flow
Lab Constant Head Results

- Clear nonlinear relationship – Forchheimer equation
Lab Hydraulic Conductivity Results

- Average hydraulic conductivity ± one standard deviation

![Graph showing hydraulic conductivity over years for different loops such as Loop 360, FM 1431, and RR 620.](image-url)
PFC can become clogged with trapped sediment over time
Need quick, non-destructive field test to determine in-situ hydraulic conductivity
Use to assess the water quality performance of the BMP
Falling head test with nonlinear flow
Loop 360: $K = 3.0 \text{ cm/s}$
FM 1431: $K = 0.6 \text{ cm/s}$
RR 620: $K = 1.5 \text{ cm/s}$
Hydraulic Modeling

- Model PFC as an unconfined aquifer on a sloping boundary
- Couple subsurface flow with surface flow when PFC layer becomes saturated (PERFCODE)
- Solve for water depth in pavement and sheet flow depth on surface
Conclusions

- PFC provides improved water quality for TSS, total Cu, total Pb, and total Zn (sediment-bound pollutants)
- Mixed results for nutrient removal
- Effective porosity range from 12% to 23% (decrease over time?)
- Two-dimensional nonlinear flow (Forchheimer equation) modeling to determine hydraulic conductivity
- Field test for in-situ hydraulic conductivity
- Hydraulic conductivity range 0.2 to 3.0 cm/s
- PERFCODE modeling to predict water depth for design
- No maintenance on PFC in Texas with continued water quality benefits
- The roadway itself acts as the BMP!
Acknowledgements

- TxDOT Project No. 0-5220
- Gary Lantrip
- Dr. Randall Charbeneau
- Dr. Michael Barrett
- Dr. Brad Eck
Questions or Comments?

- Thank you!
**TxDOT Method**
- Water immediately surfaces outside of pipe resulting in little flow through PFC
- No indication of actual $K$

**New Method**
- Water is forced to flow through PFC
- Can determine Forchheimer coefficients and $K$
What is Nonlinear Flow?

- Darcy’s Law – linear flow
  \[ Q = K A \frac{\Delta h}{L} \quad \rightarrow \quad q = K I \quad \rightarrow \quad I = \frac{1}{K} q \]

- Forchheimer equation – nonlinear flow
  \[ I = \frac{1}{K} q + bq^2 \]
Numerical Modeling

- **Continuity equation** in two-dimensional cylindrical coordinates

\[
\frac{1}{r} \frac{\partial}{\partial r} (rq_r) + \frac{\partial q_z}{\partial z} = 0
\]

\[I = aq + bq^2\]

- Finite difference scheme to solve continuity
- Input: core dimensions, \( h_s \), \( a \) and \( b \)
  - Calculate \( Q \) from outflow gradient
  - Develop curve of \( h_s \) vs. \( Q \)
- Output: \( \alpha \) and \( \beta \)
Approximate Analytical Solution

- Exact analytic solution provided by Carslaw and Jaeger (1959) for “infinite” core for Darcy flow

\[
h(r, z; N_i) = \frac{2}{\pi} h_s \sum_{j=-N_i}^{N_i} \sin^{-1}\left(\frac{2R_s}{\sqrt{(r - R_s)^2 + (z + 2jb_c)^2} + \sqrt{(r + R_s)^2 + (z + 2jb_c)^2}}\right)
\]

\[Q = 4Kh_sR_s\]