Performance Evaluation of Permeable Pavement Systems

Jaehun Ahn\textsuperscript{1}, Hyangseon Jung\textsuperscript{1}, Hyungwon Kim\textsuperscript{1}, Hyunsuk Shin\textsuperscript{1}, Shinin Han\textsuperscript{2}

\textsuperscript{1}Civil and Environmental Eng., Pusan National University
\textsuperscript{2}Seoyeong Engineering Co., Ltd.
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Contents

- Introduction

- Element, Model and Prototype Scale Tests
  - Element Scale Example
    - Permeability and Clogging
  - Model Scale Example
    - Rainfall Infiltration / SWCC Back-Calculation

- Summary
Introduction
Introduction

Nakdong River LID

[Images of Nakdong River LID projects]

[Link: (http://glenc.co.kr/intro/idx44.htm)]
**Nakdong River LID**

[http://glenc.co.kr/intro/idx44.htm](http://glenc.co.kr/intro/idx44.htm)
Introduction
## Cement Concrete Mixture Design

<table>
<thead>
<tr>
<th>Variable</th>
<th>Korea (Ministry of Land, Infrastructure and Transport)</th>
<th>Japan (Japan Road Institute)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-Pervious Concrete</td>
<td></td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>≥ 4.5 MPa</td>
<td>≥ 4.5 MPa</td>
</tr>
<tr>
<td>Permeability</td>
<td>≥ 0.01 cm/s</td>
<td>≥ 0.1 cm/s</td>
</tr>
<tr>
<td>Porosity</td>
<td>15-20%</td>
<td>20-25%</td>
</tr>
</tbody>
</table>

## Permeable Block Design

<table>
<thead>
<tr>
<th>Variable</th>
<th>Korea (Seoul Metropolitan City)</th>
<th>Japan (Interlocking Block Pavement Technology Institute)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Porous Block</td>
<td>Interlocking Block</td>
</tr>
<tr>
<td></td>
<td>Vehicle Road</td>
<td>Pedestrian Road</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>≥ 5 Mpa</td>
<td>≥ 4 MPa</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>≥ 20 MPa</td>
<td>≥ 16 MPa</td>
</tr>
<tr>
<td>Permeability</td>
<td>≥ 0.01 cm/s</td>
<td>≥ 0.01 cm/s</td>
</tr>
</tbody>
</table>
## Asphalt Concrete Mixture Design

<table>
<thead>
<tr>
<th>Variable</th>
<th>Permeable Friction Course</th>
<th>Permeable Pavement (Infiltration to Base)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Korea</td>
<td>United States</td>
</tr>
<tr>
<td></td>
<td>Ministry of Land, Infrastructure and Transport</td>
<td>Seoul Metropolitan City</td>
</tr>
<tr>
<td>Porosity</td>
<td>20±0.3%</td>
<td>20±1%</td>
</tr>
<tr>
<td>Permeability</td>
<td>≥ 0.01 cm/s</td>
<td>≥ 0.01 cm/s</td>
</tr>
<tr>
<td>Cantabro Loss</td>
<td>≤ 20% (20°C)</td>
<td>≤ 30% (-20°C)</td>
</tr>
<tr>
<td>Drain-Down</td>
<td>≤ 30%</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength Retained (TSR)</td>
<td>≥ 85%</td>
<td>≥ 70%</td>
</tr>
<tr>
<td>Wheel Tracking Test</td>
<td>≥ 3000 cycles/mm</td>
<td>≥ 3000 cycles/mm</td>
</tr>
<tr>
<td>Overlay Tester</td>
<td></td>
<td>≥ 200 cycles</td>
</tr>
<tr>
<td>Marshall Stability</td>
<td>≥ 5.0 kN</td>
<td></td>
</tr>
<tr>
<td>Flow Value</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Model Scale Test

Hydrological Cycle Implementation

- Distributed Rainfall Simulator
- Precipitation
- Evaporation
- Infiltration
- Overland Flow
- Groundwater Runoff
- Surface Runoff
- Subsurface Runoff
- Runoff Container
- Runoff Plot

Flow meters 1 and 2
Prototype Test

Pressure head observation

Water quality sampling

Underdrain effluent flux collection
Prototype Test
# Element, Model and Prototype Scale Tests

<table>
<thead>
<tr>
<th>Test Scale</th>
<th>Material</th>
<th>Structural</th>
<th>Hydrologic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>Pavement</td>
<td><strong>Cantabro Test</strong>&lt;br&gt;Tensile Strength Reduced&lt;br&gt;<em>Drain-Down</em> (Asphalt)&lt;br&gt;Wheel Tracking (Asphalt)&lt;br&gt;Marshall Stability (Asphalt)&lt;br&gt;Dynamic Modulus (Asphalt)&lt;br&gt;<strong>Flexural Strength (Concrete, Block)</strong>&lt;br&gt;Compressive Strength (Concrete, Block)</td>
<td><strong>Porosity Permeability Clogging</strong>&lt;br&gt;Soil-Water Characteristic Curve</td>
</tr>
<tr>
<td>Aggregate &amp; Soil</td>
<td><strong>Particle Size Distribution</strong>&lt;br&gt;<strong>Maximum Unit Weight</strong>&lt;br&gt;<strong>California Bearing Ratio</strong>&lt;br&gt;Compression Test&lt;br&gt;Resilient Modulus&lt;br&gt;Cantabro Test (Aggregate)</td>
<td><strong>Porosity Permeability</strong>&lt;br&gt;Soil-Water Characteristic Curve</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Scale</th>
<th>Environmental &amp; Thermal</th>
<th>Hydrologic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Contamination (Controlled)</td>
<td><strong>Infiltration – Rainfall</strong>&lt;br&gt;Infiltration – Ponding&lt;br&gt;Clogging&lt;br&gt;Evapotranspiration</td>
</tr>
<tr>
<td>Prototype</td>
<td>Contamination (Uncontrolled)&lt;br&gt;Surface Temperature</td>
<td><strong>Infiltration – Rainfall</strong>&lt;br&gt;Infiltration – Ponding&lt;br&gt;Evapotranspiration</td>
</tr>
</tbody>
</table>

**Bold** – may be used for design criteria  
**Italic** – may not be equipped in Korean LID Research Center
Element Scale Test – Permeability and Clogging

Test Procedure - Clogging

1. Sample setup
2. Sample saturation
3. Heads adjustment
4. Water flow for 10 mins
5. Hold water flow
6. Apply 40 g clogging particle
7. Brush clogging particle into pore
8. End

Repeat until no more clogging applicable
Element Scale Test – Permeability and Clogging

**Mixing Tank**

- Tank Capacity: 200 L
- Mixer Speed: 5.5 rps Max

**Pump**

- Capacity: 150 L/h Max
- Water can circulate into the tank using a bypass value
Element Scale Test – Permeability and Clogging

### Stand Column
- Cross-Section: 300x300 mm
- Three sections assembled

### Column Section
- Outlet valves at 150, 300, 600 mm for constant heads
- Overflow can circulate to mixing tank

### Pavement Section
- Height: 100, 150, 200 mm
- 꼴, ⌒ shape assembled

### Aggregate Section
- Height can adjust up to 400mm
Element Scale Test – Permeability and Clogging

Flow Meter

Tipping bucket

100, 200, 300 ml buckets
Counter connected to data acquisition
Calibration required
Element Scale Test – Permeability and Clogging

**Test Material**

**Pervious Concrete**

- **Mixing (KS F2425)** - Mixer used with following proportion
- **Compaction (KS F2043)**

**Mixture proportions of the pervious concrete mixtures**

<table>
<thead>
<tr>
<th>Pervious concrete No.</th>
<th>Cement (kg/m³)</th>
<th>3/8” aggregates 12.5~9.5 mm (kg/m³)</th>
<th>#8 aggregates 4.75~2.36mm (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>312</td>
<td>1558</td>
<td>-</td>
<td>103</td>
<td>0.20</td>
</tr>
<tr>
<td>Type B</td>
<td>312</td>
<td>-</td>
<td>1559</td>
<td>103</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Element Scale Test – Permeability and Clogging

### Test Material

#### Base

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>40</th>
<th>20</th>
<th>5</th>
<th>2</th>
<th>0.4</th>
<th>0.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>100</td>
<td>79</td>
<td>49</td>
<td>31</td>
<td>14</td>
<td>5.5</td>
</tr>
</tbody>
</table>

#### Water Content (%)

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Dry Density (g/cm³)</th>
<th>Relative Density (%)</th>
<th>Volume (cm³)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>1.969</td>
<td>90</td>
<td>36000</td>
<td>72.36</td>
</tr>
</tbody>
</table>

#### Clogging Particle

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Sieve No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>#6 Silica Sand</td>
<td>0.25~0.6</td>
</tr>
<tr>
<td>#8 Silica Sand</td>
<td>0.075~0.1</td>
</tr>
</tbody>
</table>
Element Scale Test – Permeability and Clogging

**Permeability – No Clogging**

- Pervious Concrete (Type A)
- Base
- Pervious Concrete (Type A) + Base

**Permeability – Clogging**

- Pervious Concrete (Type A) with Clogging Sand #6
- Pervious Concrete (Type A) with Clogging Sand #8
- Pervious Concrete (Type B) with Clogging Sand #6
- Pervious Concrete (Type B) with Clogging Sand #8
**Pervious Concrete (Type A)**

\[ v = k_i^n \]
\[ v = 0.246i^{0.728} \]

\[ n = 0.72 \]
\[ k = 0.246 \text{ (cm/s)} \]

**Base**

\[ v = k_i^n \]
\[ v = 0.066i^{0.80} \]

\[ n = 0.80 \]
\[ k = 0.066 \text{ (cm/s)} \]
Element Scale Test – Permeability and Clogging

Permeability – No Clogging

Pervious Concrete + Base

\[ v = k i^n \]
\[ v = 0.072 i^{0.74} \]
\[ n = 0.74 \]
\[ k = 0.072 \text{ (cm/s)} \]

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pervious Concrete</td>
<td>0.72</td>
<td>0.246</td>
</tr>
<tr>
<td>Base</td>
<td>0.80</td>
<td>0.066</td>
</tr>
<tr>
<td>Pervious Concrete + Base</td>
<td>0.74</td>
<td>0.072</td>
</tr>
</tbody>
</table>
Element Scale Test – Permeability and Clogging

Permeability – Clogging

Type A Clogged with #6 Sand

<table>
<thead>
<tr>
<th>Clogged Sediment</th>
<th>k (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No clogging</td>
<td>0.1932</td>
</tr>
<tr>
<td>40 g</td>
<td>0.1611</td>
</tr>
<tr>
<td>80 g</td>
<td>0.1361</td>
</tr>
<tr>
<td>120 g</td>
<td>0.1181</td>
</tr>
<tr>
<td>160 g</td>
<td>0.0899</td>
</tr>
<tr>
<td>200 g</td>
<td>0.0767</td>
</tr>
</tbody>
</table>

Type A Clogged with #8 Sand

<table>
<thead>
<tr>
<th>Clogged Sediment</th>
<th>k (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No clogging</td>
<td>0.2237</td>
</tr>
<tr>
<td>40 g</td>
<td>0.2049</td>
</tr>
<tr>
<td>80 g</td>
<td>0.1791</td>
</tr>
<tr>
<td>120 g</td>
<td>0.1666</td>
</tr>
<tr>
<td>160 g</td>
<td>0.1634</td>
</tr>
<tr>
<td>200 g</td>
<td>0.1400</td>
</tr>
<tr>
<td>240 g</td>
<td>0.1282</td>
</tr>
</tbody>
</table>
Element Scale Test – Permeability and Clogging

### Permeability – Clogging

#### Type B Clogged with #6 Sand

<table>
<thead>
<tr>
<th>Clogged Sediment</th>
<th>k (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No clogging</td>
<td>0.0320</td>
</tr>
<tr>
<td>40 g</td>
<td>0.0226</td>
</tr>
<tr>
<td>80 g</td>
<td>0.0148</td>
</tr>
<tr>
<td>120 g</td>
<td>0.0109</td>
</tr>
</tbody>
</table>

#### Type B Clogged with #8 Sand

<table>
<thead>
<tr>
<th>Clogged Sediment</th>
<th>K (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No clogging</td>
<td>0.0539</td>
</tr>
<tr>
<td>40 g</td>
<td>0.0434</td>
</tr>
<tr>
<td>80 g</td>
<td>0.0340</td>
</tr>
<tr>
<td>120 g</td>
<td>0.0340</td>
</tr>
<tr>
<td>160 g</td>
<td>0.0281</td>
</tr>
</tbody>
</table>
More sediments are clogged in the concrete with larger pore.

When the same amount of sediments are applied, #6 sand tends to reduce permeability more.
Model Scale Test – Rainfall Infiltration

- Pavement Permeameter
  - Upper Section
  - Lower Section
- Counter
- Data Logger
- Lysimeter
- Tipping Bucket
Model Scale Test – Rainfall Infiltration

Upper Section

- For pavement section of height 10, 15 and 20 cm
- Dimensions: 30x30x15 cm, x20 cm, x25 cm
- Values 5 cm below the top for runoff
- ▲, ▼ shape to assemble pavement

Lower Section

- For base layer
- Drainage at the bottom
Model Scale Test – Rainfall Infiltration

**Bottom Support**

- Accommodate base section up to 40 cm
- Geotextile layered

**Lysimeter**

- Record evapotranspiration
- Load Cell Capacity: 300 kg
- Load Cell Resolution: 0.01 kg
- Waterproof roof
Model Scale Test – Railfall Infiltration

**Tipping Bucket**
- Measure flow rate
- 100, 200, 500 ml buckets

**Counter**

**Data Logger**
Model Scale Test – Infiltration

**Material**

**Pervious Concrete**
- Dimensions: 30x30x10 cm
- Compaction following KS F 2043
- Weight: 17.64kg
- Unit Weight: 19.21 kN/m³

**40 mm Aggregate Well-Graded**

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>50</th>
<th>40</th>
<th>20</th>
<th>5</th>
<th>2</th>
<th>0.4</th>
<th>0.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>100</td>
<td>100</td>
<td>79</td>
<td>49</td>
<td>31</td>
<td>14</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- Dimensions: 30x30x40 cm
- 90% Relative Compaction
- Compacted in two layers (20 cm each)
- Weight: 72kg

**40 mm Aggregate Uniform**

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>50</th>
<th>40</th>
<th>20</th>
<th>10</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>100</td>
<td>100</td>
<td>51</td>
<td>15</td>
<td>2</td>
</tr>
</tbody>
</table>

- Dimensions: 30x30x40 cm
- Compacted in four layers (10 cm each)
- Weight: 72kg
Model Scale Test – Rainfall Infiltration

Test Procedure

• Compact base layer
• Assemble and setup pavement layer
• Adjust and calibrate rainfall intensity
• Setup permeameter and rainfall simulator
• Spray water and measure runoff and drainage
Model Scale Test – Rainfall Infiltration

Test Results – Infiltration to Pervious Concrete + Base

- Rainfall Intensity: 148 mm/hr
- Duration: 3600 s

Graphs showing cumulative flux over time for Well-Graded Base and Uniform Base.
Van Genuchten-Mualem Model (Van Genuchten, 1980; Mualem, 1976)

### Soil-Water Characteristics Curve

\[
\theta(h) = \begin{cases} 
\theta_r + \frac{\theta_s - \theta_r}{[1 + \alpha h l^m]^m} & h < 0 \\
\theta_s & h \geq 0 
\end{cases}
\]

- \(\theta_r\) = residual water content
- \(\theta_s\) = saturated water content (or porosity)
- \(\alpha\) = suction head at air entry (\(\alpha > 0\))
- \(n\) = coefficient regarding pore size distribution (\(n > 1\))
- \(m = 1 - 1/n\)
- \(h\) = suction head

### Relative Permeability Function

\[
K(h) = K_s S_e^l [1 - (1 - S_e^{l/m})^m]^2
\]

- \(K_s\) = saturated permeability
- \(S_e\) = effective degree of saturation
  \[= \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\]
- \(l\) = coefficient regarding connectivity of pore
  \[= 0.5\] for geotechnical material
## Model Scale Test – SWCC Back-Calculation

### Pervious Concrete

- Dimensions: 30x30x20 cm
- Weight: 34.5 kg
- Mixed for construction (The GL, 2015)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>0.0755 cm/s</td>
<td>Lab Test</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>0.216</td>
<td>Lab Test</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>0.0001</td>
<td>Kim et al. (2015)</td>
</tr>
<tr>
<td>$l$</td>
<td>0.5</td>
<td>Mualem (1976)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Unknown</td>
<td>Inverse Analysis</td>
</tr>
<tr>
<td>$n$</td>
<td>Unknown</td>
<td>Inverse Analysis</td>
</tr>
</tbody>
</table>
Model Scale Test – SWCC Back-Calculation

### Constant Head Test

\[
k = \frac{L}{h} \times \frac{Q}{A(t_2 - t_1)}
\]

- \(h\) = head difference (\(= 20\) cm)
- \(Q\) = volume of flow
- \(t\) = duration (\(= 600\) s)

\(k\) = permeability
\(= 0.0755\) cm/s

<table>
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</tr>
</thead>
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<tr>
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<td>Lab Test</td>
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<tr>
<td>(\theta_s)</td>
<td>0.216</td>
<td>Lab Test</td>
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<tr>
<td>(\theta_r)</td>
<td>0.0001</td>
<td>Kim et al. (2015)</td>
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<tr>
<td>(l)</td>
<td>0.5</td>
<td>Mualem (1976)</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Unknown</td>
<td>Inverse Analysis</td>
</tr>
<tr>
<td>(n)</td>
<td>Unknown</td>
<td>Inverse Analysis</td>
</tr>
</tbody>
</table>

### Porosity

\[P(\%) = 1 - \frac{W_D - W_S}{\gamma_w V_T} (\times 100\%)
\]

- \(W_D\) = dry weight
- \(W_S\) = submerged weight
- \(V_T\) = total volume
- \(\gamma_w\) = unit weight of water

\(P = 21.6\%\)
Model Scale Test – SWCC Back-Calculation

**Parameter** | **Value** | **Source**
---|---|---

\( K_s \) | 0.0755 cm/s | Lab Test
\( \theta_s \) | 0.216 | Lab Test
\( \theta_r \) | 0.0001 | Kim et al. (2015)
\( l \) | 0.5 | Mualem (1976)
\( \alpha \) | Unknown | Inverse Analysis
\( n \) | Unknown | Inverse Analysis

**Diagram Description**
- **Unknown System**
  - Finite Element Model – HYDRUS 2D (PC-Progress, 2011)

- **Model**
  - **UNKNOWN SYSTEM**
  - **MODEL**
    - Drainage Measured
    - Drainage Calculated
- **Error minimized?**
  - **No**
    - **PARAMETER ADJUSTMENT ALGORITHM**
    - \( \alpha^{(n+1)} \) and \( n^{(n+1)} \)
  - **Yes**
    - **PARAMETER DETERMINATION**
    - \( \alpha^{(n)} \) and \( n^{(n)} \)
Model Scale Test – SWCC Back-Calculation

Test Case
- Rainfall Intensity: 136 mm/hr
- Duration: 1400 s (23 min)

Measured and Calculated Drainage for Inverse Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>0.0755 cm/s</td>
<td>Lab Test</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>0.216</td>
<td>Lab Test</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>0.0001</td>
<td>Kim et al. (2015)</td>
</tr>
<tr>
<td>$l$</td>
<td>0.5</td>
<td>Mualem (1976)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>3.69</td>
<td>Inverse Analysis</td>
</tr>
<tr>
<td>$n$</td>
<td>4.42</td>
<td>Inverse Analysis</td>
</tr>
</tbody>
</table>

$\alpha = 3.69$ and $n = 4.42$ estimated
Model Scale Test – SWCC Back-Calculation

Soil-Water Characteristics Curve of Pervious Concrete

Soil-Water Characteristics Curve of Soils (Schanz, 2007)
Summary

- A test program and facility with scales of element, model and prototype experiments is under development.

- Equipment for infiltration and permeability, considering clogging, of permeable pavement systems is developed and being tested.

- Soil-Water Characteristic Curve of a pervious concrete sample was successfully back-calculated based on rainfall infiltration model test.