Prediction of Thermal Behavior of Pervious Concrete Pavements in Winter

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Research Impetus

• Increased use of pervious concrete pavements in cold climate areas
• Maintaining winter safety/mobility require proper winter maintenance
  • Timely salting, anti-icing, deicing
• Research needs
  • 1) PCP thermal properties & behavior
  • 2) PCP temperature prediction as groundwork for winter maintenance practices
Project Objectives

1. Experimentally determine thermal conductivity ($k$) of pervious concrete in variable porosity
2. Predict PCP surface temp in winter based on field data
3. Develop relationship to predict surface temperature based on ambient conditions
Laboratory Experiment

• Two methods to determine $k$:
  • ASTM C518-15 Heat flow meter (FOX 304 by LaserComp TA instruments)
  • ASTM D5334-14 Heat impulse (Decagon RK-1 Rock Sensor Kit)
Mixture Design

• Mixture design

<table>
<thead>
<tr>
<th>Constituents in SSD conditions</th>
<th>lb/yd³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregate</td>
<td>2,635</td>
</tr>
<tr>
<td>Type I/II Cement</td>
<td>568</td>
</tr>
<tr>
<td>Class F Fly ash</td>
<td>100</td>
</tr>
<tr>
<td>Water</td>
<td>161</td>
</tr>
</tbody>
</table>

• Specimens
  • 20 Cylinders (φ4”× 8”) cut in half
  • 6 Slabs (~11”×11”×3”)
Specimens Casting & Curing

• Compaction
  • Slabs porosity: 19, 21, 24, 26, 31, 36%
  • Cylinders: 16-23%

• Curing
  • Demolded & tested after 7 days air cured in lab

Compaction using Proctor hammer
Physical Properties

• Hardened Porosity (ASTM C1754)

\[
Air \text{ Void Content} = (1 - \frac{M_w - M_d}{\rho_w V})
\]

• Infiltration Test (ASTM C1701)

\[
I = \frac{KM}{D^2 t}
\]

M: mass of infiltrated water in lbs,
D: inside diameter of infiltration ring in inch
T: time required for designated mass of water to infiltrate through PC in seconds
K: correction factor equal to 126,870 inch.
1. **Heat flow meter** (ASTM C518)
   
   • Conductivity based on Fourier’s Law: ability of material to transfer heat through a unit-length thickness.

   \[ q = -K \frac{\partial T}{\partial x} \]

   FOX 304 Heatflow meter
2. **Sensor probe** RK-1 Rock Sensor Kit
   - Applies heat impulse
   - Auto log data
Test Results-Slabs

- RK-1 higher $k$ than FOX 304
- FOX 304 shows less variation
  - Due to temp-controlled environment

$k_{probe} = -1.25\phi + 0.76$
$R^2 = 0.76$

$k_{heatflow} = -1.52\phi + 0.93$
$R^2 = 0.67$

$1 \text{ W/(mK)} = 1.7307 \times \text{Btu/(hr ft °F)}$
Comparison of Two Methods

- Heat Flow Meter captures $k$ of slabs using whole depth from top to bottom in several heat steps.
- Values of $k$ from **RK-1** Sensor based on contact area of probe & specimen. Probe length 2.33 in $\Rightarrow$ bottom 1.67 in of slab neglected.

![Graph showing conversion from RK2 to heatflow](attachment:chart.png)

- $y = 0.8225x - 0.019$
- $R^2 = 0.8813$
• Bottom halves: $k = 0.49 \text{ W/(mK)}$
• Top halves: $k = 0.56 \text{ W/(mK)}$ for top halves
Geometric Parallel Model

\[
\log K_p = V_{air} \log K_{air} + V_{paste} \log K_{paste} + V_{agg} \log K_{agg}
\]

Air voids, \(V_{air}, k_{air}\)

Cement Paste, \(V_{paste}, k_{paste}\)

Coarse Aggregate, \(V_{agg}, k_{agg}\)

\(Q\)

(Nassiri & Nantasai 2017)

<table>
<thead>
<tr>
<th>(k_{agg}) (crushed Basalt) W/(mK)</th>
<th>(K_{paste}) W/(mK)</th>
<th>(K_{air}) W/(mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.69</td>
<td>0.98</td>
<td>0.026</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(V_{air} = \varphi)</th>
<th>(V_{agg})</th>
<th>(V_{paste})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td>0.47</td>
<td>0.34</td>
</tr>
<tr>
<td>0.21</td>
<td>0.46</td>
<td>0.33</td>
</tr>
<tr>
<td>0.24</td>
<td>0.44</td>
<td>0.32</td>
</tr>
<tr>
<td>0.26</td>
<td>0.43</td>
<td>0.31</td>
</tr>
<tr>
<td>0.31</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>0.36</td>
<td>0.37</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Model’s Accuracy

- Slabs

\[ y = 1.016x + 0.011 \]

\[ R^2 = 0.80 \]

Dry slabs - 1:1 line
Model Predictions

• Cylinders

![Graph showing predicted vs measured K (W/mK)]

- Predicted K (W/mK)
- Measured K (W/mK)

1:1 Line

- Bottom Half
- Top Half

Equations:

\[ y = 0.72x + 0.24 \quad \text{R}^2 = 0.49 \]

\[ y = 0.66x + 0.21 \quad \text{R}^2 = 0.21 \]
Field Data Collection
Instrumented Field Project

- Weather station on campus
  - Ambient temp, RH, wind speed
  - Solar radiation from on-site pyranometer
Sensor Tree Details

- Two sensor trees:
  - Monitor volumetric water content & temp of PCP (5TE sensors)
  - Seven thermocouples
• No. of days that temp fell below 32°F:
  • Year 1: 39 days
  • Year 2: 64 days
Pavement Temp Data

- Sensor Tree A and B same data
- No. of days that temp fell below 32F:
  - Year 1: 43 days
  - Year 2: 66 days
Zone A Temperature Comparison @ Different Depths

Days from 5/21/2015 - 4/4/2017

Temperature at (°F)

0.5"
1.5"
2"
3"
Boundary Conditions

• Predict surface temperature for winter maintenance
• Enhanced Integrated Climatic Model (EICM)

\[
\frac{d}{dx} \left( K \cdot \frac{dT}{dx} \right) = \rho \cdot C_p \cdot \frac{dT}{dt}
\]

(Dempsey et al. 1983)

\[
Q_{rad} = Q_s - Q_r - Q_e + Q_a
\]

\(Q_s\) = Radiation from space, Btu/hr·ft²·°F,
\(Q_r\) = Reflection from clouds, Btu/hr·ft²·°F,
\(Q_e\) = Reflection from the pavement, Btu/hr·ft²·°F,
\(Q_a\) = Radiation bounced from clouds, Btu/hr·ft²·°F.
In-situ Porosity

• Total Porosity & Infiltration

\[ P = 0.002I + 20 \]

P = whole porosity, %
I = Infiltration (cm/hr)

(Haselbach & Freeman 2006)

• Porosity of each Layer

\[ P_{\text{top}} = 1.07P - 7 \quad P_{\text{mid}} = P \quad P_{\text{bot}} = 0.93P + 7 \]

\[ P_{\text{top}} = \text{Porosity 1/3 PCP depth, \%} \]
\[ P_{\text{mid}} = \text{Porosity 2/3 PCP depth, \%} \]
\[ P_{\text{bot}} = \text{Porosity 3/3 PCP depth, \%} \]

(Haselbach et al. 2016)
Estimate Thermal Properties

• Thermal conductivity:

\[ \log K_p = n_{air} \log K_{air} + n_{paste} \log K_{paste} + n_{agg} \log K_{agg} \]

• Specific heat (\(C_p\)) of PC from \(C_p\) of components

\[ C_p = x_{agg} C_{agg} + x_{conc} C_{conc} + x_{air} C_{air} \]

• \(x_{agg}, x_{conc} \) & \(x_{air}\): volumetric fractions

• \(C_{agg}, C_{conc} \) & \(C_{air}\): specific heat of aggregate, cement paste, & air

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Volume Fraction (%)</th>
<th>(C_p) Btu/(lb˚F)</th>
<th>(K) BTU/(ft(^2)hr˚F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone Coarse Aggregate</td>
<td>60.7</td>
<td>1214.2</td>
<td>3.72</td>
</tr>
<tr>
<td>Cement Paste</td>
<td>19.3</td>
<td>837.3</td>
<td>0.77</td>
</tr>
<tr>
<td>Air</td>
<td>20.0</td>
<td>100.5</td>
<td>0.036</td>
</tr>
</tbody>
</table>

References available in Nantasai (2016)
EICM Prediction Discussion

- Overall good agreement
- Past Day 100: highly influenced by solar radiation & require characterization of surface emissivity

0.5-inch depth
• Best agreements achieved when ambient temp between 20-50°F

\[ y = 0.82x + 7.36 \]

\[ R^2 = 0.80 \]
Regression Model

\[ T_{surf} = 15.28 + 0.3486 \cdot T_{amb} + 0.1152 \cdot h_c + 0.03 \cdot S - 108.6 \cdot P - 0.0458 \cdot RH \\
+ 0.006350 \cdot T_{amb}^2 - 0.004546 \cdot h_c^2 + 0.005284 \cdot T_{amb} \cdot h_c - 0.000869 \cdot T_{amb} \cdot S \\
+ 0.001159 \cdot T_{amb} \cdot RH + 0.001394 \cdot h_c \cdot S - 0.000199 \cdot S \cdot RH + 1.211 \cdot P \cdot RH \]

- \( T_{amb} \) = Ambient temperature, F
- \( h_c \) = Wind speed, mph
- \( S \) = Percent sunshine, %
- \( P \) = Precipitation, in
- \( RH \) = Relative Humidity, %.

- Identify freezing potential of surface out of 121 days:
  - 67 days measured Vs. 57 days predicted
Conclusions

• Thermal conductivity of slabs obtained using heat flow
• Experiment expanded to cylinders using needle probe
• Relationship developed between $k$ and porosity
• Linear relationship developed to predict thermal properties based on mixture design
• Best estimate of in-situ porosity required
Conclusions

• In-field temp measurements form instrumented section used to validate a temp model

• EICM surface temp prediction agreed with 85% of measured temp

• Linear regression model developed using major climatic indices to estimate surface temp with good agreement
Recommendations

- More mixtures designs, structural designs need tested to expand parallel model
- Mixtures with a variety of aggregate to be tested
- Expand modeling to non-overcast conditions
  - Surface emissivity
  - Evaporation at surface
  - Presence of water
Acknowledgements

- Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) for funding
- Washington State Facilities for in-kind support and collaboration during pavement installation & instrumentation
- Benjamin Nantasai, MS student that worked on the project at the time
- Dr. Liv Haselbach for collaboration
Ongoing Research

- Skid Resistance in dry, wet, ice
- Application of anti/deicer agents
References


Thank you! Questions?