Why Noise Reducing Concrete Pavements?

- Road Traffic Noise – Dominant source of urban noise pollution
  - Tire-Road Interaction Noise most significant
- Conventional concrete is a good sound reflecting material
  - Used for Noise Barriers
  - Does Not Attenuate Sound
  - Noise Barriers impractical along bridges / urban highways
Noise Components

Source of Tire-Pavement Noise

Presentation Outline

- Modifications to the material structure of concrete
  - Enhanced Porosity Concrete (EPC)
    - Mix composition, properties, characterization, modeling, testing
  - Concrete incorporating Inclusions
    - Inclusion materials, properties, energy dissipation
- Modifications to the surface texture
  - Tining, Grooving
    - Features of the textures, testing
Conventional Concrete and Sound

- Conventional concrete is a very good sound reflecting material
  - Air-borne sound reflected
  - Noise barriers along highways
- Does little in dissipating sound inside an enclosure
  - Both air-borne and structure-borne sound not attenuated
  - Path difference between the direct and reflected rays minimal

Highway Noise Barriers

- Noise Barriers are less effective/ineffective on bridge overpasses and in urban settings

Modification of the Material Structure
Quieter PCC Pavements

- Incorporate enough porosity in concrete so as to absorb sound

- Two Methods:
  - Increase the porosity of the non-aggregate component of the mixture
    - Enhanced Porosity Concrete (EPC)
  - Increase the aggregate phase porosity
    - Porous inclusions

Enhanced Porosity Concrete (EPC)

- Array of tortuous pores distributed in a rigid-framed matrix
- Dissipates energy through friction
- Reducing surface area and resulting slap sound
- Reduces horn effect

The Challenge

Low Noise Surfaces
Long-Term Durability
Low Spray/Good Visibility
Safety/Skid Resistance
Keep the Cost Low

Hans Arrino, mid 19th Century
Salient Features

• Open porosity (~20-25%) achieved using
  – gap graded coarse aggregates
  – little / no sand
• Rapid drainage of water through interconnected voids
  – Minimizes wet weather spray, improves visibility
  – Minimizes glare

Influence of Porous Pavements in Reducing Noise

Focus of the Study

• Determine whether porous pavements can reduce the total noise level while avoiding potential problems associated with high-porosity pavements such as reduced durability
• Develop mixture proportions incorporating significant porosity to achieve noise reduction
• Quantify the noise reduction capabilities, physical, and mechanical properties of pervious concrete
Mixture Characteristics

- Three aggregate sizes - #8 (2.36 – 4.75 mm), #4 (4.75 – 9.5 mm) and 3/8” (9.5 – 12.5 mm)
- Gap graded mixtures
- Single sized aggregate mixtures
- Binary Blends (any of the 2 above sizes)
  – Replacement in steps of 25%
- Aggregate-cement ratio of 1:5.67
- w/c 0.33
- Sand / Silica fume addition

How to Quantify Porosity?

- Sectioned, epoxied specimen
- Scanned
- Thresholded
- White Pixels: Total Porosity
- Painted black
- Rescanned
- Thresholded
- Black Pixels: Inaccessible Porosity
- Accessible porosity = Total porosity – Inaccessible porosity

Pore Size Estimation

- Using Image analysis
- Maximum and minimum size of each feature
- Average pore size – misleading
- Median pore size – representative of the sizes in the system – characteristic pore size
- Not extremely accurate – gives an estimate of sizes – good for comparison
Acoustic Absorption of EPC Mixtures

150 mm Thick Specimens

Single Sized Aggregate System
Blended Aggregate System
#4 and #8

Thickness and Absorption

• Frequency at maximum absorption coefficient depends on the specimen thickness

\[ f_{\text{peak}} = \frac{n \cdot c}{4 \cdot t} \]

Blend of 75% #4 and 25% #8

Summary of Absorption Trends

• Porosity and pore size significant
• Materials with higher porosity and pore size are not necessarily more efficient acoustically
  – Lesser tortuosity
  – Lesser frictional losses
• An optimal pore size exists depending on the mixture
• Blending of aggregates
  – #4 and #8: smaller pore sizes; most effective
  – #8 and 3/8": smaller aggregates fill the pores – effective at some proportions
  – #4 and 3/8": less effective; effective at some proportions
Modeling Acoustic Absorption

- Idealized model
- Electro-acoustic analogy

\[
\begin{align*}
\text{Specimen length} &= n(L_a + L_p) \\
L_a &= \frac{L_p}{D_p} \frac{D_p}{D_a}
\end{align*}
\]

Model Parameters

- Equating unit cell porosity to overall porosity
- Approximating pores as spherical (so that \(L_p = D_p\))
- \(L_p\) and \(D_p\) from image analysis
- Choosing pore to aperture size (\(D_p/D_a\)) ratios to calculate aperture length (\(L_a\))

Model Predictions and Experiment

- Graphs showing model predictions and experimental values for different aggregate proportions and frequencies.
**Simulated Influence of Pore Geometry**

- 3 pore diameters and a set of $D_p/D_a$ values
- Optimal $D_p/D_a$ value for each $D_p$ where $\alpha$ is max.
  - High $D_p/D_a$: small aperture size, more energy reflected
  - Small $D_p/D_a$: large aperture size, air trapped in pores
  - Both cases: lower absorption

**Characterizing the Pore Structure**

- Electrical Impedance Spectroscopy (EIS)
- For a porous medium filled with an electrolyte, effective electrical conductivity ($\sigma_{eff}$) depends on
  - Conductivity of individual phases ($\sigma_i$)
  - Relative volumes of the phases ($\phi_i$)
  - Connectivity and distribution of the phases ($\beta_i$)

**Typical Measurement Results**

- Electrolyte – Sodium Chloride solution
  - $\sigma_{NaCl}$ (1%) 1.56 S/m
  - $\sigma_{NaCl}$ (3%) 4.40 S/m
  - $\sigma_{NaCl}$ (1%) 12.40 S/m
- Latex membrane coating the specimen to contain the electrolyte
- Stainless steel plates as electrodes
- Frequency – 1 MHz to 1 Hz, 250 mV AC Signal
- Nyquist Plots
### Modified Parallel Model

- **Parallel Model - Rule of Mixtures**
  \[ \sigma_{\text{eff}} = \sigma_{\text{pore}} \phi_{\text{pore}} + \sigma_{\text{solid}} \phi_{\text{solid}} \]

- Modified by incorporating the connectivities of the constituent phases
  \[ \sigma_{\text{eff}} = \frac{\sigma_{\text{pore}} \phi_{\text{pore}} + \sigma_{\text{solid}} \phi_{\text{solid}}}{\phi_{\text{solid}} + \frac{\phi_{\text{pore}}}{\beta_{\text{pore}}}} \]

- Introducing a new term: **Modified Normalized Conductivity** \( (\sigma_{\text{N}}) \)
  \[ \phi_{\text{solid}} \beta_{\text{solid}} \approx 1 \]
  \[ \phi_{\text{solid}} \sigma_{\text{solid}} \phi_{\text{solid}} \beta_{\text{solid}} = 1 \]
  \[ \sigma_{\text{N}} = \frac{\sigma_{\text{eff}} - \sigma_{\text{solid}}}{\sigma_{\text{pore}}} = \phi_{\text{pore}} \beta_{\text{pore}} \]

### Pore Connectivity Factor \( (\beta_{\text{pore}}) \)

- Accounts for constrictions in the pore space
  \[ \beta_{\text{pore}} = \frac{(\sigma_{\text{eff}} - \sigma_{\text{solid}})}{\sigma_{\text{pore}}} = \frac{1}{\phi_{\text{pore}}} \]

- Influences acoustic absorption coefficient
- Pore connectivity can be used to characterize acoustic absorption behavior of EPC

### Porosity and Pore Connectivity Factor

- Connectivity factor generally increases with porosity
  \[ L_1/L_2 = (L_1 + L_2)/2 \]
  \[ \beta_{\text{pore}} \cdot L/L_2 = 1.0 \]

Two systems of same porosity
But different connectivities
Quantifying Water Flow through Pervious Concrete

- Falling Head Permeameter
- Measures coefficient of permeability under saturated conditions
- Darcy’s Law
  \[ K = \frac{A}{L} \log \left( \frac{h_2}{h_1} \right) \]

Permeability, Porosity, Pore Size

- Permeability not a function of porosity and pore size alone
- Pore connectivity also needs to be considered

Relating Pore Structure and Permeability

- Kozeny-Carman Equation
  \[ k = \frac{\phi^3}{\frac{3}{4} F e^{3} S_{e} (1 - \phi)^2} \]
  
- Relating electrical conductivity to hydraulic conductivity

- Modified Kozeny-Carman Equation
  \[ k = \frac{1}{F e^{3} S_{e}^{2} \left( \frac{\sigma_{\text{void}} - \sigma_{\text{solid}}}{\phi_{\text{pore}}} \right)^{3/2} \left( 1 - \phi_{\text{pore}} \right)} \]
  
  Hydraulic connectivity factor (βₕ)
Linking the “Connectivities”

Acoustic and hydraulic properties of EPC can be characterized using one parameter:

\[ k = \frac{1}{F_p S_F} \left( \frac{\sigma_{e,eff} - \sigma_{solid}}{\sigma_{pore}} \right) \left( \phi_{pore} \right) \]

\[ \beta_H = \frac{1}{\sigma_{pore} S_F} \left( \frac{\sigma_{e,eff} - \sigma_{solid}}{\sigma_{pore}} \right) \left( \phi_{pore} \right) \]

Conclusions

- EPC results in higher acoustic absorption
- Blending of aggregates result in higher acoustic absorption than single sized mixtures
- Acoustic absorption depends on the porosity, pore size and geometry and pore connectivity
- A shape specific model to describe the acoustic absorption of EPC
- Quantifying the water flow through EPC
- Using a single measured characteristic (Electrical conductivity), information about acoustic and hydraulic performance of the EPC system could be deduced

TPTA Testing

- One porous concrete specimen shows higher SPL (Porous 3)
- Attributed to the irregular texture
- Grinding such specimens provides more similar SPLs as that of other porous specimens
Concrete Incorporating Inclusions

- Cellulose-Cement Composites
- Macro Nodule fibers (2 to 6 mm in size)
- Acts as porous aggregates

Acoustic Absorption

- Absorption spectra for macro nodules (75 mm thick specimens)

Elastic Damping

- Complex modulus of a viscoelastic material:
  \[ E' = E_0 e^{i \delta} = E (\cos \delta + i \sin \delta) \]
  \[ E \cos \delta = E' \] (Storage modulus)
  \[ E \sin \delta = E'' \] (Loss modulus)
  \[ E'' / E' = \tan \delta \] (Loss Tangent)
  \[ E'' = E' \tan \delta \]

- Combines storage modulus and damping capacity
- Best reflects the energy dissipating capacity of the material
Stiffness-Loss Relationships

- Relation between storage modulus and viscoelastic loss tangent
  - Stiff material with low to moderate loss tangent
- $E'$-tan $\delta$ relation heavily dependent on moisture conditions
- Increasing loss tangent and reducing stiffness with increasing fiber volume

Conclusions

- Cellulose-cement composites have moderate potential to absorb sound
  - Absorption coefficient increases with fiber volume
  - Related to fiber morphology
- Storage modulus and Loss tangent are inversely related
- Loss Modulus follows a Voigt composite relationship
  - Large reduction in stiffness, low loss tangent

Modification of the Surface Texture
Modeling the Effect of Tine Geometry

Influence of Tine Width

Influence of Tine Depth
Surfaces Tested on TPTA

- Magnesium trowel
- Broom transverse
- Broom longitudinal
- Astroturf longitudinal

Comparison of the Effects of Textures

- Different textures produce different noise levels and frequency spectra
- Rougher textures produce higher noise levels in both frequency and time averaging
- Exception is the ground surface that produces higher noise levels due to the lack of randomness in the surface

Effect of Multiple Tines

- The influence of having a series of tines versus a single tine is only seen at frequencies higher than 1500 Hz resulting in an increment on the noise levels
Characterizing Surface Textures

• A laser profilometer was used to characterize the surface texture
• Leveling done manually, to start with, followed by mathematical leveling
  – obtaining a trend line and subtracting on a “point by point” basis to obtain a level surface

Typical Texture Profiles

Friction and Skid Resistance
### Friction Results

<table>
<thead>
<tr>
<th>Turf texture longitudinal</th>
<th>Turf texture transverse</th>
<th>Long brushed</th>
<th>Longitudinal</th>
<th>Grinded tines transverse</th>
<th>Grinded tines longitudinal</th>
<th>Magnesium trowel</th>
<th>Broom transverse brushed</th>
<th>Broom transverse</th>
<th>Skewed tines</th>
<th>Transverse random</th>
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<tbody>
<tr>
<td>44.8</td>
<td>58.6</td>
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<td>58.3</td>
<td>58.6</td>
<td>72.9</td>
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</tbody>
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### Conclusions

- The influence of tine geometry modeled, and tested in the TPTA
- The geometry of the tined edges does not affect the noise generated as long as the size of the tine remains constant
- Tine width is a predominant factor in noise generation. Reducing tine and joint width results in a reduction in the overall sound level
- Concrete surface texture characterized using Laser Profilometer

### Acknowledgements

Institute for Safe, Quiet and Durable Highways, Purdue University

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