School of Civil Engineering
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Innovative Concrete Pavements for Noise Reduction Purposes

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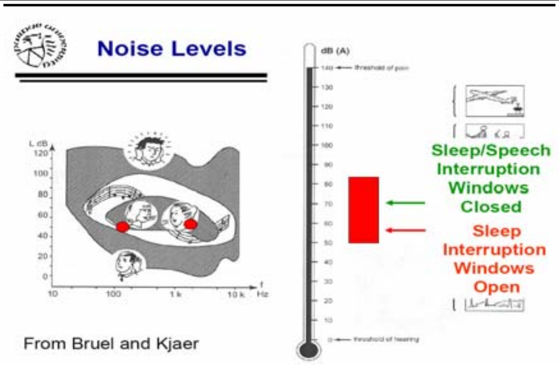
Why Noise Reducing Concrete Pavements?

- 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 Levels



Noise Components

Source

What Makes The Noise

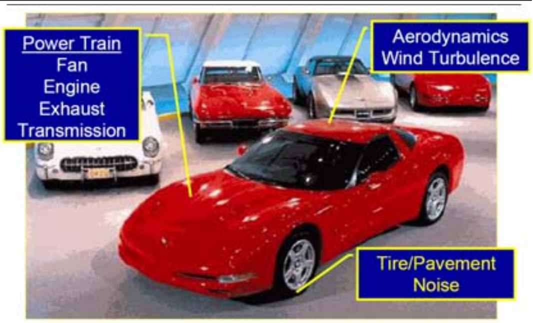
Path

How the Noise Travels

Receiver

Who Is Bothered By the Noise

Source of Tire-Pavement Noise

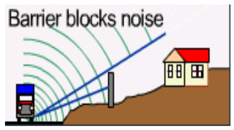


Presentation Outline

- 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



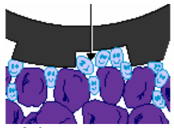
Highway Noise Barriers

- Noise Barriers are Less Effective/ Ineffective on Bridge Overpasses and In Urban Settings

Modification of the Material Structure

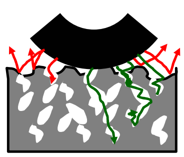
Quieter PCC Pavements

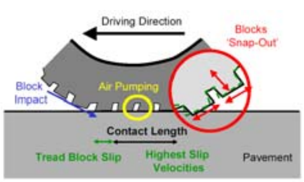
- Incorporate enough porosity in concrete so as to absorb sound



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

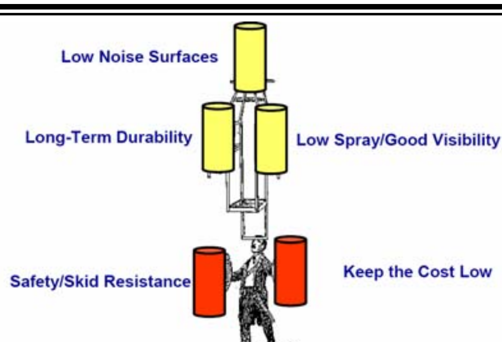
Enhanced Porosity Concrete (EPC)





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

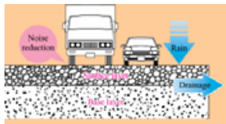
The Challenge



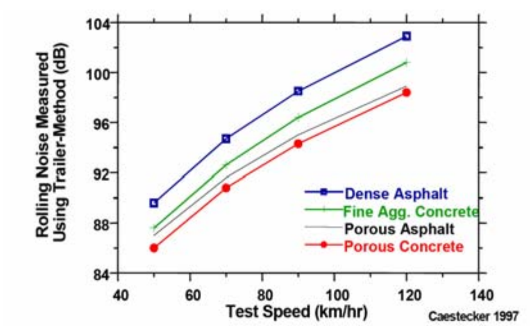
Hans Arrino, mid 19th Century

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



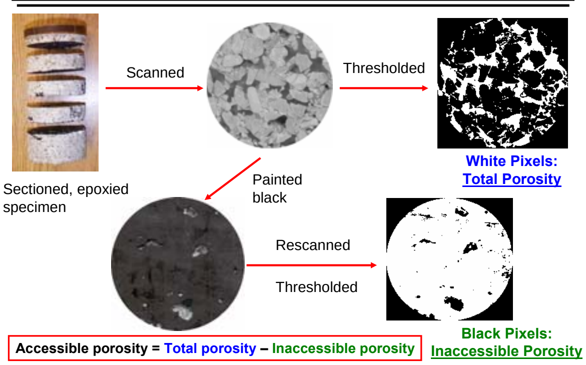
Focus of the Study

- 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

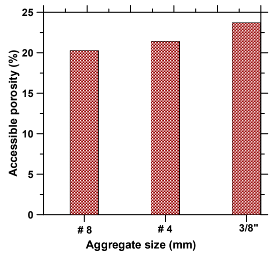
How to Quantify Porosity ?

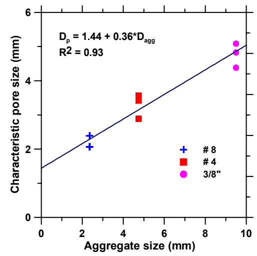


Pore Size Estimation

- 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

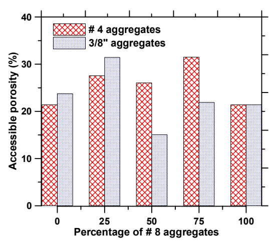
Porosity and Pore Sizes

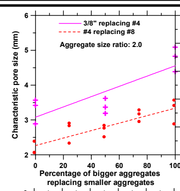


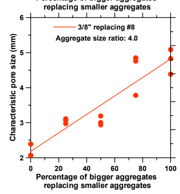


Single Sized Aggregate Mixtures

Porosity and Pore Sizes

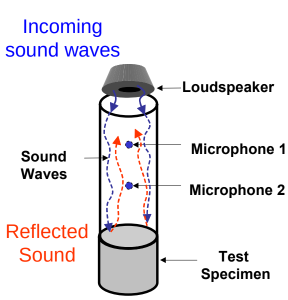


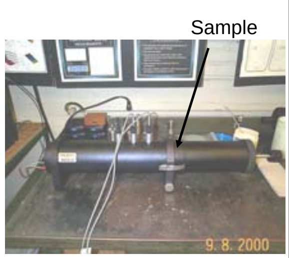




Blended Aggregate Mixtures

An Effective Tool to Screen Potential Sound Absorbing Mixtures

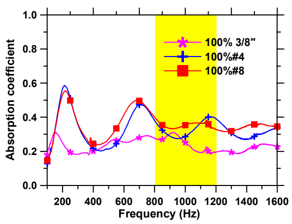




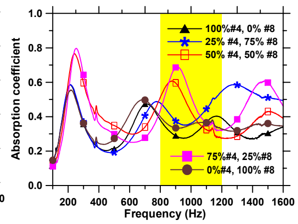
Impedance Tube

Acoustic Absorption of EPC Mixtures

150 mm Thick Specimens

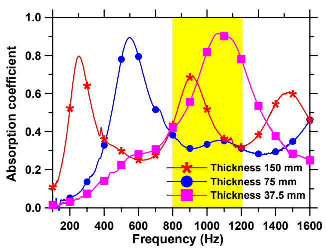


Single Sized Aggregate System



Blended Aggregate System
4 and # 8

Thickness and Absorption



Blend of 75% # 4 and 25% # 8

- Frequency at maximum absorption coefficient depends on the specimen thickness

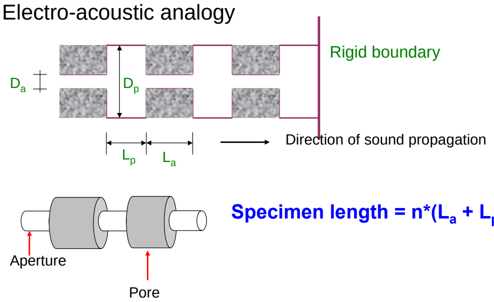
$$f_{peak} = \frac{n \cdot c}{4 \cdot t}$$

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 fills the pores – effective at some proportions
  - # 4 and 3/8": less effective; effective at some proportions

Modeling Acoustic Absorption

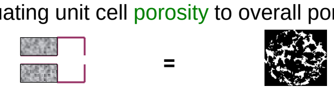
- Idealized model
- Electro-acoustic analogy



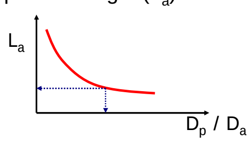
Specimen length = n*(L_a + L_p)

Model Parameters

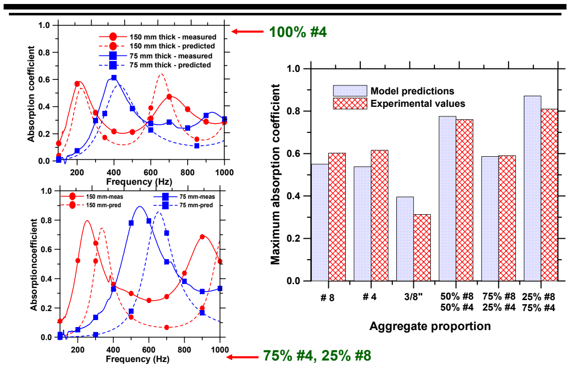
- Equating unit cell porosity to overall porosity



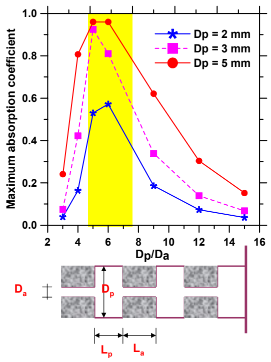
- Approximating pores as spherical (so that L_p=D_p)
- L_p and D_p from image analysis
- Choosing pore to aperture size (D_p/D_a) ratios to calculate aperture length (L_a)



Model Predictions and Experiment



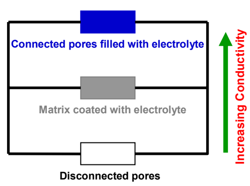
Simulated Influence of Pore Geometry



- 3 pore diameters and a set of D_p/D_a values
- Optimal D_p/D_a value for each D_p where α 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

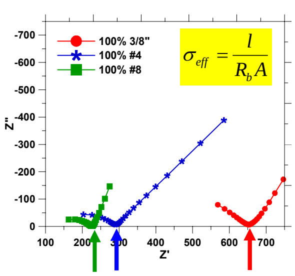
Characterizing the Pore Structure

- Electrical Impedance Spectroscopy (EIS)
- For a porous medium filled with an electrolyte, effective electrical conductivity (σ_{eff}) depends on
  - Conductivity of individual phases (σ_i)
  - Relative volumes of the phases (ϕ_i)
  - Connectivity and distribution of the phases (β_i)



Typical Measurement Results

- Electrolyte – Sodium Chloride solution
  - σ_{NaCl} (1%) 1.56 S/m
  - σ_{NaCl} (3%) 4.40 S/m
  - σ_{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



$$\sigma_{eff} = \frac{l}{R_b A}$$

Bulk Resistance R_b

Modified Parallel Model

- Parallel Model - **Rule of Mixtures**

$$\sigma_{eff} = \sigma_{pore}\phi_{pore} + \sigma_{solid}\phi_{solid}$$

- Modified by incorporating the connectivities of the constituent phases

$$\sigma_{eff} = \sigma_{pore}\phi_{pore}\beta_{pore} + \sigma_{solid}\phi_{solid}\beta_{solid}$$

- Introducing a new term: Modified Normalized Conductivity (σ_N)
  - since $\phi_{solid}\,\beta_{solid} \approx 1$

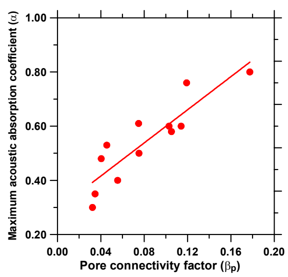
$$\sigma_N = \left(\frac{\sigma_{eff} - \sigma_{solid}}{\sigma_{pore}}\right) = \phi_{pore}\beta_{pore}$$

Pore Connectivity Factor (β_{pore})

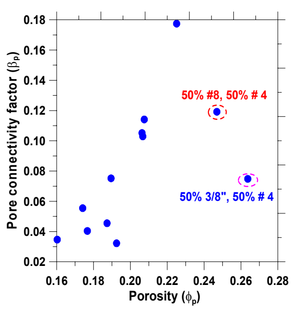
- Accounts for constrictions in the pore space

$$\beta_{pore} = \frac{(\sigma_{eff} - \sigma_{solid})}{\sigma_{pore}}\frac{1}{\phi_{pore}} = \sigma_N \frac{1}{\phi_{pore}}$$

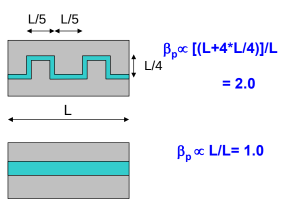
- Influences acoustic absorption coefficient
- Pore connectivity can be used to characterize acoustic absorption behavior of EPC



Porosity and Pore Connectivity Factor



- Connectivity factor generally increases with porosity

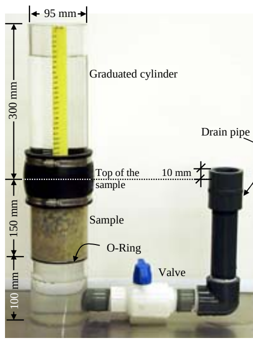


Two systems of same porosity
But different connectivities

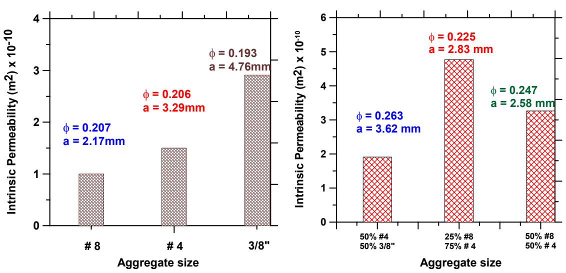
Quantifying Water Flow through Pervious Concrete

- Falling Head Permeameter
- Measures coefficient of permeability under saturated conditions
- Darcy's Law

$$K = \frac{A_1 l}{A_2 t}\log\left(\frac{h_2}{h_1}\right)$$



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

$$k = \frac{\phi^3}{F_s \tau^2 S_0^2 (1-\phi)^2}$$

- Relating electrical conductivity to hydraulic conductivity
- Modified Kozeny-Carman Equation

$$\boldsymbol{k} = \frac{1}{\boldsymbol{F_s S_0^2}}\left[\frac{\sigma_{eff} - \sigma_{solid}}{\sigma_{pore}}\right]^2 \left(\frac{\phi_{pore}}{(1-\phi_{pore})^2}\right)$$

Hydraulic connectivity factor (β_H)

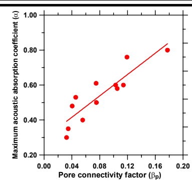
Linking the "Connectivities"

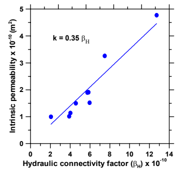
$$\beta_{pore} = \frac{(\sigma_{eff} - \sigma_{solid})}{\sigma_{pore}} \frac{1}{\phi_{pore}} = \sigma_N \frac{1}{\phi_{pore}}$$

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

$$k = \frac{1}{F_s S_0^2} \left[\frac{\sigma_{eff} - \sigma_{solid}}{\sigma_{pore}} \right]^2 \left(\frac{\phi_{pore}}{(1-\phi_{pore})^2} \right)$$

β_H

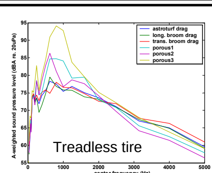


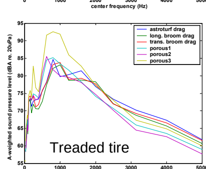


Conclusions

- 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 characterisitc (Electrical conductivity), information about acoustic and hydraulic performance of the EPC system could be deduced

TPTA Testing





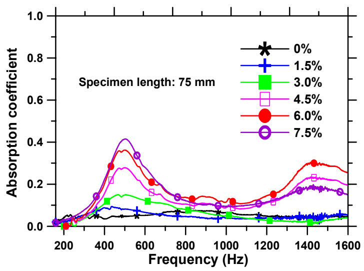
- One porous concrete specimen shows higher SPL (Porous 3)
- Attributed to the irregular texture
- Grinding such specimens provides more similar SPLs as that of other porous specimens

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:

$E^* = E.e^{i\delta} = E (\cos \delta + i \sin \delta)$

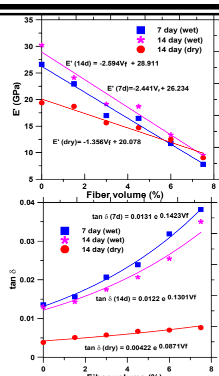
$E \cos \delta = E'$ (Storage modulus)

$E \sin \delta = E''$ (Loss modulus)

$E'' / E' = \tan \delta$ (Loss Tangent)

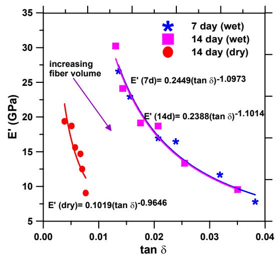
$E'' = E' \tan \delta$

  - 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 δ relation heavily dependent on moisture conditions
- Increasing loss tangent and reducing stiffness with increasing fiber volume

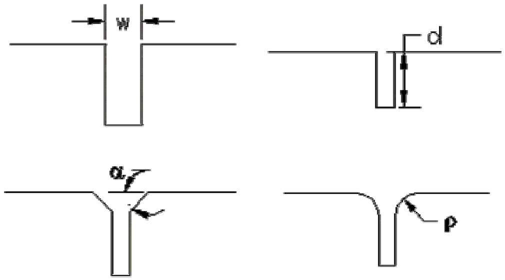


Conclusions

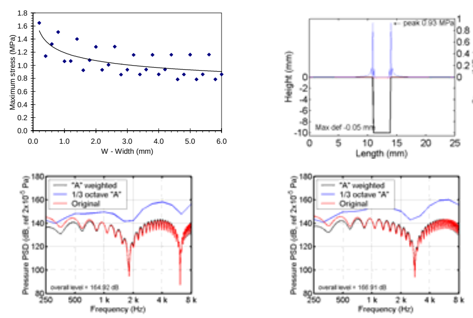
- Cellulose-cement composites have moderate potential to absorb sound
  - Absorption coefficient increases with fiber volume
  - Related to fiber morphology
- Storage modulus and Loss tangent are inversely related
- Loss Modulus follows a Voigt composite relationship
  - Large reduction in stiffness,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

Modification of the Surface Texture

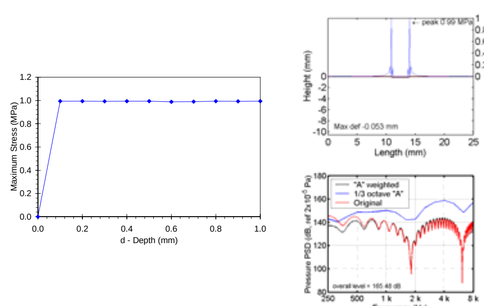
Modeling the Effect of Tine Geometry



Influence of Tine Width



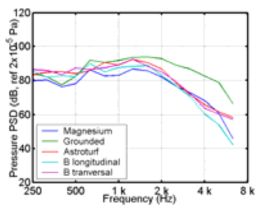
Influence of Tine Depth



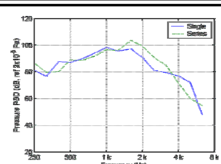
Surfaces Tested on TPTA

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

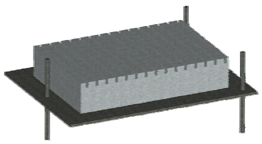


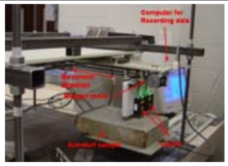
Effect of Multiple Tines



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

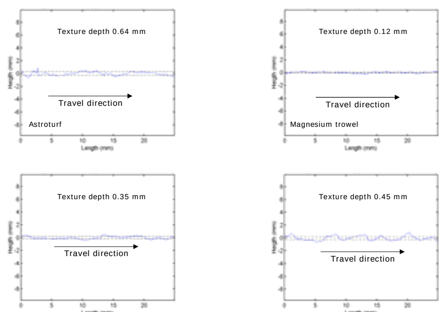
Characterizing Surface Textures





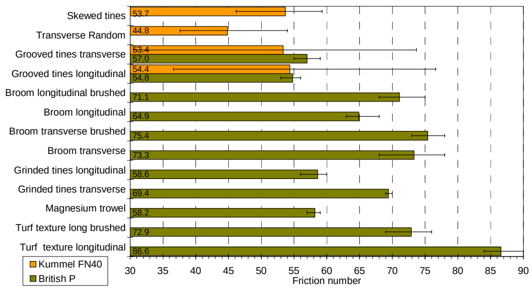
- A laser profilometer was used to characterize the surface texture
- Leveling done manually, to start with, followed by mathematical leveling
  - obtaining a trend line and subtracting on a "point by point" basis to obtain a level surface

Typical Texture Profiles



Friction and Skid Resistance

Friction Results



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

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