Outline

- Objective
- Motivation
- Background
- Macroscale constitutive model for fatigue in asphalt concrete
- Bridging characteristic length scales in asphalt concrete materials
- Scale-up to structural performance assessment
- Closing
Objective

To describe how constitutive models in combination with a multiscale approach can be of use in the asphalt concrete and asphalt pavement field.
Motivation

Sustainability and Resiliency

- System Definition
- Multipurpose Applications
- New Materials
- Operations/Maintenance
- Design Paradigms
- Unified Analysis and Modeling Methodology

- Resource Competition
- Economic
- Technical Knowledge
Multiscale Modeling as a Unifying Concept

Molecular Range

- Chromatography, AFM, DSC

Materials Range

- DMA, Rheology, Viscoelasticity, Viscoplasticity, Continuum Damage Mechanics, Fracture Mechanics

Engineering Range

- Loading, Environmental, Structure

- Molecular Simulation
- Molecular Dynamics

- Microstructural Models
- Empirical Models

- Empirical Models
- Phenomenological Models
- Analy. Suspension Models
- Discrete Element Models

- Empirical Models
- Mech.-Empirical Models
- Finite Element Models
Performance modeling is the process of predicting how well a material or structure will perform in-service, e.g., classic performance laws.

\[ N_f = K_1 \left( \frac{1}{\varepsilon} \right)^{K_2} \]

\[ \varepsilon_p = B_1 (N)^{B_2} \]
Constitutive Model

- A mathematical function that relates stress and strain.

\[ \sigma = E\varepsilon \]
MACROSCALE MODELING:
CONSTITUTIVE MODELING THE
FATIGUE PROCESS IN ASPHALT
CONCRETE
Constitutive Material Model

Fatigue in Asphalt Concrete

![Graph showing fatigue properties of asphalt concrete mixtures]
Under load damage is observed as a reduction in stiffness thus the key function is the relationship between damage, $S$, and material stiffness, $C$. The constitutive relationship for this model is:

$$\sigma = C \varepsilon$$
Constitutive Material Model

Continuum Damage Mechanics

Viscoelastic Continuum Damage (VECD) Model

Elastic-Viscoelastic Correspondence Principle

Continuum Damage Mechanics

Time-Temperature Superposition with Growing Damage

Linear viscoelastic effects

Microcracking related strength/stiffness degradation

Joint time/rate-Temperature effects
Baseline Pavement Response

$|E^*|$ (MPa)

Reduced Frequency (5C)

Control
CRTB
SBS
Terpolymer

Baseline Pavement Response

$E, \sigma, \varepsilon$
Damage Characteristic Curve

\[ C = \sigma, \varepsilon \]

- Monotonic-Fast
- Monotonic-Slow
- CX-High
- CX-Low
- CS0-High
- CS0-Low
Prediction of Fatigue Relationship

Testing Requirement

Conventional Fatigue Approach

- Temperature: 3
- Load amplitude: 3
- Mode of loading: 2
- Replicates: 3

54 tests (2 months)

Constitutive Model Approach

- LVE characterization
- Cyclic test at 2 levels and 1 temperature
- Replicates: $|E^*| - 3$
- Cyclic - 4

7 tests (3 days)
"Sustainable" Material Evaluation

Lowered Production Temperature Mixtures

Recycled Asphalt Pavement Mixtures

- HMA Dry
- HMA Moisture
- WMA Dry
- WMA Moisture

70-80% Difference in $N_f$

0-20% Difference in $N_f$

*Experimental work completed by Mr. Jongsub Lee and Mr. Tian Hou
Thermal Cracking Evaluation

TSRST

*Chehab et al. (2005). “VEPCD Model Application to Thermal Cracking of AC,” JMCE, 17(4)
Limits of Macro-Level Constitutive Models

Many of these phenomena are directly related to mechanisms at the local scale, which multiscale models account for directly.

Source: Rozeveld et al. 1997
MULTISCALE MODELING: LINKING MECHANICAL BEHAVIORS ACROSS MATERIAL LENGTH SCALES
Upscaling Constitutive Behaviors

**Molecular Range**
- Particles smaller than 0.075 mm

**Materials Range**
- Particles smaller than 0.6 – 1.18 mm
  - Binder
  - Mastic
  - FAM

**Engineering Range**
- Particles smaller than 9.5 – 37.5 mm
  - Mix

Characteristic Length Scale (meters):
- $10^{-12}$
- $10^{-9}$
- $10^{-6}$
- $10^{-3}$
- $10^{-0}$
- $10^{3}$
Primary Research Questions

How do the different material phases exist within the mixture?

- Sieved Ignition
- Digital Microscopy
- Scanning Electron Microscopy (SEM)
- Meso-Gravimetric and SEM

What are the constitutive behaviors of individual material phases?

- Fatigue
  - LVE
  - NLVE
  - Damage

How do the individual phases interact to yield the observed behaviors of the complete composite?

- Very Low Concentration Mastic
- Low Concentration Mastic
- High Concentration Mastic
- Rheological Liquid
- FAM
- Mix
Macro Assembly

Post Mixing

Post Ignition (no disturbance)
Macro Assembly

Filled with:
- #200 Sized Filler
- #100 Sized Filler
- #50 Sized Filler

Large Filler:
- #200 Sized

Agglomerations of Filler:
- #100 Sized
- #200 Sized
Meso-Sampling for Microstructural Study

Image Analysis and 2-D to 3-D Distribution Algorithm

Known Gradation
SEM Calibration
SEM Verification 1
SEM Verification 2
Microstructural Study

![Graphs showing microstructural study results for different samples.]

- **S9.5B**
- **I19.0C**

Coarse Avg.
FAM Avg.

Coarse Samples
FAM Samples
Multiscale Characteristics

|G*| (Pa) Mix

FAM
Mastic
Binder

Multiscale Characteristics
Experiments characterize aggregate and mastic.
Constitutive behaviors of mixture are then predicted from analytical model.
Performance Based Mix Design

Macroscale Constitutive Model Approach

- Effect of AC Content: x4
- AV Contents at single AC: x3
- Gradation: x2

24 mixes (3 months)

Multiscale Approach

- Binder LVE
- Mastic LVE: x5
- FAM or Mix LVE: x2
- Void Content Tests

18 mechanical tests
2-6 void content tests (7 days)
Upscaling with Computational Methods

Prony Series

\[ E(t) = E_\infty + \sum_{i=1}^{\infty} E_i \left(1 - e^{-t/\rho_i}\right) \]

Multiple Replicates

Scale (n)

Scale (n-1)

Scale 1

2D Gradation

% Passing

Scale n

Scale n-1

Sieve Size

Input from Scale (n-1)

Output to Scale (n-1)

Output from Scale (n-1)

Input to Scale (1)

Multiple Replicates

ZHANG P, (2003). “Microstructure generation of asphalt concrete and lattice modeling of its cracking behavior under low temperature” Theses and Dissertations, NCSU. Thanks to Arash Banadaki for the slide contents
MULTISCALE MODELING: STRUCTURAL ANALYSIS
Mechanistic-Empirical Paradigm

**Inputs**

| Structure | Materials | Traffic | Climate |

Layered Analysis $(\sigma, \varepsilon, \delta)$

Performance Assessment

\[ D_{ijk} = \frac{N_{ijk}}{N_f} = \frac{N_{ijk}}{K_1 \left( \frac{1}{\varepsilon} \right)^{K_2}} \]

Damage Accumulation

\[ D = \sum_{i=1}^{M} \sum_{j=1}^{J} \sum_{k=1}^{K} D_{ijk} \]

Distress Accumulation

\[ Crack = \left( \frac{1000}{1 + e^{C_1 + C_2 \log(D)}} \right) \]
Mechanistic Paradigm

**Inputs**
- Structure
- Materials
- Traffic
- Climate

**Pavement Analysis Engine** ($\sigma$, $\varepsilon$, $\delta$)

- **Pavement Response**
  \[\sigma = E\varepsilon^R\]

- **Damage Accumulation**
  \[\sigma = C\varepsilon^R\]

- **Distress Accumulation**
  \[\text{Crack} = fcn(S)\]
Multiscale Mechanistic Paradigm

Characteristic Length Scale (meters)
Pavement Evaluation
Response Modeling

Winter

Summer

Traffic Direction
Pavement Fatigue Life Prediction

\[ y = 0.7119x + 2.321 \]

\[ R^2 = 0.8473 \]

<table>
<thead>
<tr>
<th>log Field N_f</th>
<th>log Predicted N_f</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS</td>
<td>Control</td>
</tr>
<tr>
<td>CRTB</td>
<td>Terpolymer</td>
</tr>
</tbody>
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\[ y = 0.7119x + 2.321 \]

\[ R^2 = 0.8473 \]
Assessment of Design Alternatives

![Graph 1: Damage Area vs. Base Layer Thickness for BB3, BB1, and Aggregate layers.]

- **BB3**
- **BB1**
- **Aggregate**

![Graph 2: Damage Area vs. Base Layer Thickness for 30 cm and 40 cm.]

- **30 cm**
- **40 cm**

![Graph 3: Damage Area vs. Base Layer Thickness for Subgrade and Antifrost.]

- **Subgrade**
- **Antifrost**

![Graph 4: Damage Area vs. Test Section for ASTM and PMA.]

- **ASTM**
- **PMA**
Molecular Range
• How do molecular components form and interact to yield behaviors of asphalt?
• What properties should I specify for asphalt binder materials?

Materials Range
• How do engineering materials assemble and interact to yield behaviors of asphalt concrete?
• How should the available materials be assembled (designed)?

Engineering Range
• How does asphalt concrete interact within a structure and environmental condition to prescribed loading?
• What materials should I specify for an asphalt concrete pavement?

Multiscale Analysis and Modeling
Thank You