Constitutive Modeling of Asphalt Concrete: A Multiscale Perspective

Shane Underwood
Assistant Professor

School of Sustainability and the Built Environment
Civil, Environmental, and Sustainable Engineering Program

ITE Student Chapter Seminar

October 9, 2012

Ira A. Fulton Schools of Engineering

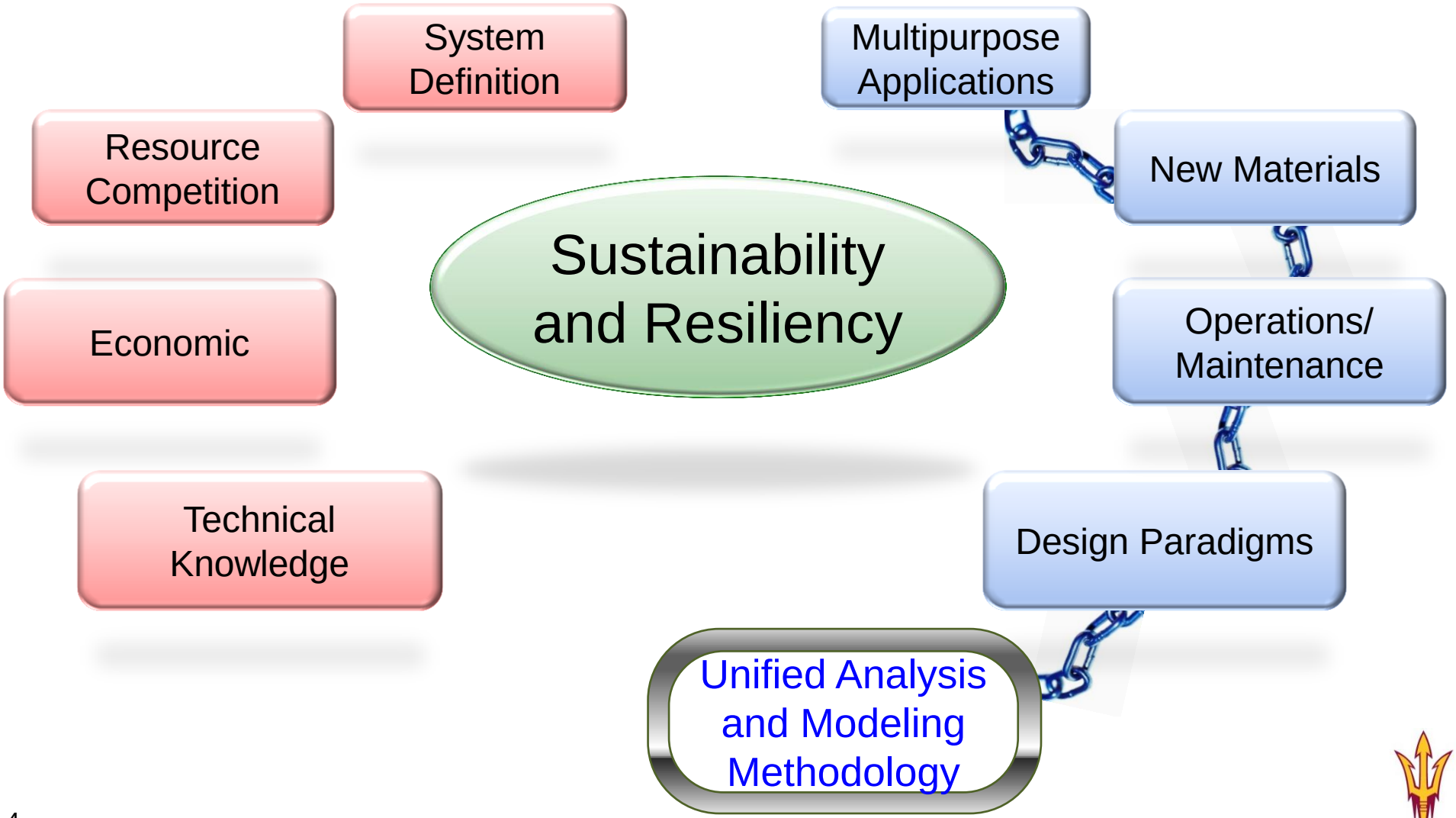
Outline

- 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


System Definition
Multipurpose Applications
Resource Competition
New Materials
Sustainability and Resiliency
Economic
Operations/ Maintenance
Technical Knowledge
Design Paradigms
Unified Analysis and Modeling Methodology

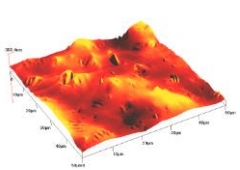
Multiscale Modeling as a Unifying Concept

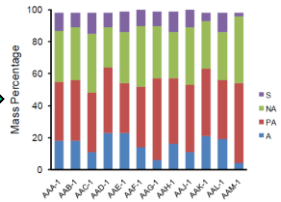
Molecular Range | Materials Range | Engineering Range

Chromotography, AFM, DSC

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

Loading, Environmental, Structure

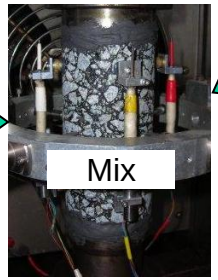




Binder

Mastic

FAM



Mix

10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{-0} 10^{3}

Molecular Simulation
Molecular Dynamics

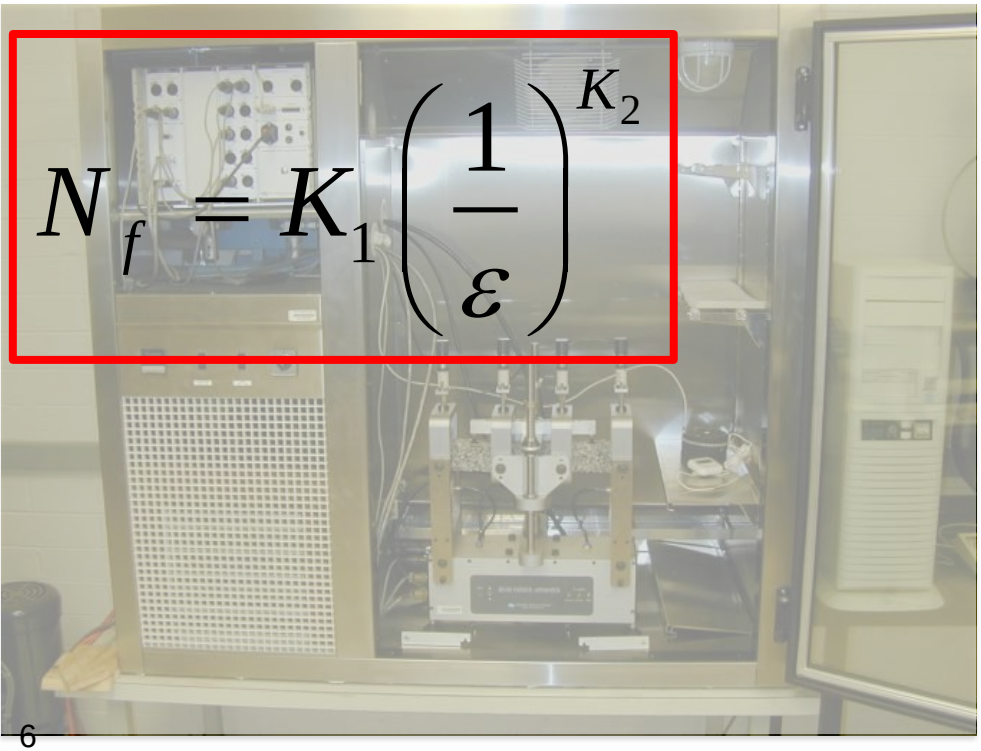
Microstructural Models
Empirical Models

Empirical Models
Phenomenological Models
Analy. Suspension Models
Discrete Element Models

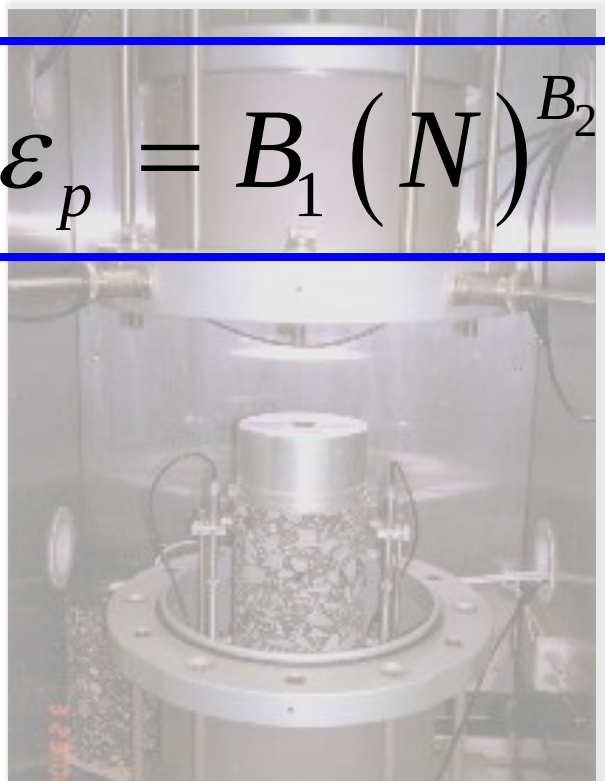
Empirical Models
Mech.-Empirical Models
Finite Element Models

Background

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



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

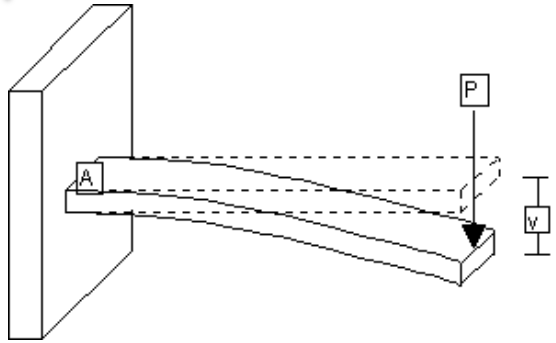


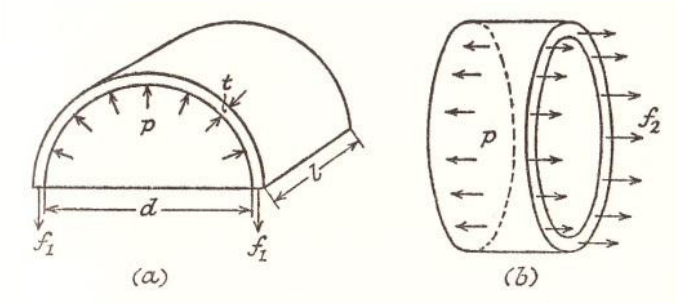
$$\varepsilon_p = B_1 \left(N \right)^{B_2}$$

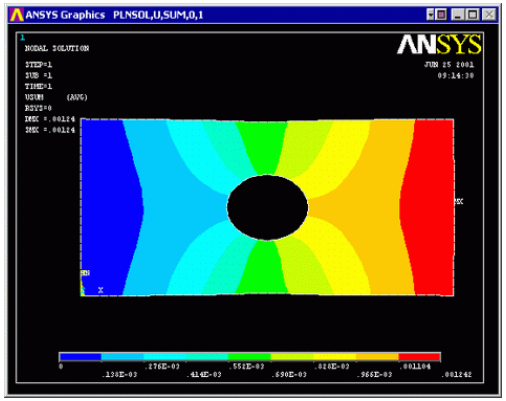
Constitutive Model

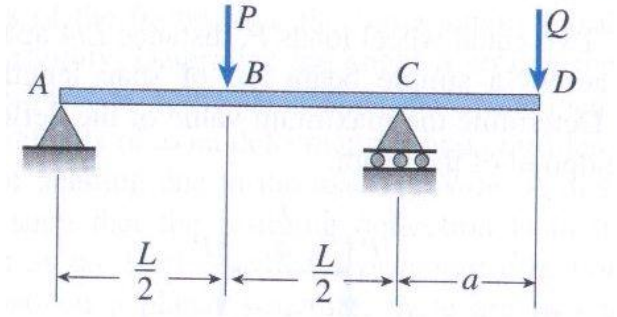
- A mathematical function that relates stress and strain.

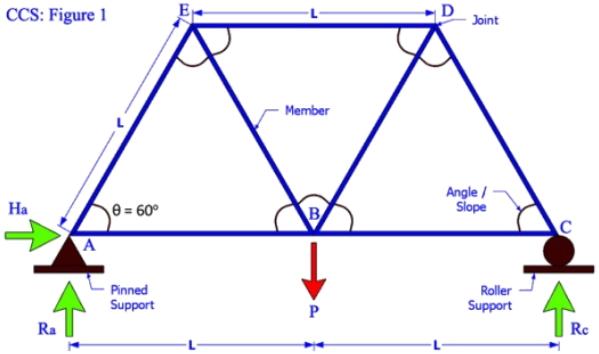
$$\sigma = E\varepsilon$$

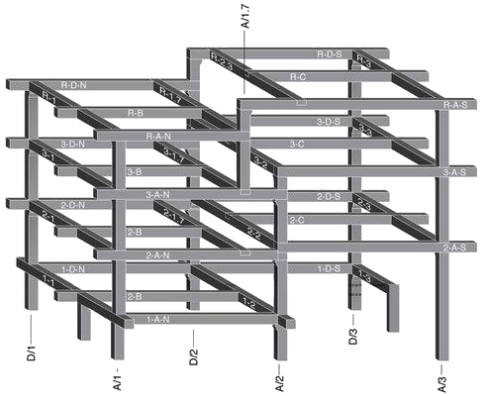








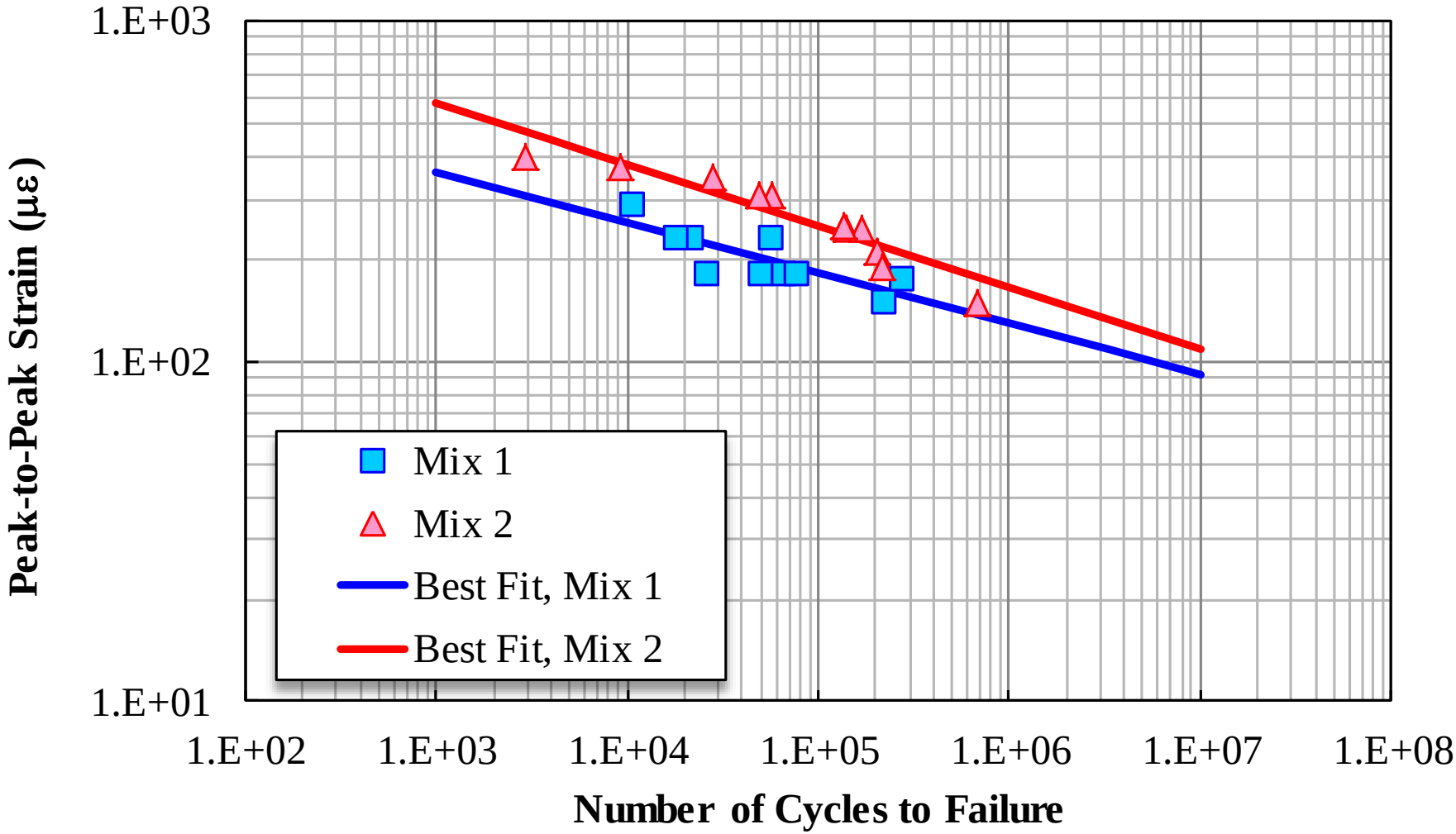




MACROSCALE MODELING: CONSTITUTIVE MODELING THE FATIGUE PROCESS IN ASPHALT CONCRETE

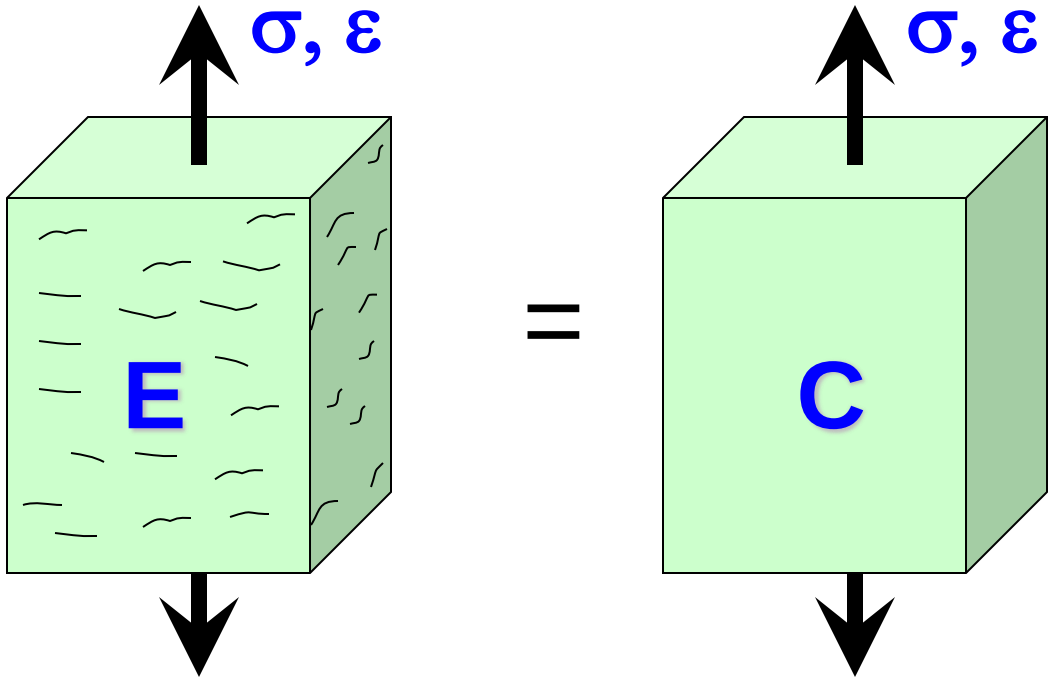
Constitutive Material Model

Fatigue in Asphalt Concrete



Constitutive Material Model

Continuum Damage Mechanics



$$\sigma = C\varepsilon$$

Under load damage is observed as a reduction in stiffness thus the key function is the relationship between damage, S, and material stiffness, C

Constitutive Material Model

Continuum Damage Mechanics

Viscoelastic Continuum Damage (VECD) Model

Elastic-Viscoelastic Correspondence Principle

Continuum Damage Mechanics

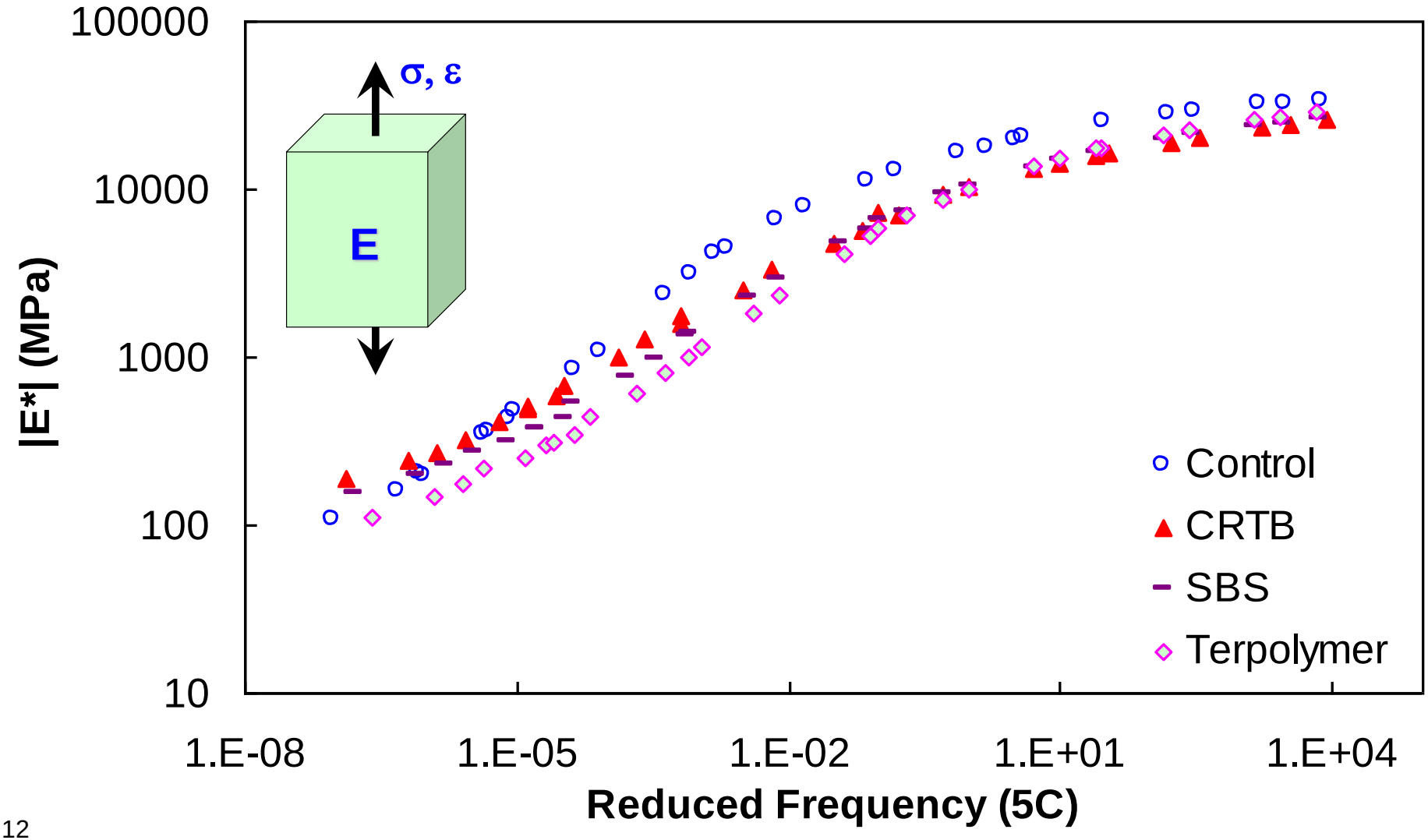
Time-Temperature Superposition with Growing Damage

Linear viscoelastic effects

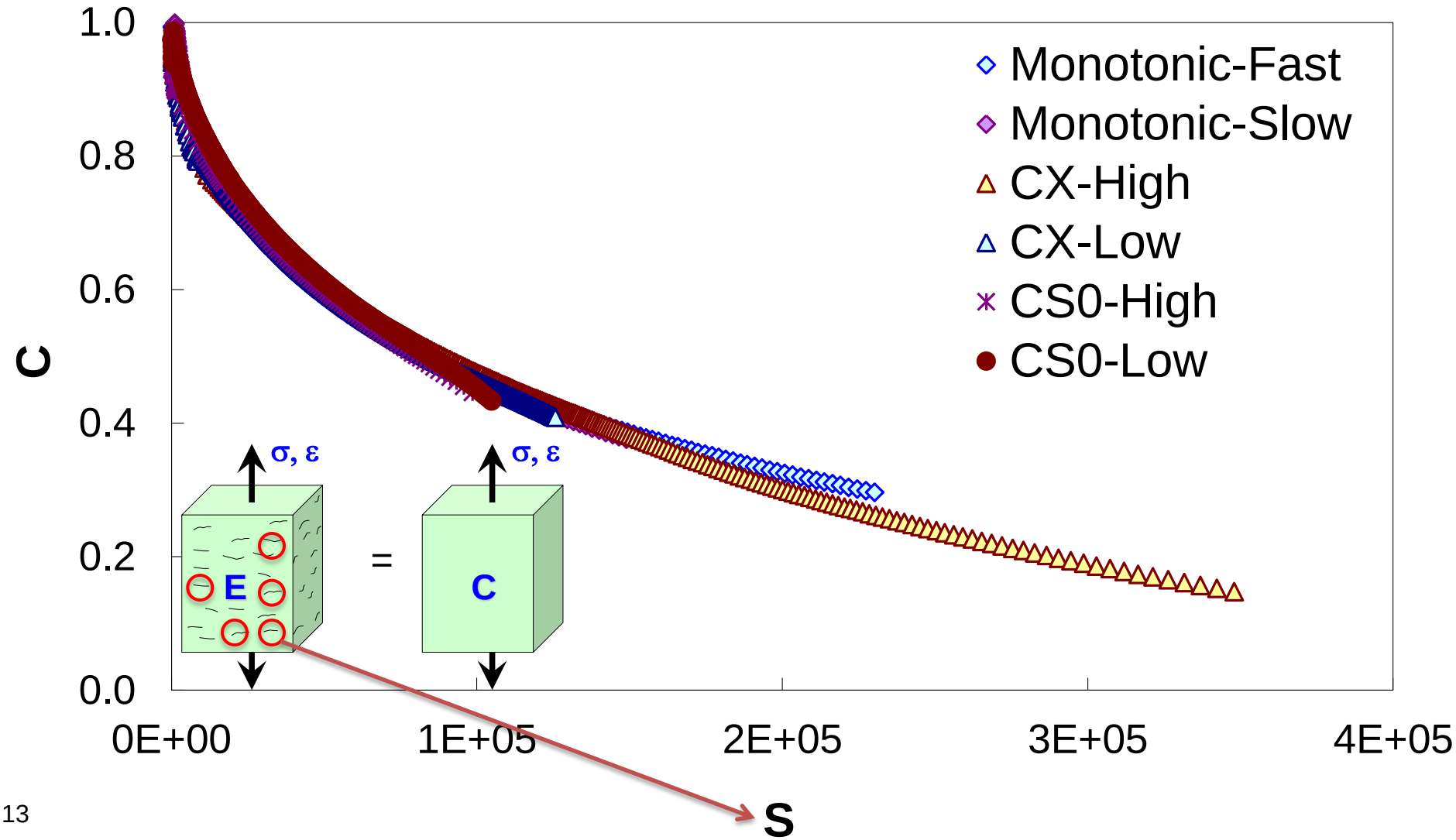
Microcracking related strength/stiffness degradation

Joint time/rate-Temperature effects

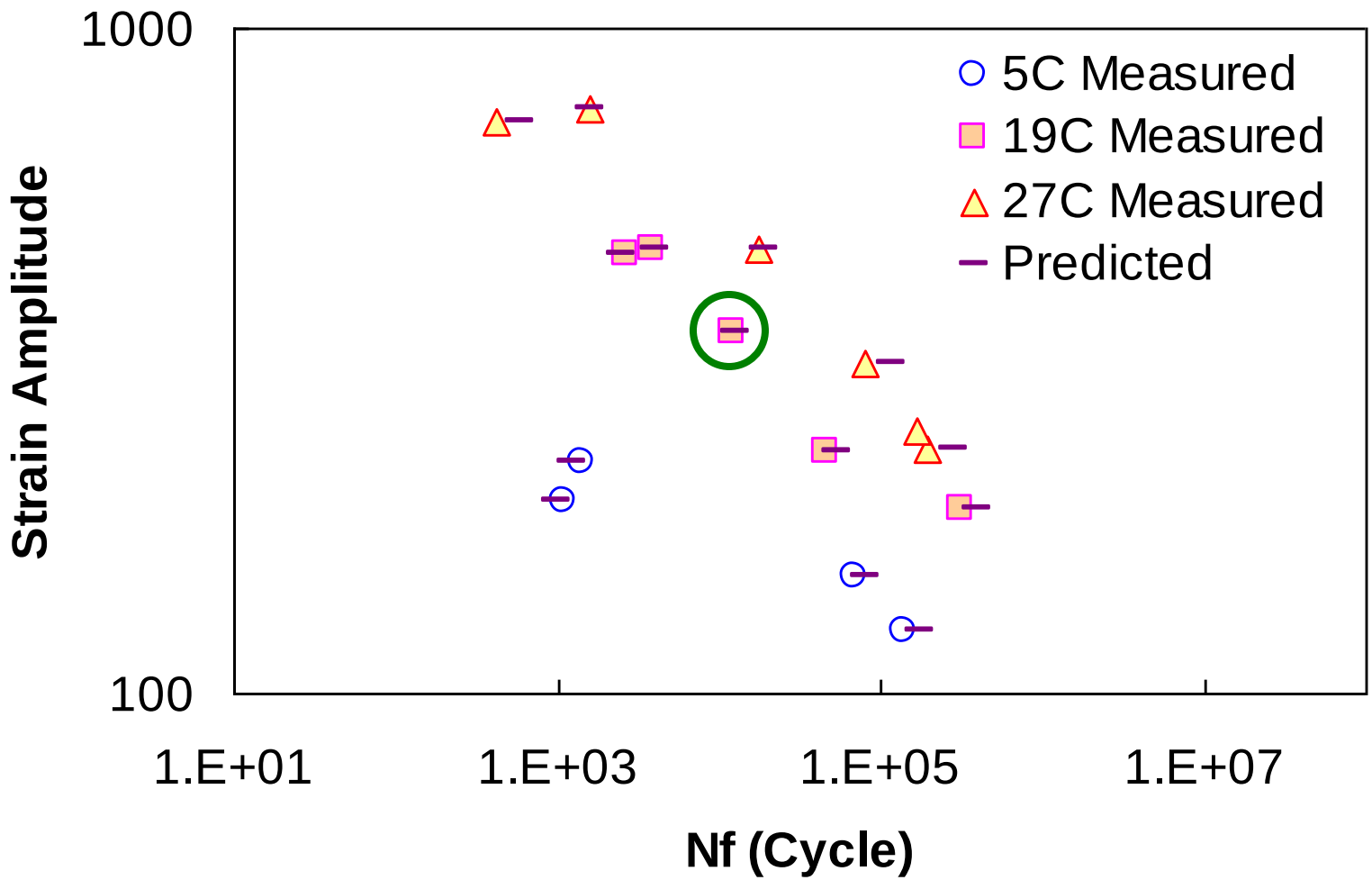
Baseline Pavement Response



Damage Characteristic Curve



Prediction of Fatigue Relationship



*Hou et al. (2010). "Fatigue Perf. Pred. of NC Mixtures using the S-VECD Model," AAPT, 79

Testing Requirement

Conventional Fatigue Approach

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

54 tests
(2 months)

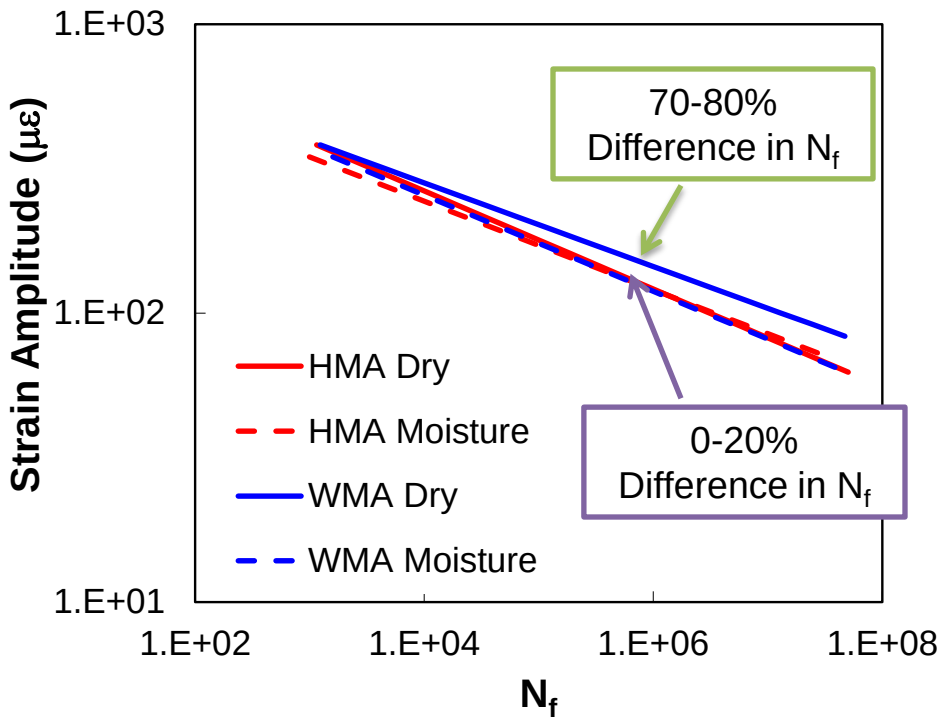
Constitutive Model Approach

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

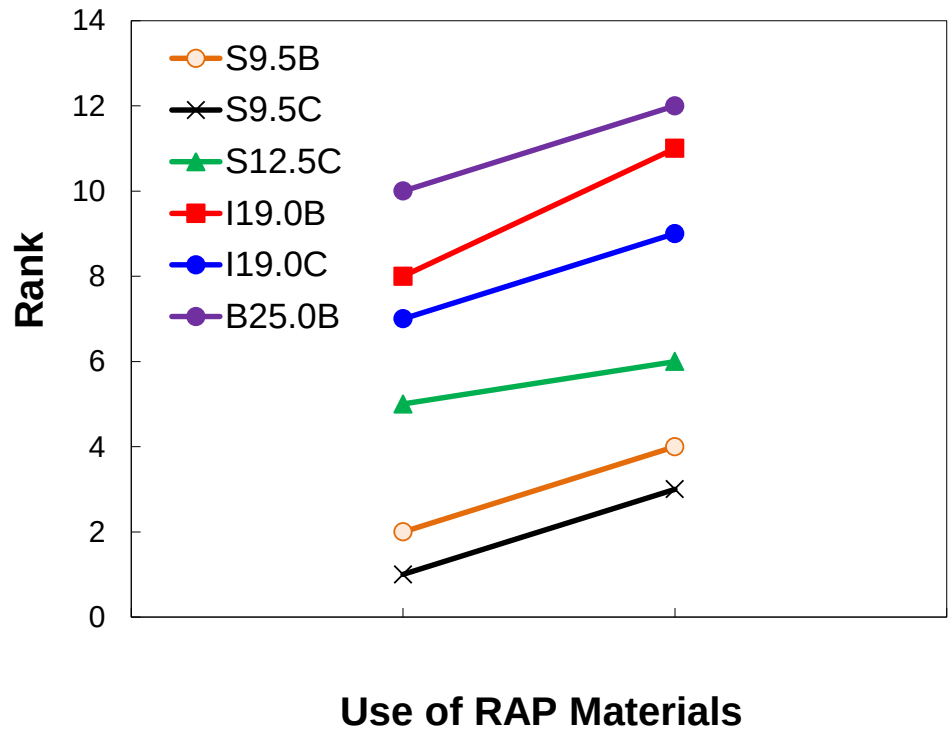
7 tests
(3 days)

"Sustainable" Material Evaluation

Lowered Production Temperature Mixtures

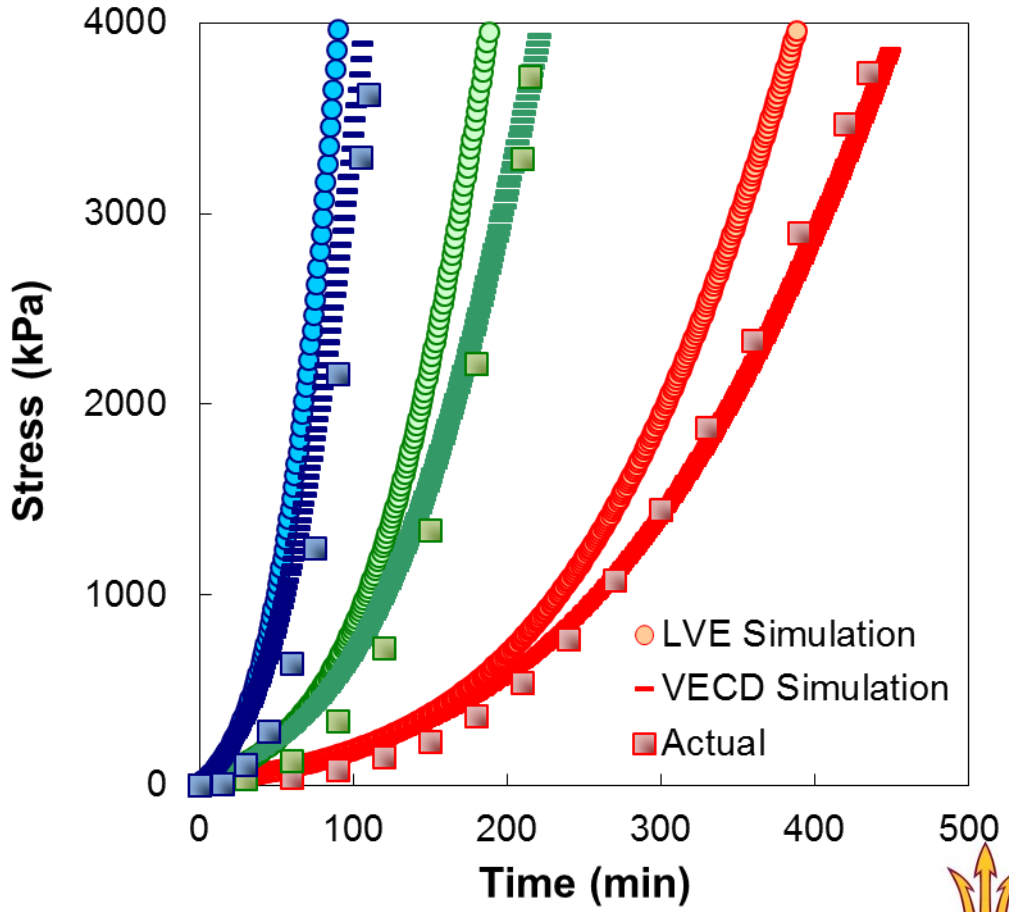


Recycled Asphalt Pavement Mixtures



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

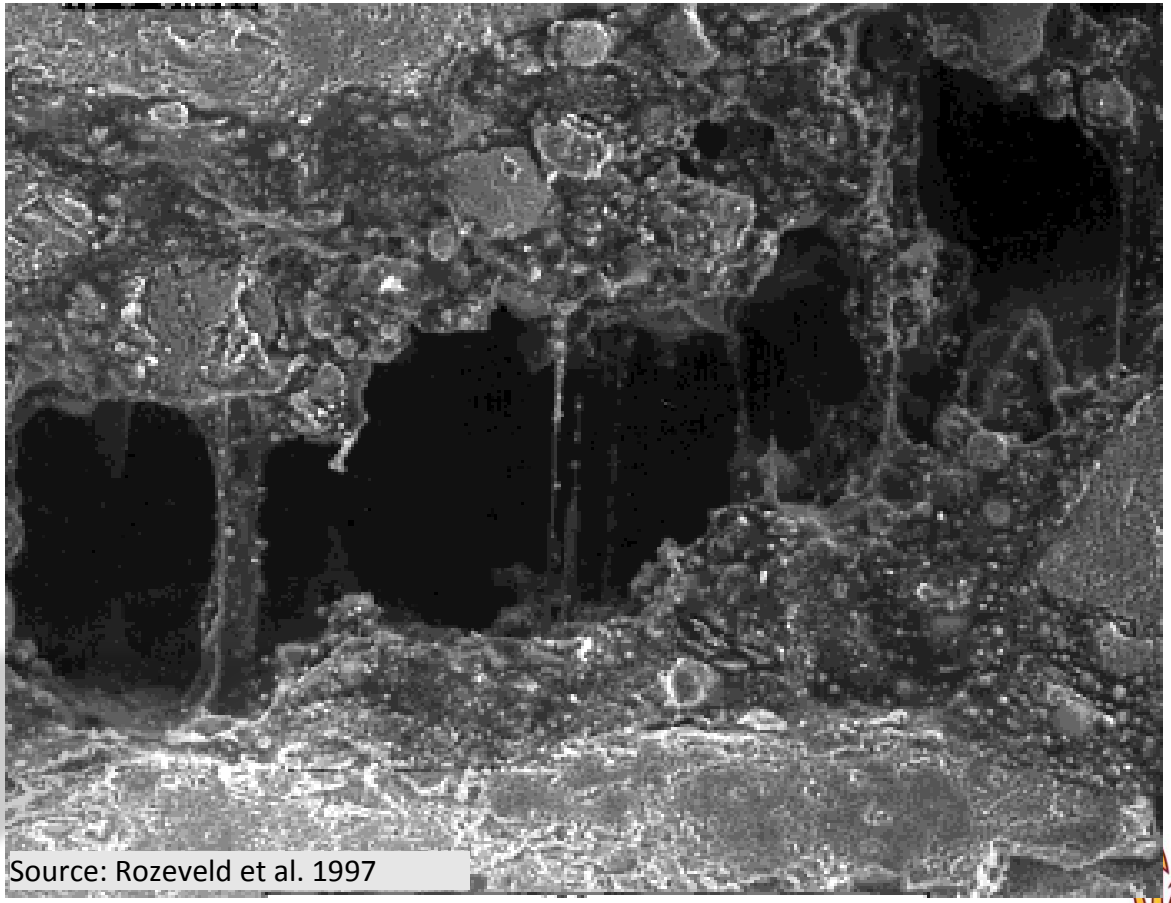
Thermal Cracking Evaluation



*Chehab et al.. (2005). "VEPCD Model Application to Thermal Cracking of AC," JMCE, 17(4)

Limits of Macro-Level Constitutive Models

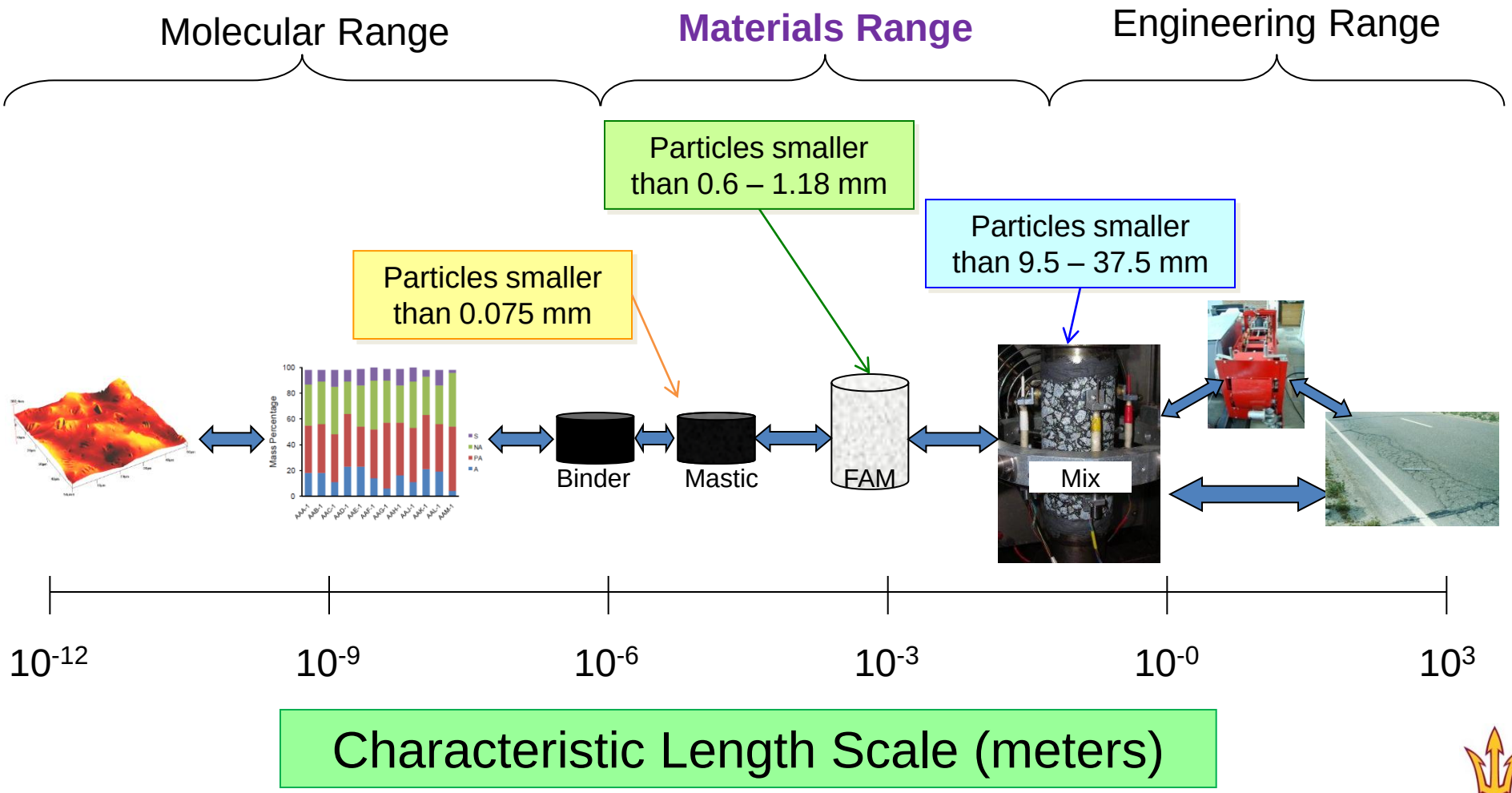
Many of these phenomena are directly related to mechanisms at the local scale, which multiscale models account for directly.



Source: Rozeveld et al. 1997

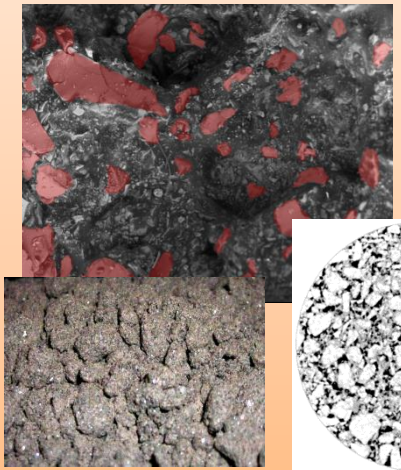
MULTISCALE MODELING: LINKING MECHANICAL BEHAVIORS ACROSS MATERIAL LENGTH SCALES

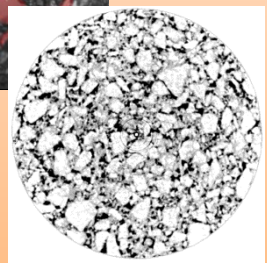
Upscaling Constitutive Behaviors



Primary Research Questions

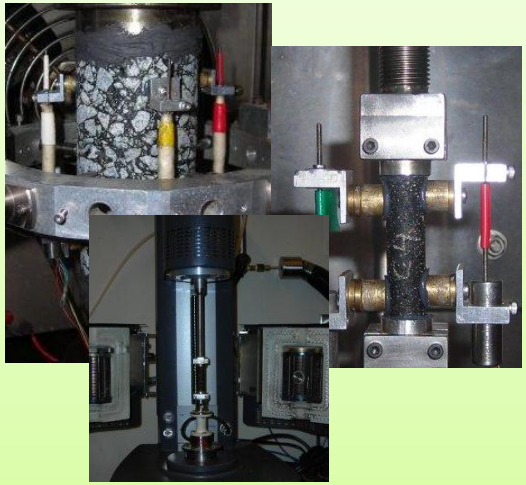
How do the different material phases exist within the mixture?





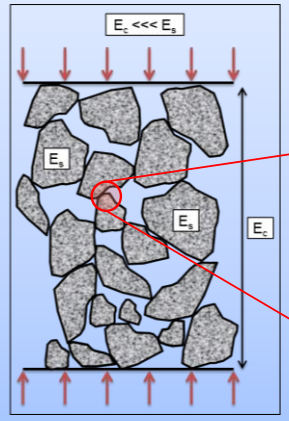
Sieved Ignition
↓
Digital Microscopy
↓
Scanning Electron Microscopy (SEM)
↓
Meso-Gravimetric and SEM

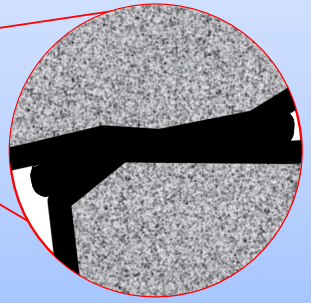
What are the constitutive behaviors of individual material phases?



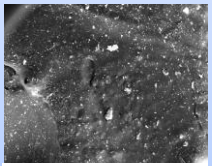
- Fatigue
  - LVE
  - NLVE
  - Damage

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

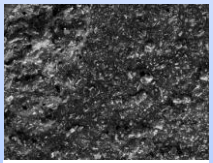




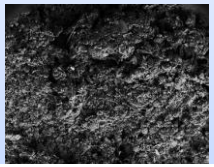
Rheological Liquid



Very Low Concentration Mastic



Low Concentration Mastic

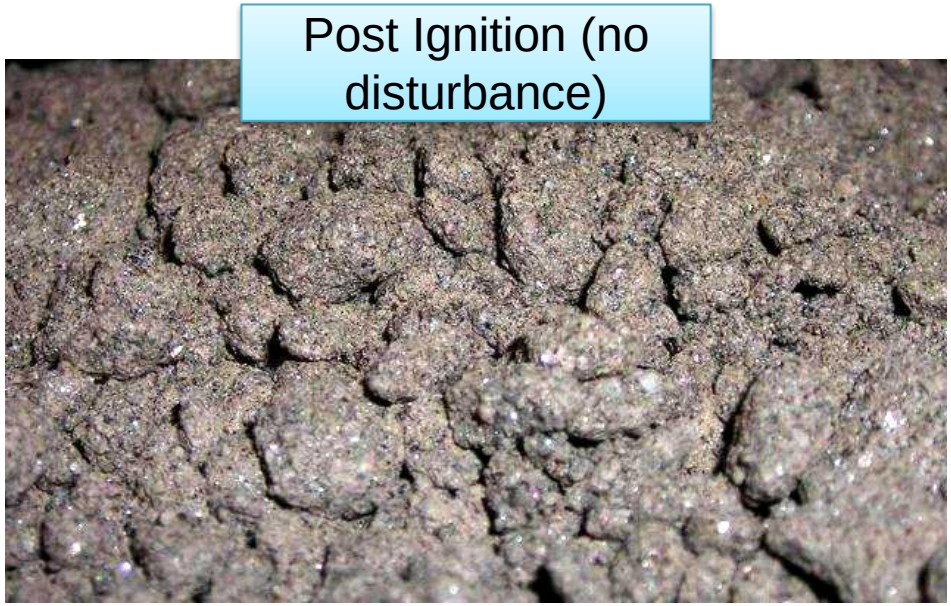


High Concentration Mastic

FAM

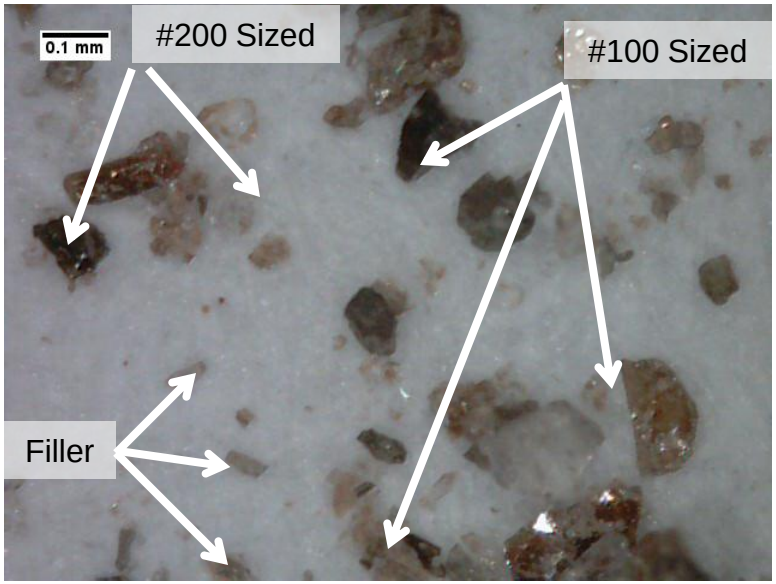
Mix

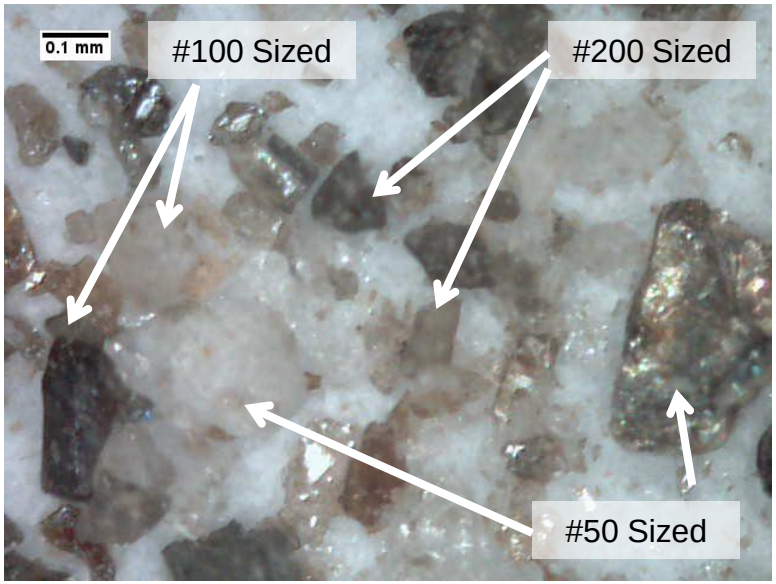
Macro Assembly

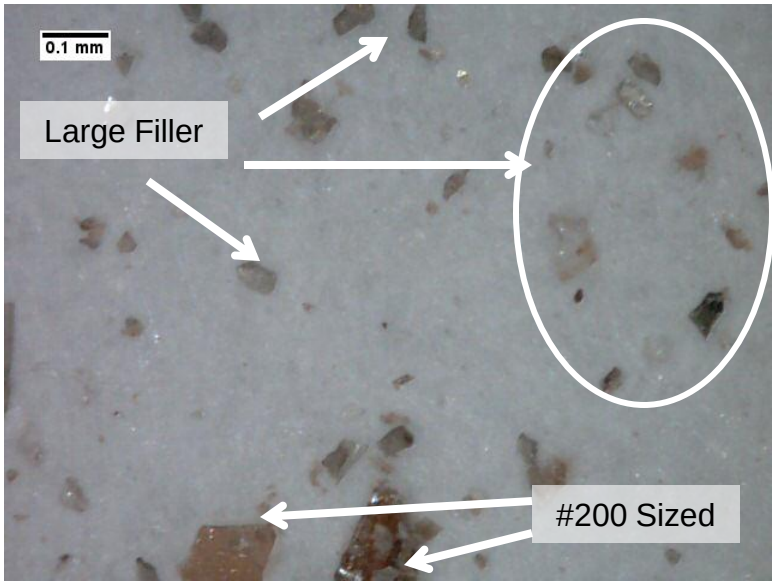


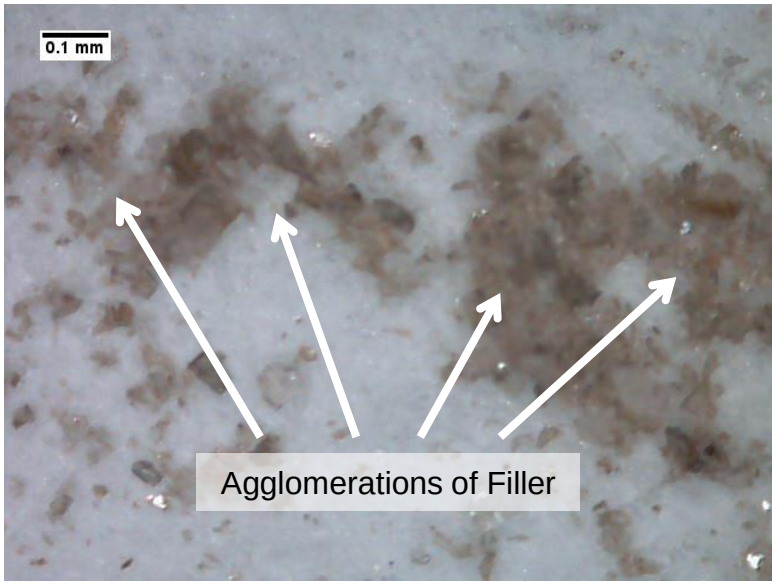
22

Macro Assembly



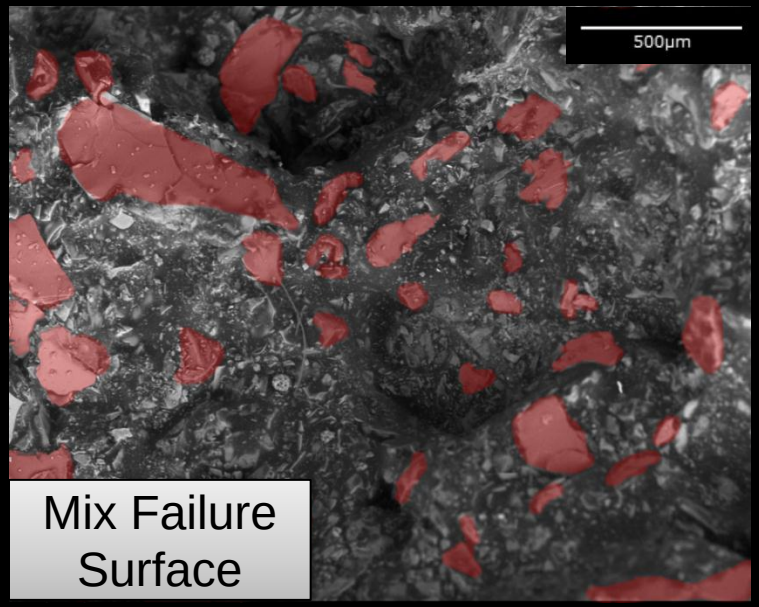


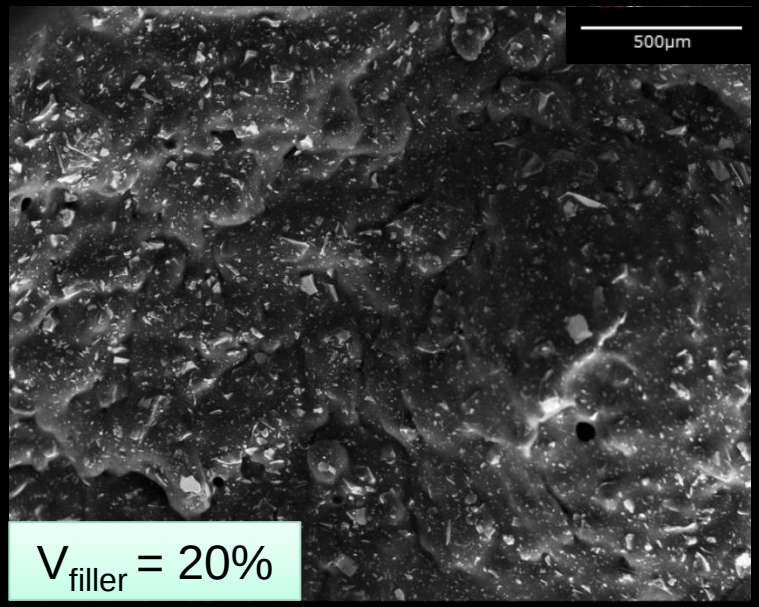


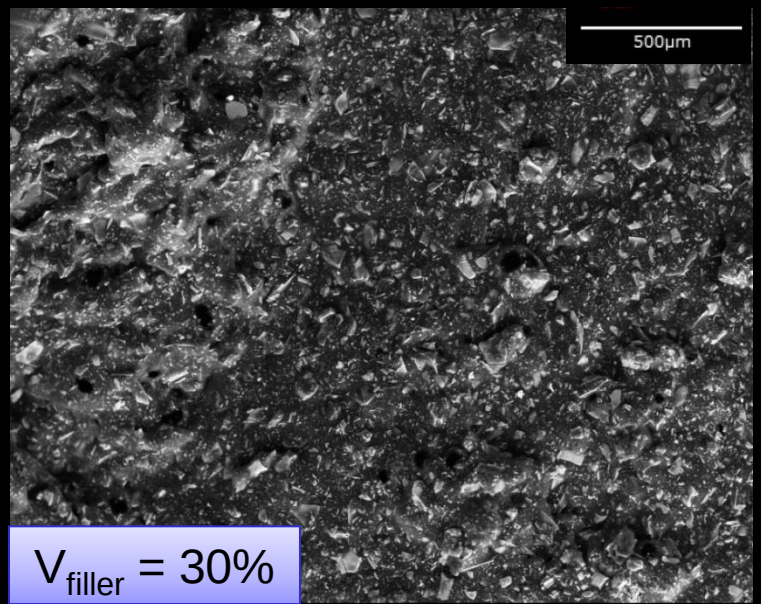


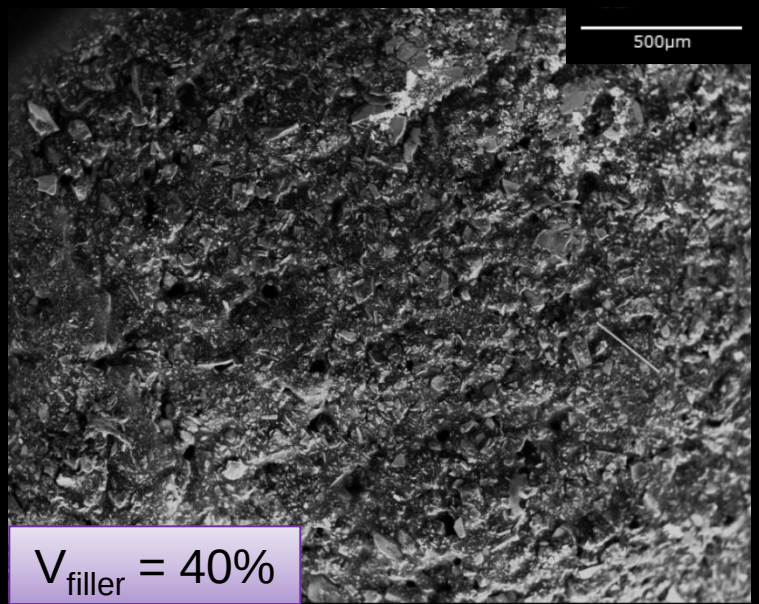
Micro Assembly

Scanning Electron Microscope

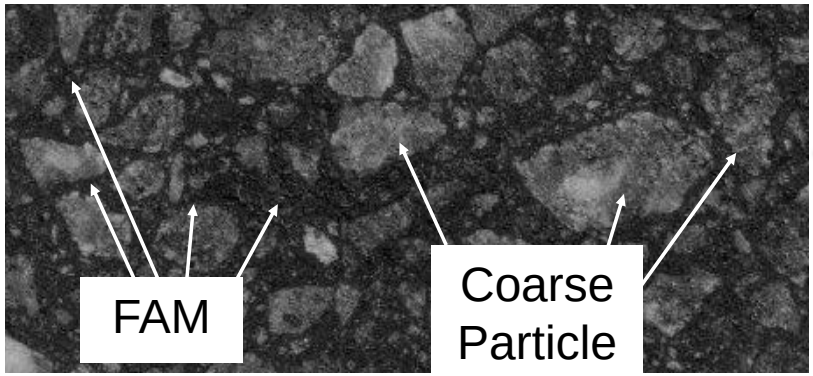








Meso-Sampling for Microstructural Study



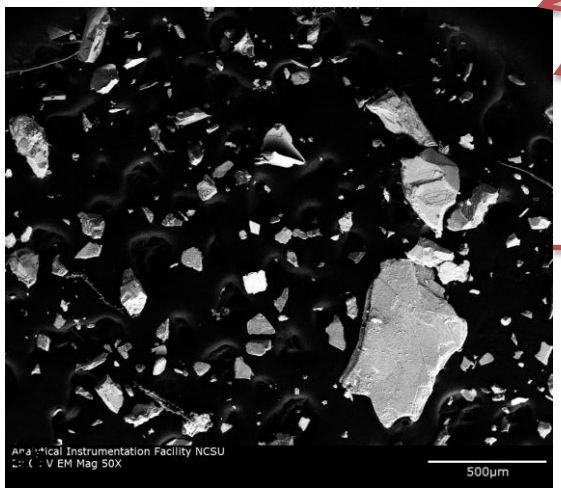
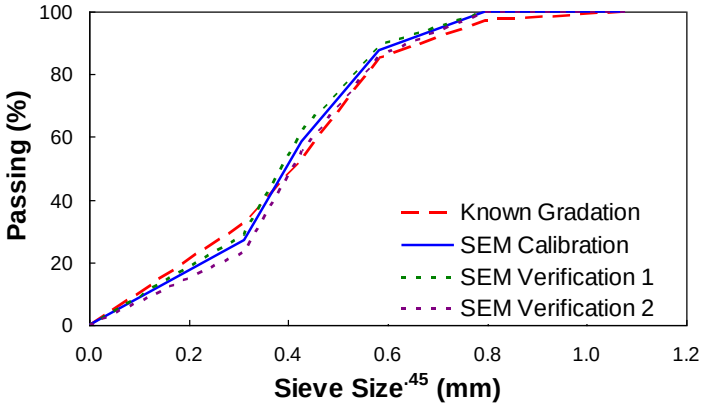
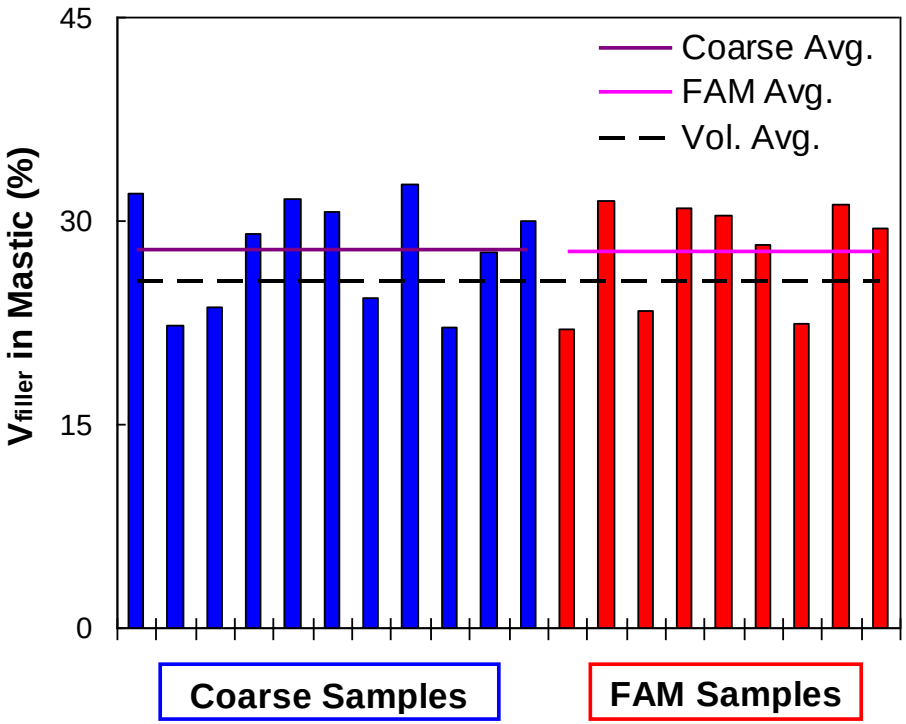


Image Analysis and 2-D to 3-D Distribution Algorithm

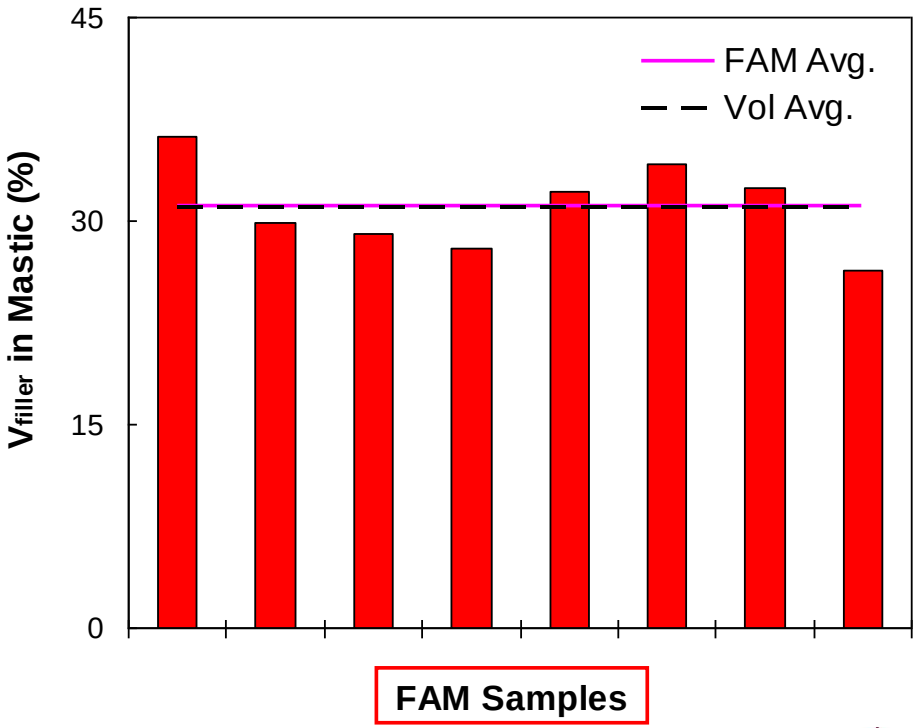


Microstructural Study

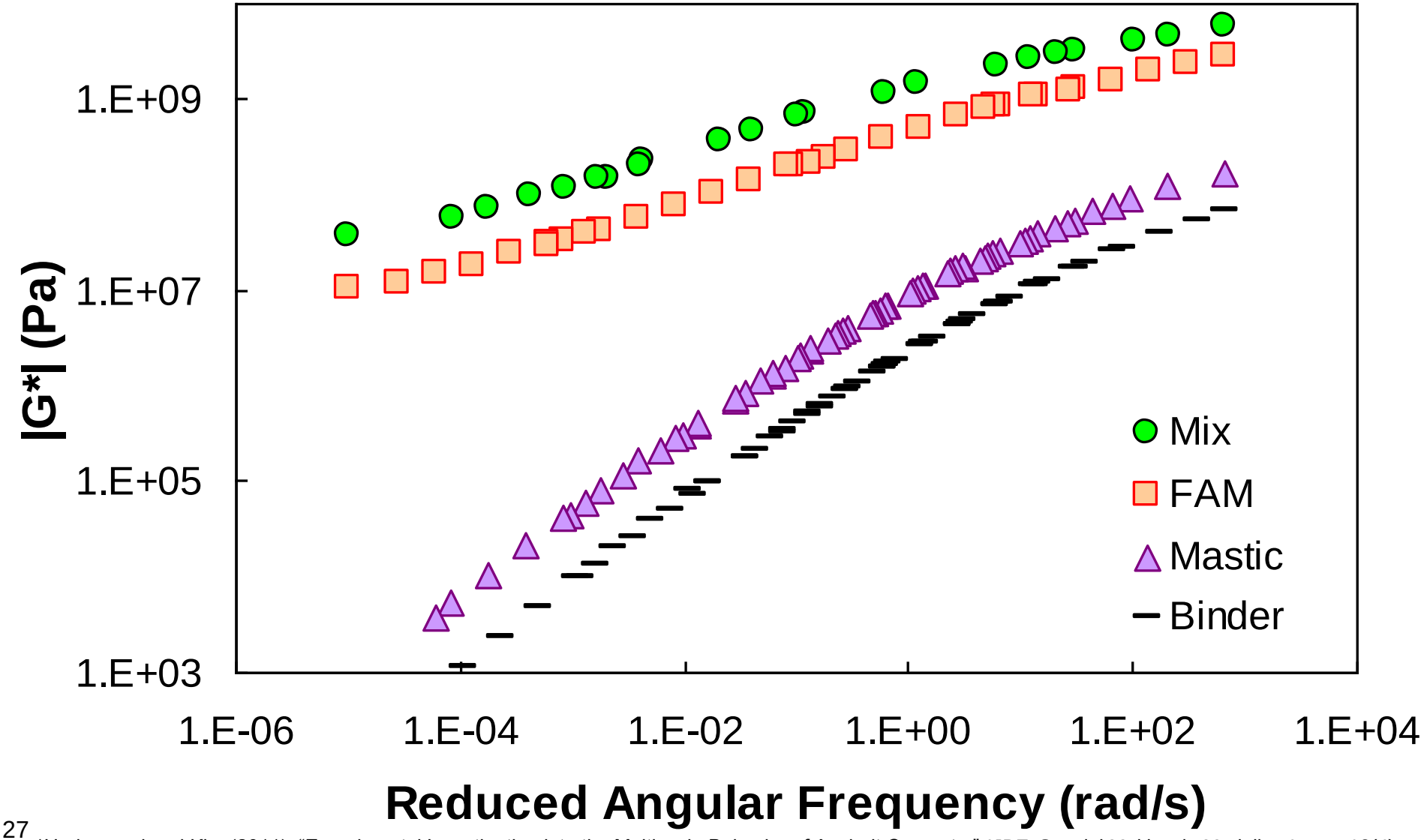
S9.5B



I19.0C

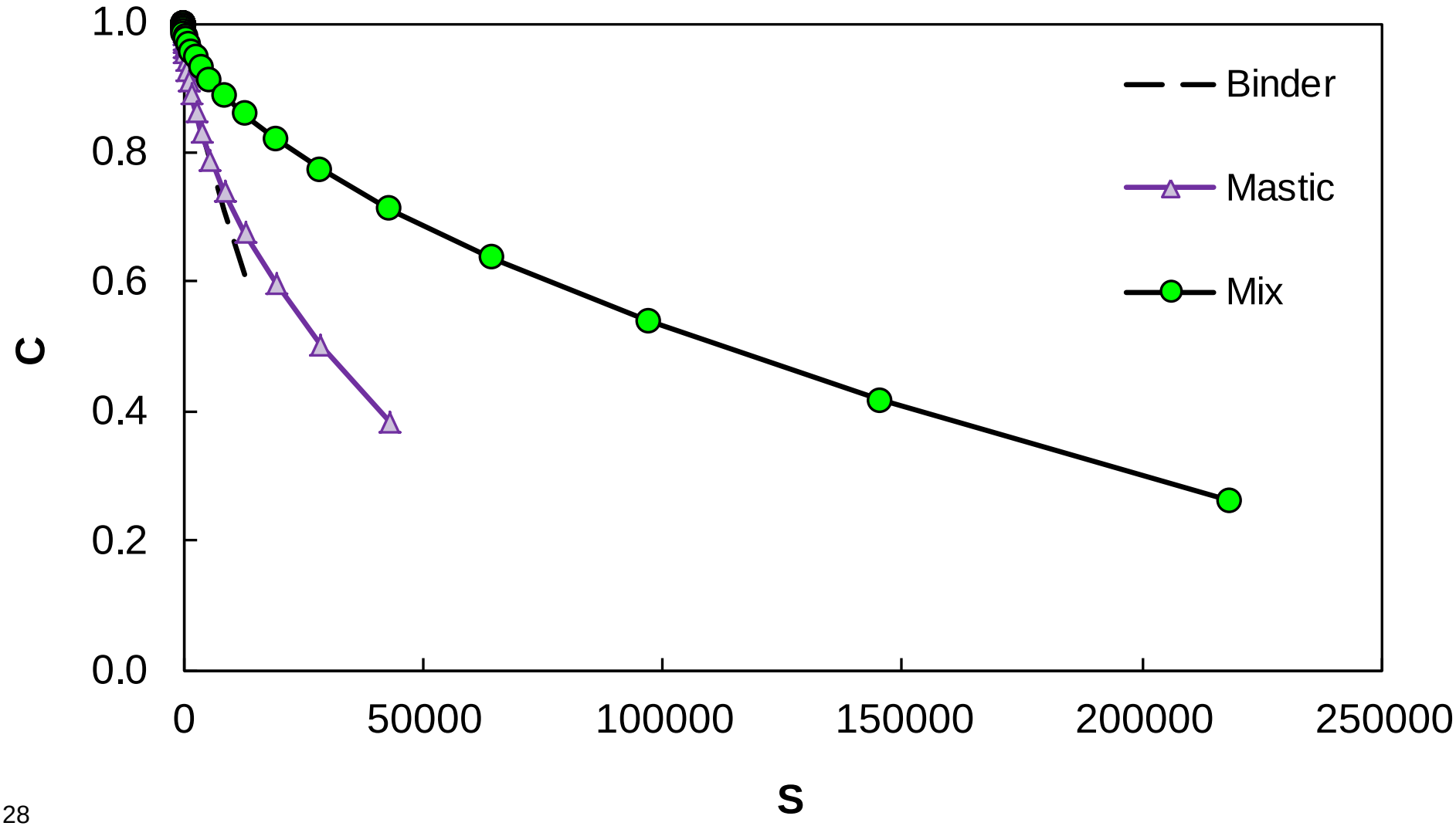


Multiscale Characteristics



*Underwood and Kim (2011). "Experimental Investigation into the Multiscale Behavior of Asphalt Concrete," *IJPE*, Special Multiscale Modeling Issue, 12(4).

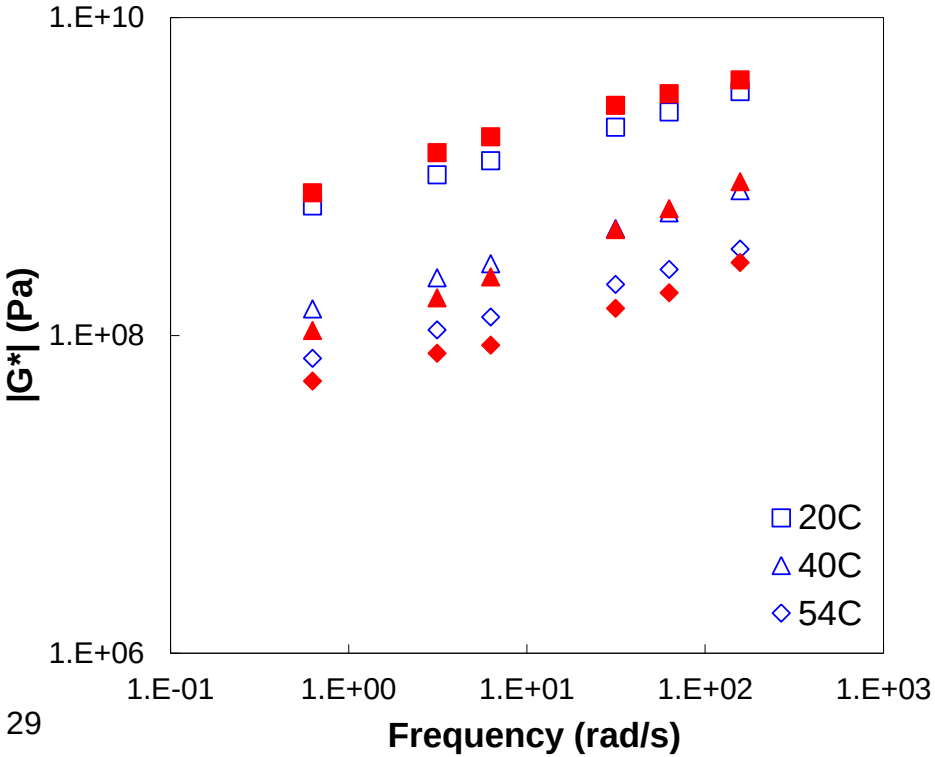
Multiscale Characteristics

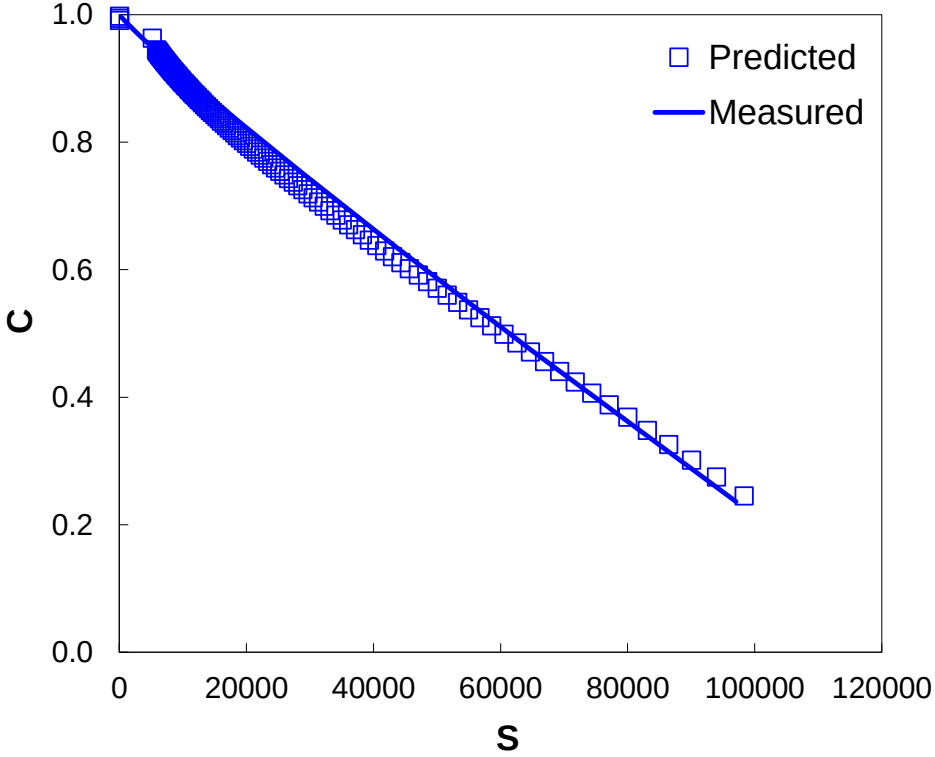


Upscaling Constitutive Behaviors

Mastic to Mixture

- 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

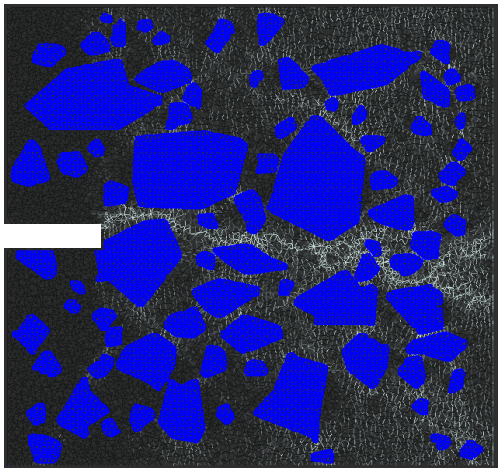
24 mixes
(3 months)

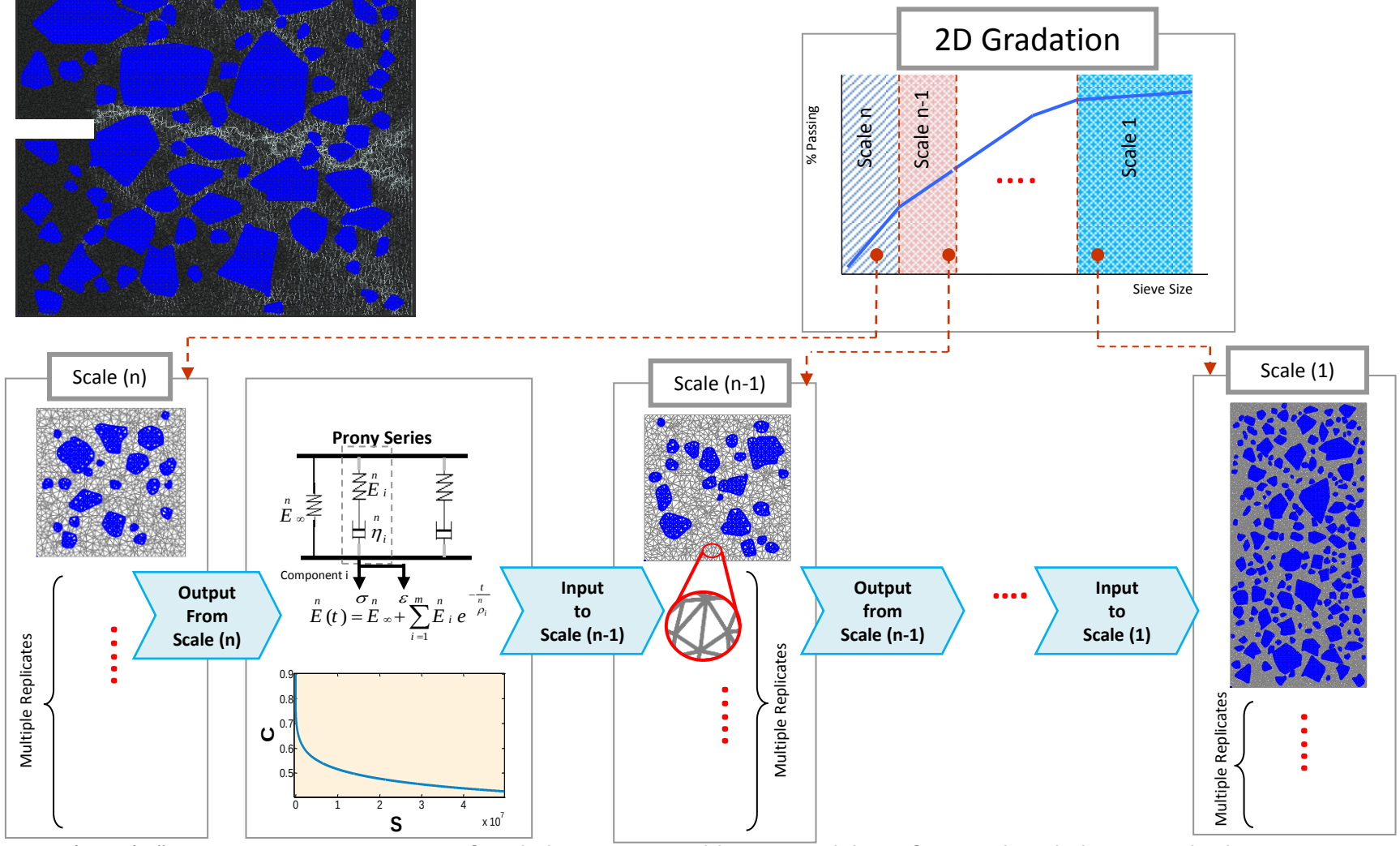
Multiscale Approach

- 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





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 (σ, ε, δ)

↓

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 (σ, ε, δ)

Pavement Response

$$\sigma = E\varepsilon^{R}$$

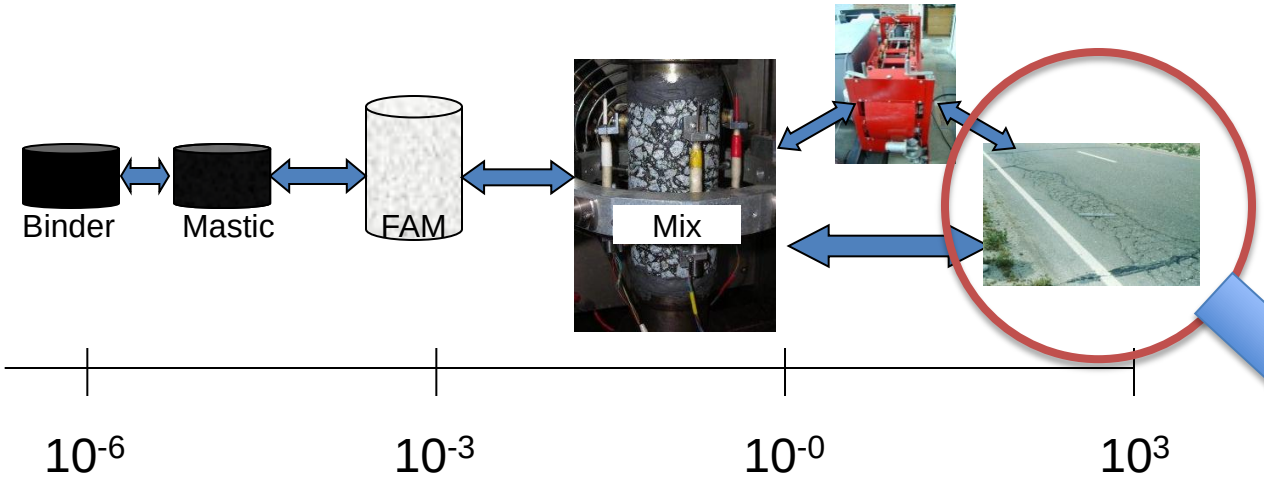
Damage Accumulation

$$\sigma = C\varepsilon^{R}$$

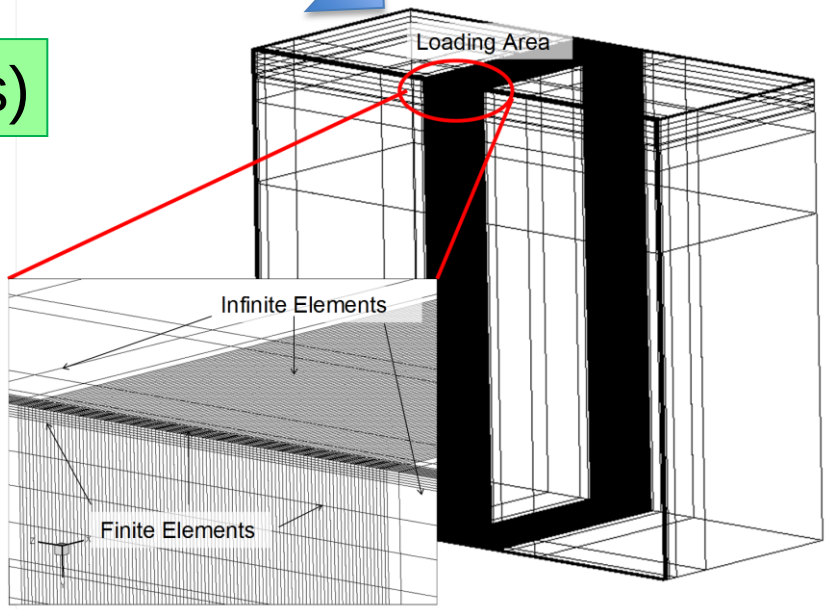
Distress Accumulation

$$Crack = fcn(S)$$

Multiscale Mechanistic Paradigm



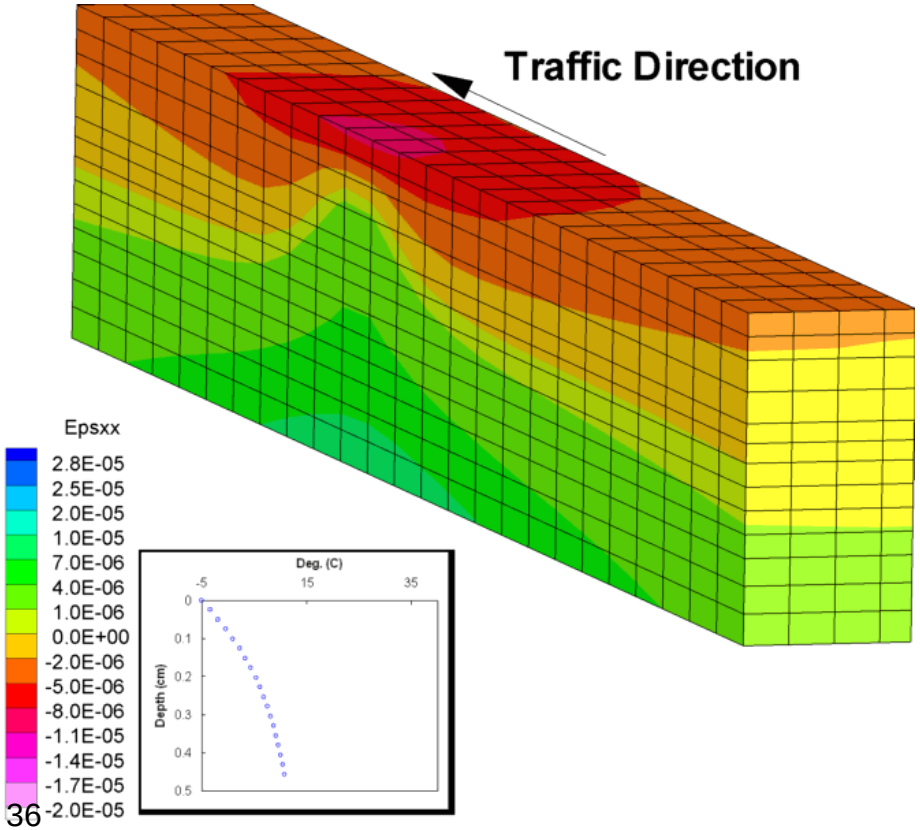
Characteristic Length Scale (meters)



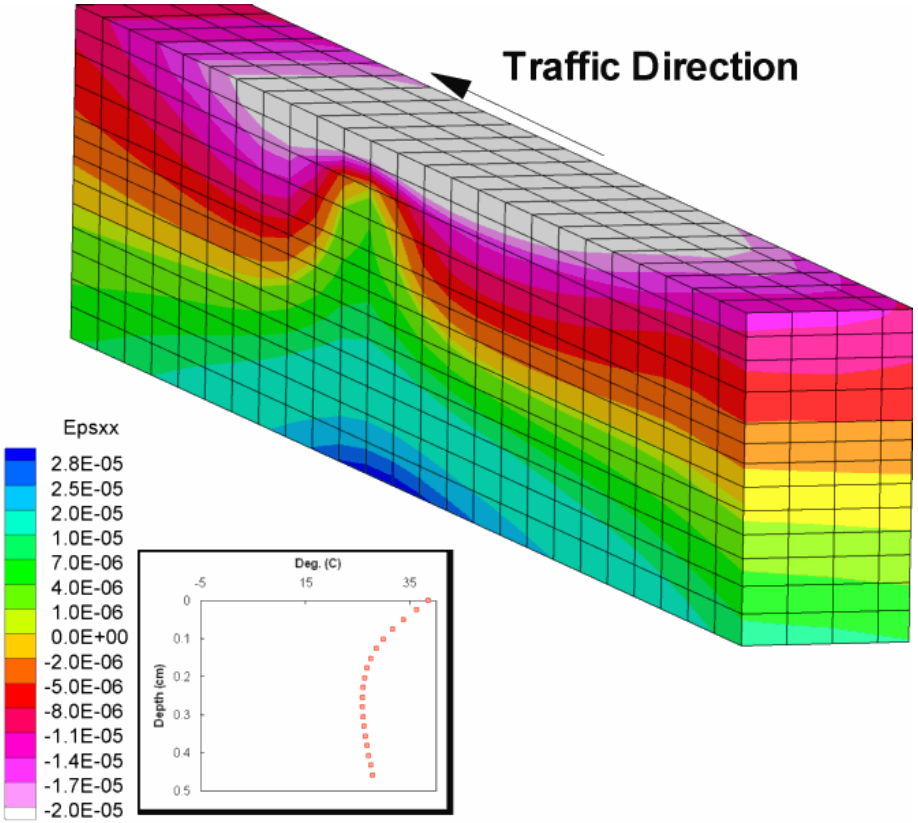
Pavement Evaluation

Response Modeling

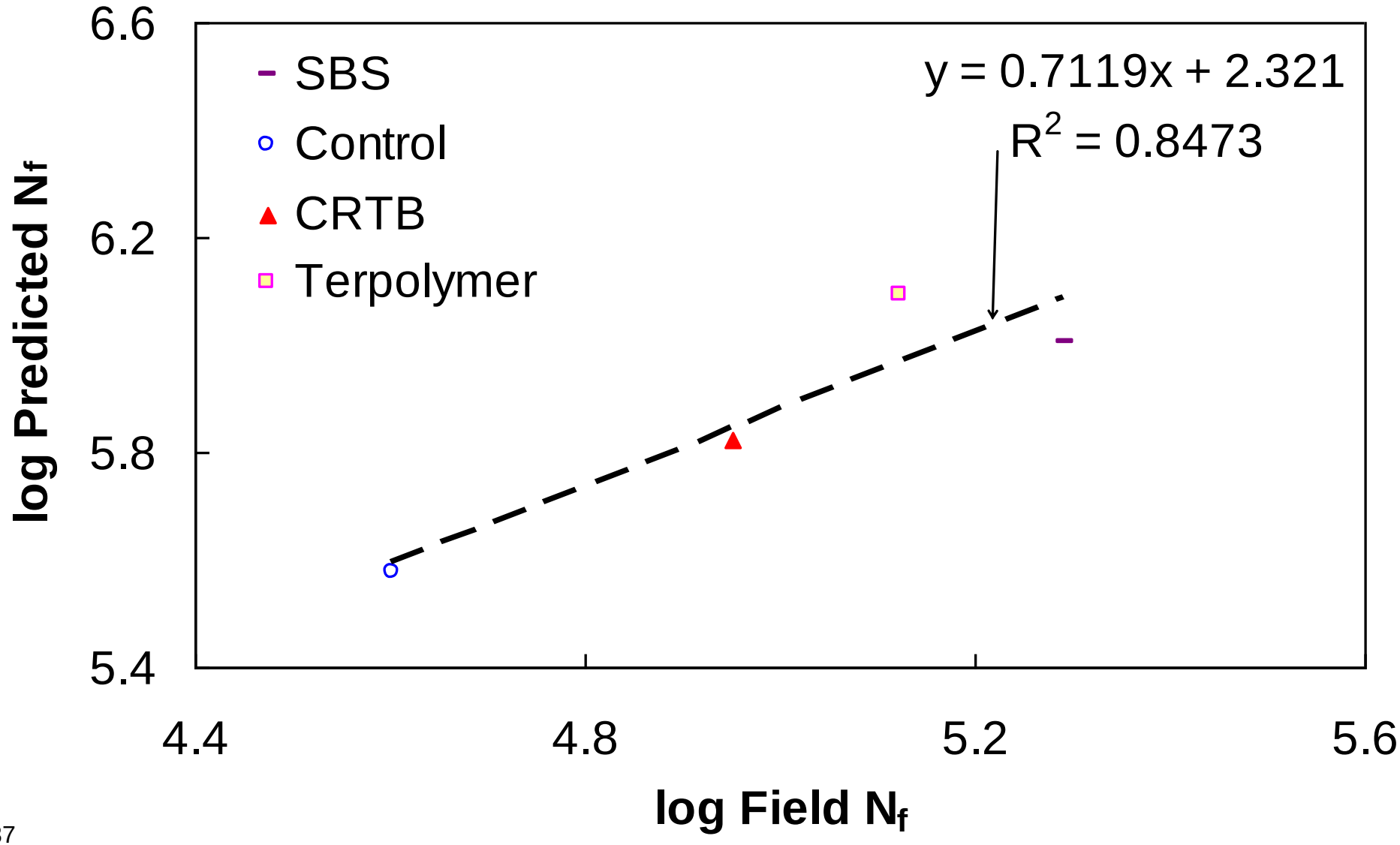
Winter



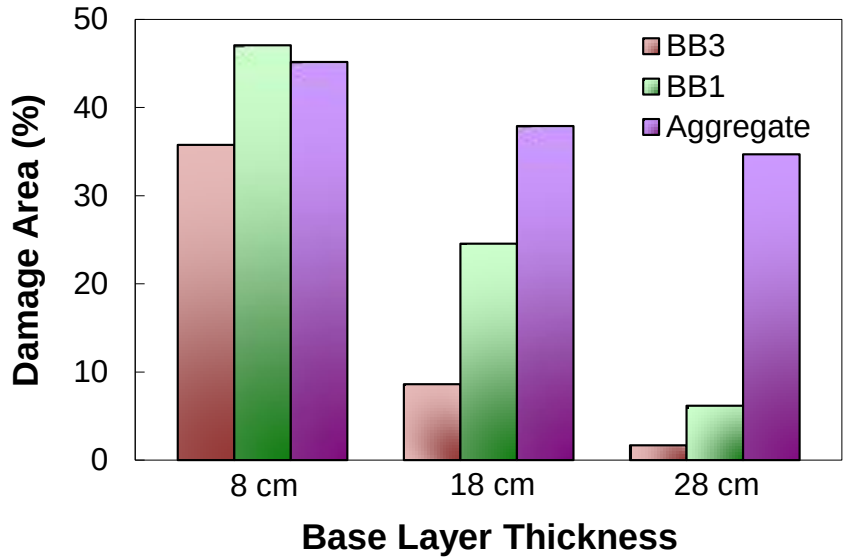
Summer

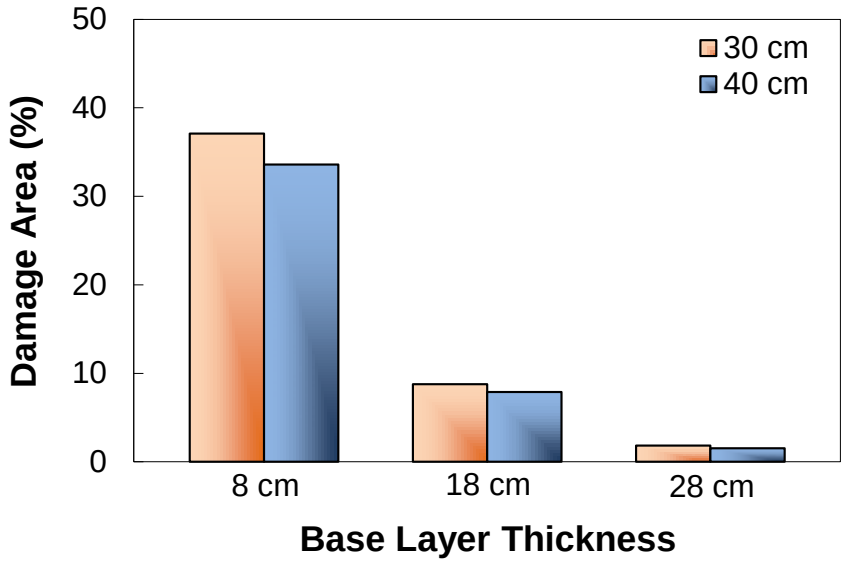


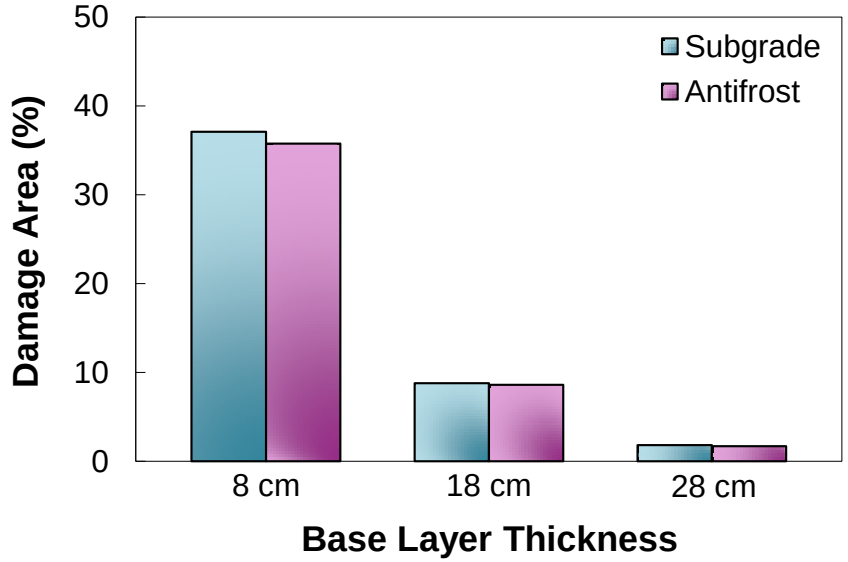
Pavement Fatigue Life Prediction

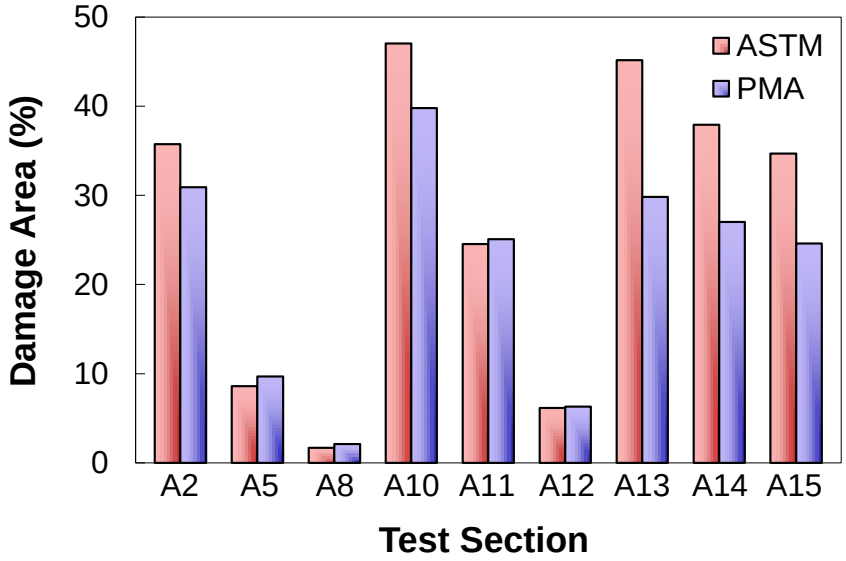


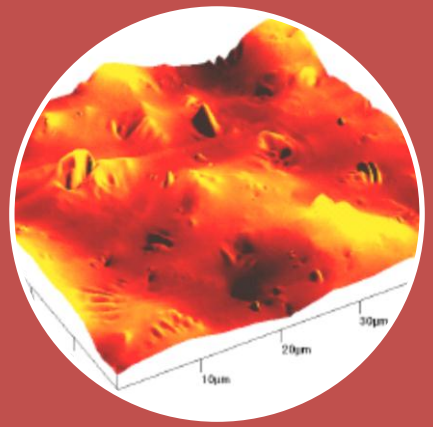
Assessment of Design Alternatives





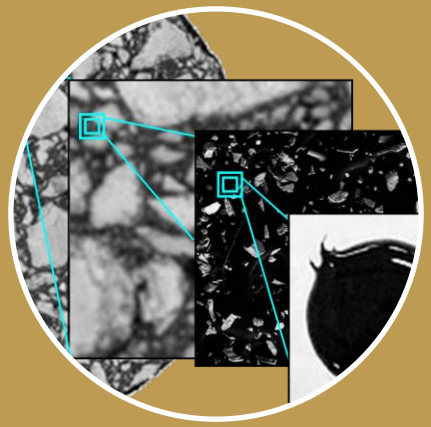






Molecular Range

- 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