A Micro-scale Approach to Evaluate the Asphalt Low Temperature Properties

Yue Hou, Ph.D., Dept. of CEE, Virginia Tech
Dong Wang, Ph.D., Dept. of CEE, Virginia Tech
Wenjuan Sun, Ph.D., Dept. of CEE, Virginia Tech
Troy Pauli, Ph.D., Western Research Institute
Linbing Wang, Ph.D., P.E., Dept. of CEE, Virginia Tech

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1. Introduction

2. Evaluation of Fatigue properties of asphalt binder, mastic and mixture

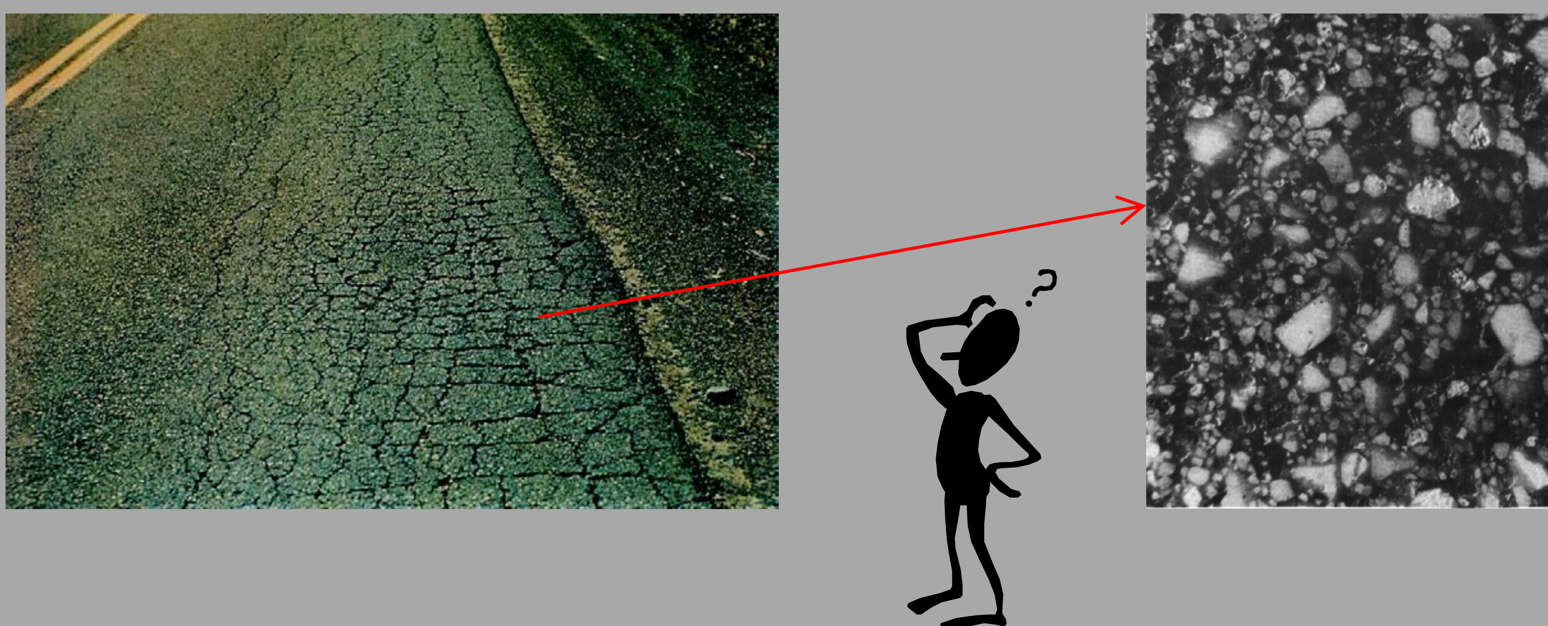
3. Application of Phase-Field Method and MD Simulations in Asphalt Binder Fracture

4. Conclusions and Challenges

Introduction

➢ Research Objectives

- The fatigue cracking and fracture are the two most common distresses on state highway.
- What are the root causes and how to evaluate them?



Introduction

- **Numerical Modeling**

  Finite Element Method; Phase-Field Method; Molecular Dynamics Simulation

- **Experiments**

  Direct Tension Test; X-ray Tomography; Atomic Force Microscopy

- **Digital Mix Design**

  Digital Specimen and Digital Test

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Evaluation of Fatigue properties of asphalt binder, mastic and mixture

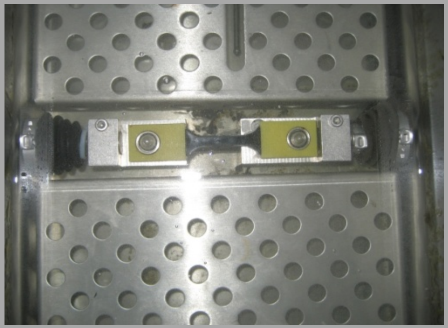
➢ Experiment: fatigue test

Direct Tension Tester (DTT) is altered to build up a new fatigue test procedure.

Loading fixture

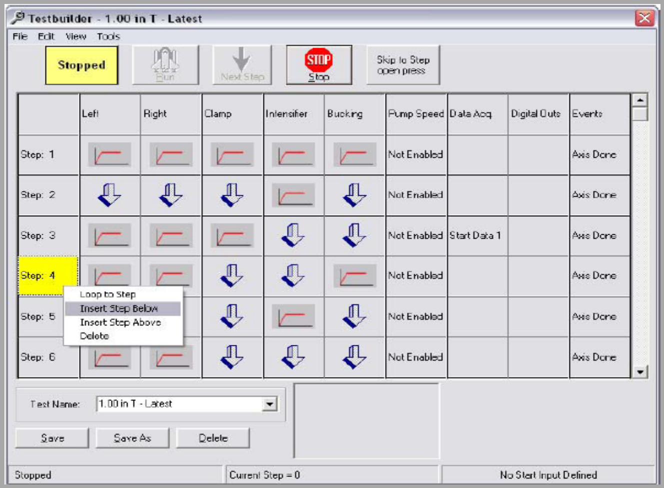
Chiller system

Sample Preparation



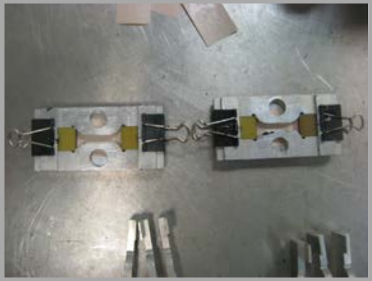
Sample Installation

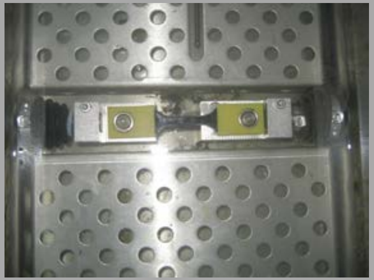
Evaluation of Fatigue properties of asphalt binder, mastic and mixture



- ✓ New fatigue test procedure can be written.
- ✓ Cyclic tensile loading can be applied.
- ✓ Test temperature can be controlled.





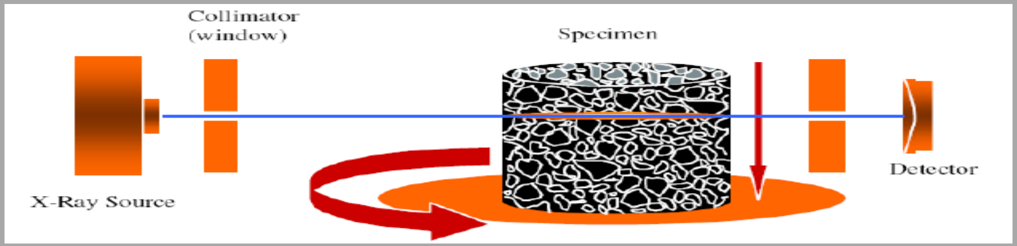
Evaluation of Fatigue properties of asphalt binder, mastic and mixture

➢ Materials

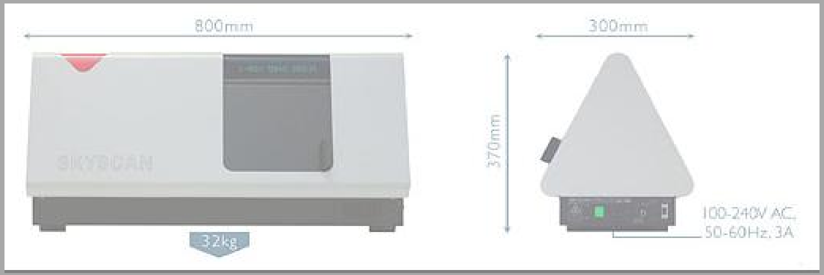
- Asphalt Binder
  - PG 70-22 Binder
- Asphalt Mastic
  - PG 70-22 Binder + Quartz Filler
- Asphalt Mixture
  - PG 70-22 Binder + Aggregates with controlled size (0.5~4.76mm)

Evaluation of Fatigue properties of asphalt binder, mastic and mixture

- **X-ray Tomography**



X-ray system (Wang, 2003)



Sky Scan 1174 Compact X-ray system

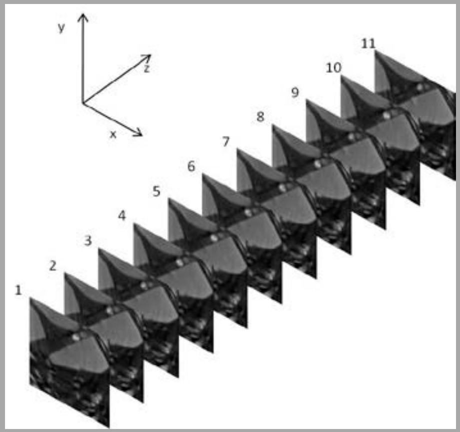
Evaluation of Fatigue properties of asphalt binder, mastic and mixture

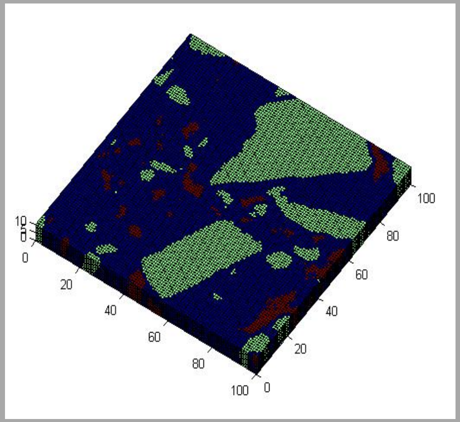
➢ Fatigue Test Comparison

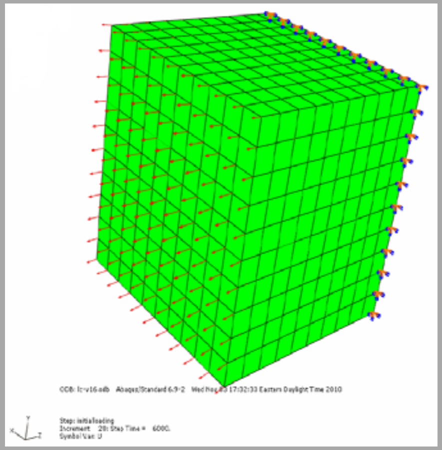
Specimens	Average final strain	Average number of cycles
Binder	0.0059	105
Mixture no filler	0.0124	1676
Mixture with 30% filler	0.0459	12226
Mastic with 20% filler	0.0587	16395
Mastic with 30% filler	0.0684	19208
Mastic with 40% filler	0.0652	17457

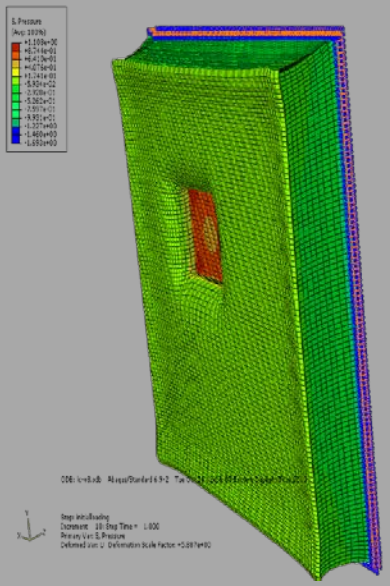
Evaluation of Fatigue properties of asphalt binder, mastic and mixture

➢ **Numerical Modeling**

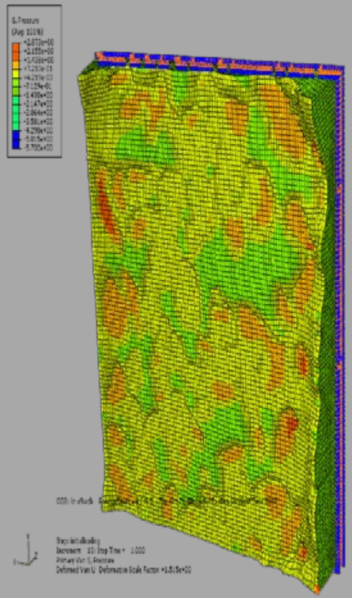








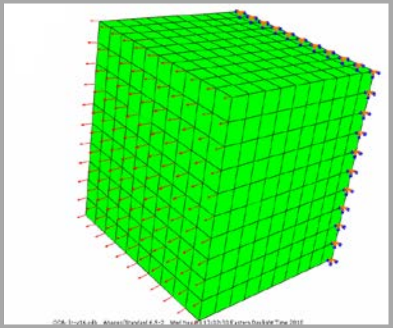
Single Aggregate



Multiple Aggregates

Application of PFM in Mode I Cracking in Asphalt Binder

➢ Digital specimen and digital test



- ✓ Center node of the loading surface
- ✓ Number of loadings and final strain

	Lab results		Simulation results	
	Number of loading cycles	Strain	Number of loading cycles	Strain
Binder	105	0.0059	105	0.0042
30% filler Mastic	19208	0.0684	19200	0.0508
Mixture with filler	12226	0.0459	12200	0.0372

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Application of Phase-Field Method in Asphalt Binder Fracture

- **Phase Field and Interface**

  Material between intact (ϕ=1) and fully broken (ϕ=0) states, is considered as 0< ϕ<1. Two kinds of interface can be used.

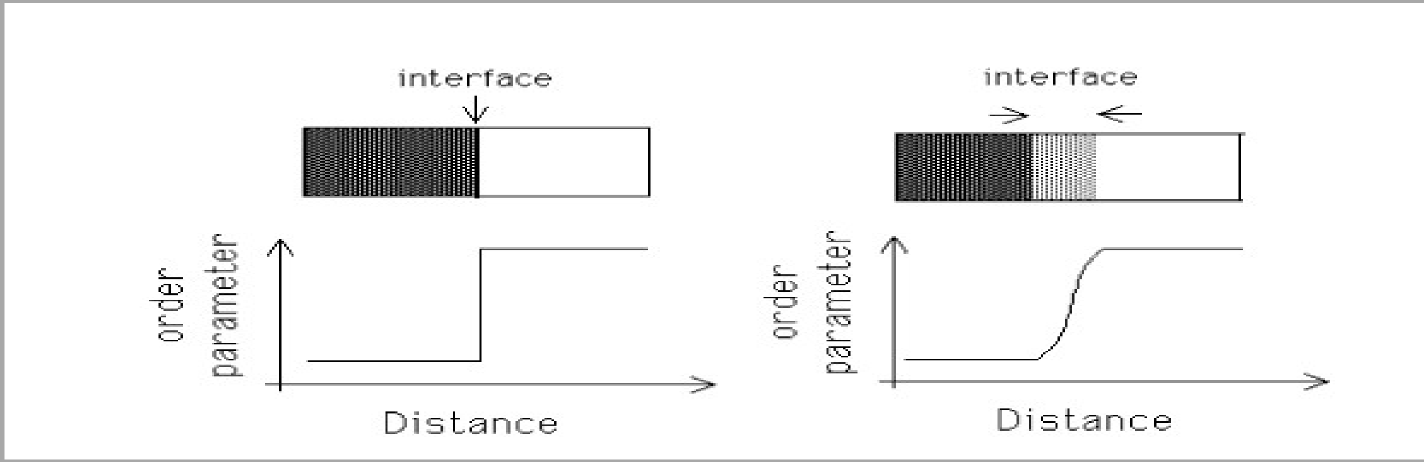


Figure 1 (a) Sharp interface (b) Diffuse interface*

*http://nele.studentenweb.org/research/?subject=PFM

Application of Phase-Field Method in Asphalt Binder Fracture

➢ Fundamental Concepts in PFM

- ❖ A model for a phase field can be constructed by physical arguments if one have an explicit expression for the free energy of the system.
- ❖ The driving force of the system is either Chemical potential or the gradient of Chemical potential.

I. Free energy ($f(\phi)$)

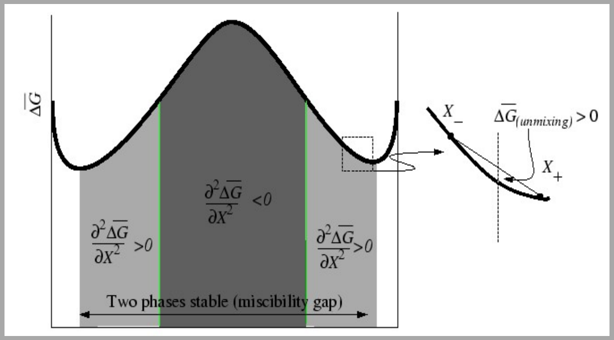
- A thermodynamic potential that measures the "useful" or process-initiating work of a system.
- It is calculated by MD simulation.

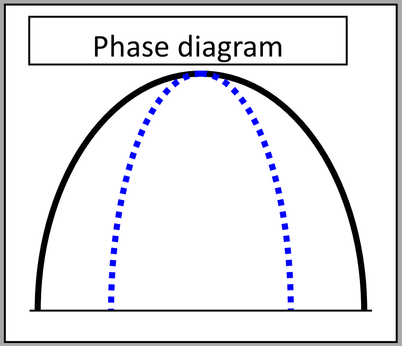
II. Chemical potential(G or μ)

- A measure of the potential that a substance has to produce in order to alter a system.
- It is calculated as the variational derivative of free energy with respect to order parameter.

Application of Phase-Field Method in Asphalt Binder Fracture

➤ Phase kinetics





- Spinodal decomposition*

Two components can separate into distinct regions (or phases) with distinctly different chemical compositions and physical properties.

- A simple example

The figure shows that a cup of red ink is well mixed with water.

After a certain time, ink and water will get separated due to different gravitational potential energy.

Asphalt fracture develops since fracture phase and intact phase has different chemical potential and they get phase separated.

*Figure is from http://pruffle.mit.edu/3.00/Lecture_32_web/node3.html

Application of Phase-Field Method in Asphalt Binder Fracture

- Phase field equations
  - Total free energy is expressed as

$$F = \int_{\Omega} (f_{gr} + f_{local} + f_{el}) d\Omega$$

    - The gradient energy density $f_{gr} = \frac{1}{2}\lambda|\nabla\phi|^2$.
    - The local free energy density $f_{local} = \frac{\lambda}{4\epsilon^2}(1-\phi)^2(1+\phi)^2$ is a commonly used double well potential.
    - The elastic energy density $f_{el} = \frac{E(\phi)}{2(1+\nu)}(\frac{\nu}{1-2\nu}(\varepsilon_{ii})^2 + \varepsilon_{ik}\varepsilon_{lk})$

      Where $E(\phi) = E + (E - E_0)h(\phi)$ is the elastic modulus

      and $h(\phi) = -\frac{1}{4}\phi^3 + \frac{3}{4}\phi + \frac{1}{2}$ interpolates the void phase ($\phi = -1$) and the intact phase ($\phi = 1$);

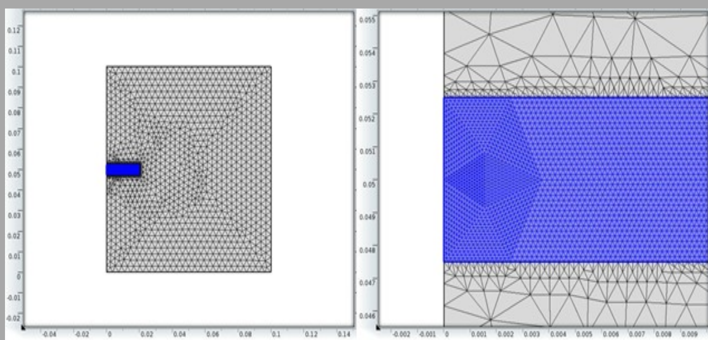
      Possion's ratio $\nu = 0.3$ is phase- independent.

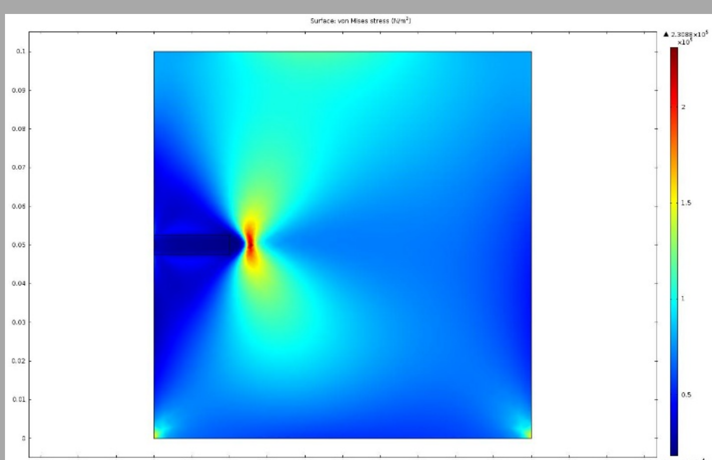
  - Allen-Cahn equation (Non-conserved case)

$$\frac{\partial\phi}{\partial t} = -M\frac{\delta F}{\delta\phi}$$

Application of Phase-Field Method in Asphalt Binder Fracture

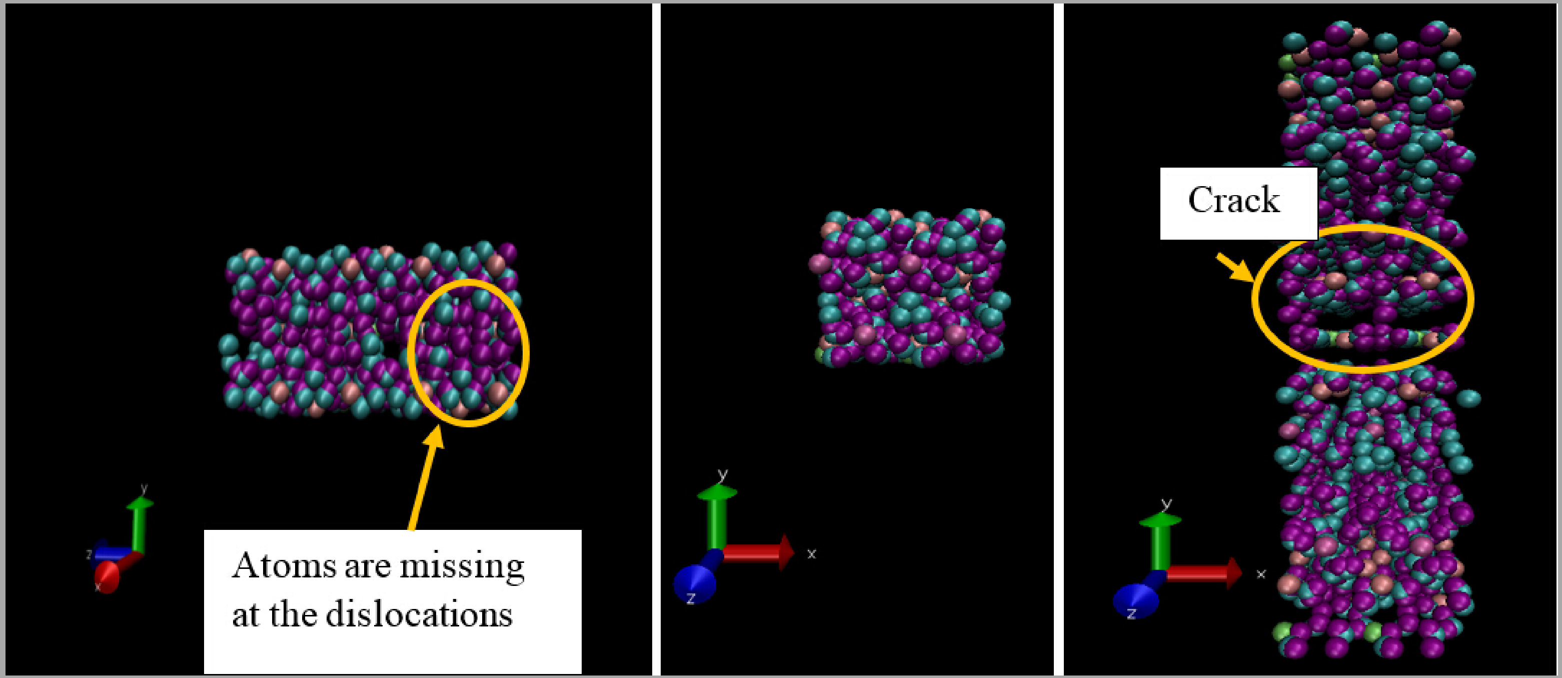
- A simple case with self-adaptive meshing





Multi-scale approach

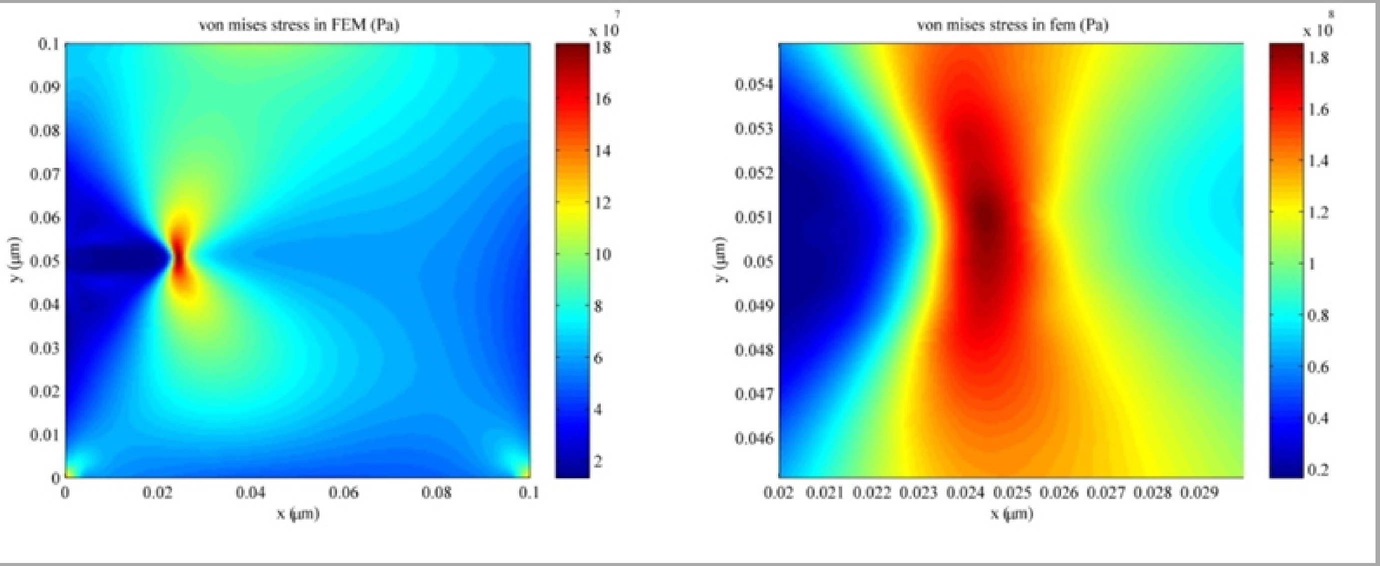
- MD simulations

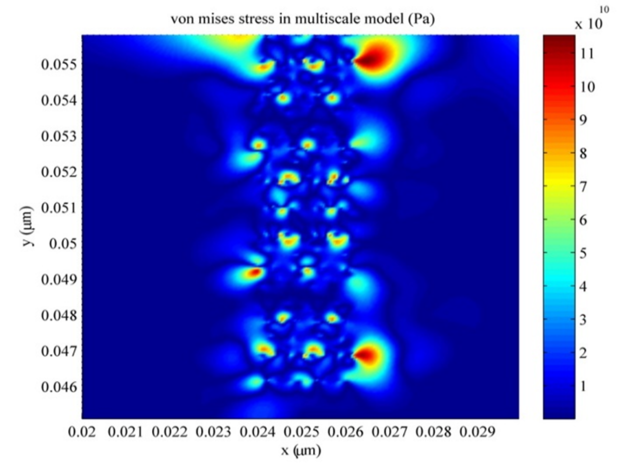


Molecular structure of crack tip in the molecular dynamics (MD) model: (a) & (b) initial view molecular structure from different views (c) molecular structure after tension failure

Multi-scale Approach

➢ Multi-scale Approach based on MD and PFM





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Conclusions and Challenges

➢ Conclusions

- Filler improves binder fatigue resistance. 30% optimum filler content.
- Digital Specimen and Digital Test improve understanding.
- Phase-field Method could capture and simulate the asphalt fracture.
- A multi-scale approach could tie macro properties such as the stress concentration with molecular structure.

➢ Future Plan

- Further verification and validation

Thank you!