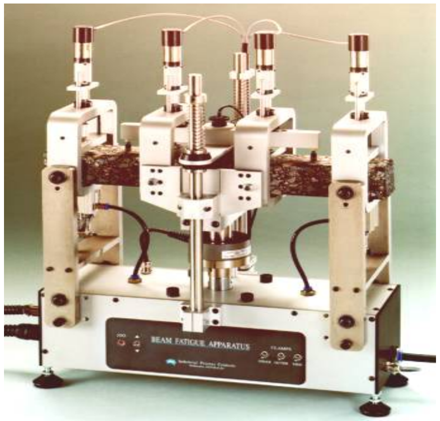
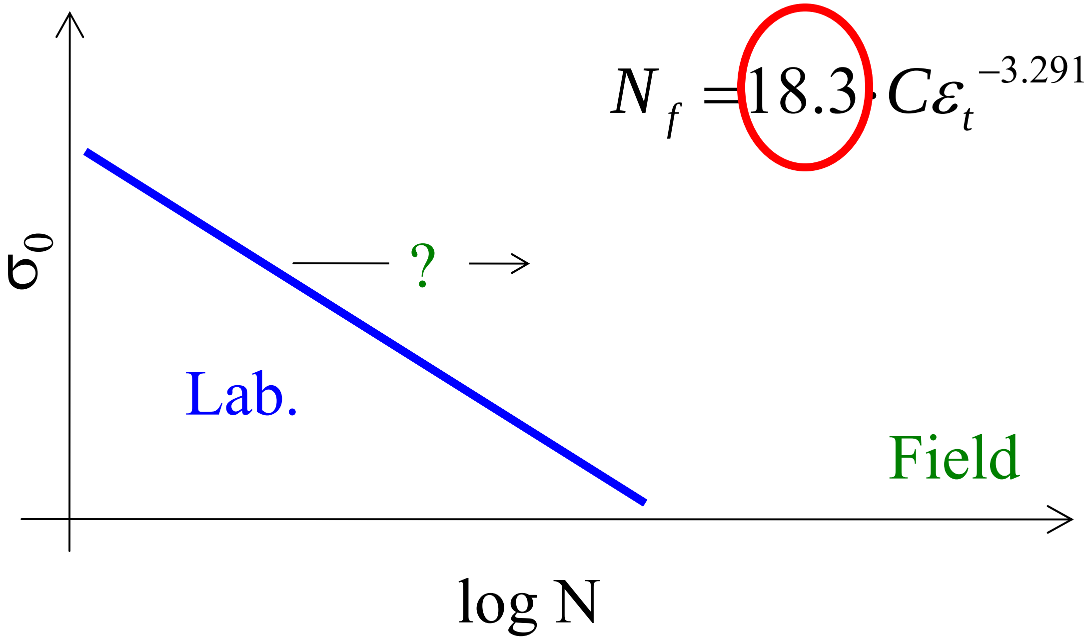
Impact of Healing



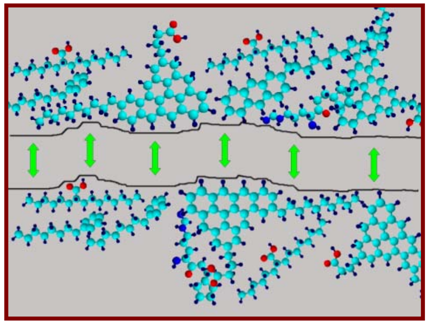
Self healing in bituminous materials

$$N_f = 18.3 \cdot C\varepsilon_t^{-3.291} E^{*-0,845}$$



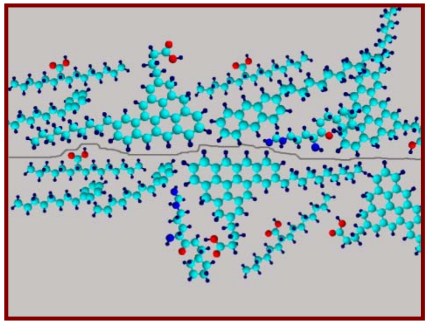
Healing Mechanism

Step 1: Interfacial Wetting



$$\frac{d\phi(t,X)}{dt} = \dot{a}_b = fn$$ (healing zone, bonding stress, creep compliance properties, work of cohesion)

Step 2: Intrinsic healing



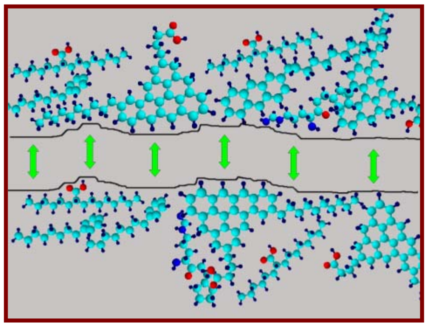
$$R_h(t) = fn$$ (work of cohesion, self diffusivity)

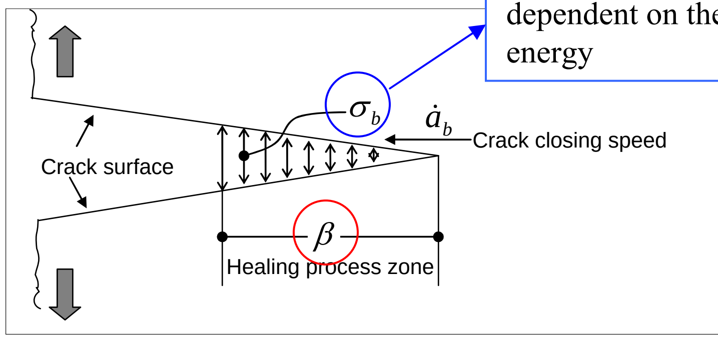
The two processes are combined using the approach originally proposed by Wool and O'Connor as follows:

$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau,X)}{dt}d\tau$$

Healing Mechanism

Step 1: Interfacial Wetting





Bonding stress: Indirectly dependent on the surface energy

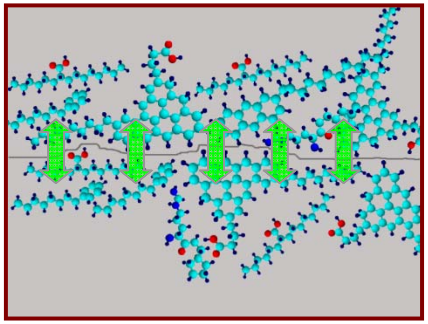
Work of cohesion: From surface energy

$$\frac{d\phi(t, X)}{dt} = \dot{a}_b = fn \text{ (healing zone, bonding stress, creep compliance properties, work of cohesion)}$$

Viscoelastic property: Creep parameters from power law, $\varepsilon(t)=D_0+D_1t^m$

Healing Mechanism

Step 2: Intrinsic healing



Strength gain of wetted surfaces over time is defined using an intrinsic healing function: $R_h(t)$

Strength gain is also a two step process:

1. Instantaneous adhesion due to surface energy

2. Time dependent self diffusion and randomization

Collectively, the intrinsic healing function can be modeled as:

$$R_h(t) = R_0 + p\left(1 - e^{-qt^r}\right)$$

Instantaneous healing proportional to work of cohesion (R_0)

Time dependent healing proportional to self diffusivity ($p\left(1 - e^{-qt^r}\right)$)

Healing Mechanism

$$R_h(t) = R_0 + p\left(1 - e^{-qt^r}\right)$$

Instantaneous healing proportional to work of cohesion

Time dependent healing proportional to self diffusivity

The approach used in polymers is based on the random walk approach

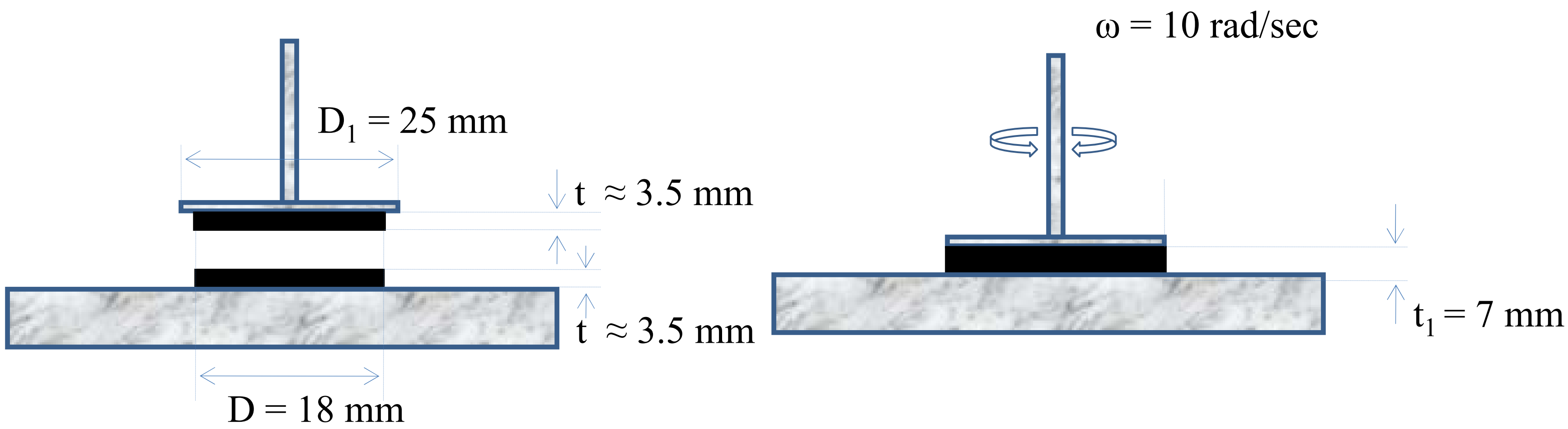
- requires detailed knowledge of the molecular structure of the material
- more applicable to materials with chain like molecules

With asphalt binders we do not have the luxury of either of the above two…

Instead we used a DSR to determine the intrinsic healing function of different asphalt binders

Quantifying Intrinsic Healing

Outline of the procedure



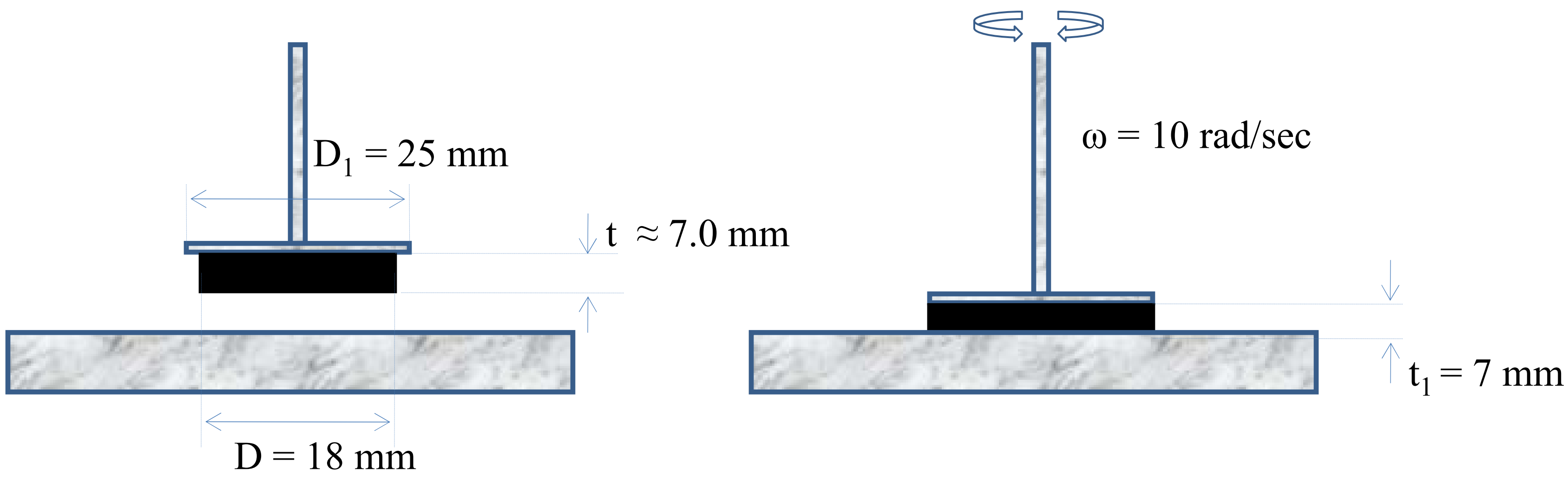
Two piece specimen of asphalt binder was brought into contact to obtain a "wetted" interface

G* was recorded intermittently at 0, 2, 4, 6, 8, 10, 15, 20, 25, 30, 40, 50 and 60 seconds after bringing the two specimens into contact with each other

Quantifying Intrinsic Healing

Outline of the procedure

The final results were normalized by repeating the test with a single specimen of the same asphalt binder and twice the thickness

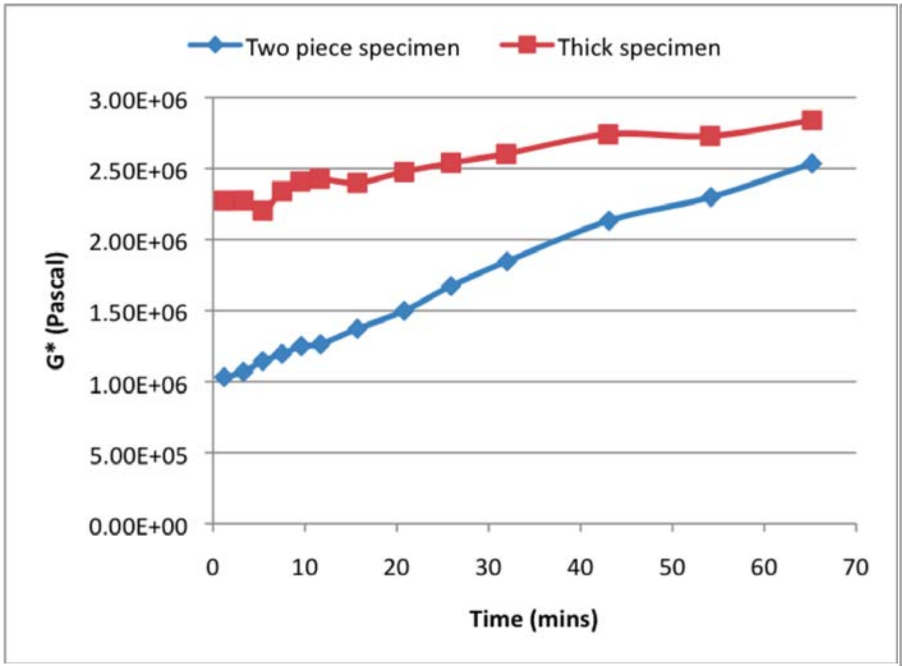


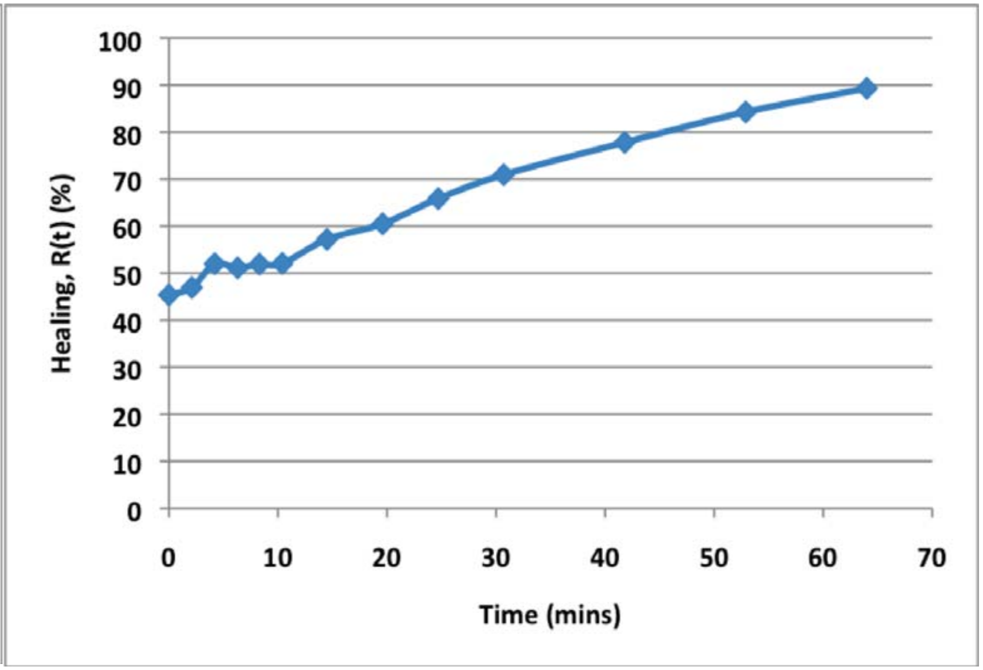
Quantifying Intrinsic Healing

Images of the test being performed with the two piece specimen before and after the test

Quantifying Intrinsic Healing

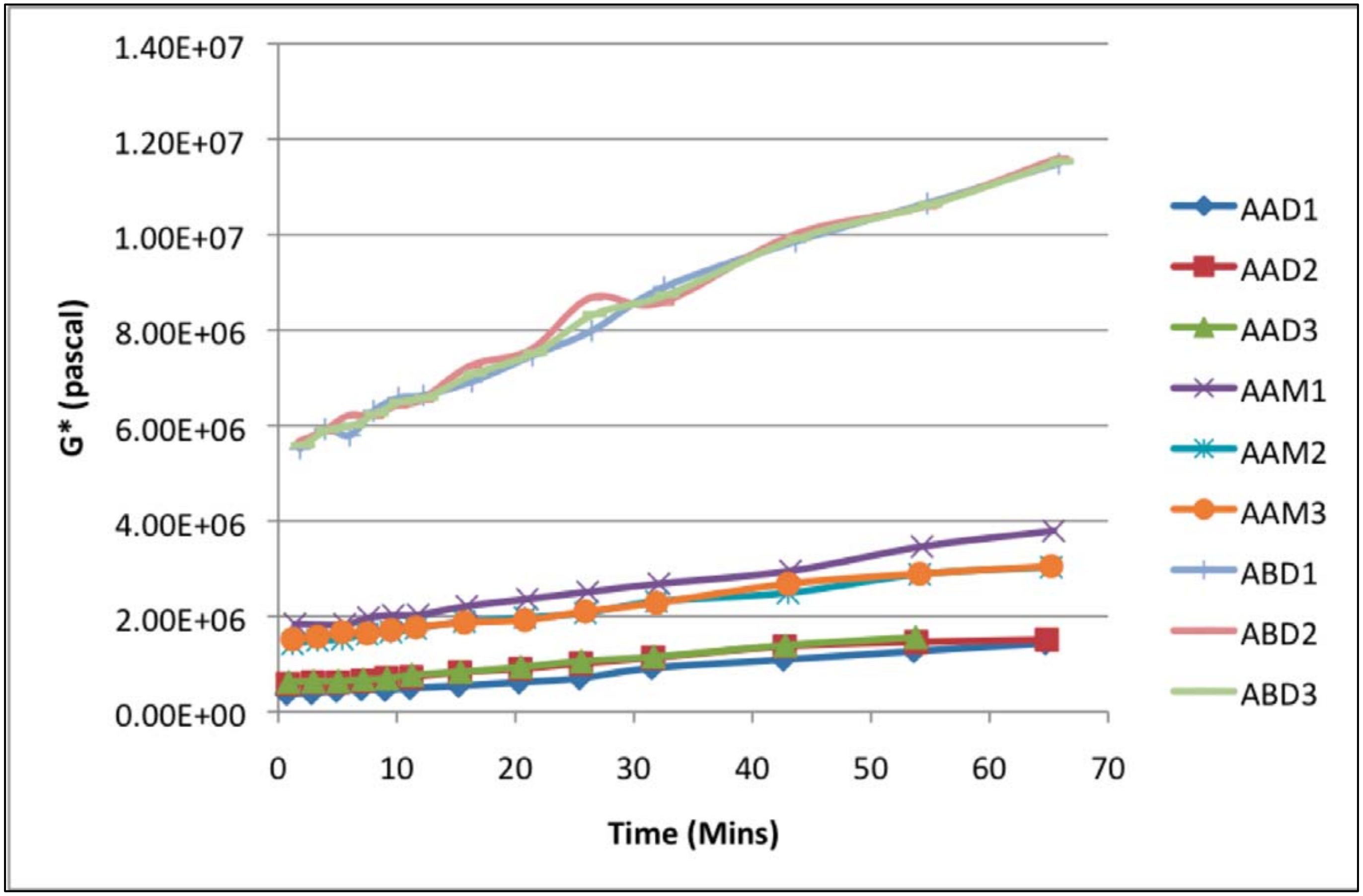
Data analysis





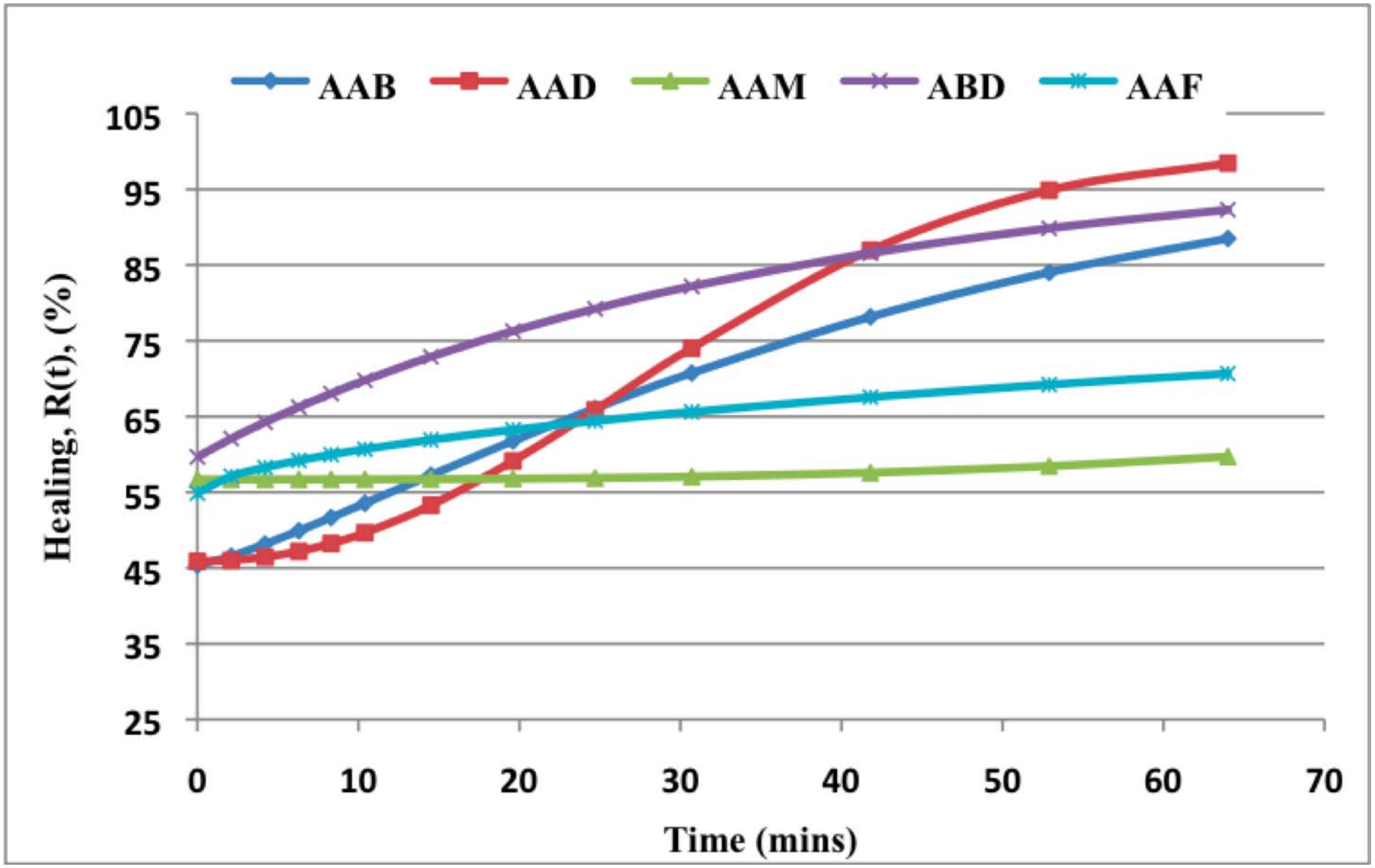
Quantifying Intrinsic Healing

Replicate data



Quantifying Intrinsic Healing

Results for the SHRP binders

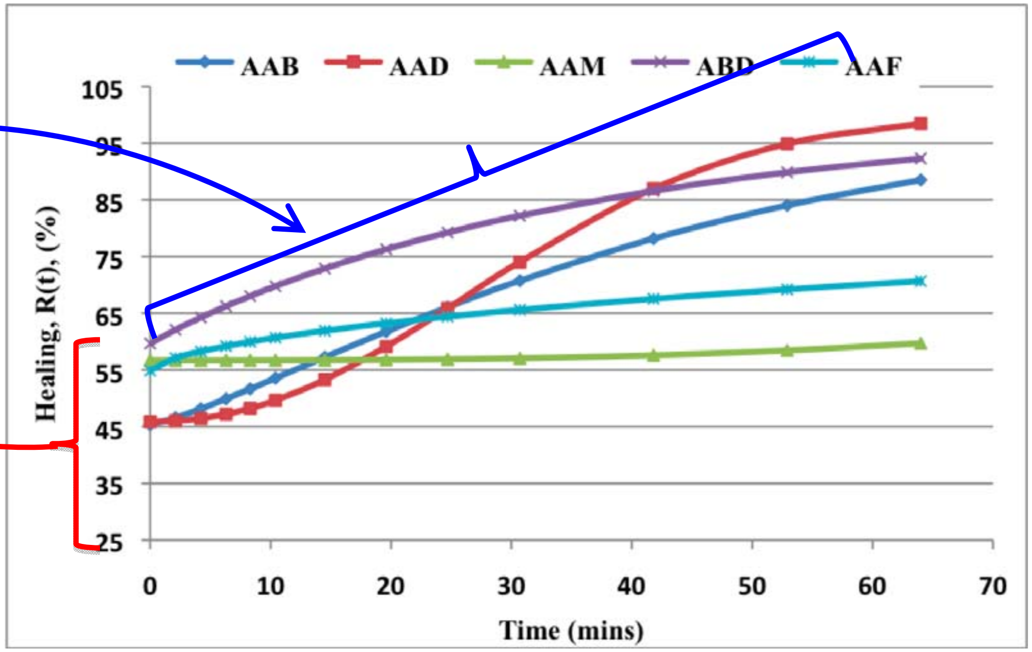


Quantifying Intrinsic Healing

Results for the SHRP binders

This data were fit to the functional form for intrinsic healing to obtain the relevant parameters

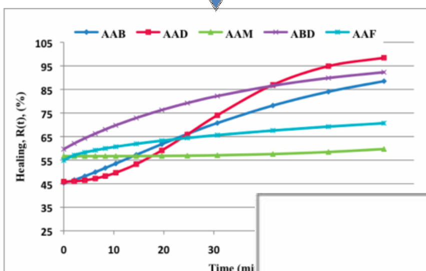
$$R_h(t) = R_0 + p\left(1 - e^{-qt^r}\right)$$

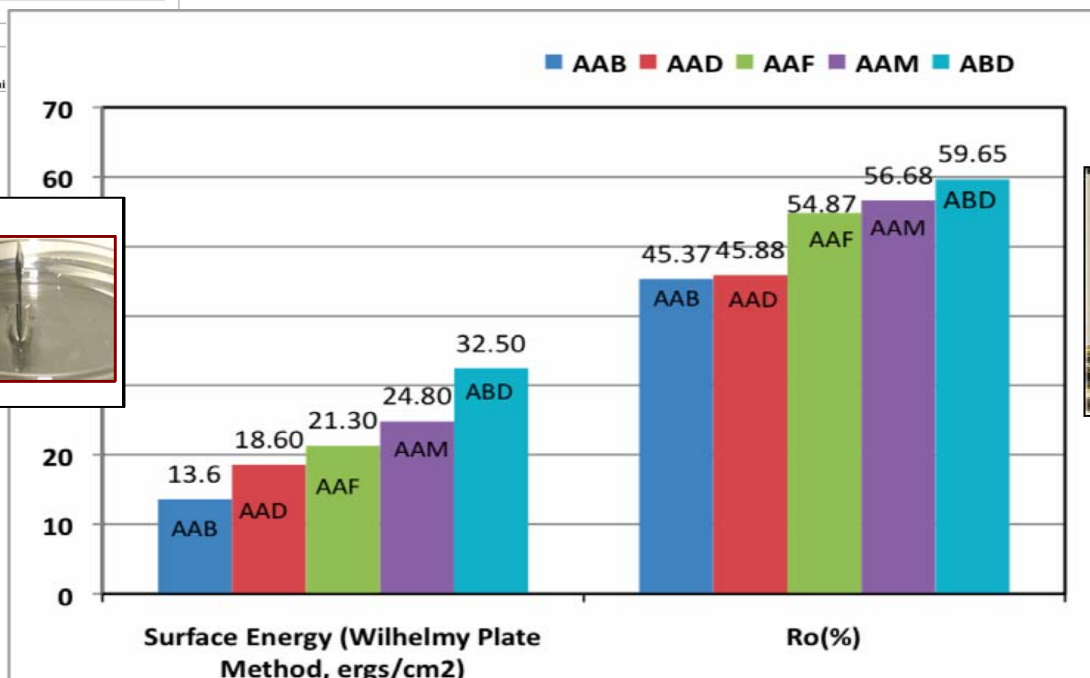


Recall that the term Ro, was due to the surface free energy or work of cohesion of the binder

Validation of Model

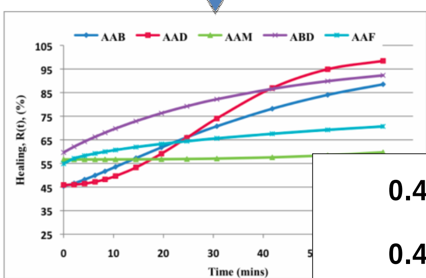
$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau, X)}{dt}d\tau$$

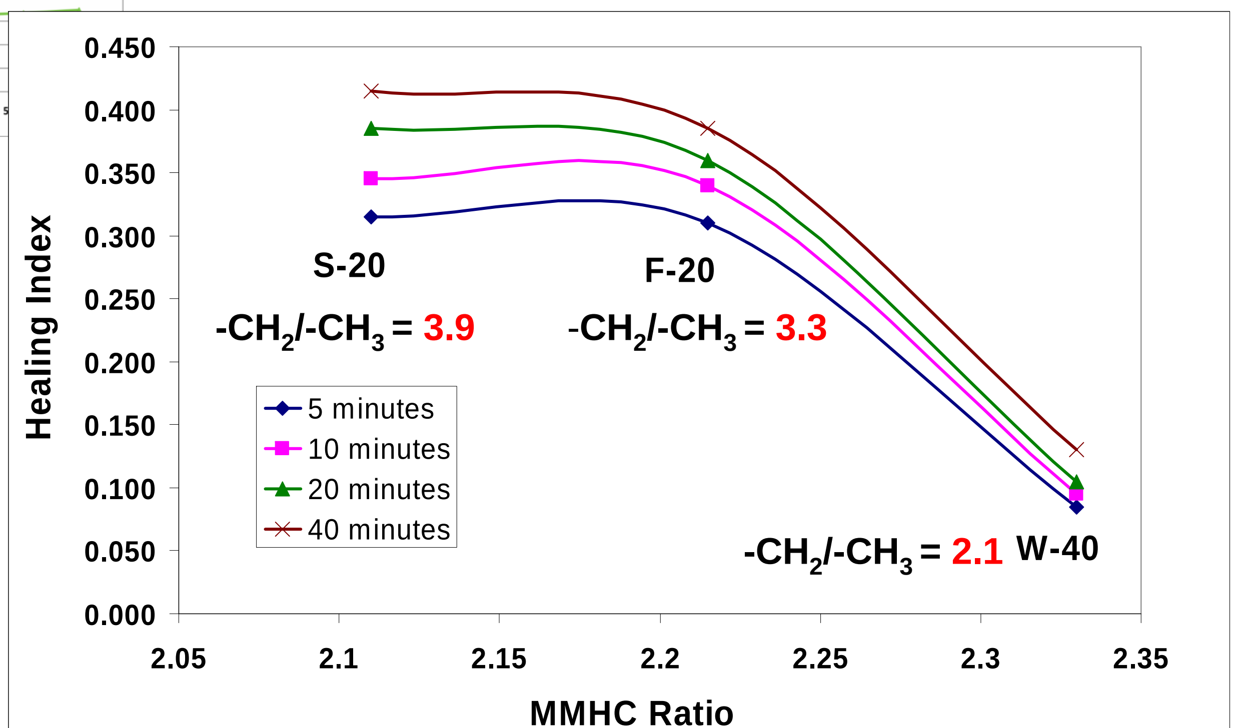




Validation of Model

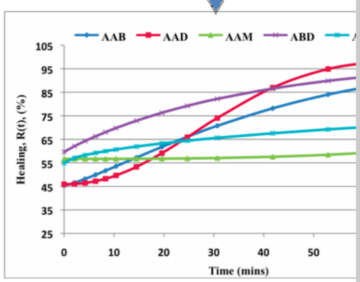
$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau, X)}{dt}d\tau$$

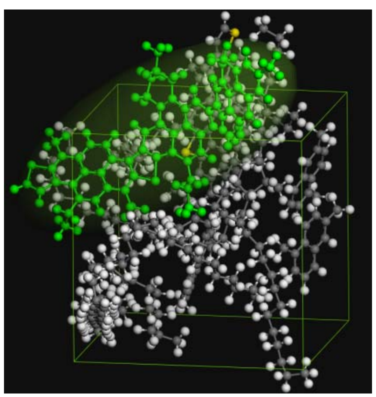


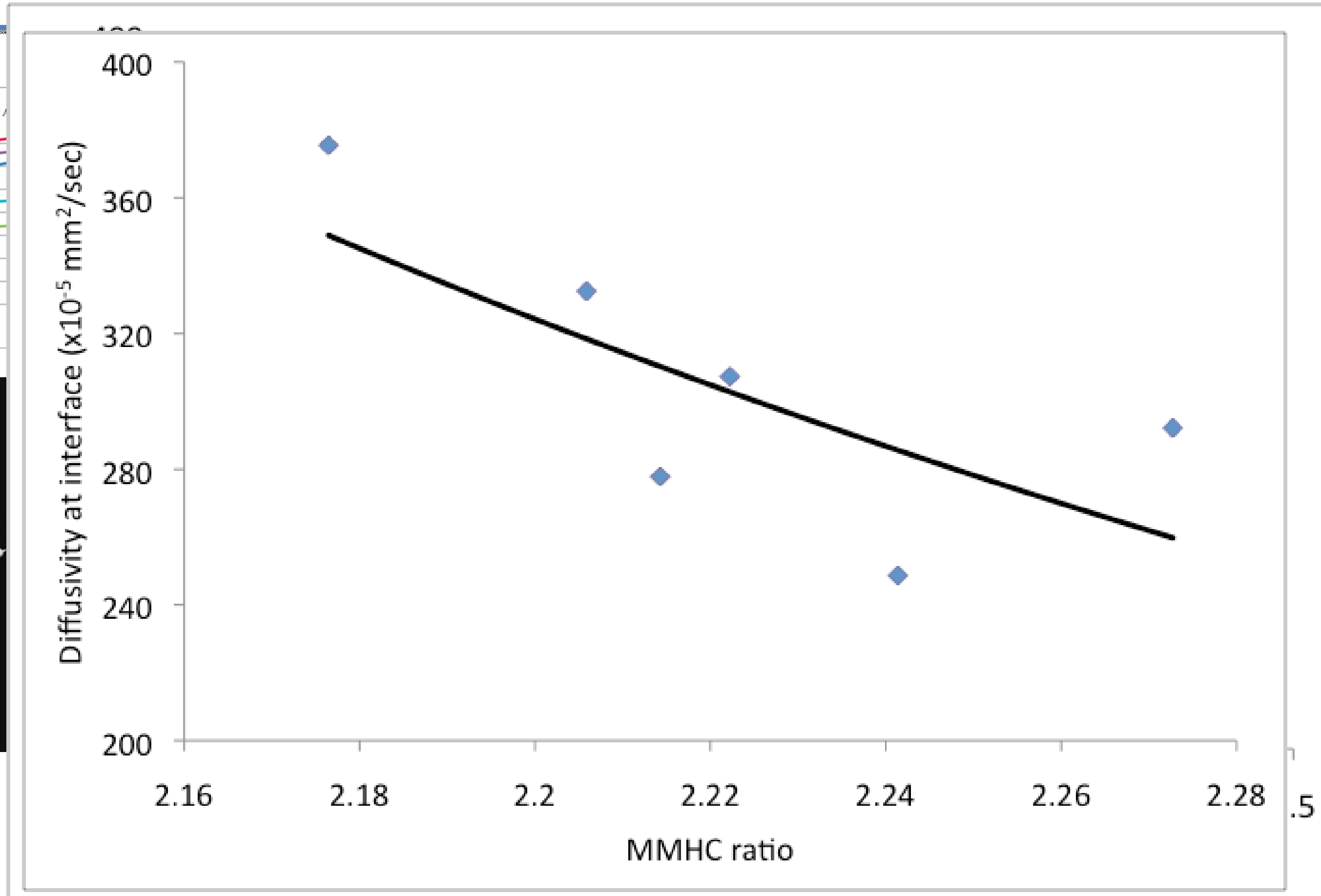


Validation of Model

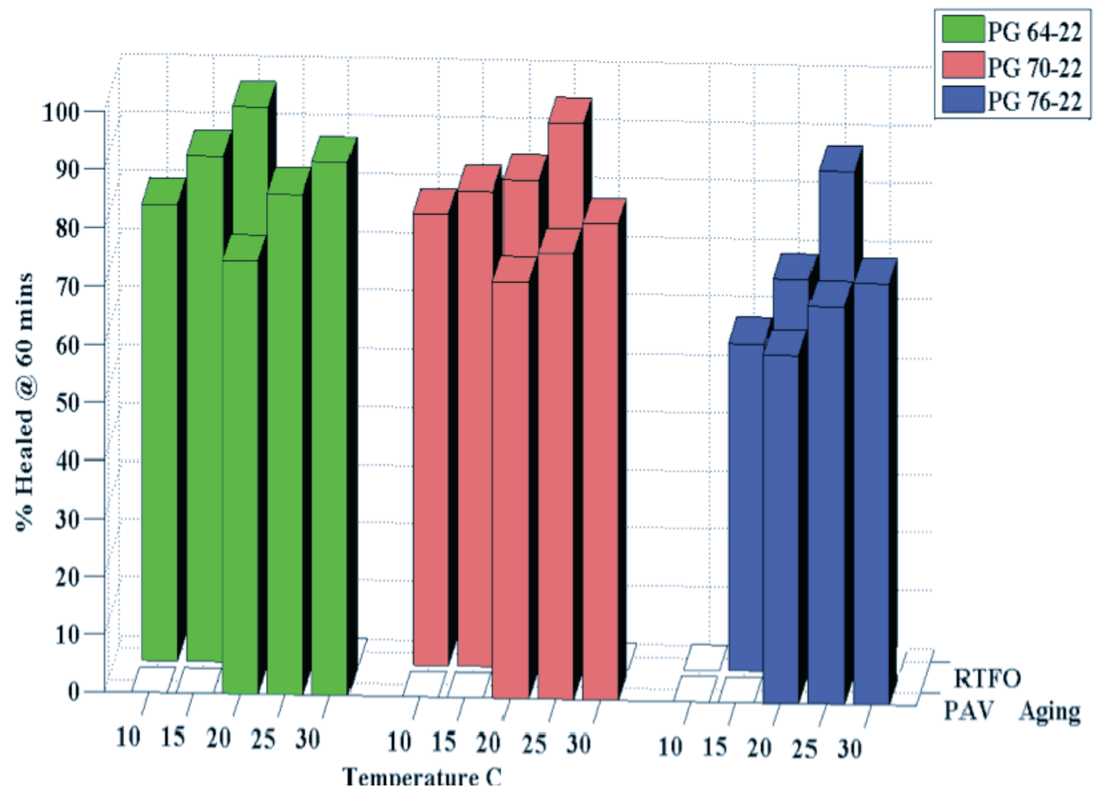
$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau, X)}{dt}d\tau$$





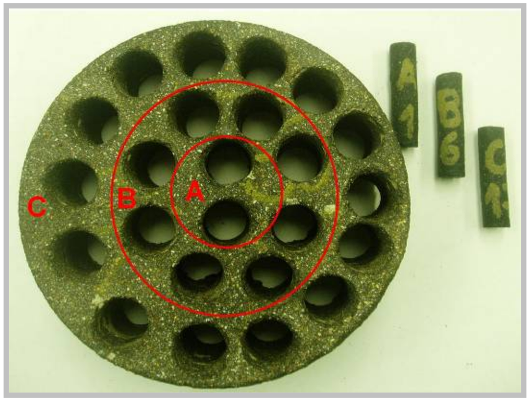


Intrinsic Healing – Temperature and Age Dependency



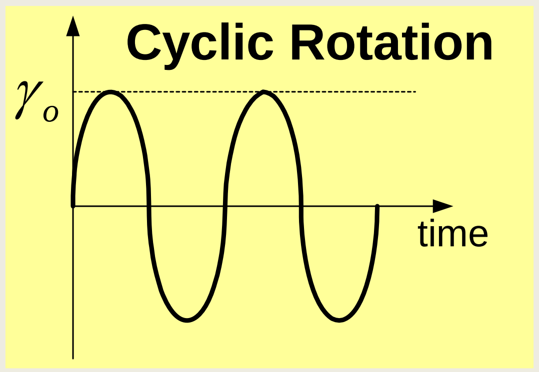
Total intrinsic healing at the end of 1 hour for RTFO and PAV aged binders at different temperatures

Quantifying Healing: DMA



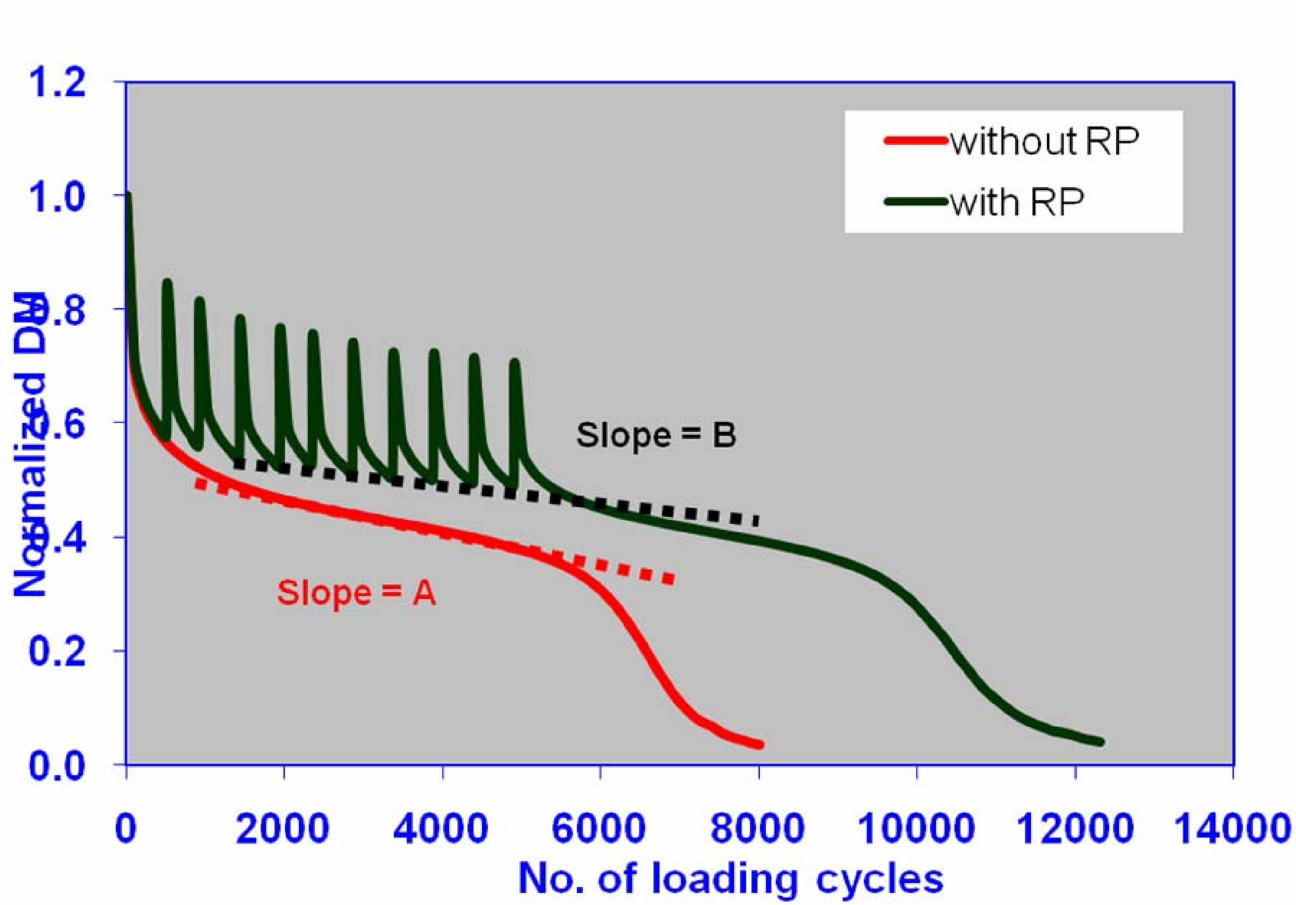
Specimen Fabrication

Test Setup

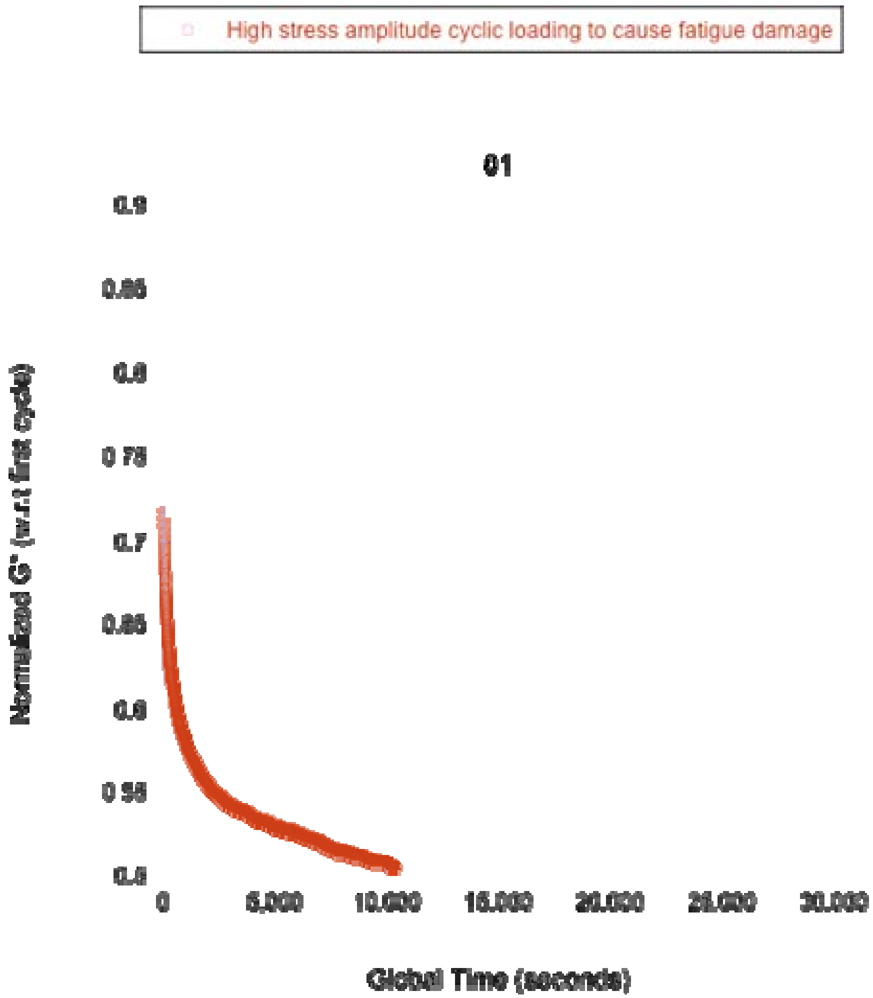


Test Form

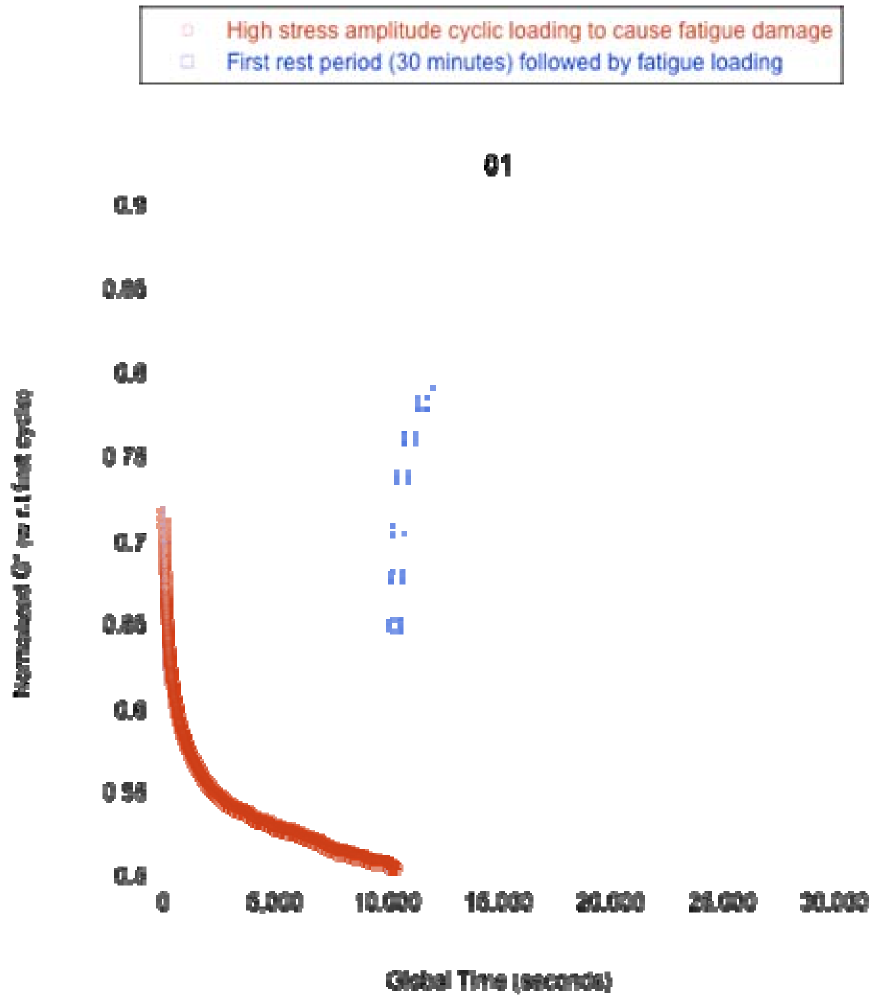
Quantifying Healing: DMA



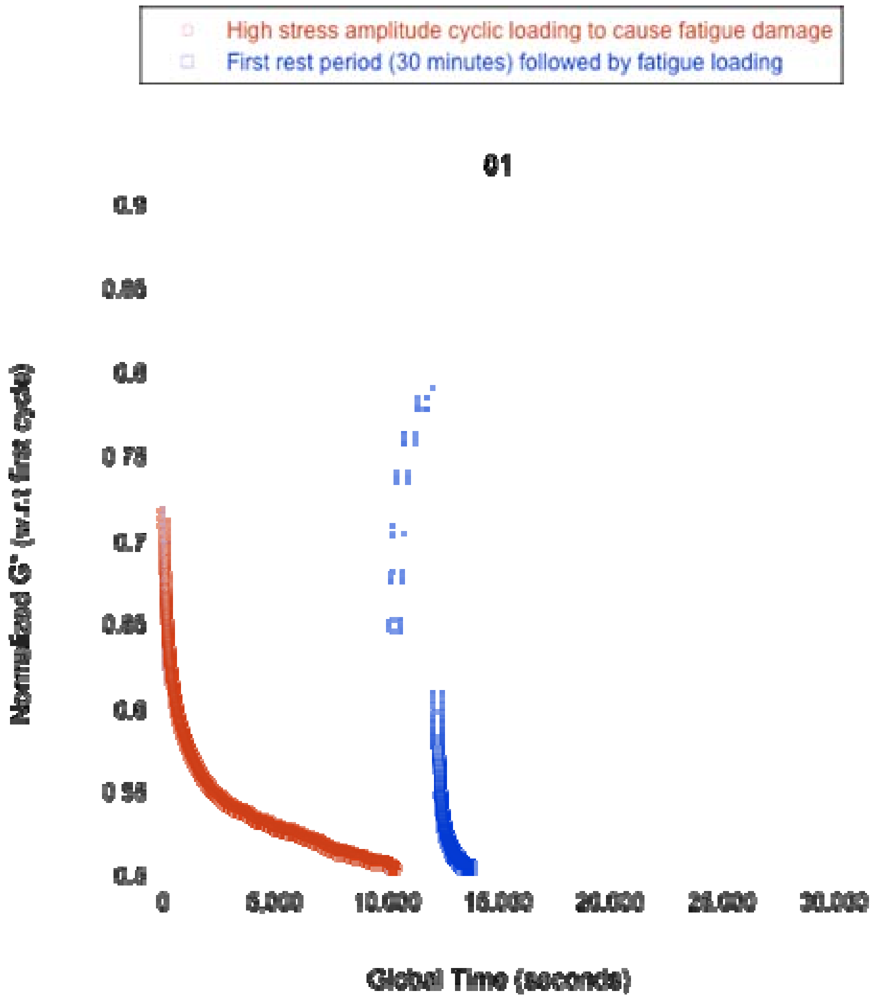
Healing: Convolution of Wetting/Intrinsic Healing



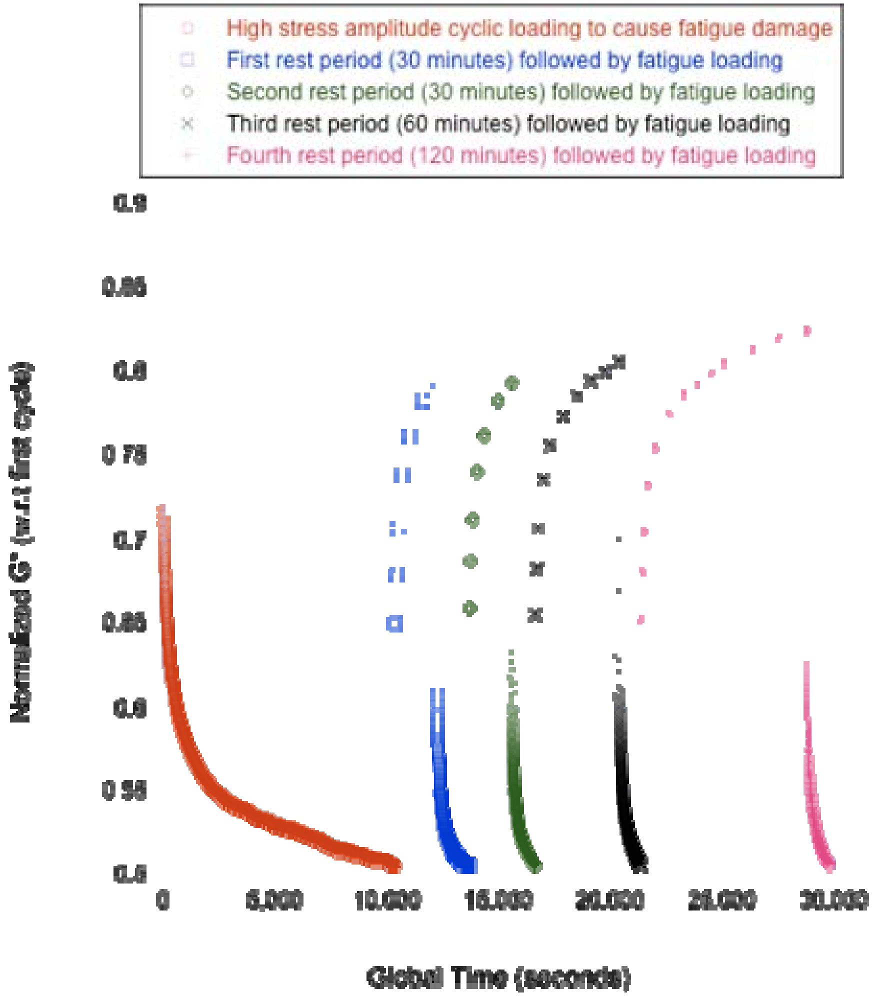
Healing: Convolution of Wetting/Intrinsic Healing



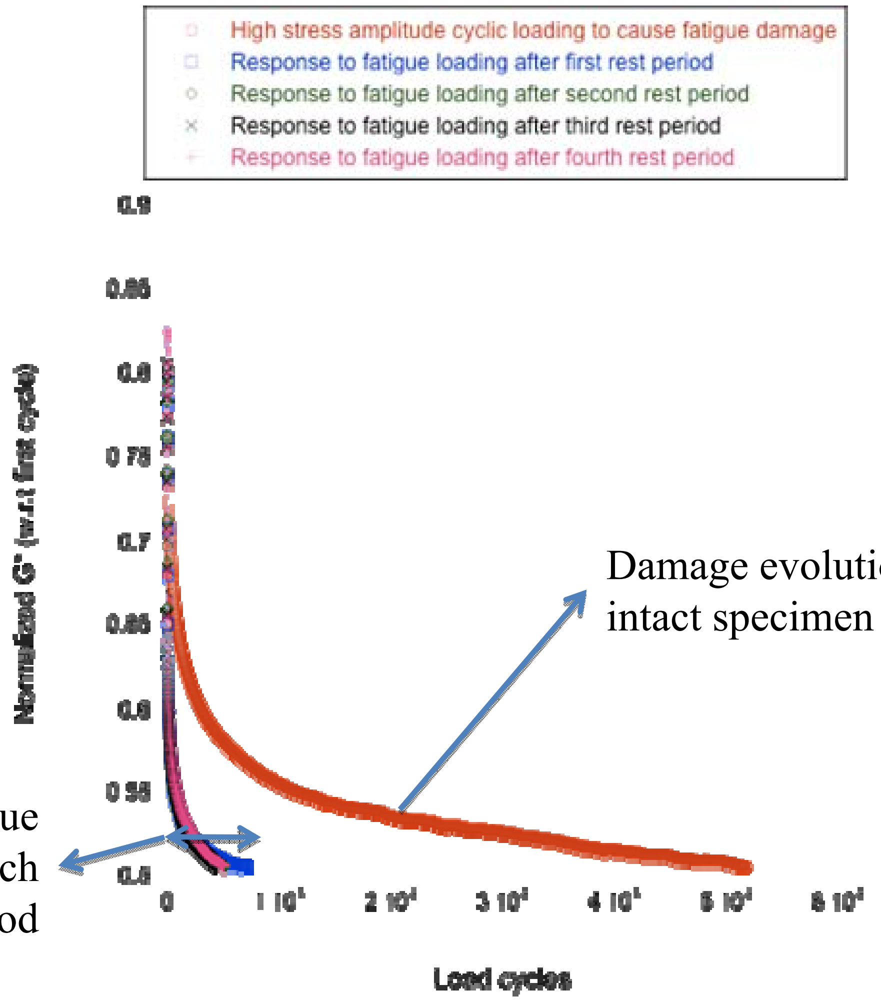
Healing: Convolution of Wetting/Intrinsic Healing



Healing: Convolution of Wetting/Intrinsic Healing



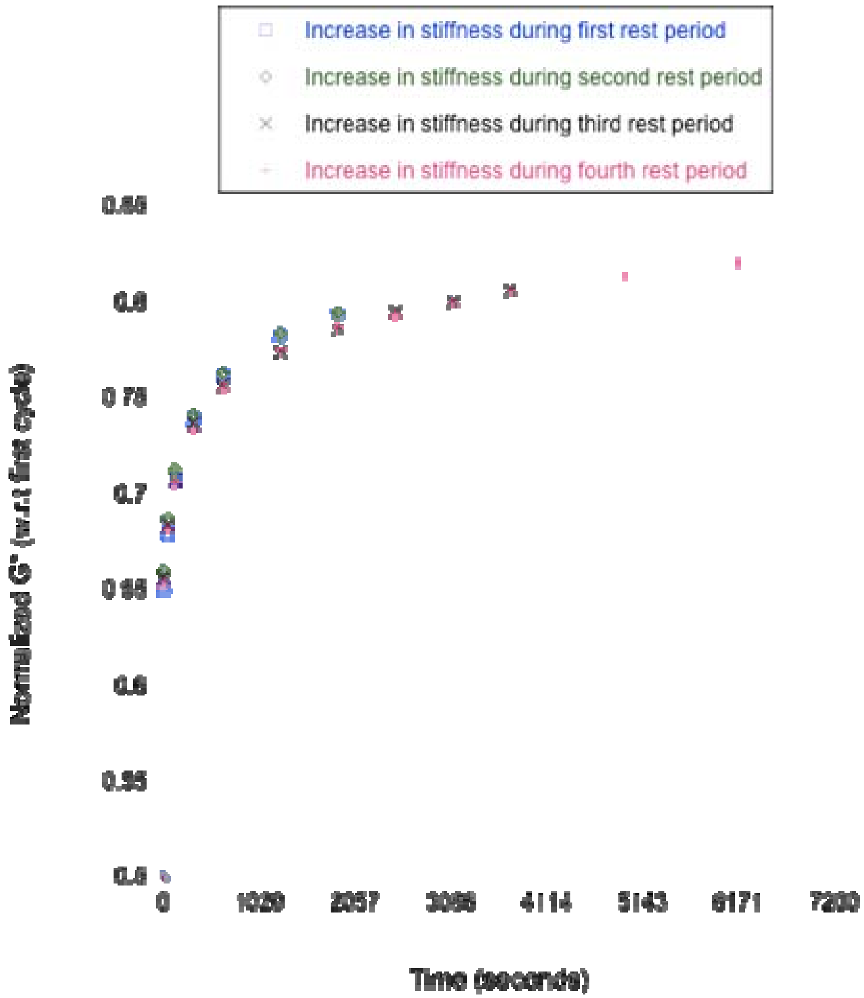
Healing: Convolution of Wetting/Intrinsic Healing



Damage evolution of the intact specimen

Extension in fatigue cracking life due to each rest period

Healing: Convolution of Wetting/Intrinsic Healing



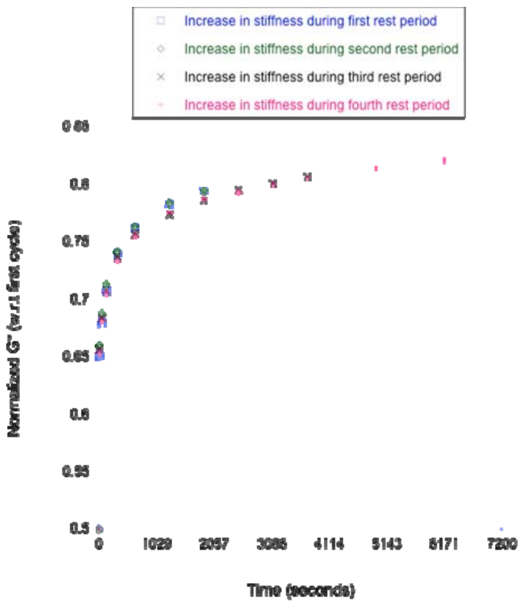
Elements of Micromechanical Model

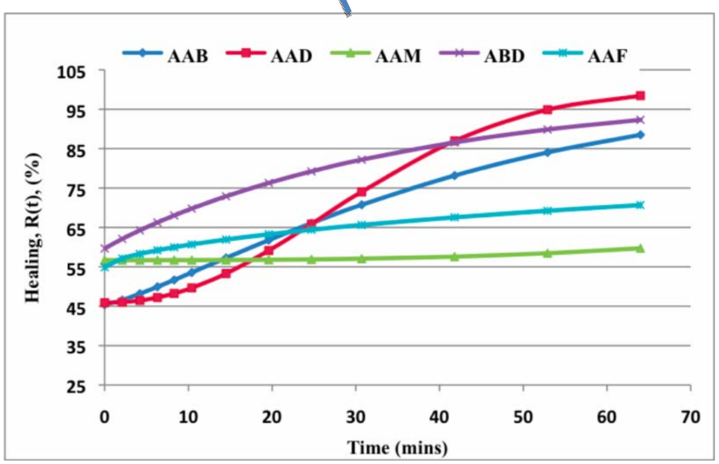
$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau, X)}{dt}d\tau$$

Measured experimentally (FAM DMA fatigue)

Measured experimentally (DSR binder)

$$\frac{d\phi(t, X)}{dt} = \dot{a}_b = \beta\left[\frac{1}{D_1 k_m}\left\{\frac{\pi W_c}{4(1-\nu^2)\sigma_b^2\beta} - D_0\right\}\right]^{-1/m}$$





Wetting function obtained using overall healing curves with different materials will be used to validate relationship to surface free energy and viscoelastic properties

Micro-damage Healing Evolution fn

Abu Al-Rub, Darabi, Little, and Masad (2010)

$$\dot{h} = \Gamma^h \left(1 - \frac{\phi_{eff}}{\phi_{cr}}\right)^{b_1} (1-h)^{b_2} \exp\left[-\theta\left(1 - \frac{T}{T_0}\right)\right]$$

b_1 & b_2	Model parameters related to history
Γ^h	Healing viscosity parameter (second^{-1}) that controls how fast healing occurs, and increases as surface energy increases.

The maximum healing rate: $\dot{h}_{\max} = \Gamma^h$

$$\dot{h} \propto \frac{\dot{a}_b}{\Delta} \quad \Longrightarrow \quad \Gamma^h \propto \left[\frac{1}{D_1 k_m}\left(\frac{2\pi G}{4(1-\nu^2)\sigma_b^2 \Delta} - D_0\right)\right]^{-\frac{1}{m}}$$

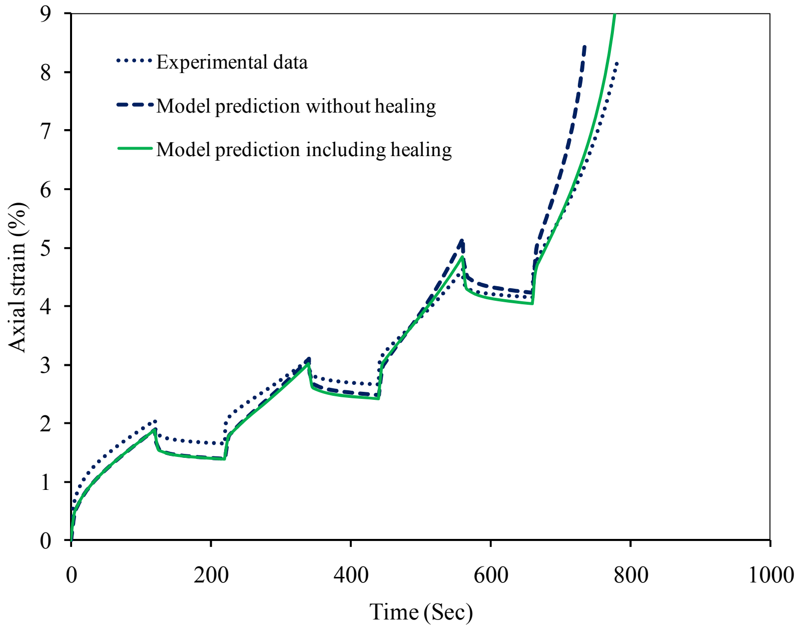
$D_0, D_1, m,$ and k_m : Viscoelastic properties

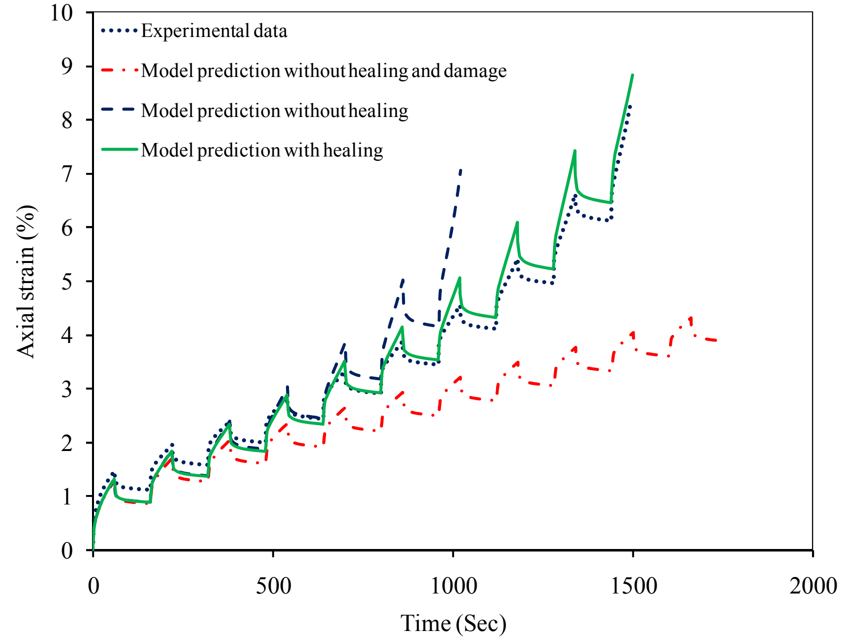
G : Surface energy

Δ : Size of the fracture process zone

ν : Poisson's ratio

Micro-damage Healing: Comparison with Experiments





σ=1500kPa

LT=120 sec, UT=100 sec

Compression

σ=1500kPa

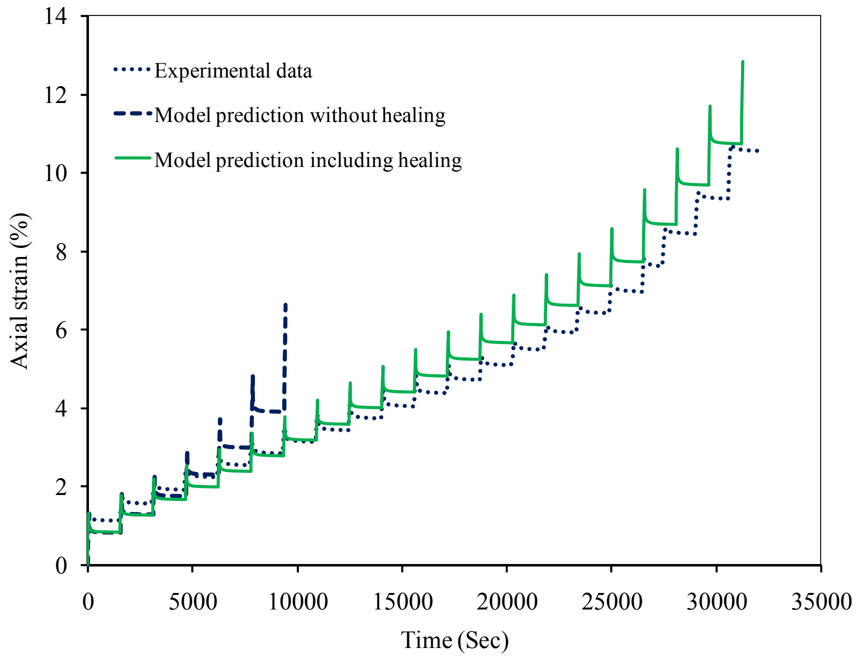
LT=60 sec, UT=100 sec

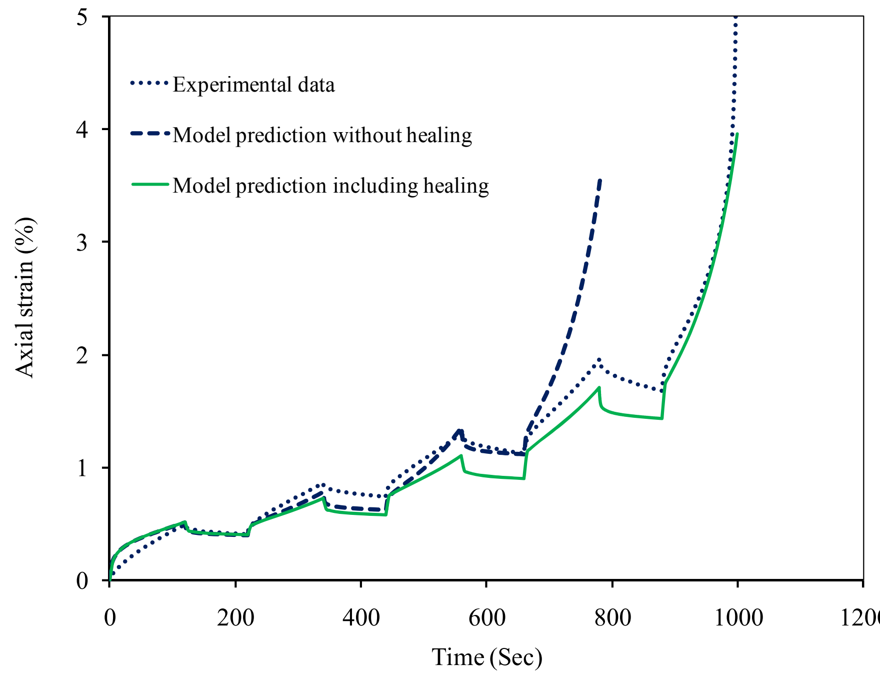
Compression

LT : loading time

UT : Rest period (unloading time)

Micro-damage Healing: Comparison with Experiments





σ=1500kPa

LT=60 sec, UT=1500 sec

Compression

σ=300kPa

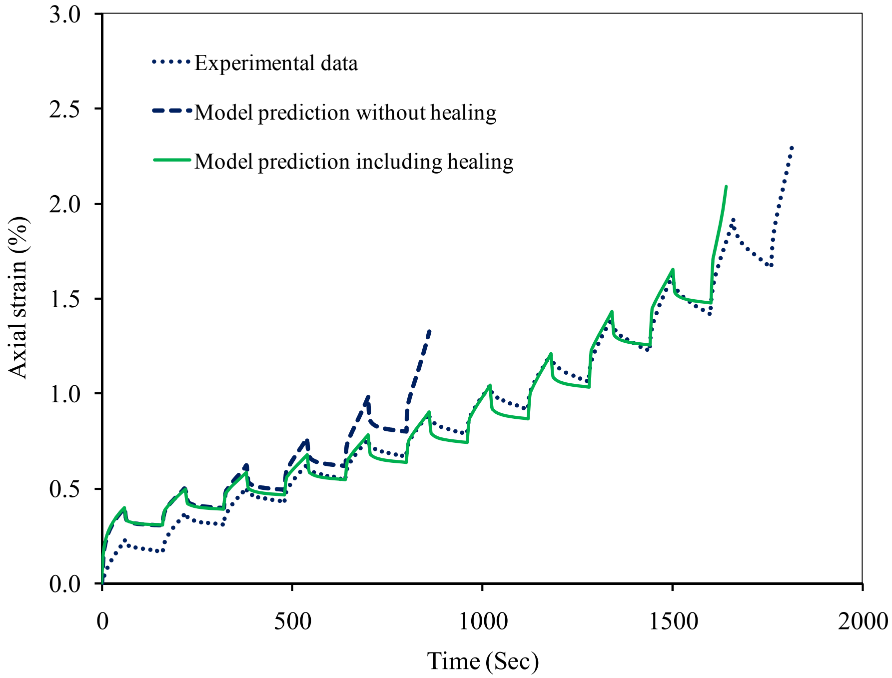
LT = 120 sec, UT = 100 sec

Tension

LT : loading time

UT : Rest period (unloading time)

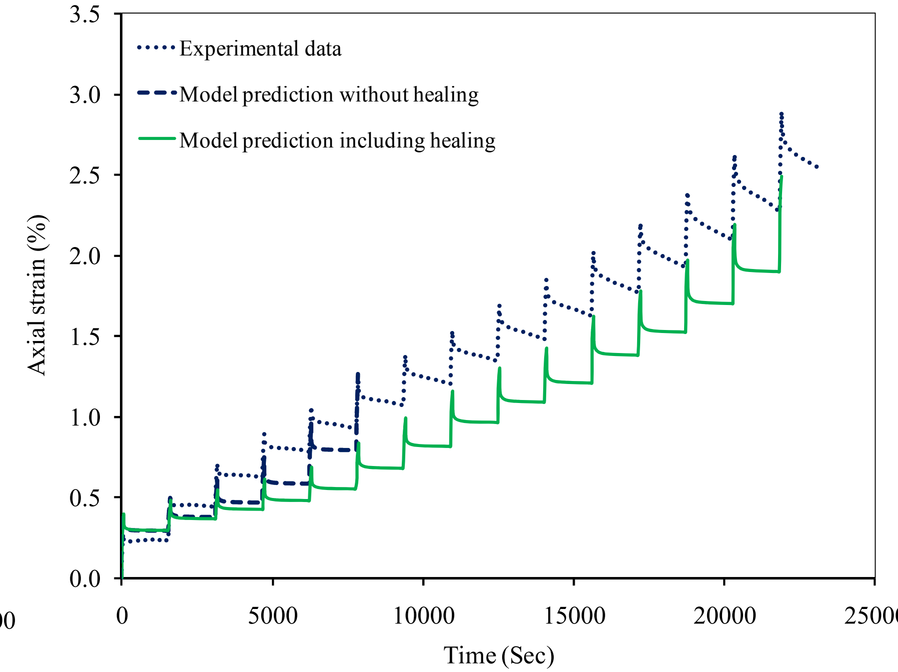
Micro-damage Healing: Comparison with Experiments



σ=300kPa

LT = 60 sec, UT = 100 sec

Tension



σ=300kPa

LT = 60 sec, UT = 1500 sec

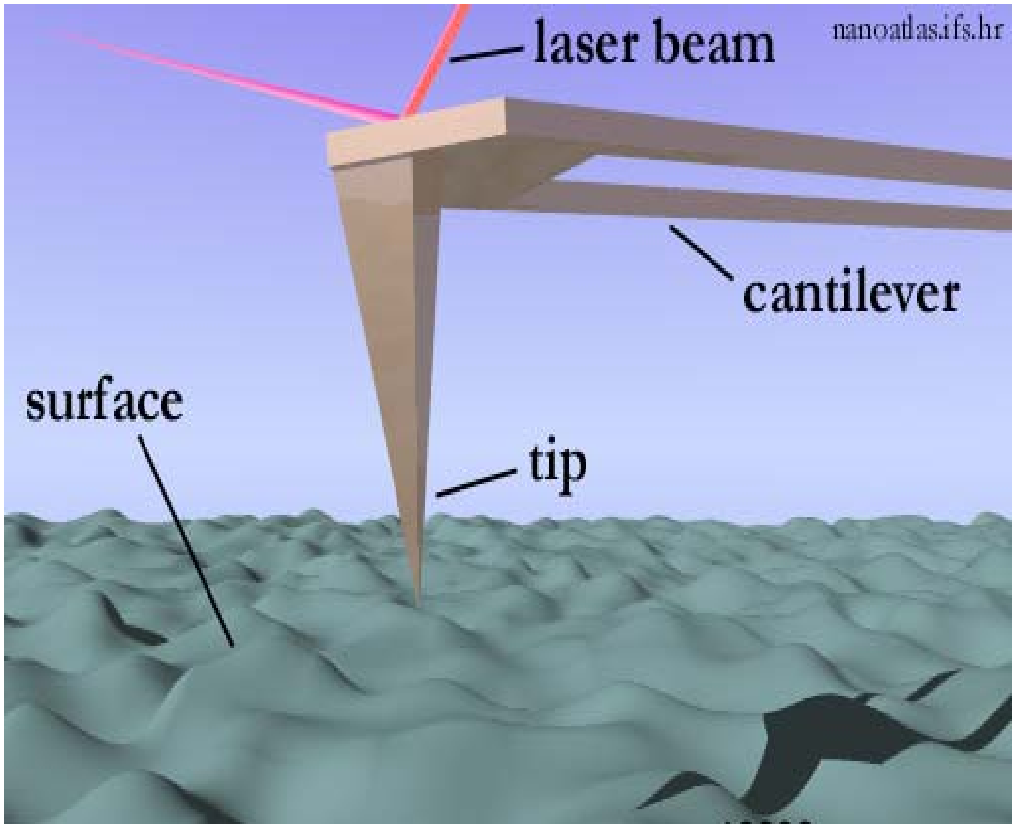
Tension

LT : loading time

UT : Rest period (unloading time)

Mechanical Properties and Morphology
Additional Work

Techniques: **AFM** Nano-indentation



Mechanical Properties and Morphology

Techniques: **AFM** Nano-indentation

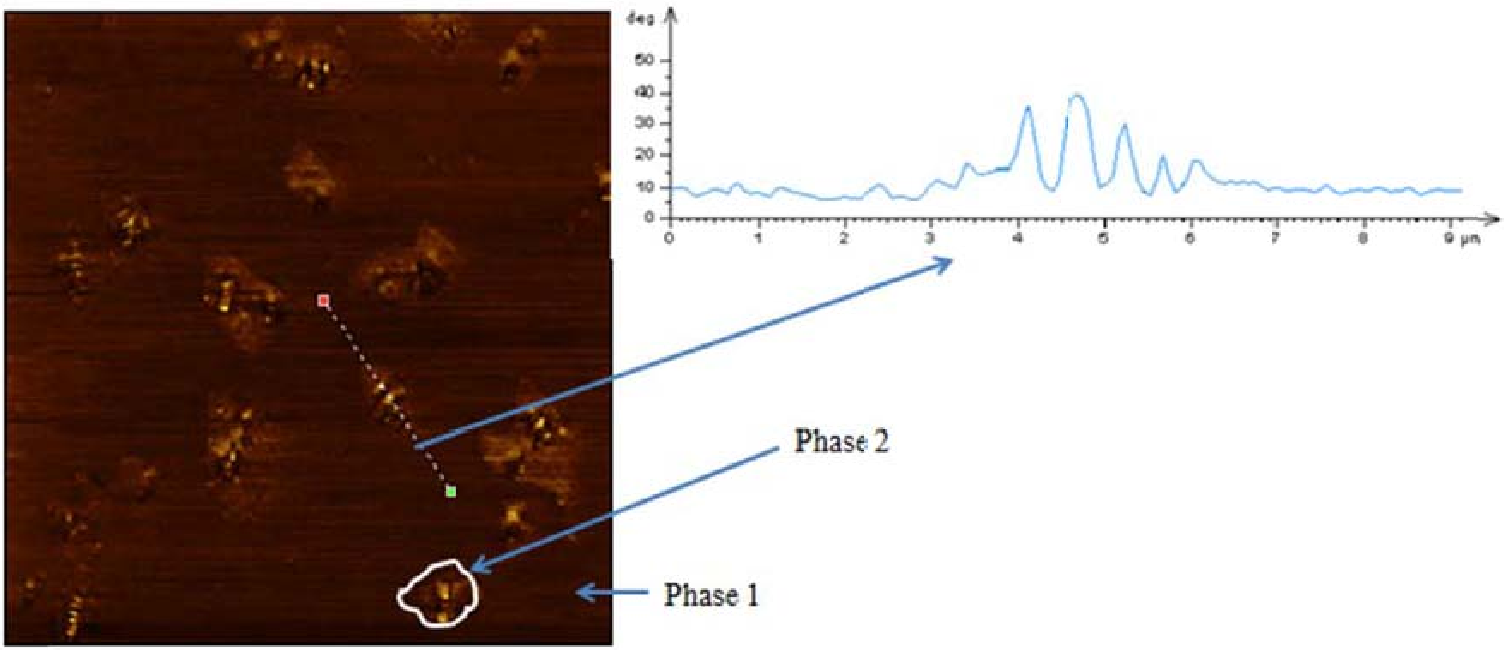
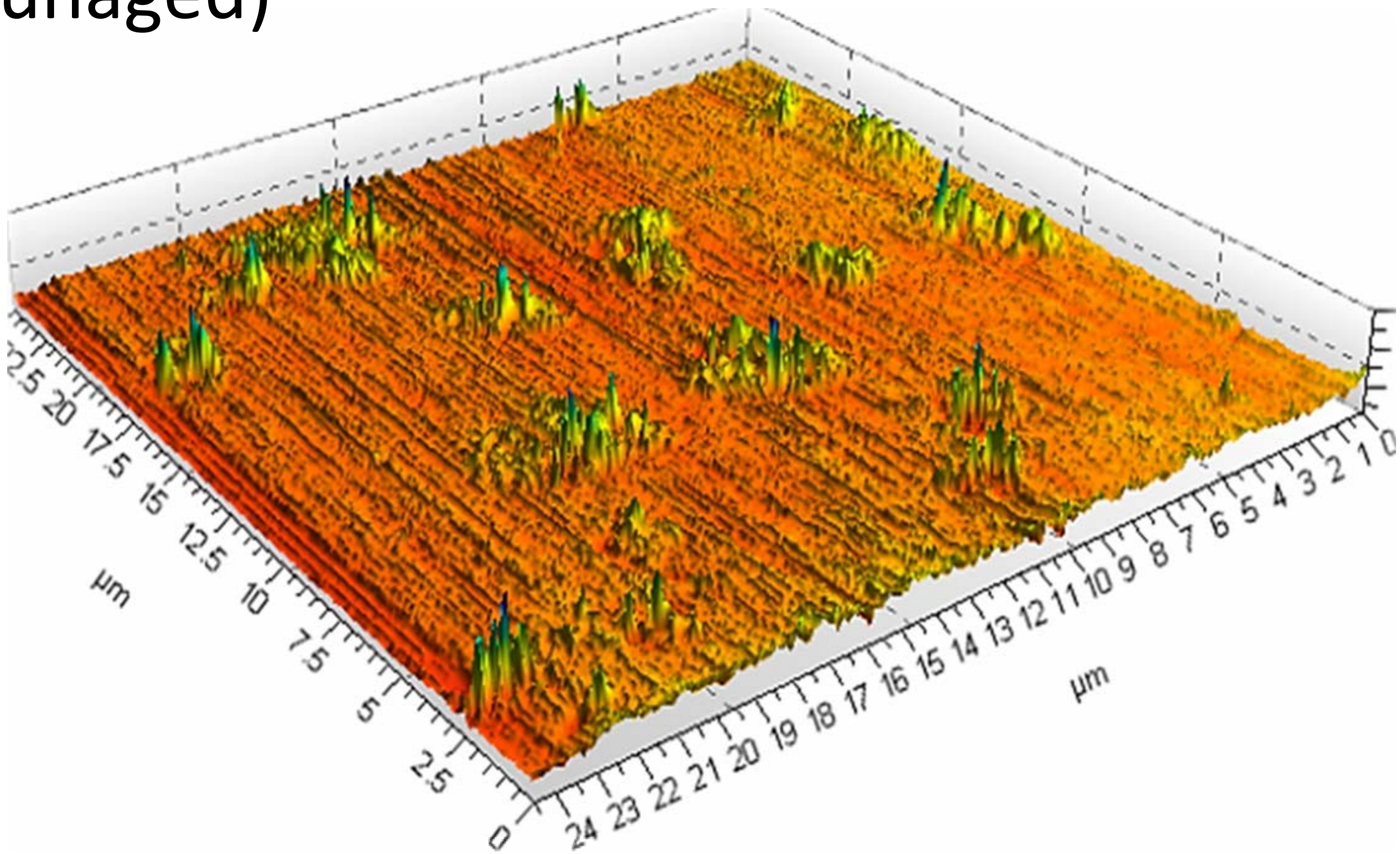


Figure 4.12. Phase image and profile extraction of asphalt AAD.

Ref: Allan Grover, Master's Thesis

Mechanical Properties and Morphology

- Three-dimensional depiction of phases (AAD unaged)



Mechanical Properties and Morphology

Techniques: **AFM** Nano-indentation

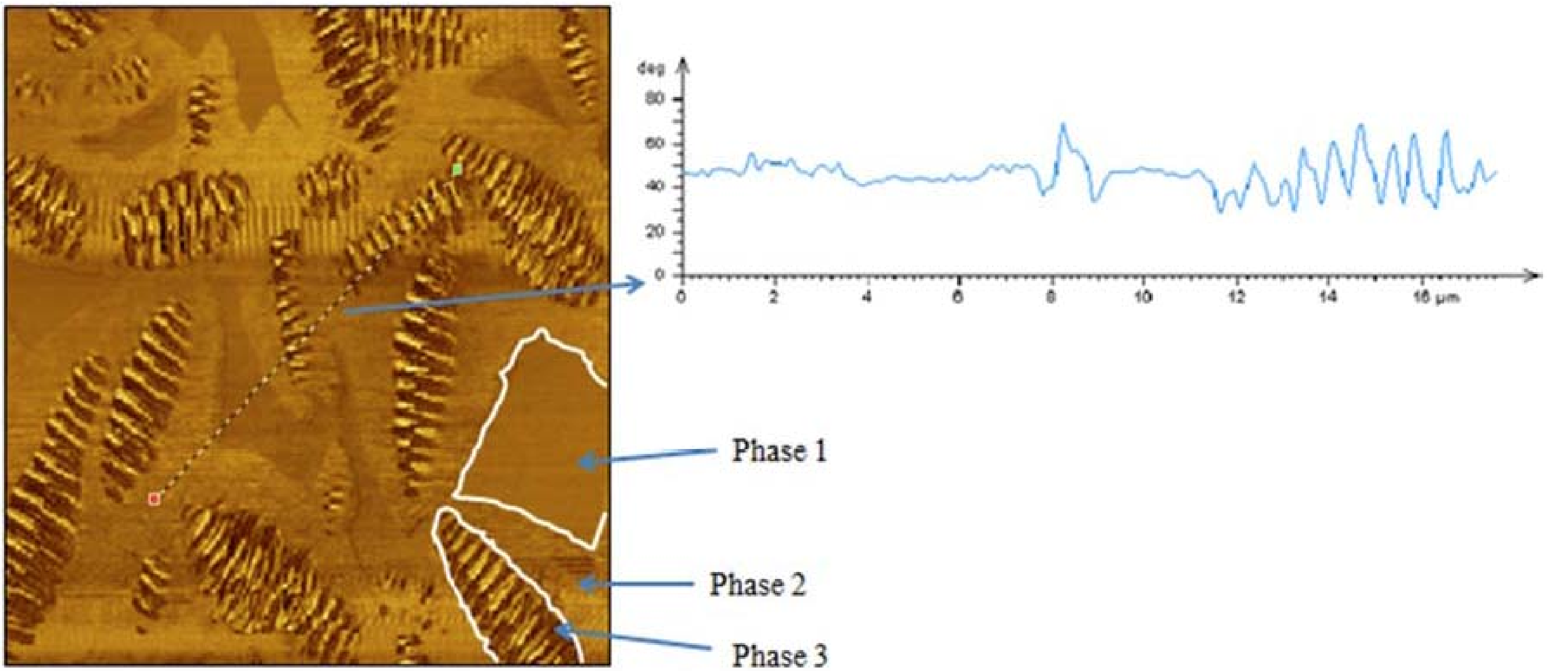
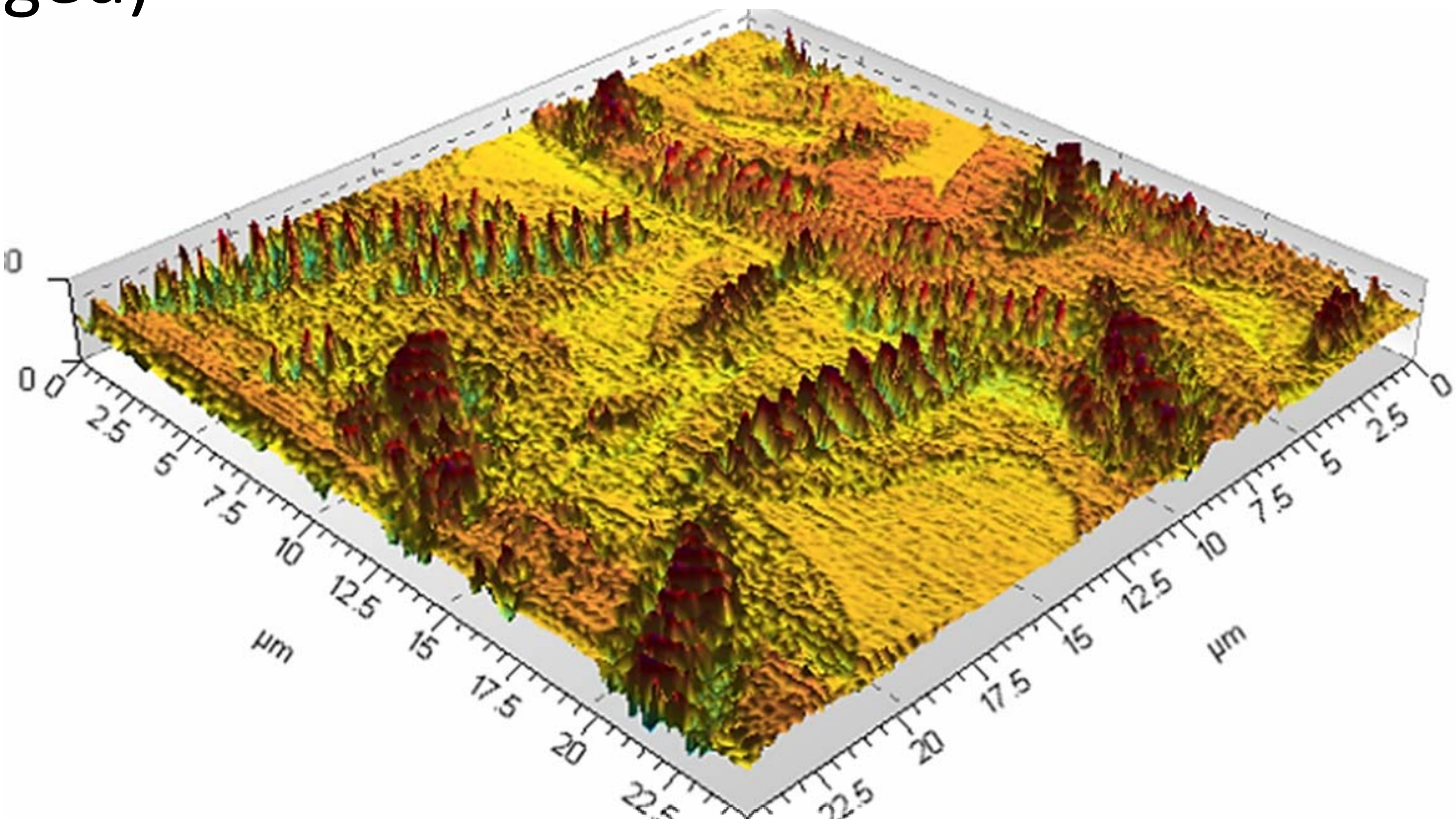


Figure 4.16. Phase image and profile extraction of aged asphalt AAD.

Ref: Allan Grover, Master's Thesis

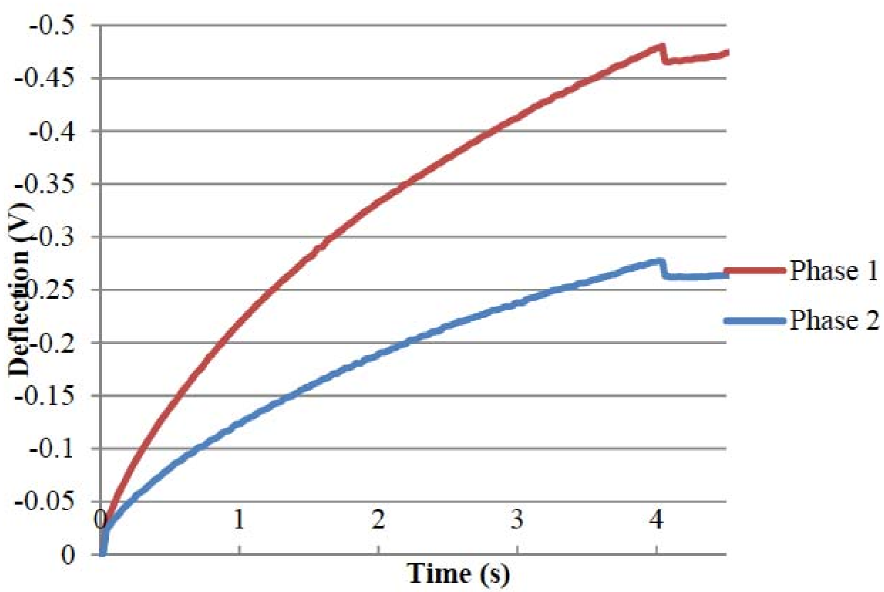
Mechanical Properties and Morphology

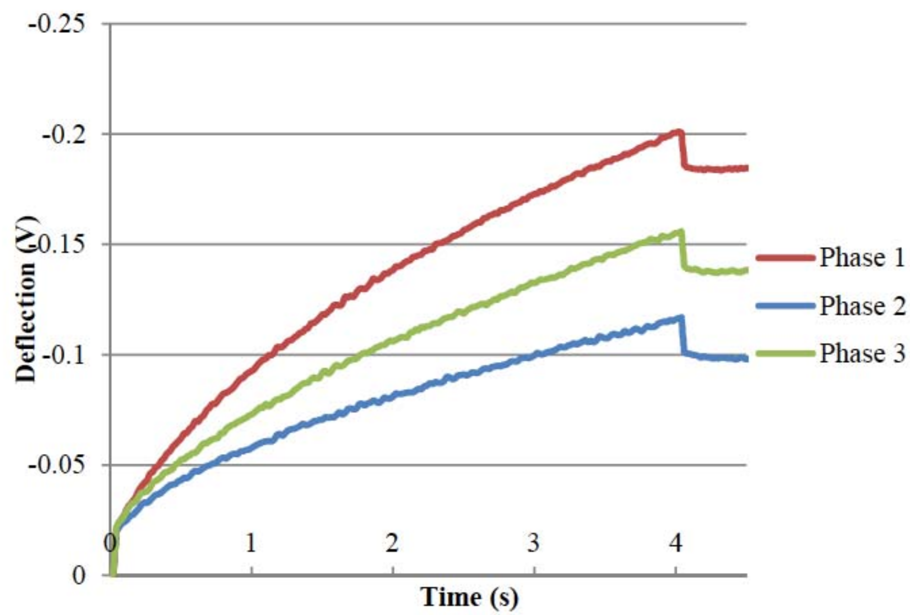
- Three-dimensional depiction of phases (AAD aged)



Mechanical Properties and Morphology

Techniques: **AFM** Nano-indentation





Creep measurements before and after aging

Ref: Allan Grover, Master's Thesis