Models for Plastic Deformation Based on Non-Linear Response for FEM Implementation

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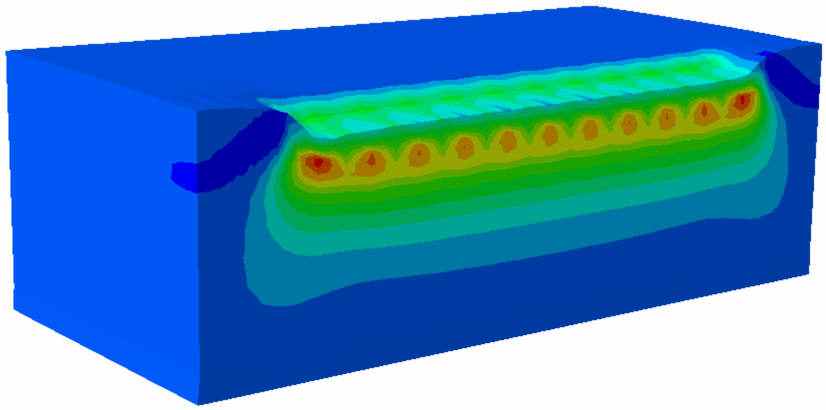


International Workshop on Asphalt Binders and Mastics
Madison, Wisconsin. September 16-17

Acknowledge Funding by

Asphalt Research Consortium

Outline

Motivation

Viscoelastic-Viscoplastic-Viscodamage Models

Identification of model parameters and model validation

Implementation procedure

Application of the model for rutting performance simulation

Conclusions and future works

Motivation

Prediction of pavement performance

Material Characteristics

- Aggregate shape
- Anisotropy
- Adhesive and Cohesive bond strengths
- Healing
- Binder rheology

Pavement Structure

- Thickness
- Sub grade type

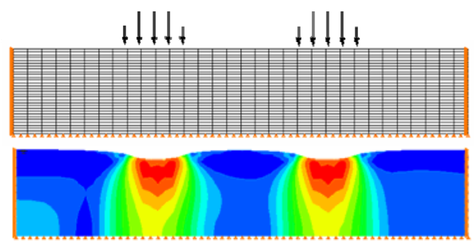
Environmental Factors

- Temperature
- Humidity differential
- Rainfall

Loading Conditions

- Type of loading
- Tire pavement interaction

FEM Modeling

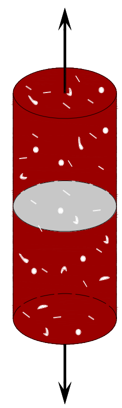


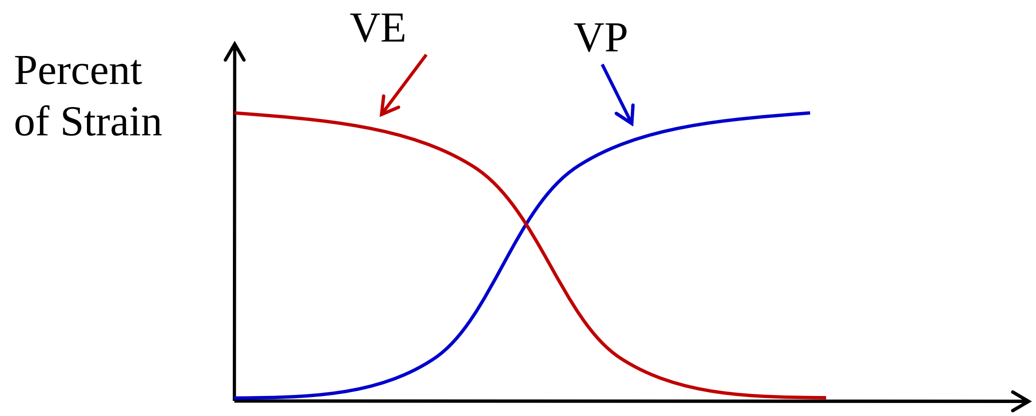
Calibration (minimize shift factor dependency)

Prediction of material distress

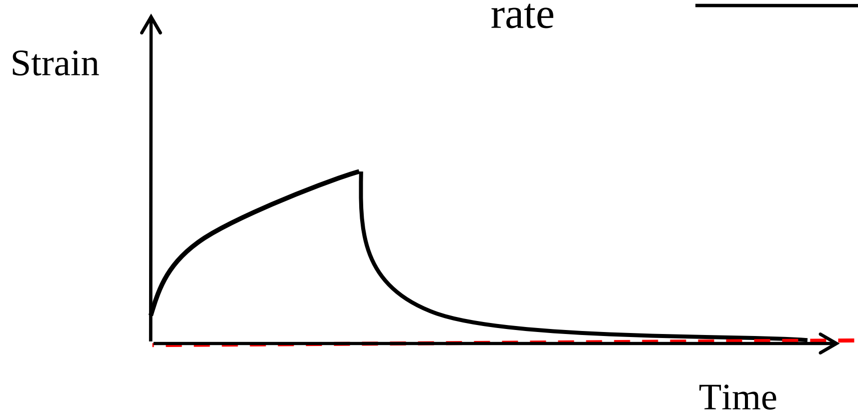
Mechanical Response of Asphalt Mixes

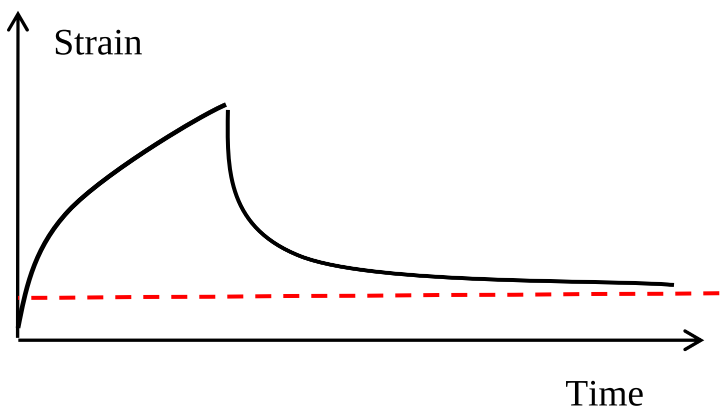
Viscoelastic-Viscoplastic-Viscodamage





Temperature Increase and/or decrease in strain rate →



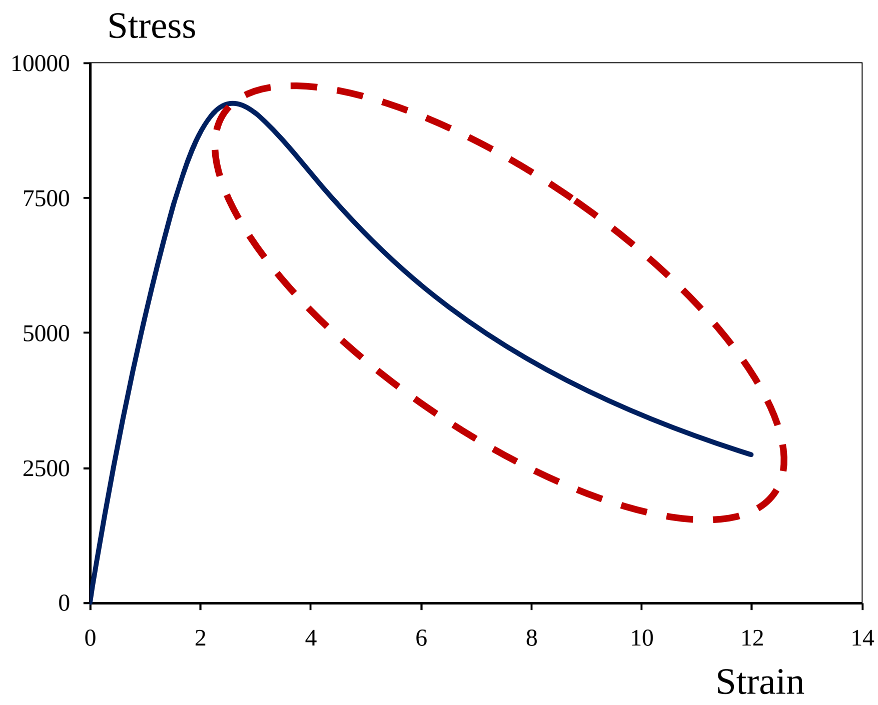


- ❑Viscoelastic
- ❑Viscoplastic

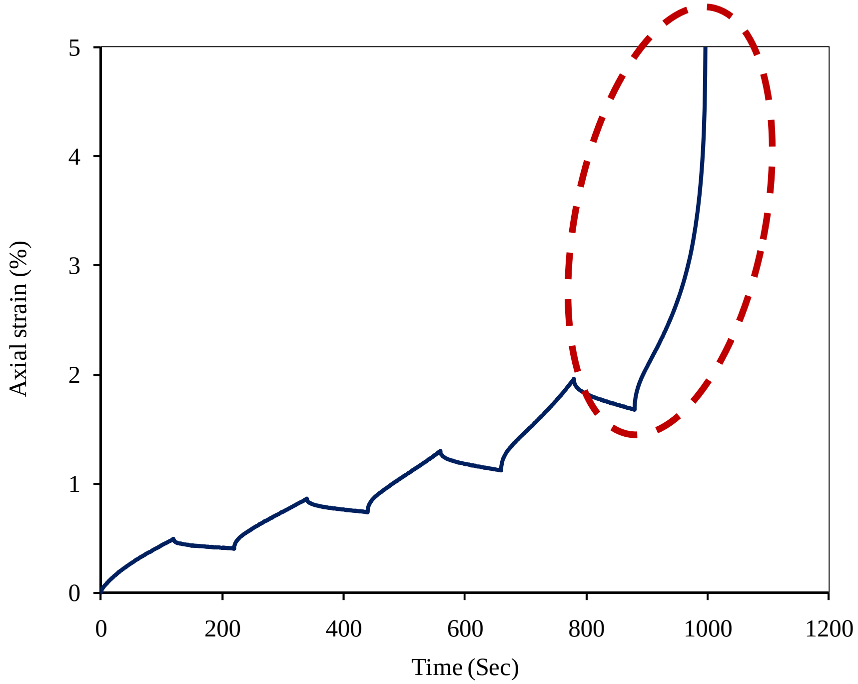
Mechanical Response of Asphalt Mixes

Viscoelastic-Viscoplastic-Viscodamage

- Rate- and Time-dependent softening



Displacement control tests



Repeated creep-recovery test

Outline

Viscoelastic-Viscoplastic-Viscodamage Models

Viscoelastic Properties

Nonlinear Viscoelastic Model (Schapery, 1969)

Nonlinear contribution in the transient response

$$\varepsilon^{ve} = g_0 D_0 \sigma + g_1 \int_0^{\psi} D\left(\psi^t - \psi^\tau\right) \frac{d}{d\tau} g_2 \sigma d\tau$$

Nonlinear contribution in the elastic response, due to the level of stress

Nonlinear contribution in the viscoelastic response due to the level of stress

$$\psi = \int_0^t \frac{dt}{a_T}$$

Temperature shift factor

$$D = \sum_{n=1}^{N} D_n \left[1 - \exp\left(-\lambda_n t\right)\right]$$

Prony series coefficients

Retardation time

Viscoplastic Properties

Viscoplastic Model (Perzyna, 1971)

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{ij}^{ve} + \Delta\varepsilon_{ij}^{vp} \longrightarrow$$ Perzyna Model

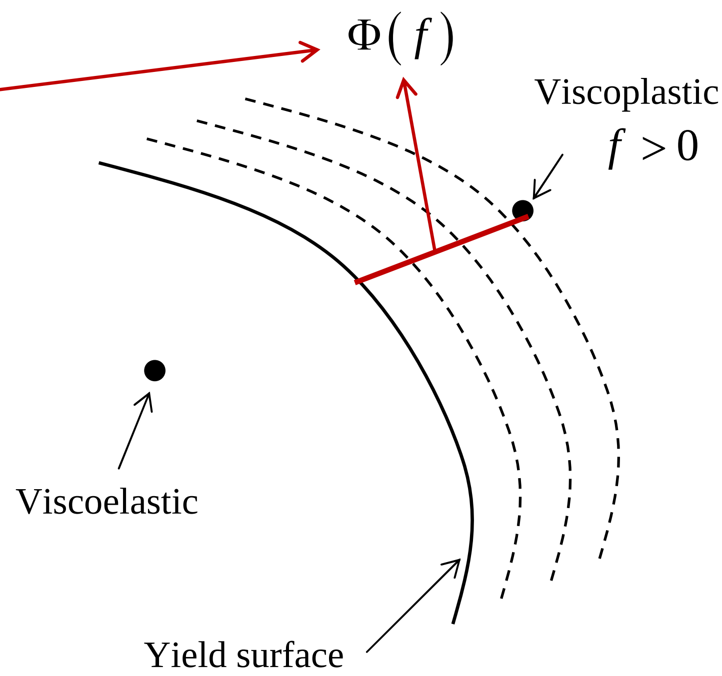
$$f = F\left(\sigma_{ij}\right) - \kappa\left(\varepsilon_e^{vp}\right) = \tau - \alpha I_1 - \kappa\left(\varepsilon_e^{vp}\right) \longrightarrow$$ Yield surface (Extended Drucker-Prager)

$$\kappa = \kappa_0 + \kappa_1\left[1 - \exp\left(-\kappa_2 \varepsilon_e^{vp}\right)\right] \longrightarrow$$ Hardening function

Flow Rule: $$\dot{\varepsilon}_{ij}^{vp} = \Gamma^{vp}\left(T\right)\left\langle \Phi\left(f\right)\right\rangle^{N} \frac{\partial g}{\partial \sigma_{ij}}$$

Plastic potential function: $$g = \tau - \beta I_1$$

Overstress function $$\left\langle \phi\left(f\right)\right\rangle = \begin{cases} 0 & f \le 0 \\ f & f > 0 \end{cases}$$



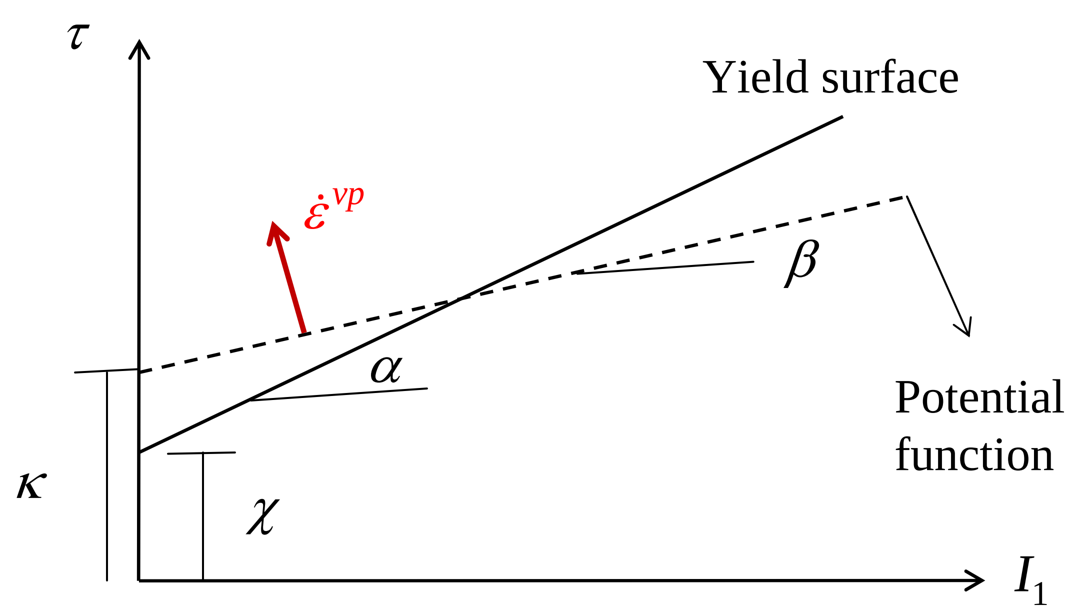
Extended Drucker-Prager Yield Surface

Accounts for:

- Dilation and confinement pressure
- The effect of shear stress
- Work hardening of the material

$$f = \tau - \alpha I_1 - \kappa$$

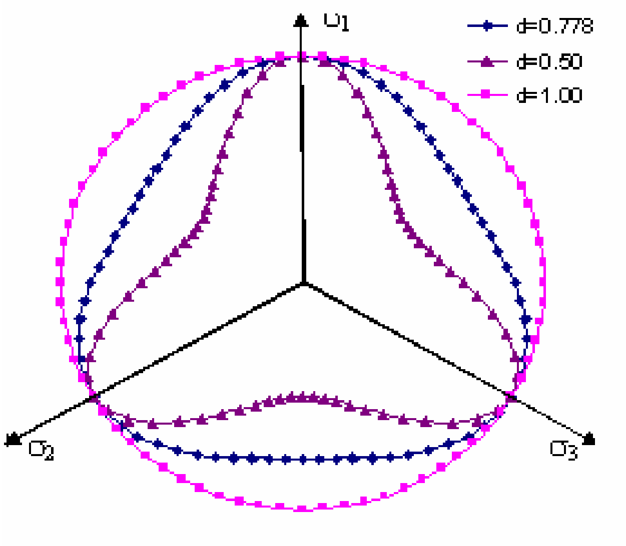
$$g = \tau - \beta I_1 - \chi$$



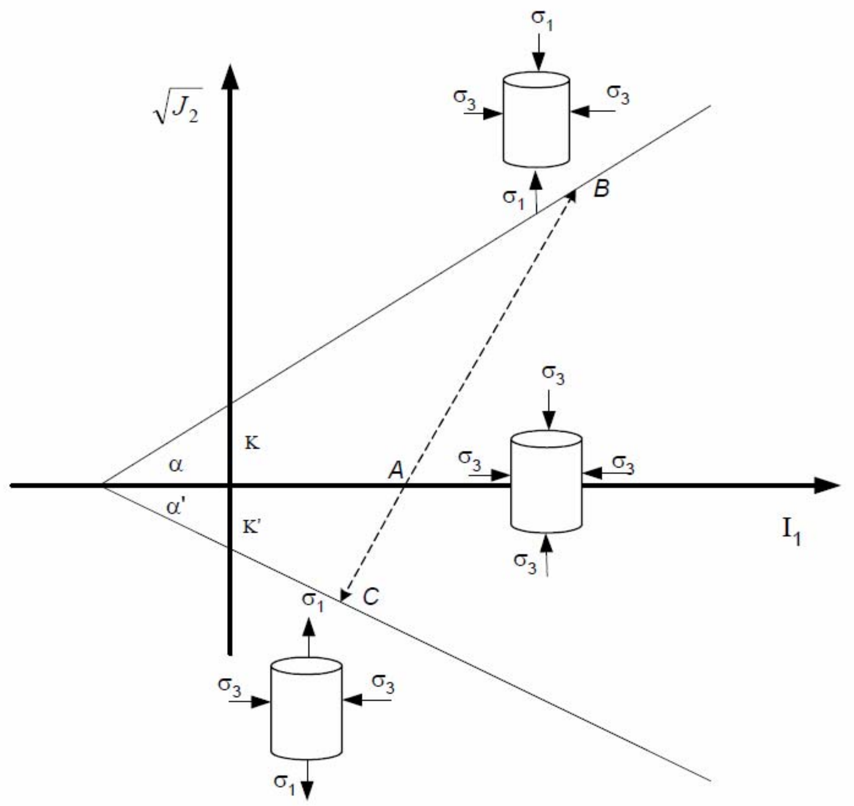
Viscoplastic Properties

Effect of parameter "*d*" on the yield surface

$$\tau = \frac{\sqrt{J_2}}{2}\left[1+\frac{1}{d}-\left(1+\frac{1}{d}\right)\frac{J_3}{J_2^{3/2}}\right]$$

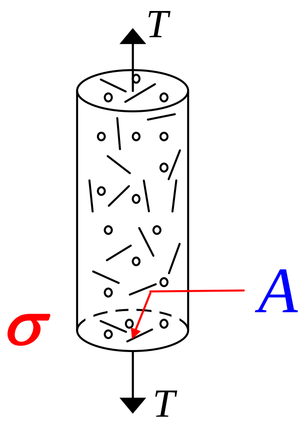


Influence of stress path on the yielding point



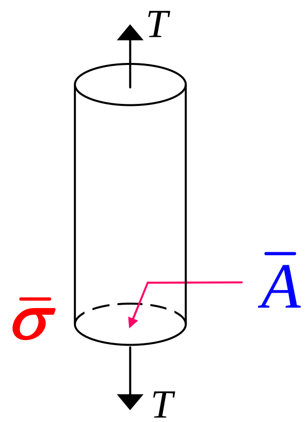
Strength Degradation due to Damage

$$\sigma = (1-\phi)\bar{\sigma}$$



Remove Both Voids and Cracks

$$\phi = \frac{A - \bar{A}}{A}$$



Damaged Configuration

$$0 \le \phi \le 1$$

Effective Undamaged Configuration

σ	Nominal (measured) stress	$\phi = 0$	No damage
$\bar{\sigma}$	Effective stress	$\phi = 1$	Failure
ϕ	Damage density	$0 \le \phi \le 1$	Damage

Viscodamage Model

Viscodamage model (Darabi, Abu Al-Rub, Masad, Little; 2010)

$$\dot{\phi} = \Gamma^{vd}\left(\frac{Y}{Y_0}\right)^q (1-\phi)^2 \exp\left(k\varepsilon^{Tot}\right)\exp\left[-\delta\left(1-\frac{T}{T_0}\right)\right]$$

Damage force

$$Y = \frac{\sqrt{J_2}}{2}\left[1+\frac{1}{d}-\left(1+\frac{1}{d}\right)\frac{J_3}{J_2^{3/2}}\right]-\alpha I_1$$

Damage response is different **in compression or extension**

Damage is sensitive to **Loading Mode**

Damage is sensitive to **hydrostatic pressure**

I_1 : First stress invariant

J_2 and J_3 : The second and the third deviatoric stress invariants

Determination of Model Parameters

Creep-Recovery test @ reference temperature	Separate viscoelastic (recoverable) and viscoplastic (irrecoverable) strains.
Recovery part of the Creep-Recovery test @ reference temperature	Determination of viscoelastic parameters @ reference temperature
Creep part of the Creep-Recovery test @ reference temperature	Determination of viscoplastic parameters @ reference temperature
Two creep tests that show tertiary behavior @ reference temperature	Determination of viscodamage parameters @ reference temperature
Creep test in tension @ reference temperature	Determination of “*d*” parameters
Creep-recovery and creep tests @ other temperatures	Determination temperature-dependent model parameters

Determination of Model Parameters

Creep-Recovery test
@ reference temperature

Separate viscoelastic (recoverable) and viscoplastic (irrecoverable) strains.

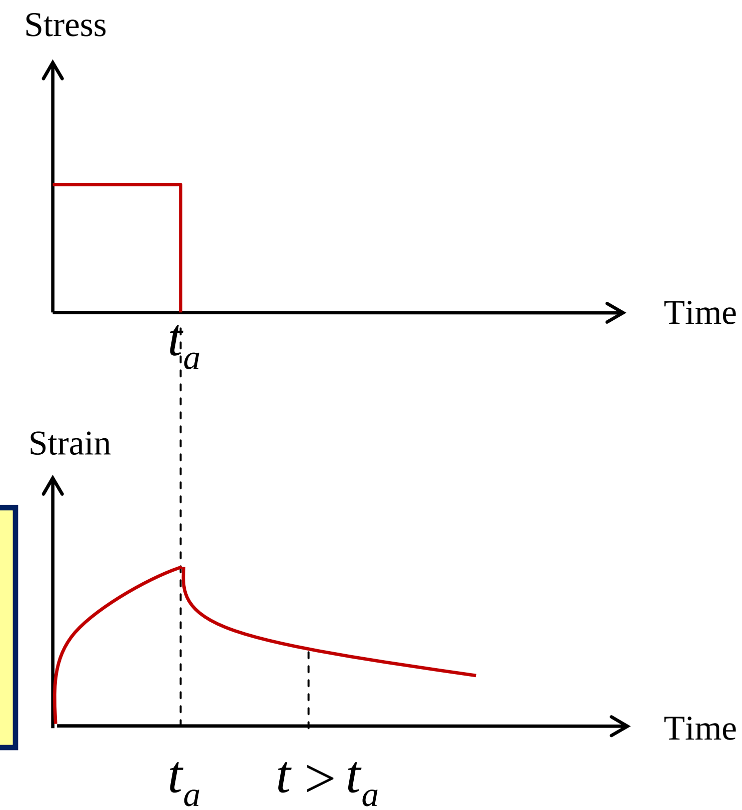
$$\varepsilon(t_a) = g_0 D_0 \sigma + g_1 g_2 D(t_a)\sigma + \varepsilon^{vp}(t_a)$$

$$\varepsilon(t) = g_1 g_2 \left[D(t) - D(t - t_a)\right]\sigma + \varepsilon^{vp}(t)$$

During the recovery: $\varepsilon^{vp}(t_a) = \varepsilon^{vp}(t)$

$$\varepsilon(t_a) - \varepsilon(t) =$$
$$g_0 D_0 \sigma + g_1 g_2 \left[D(t_a) - D(t) + D(t - t_a)\right]\sigma$$

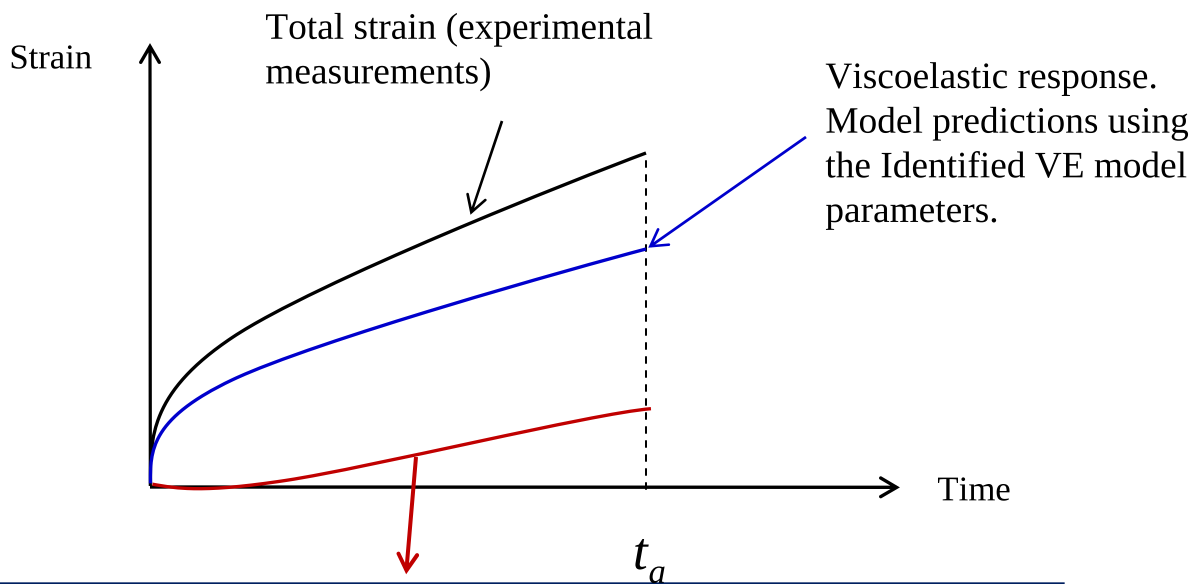
Pure viscoelastic response.
Can be used for identifying VE parameters



Determination of Model Parameters

Creep part of the Creep-Recovery test
@ reference temperature

Determination of viscoplastic parameters
@ reference temperature



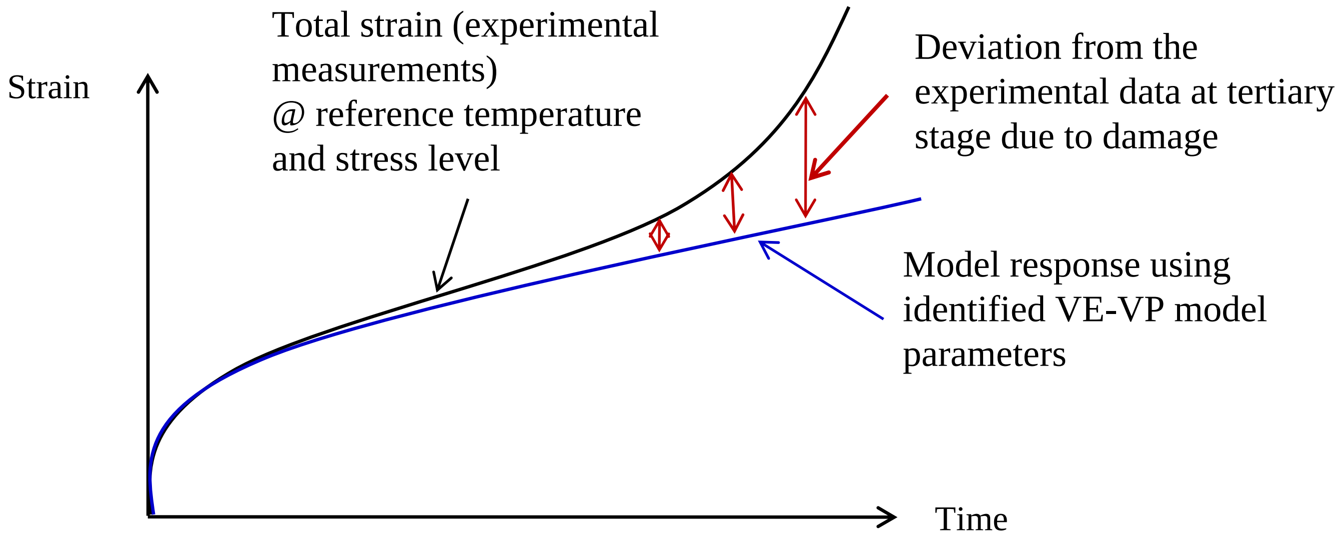
Viscoplastic response. Obtained by subtracting the VE response from the experimental measurements

Pure viscoplastic response.
Can be used for identifying VP parameters

Determination of Model Parameters

A creep tests that show tertiary behavior
@ reference temperature and stress level

Determination of viscodamage parameters
@ reference temperature



@ reference temperature T=T_0

$$\exp\left[-\delta\left(1-\frac{T}{T_0}\right)\right]=1$$

@ reference stress Y=Y_0

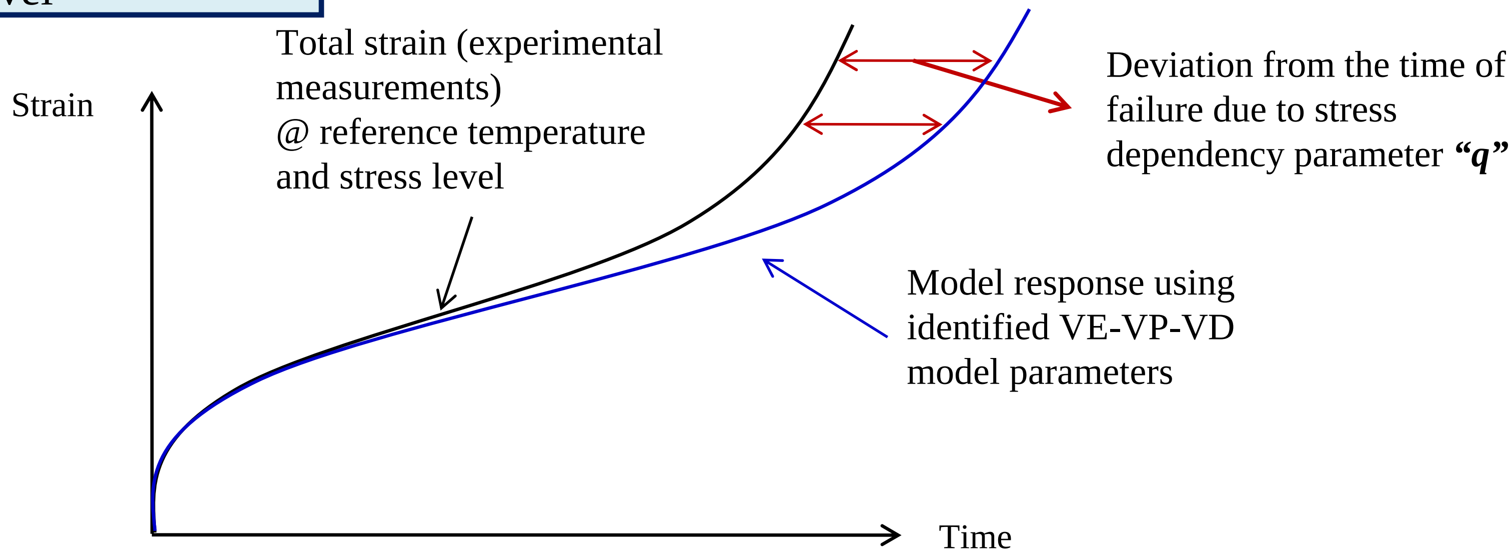
$$\dot{\phi}=\Gamma^{vd}(1-\phi)^2\exp\left(k\varepsilon^{Tot}\right)$$

Identify these damage parameters
Using the creep test at reference temperature and stress level

Determination of Model Parameters

Another creep tests that show tertiary behavior
@ reference temperature and other stress level

Determination of viscodamage parameters
@ reference temperature



@ reference temperature T=T_0

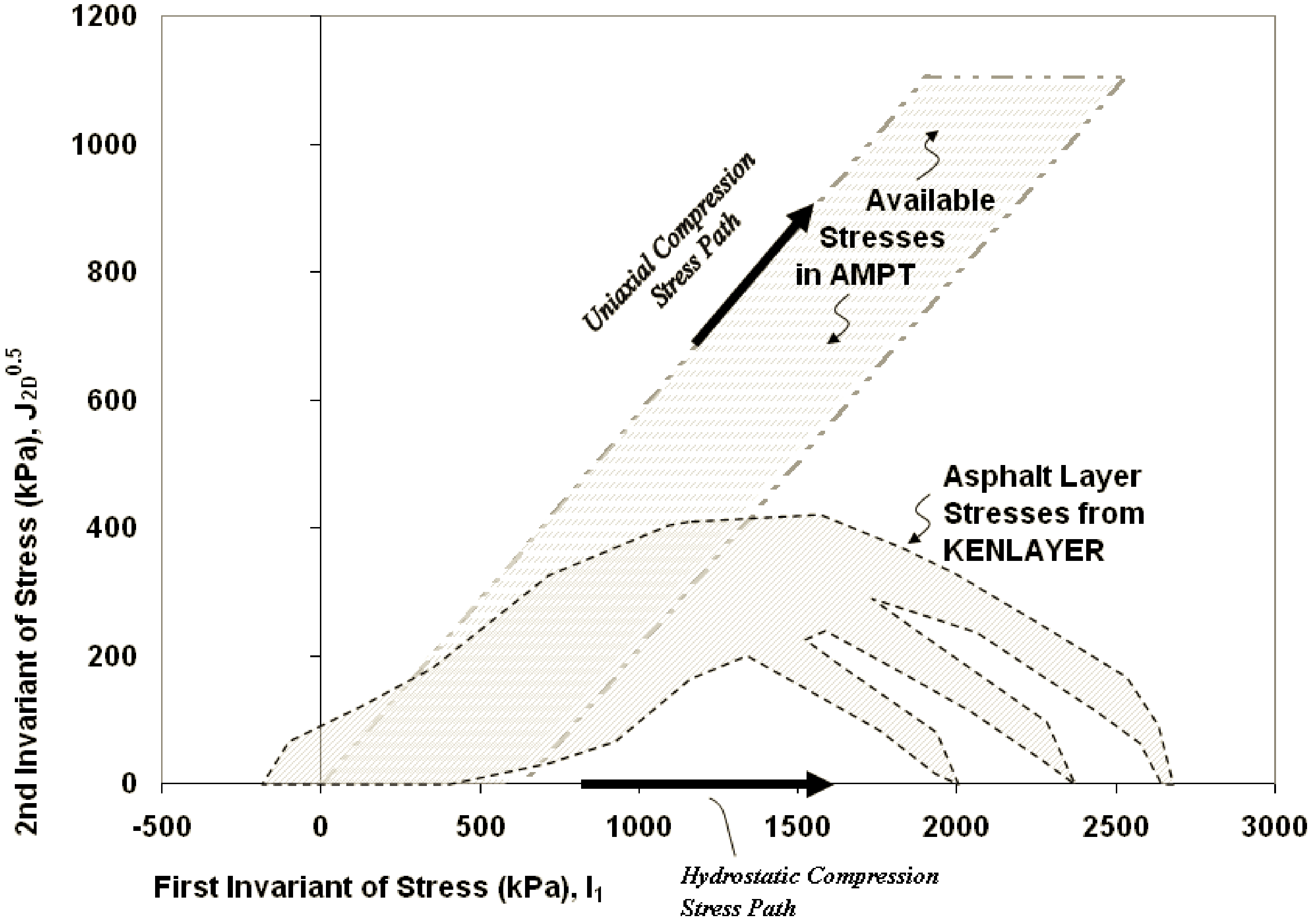
$$\exp\left[-\delta\left(1-\frac{T}{T_0}\right)\right]=1$$

$$\dot{\phi}=\Gamma^{vd}\left(\frac{Y}{Y_0}\right)^{q}(1-\phi)^2\exp\left(k\varepsilon^{Tot}\right)$$

Known

Identify the stress dependency parameter **"*q*"**

Stress Levels within the Pavements



Gibson et al., 2010

Model Validation Tests

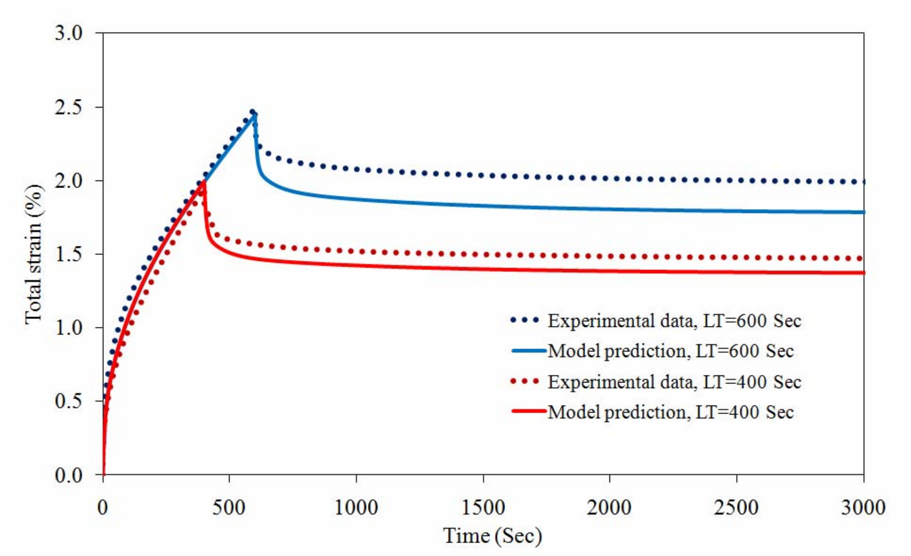
	Test	Temperature (^{o}C)	Stress Level (kPa)	Loading time (Sec)	Strain Rate (1/Sec)
Compression	Creep-Recovery	10	2000, 2500	300, 350, 400	
		20	1000, 1500	30, 40, 130, 210	
		40	500, 750	35, 130, 180	
	Creep	10	2000, 2500		
		20	1000, 1500		
		40	500, 750		
	Constant strain rate test	10			0.005, 0.005, 0.00005
		20			0.005, 0.005, 0.00005
		40			0.005, 0.005
Tension	Creep	10	500, 1000, 1500		
		20	500, 700		
		35	100, 150		
	Constant strain rate test	20			0.0167, 0.00167

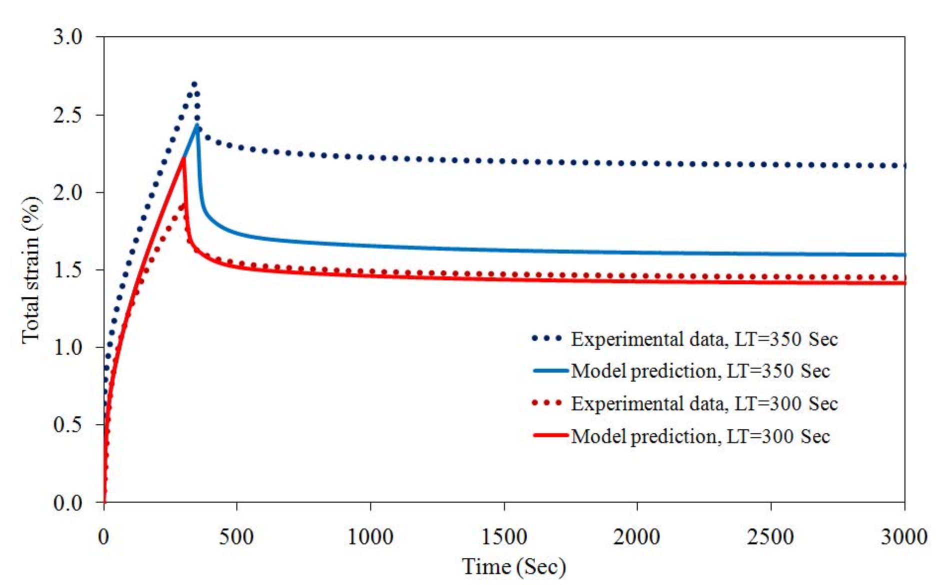
Outline

Model Validation

Model Validation (Creep-Recovery Test)

1- Model can predict creep-recovery data at different temperatures and stress levels. (Compression)





$T = 10^o C$

$\sigma = 2000\text{kPa}$

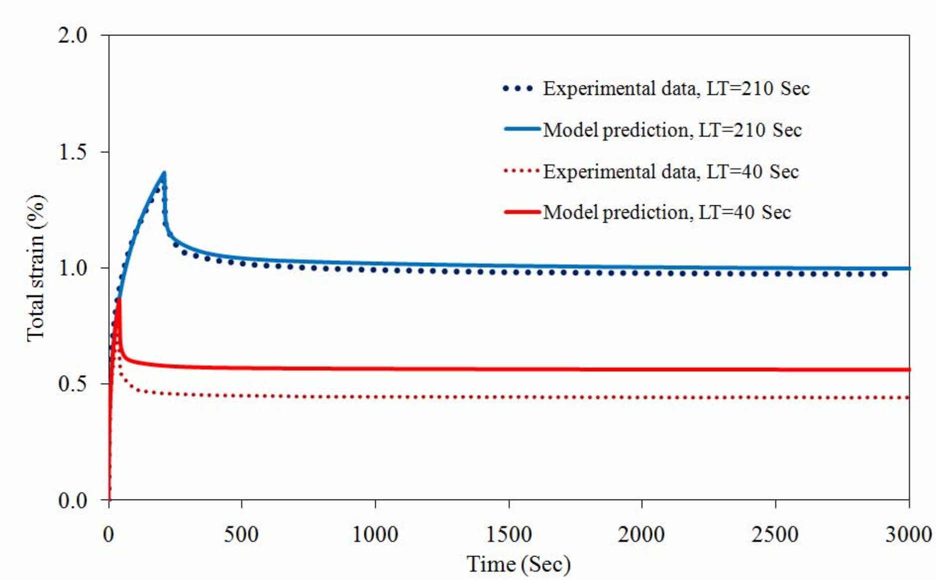
$T = 10^o C$

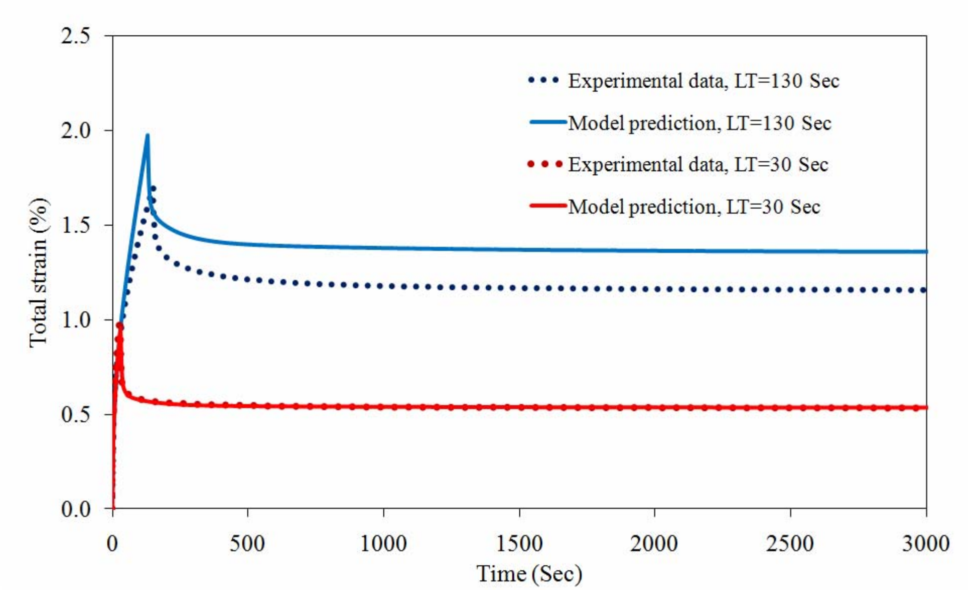
$\sigma = 2500\text{kPa}$

Creep-recovery test
Compression
@ T=10^{o}C

Model Validation (Creep-Recovery Test)

1- Model can predict creep-recovery data at different temperatures and stress levels. (Compression)





$T = 20^o C$

$\sigma = 1000\text{kPa}$

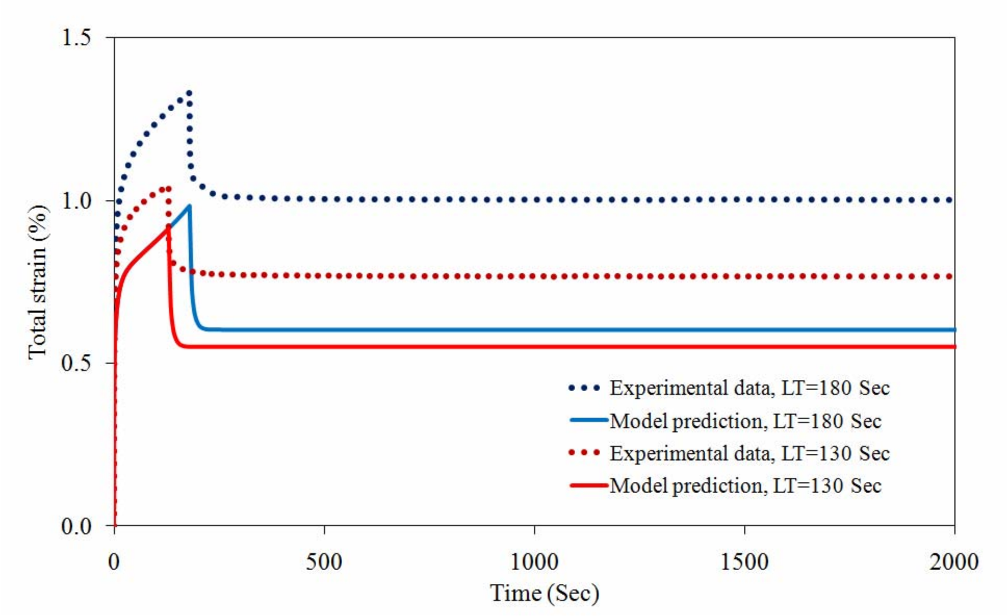
$T = 20^o C$

$\sigma = 1500\text{kPa}$

Creep-recovery test
Compression
@ T=20^{o}C

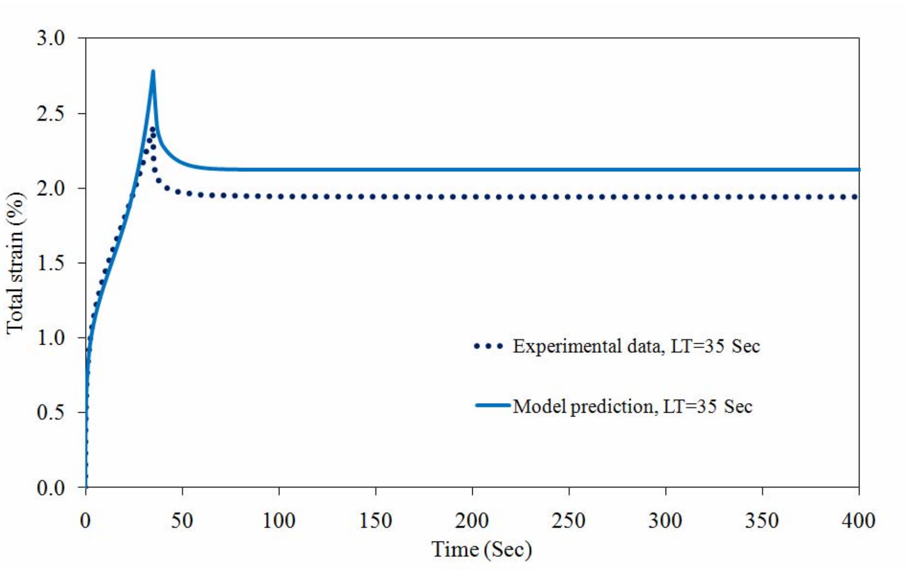
Model Validation (Creep-Recovery Test)

1- Model can predict creep-recovery data at different temperatures and stress levels. (Compression)



$T = 40^o C$

$\sigma = 500\text{kPa}$



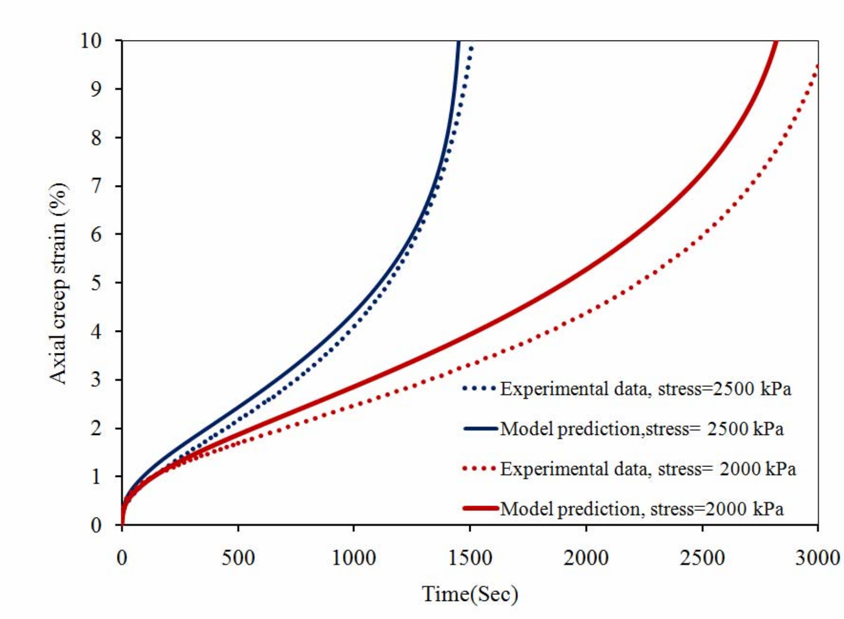
$T = 40^o C$

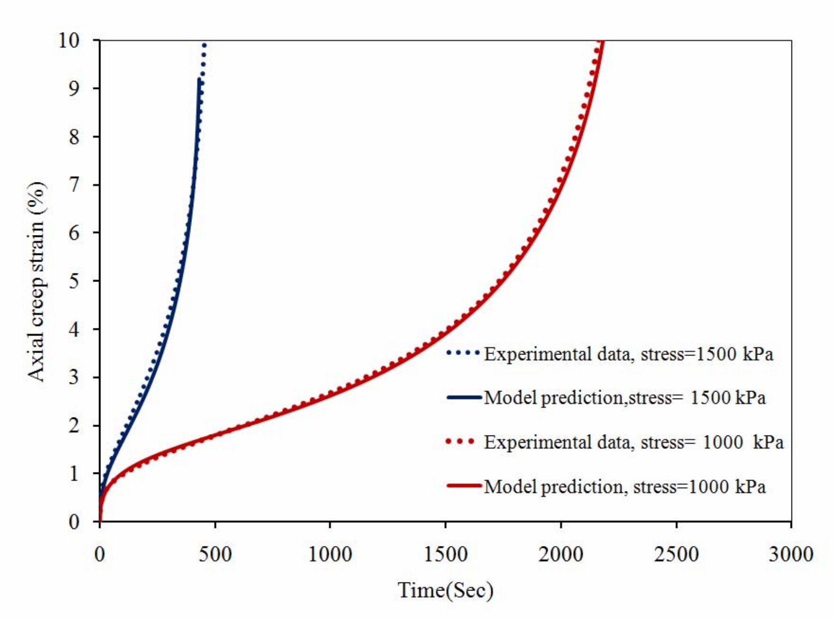
$\sigma = 750\text{kPa}$

Creep-recovery test
Compression
@ T=40^{o}C

Model Validation (Creep Test)

2-Model predictions agrees well with creep data at different temperatures and stress levels. Tertiary creep behavior is also captured.





$T = 10^o C$

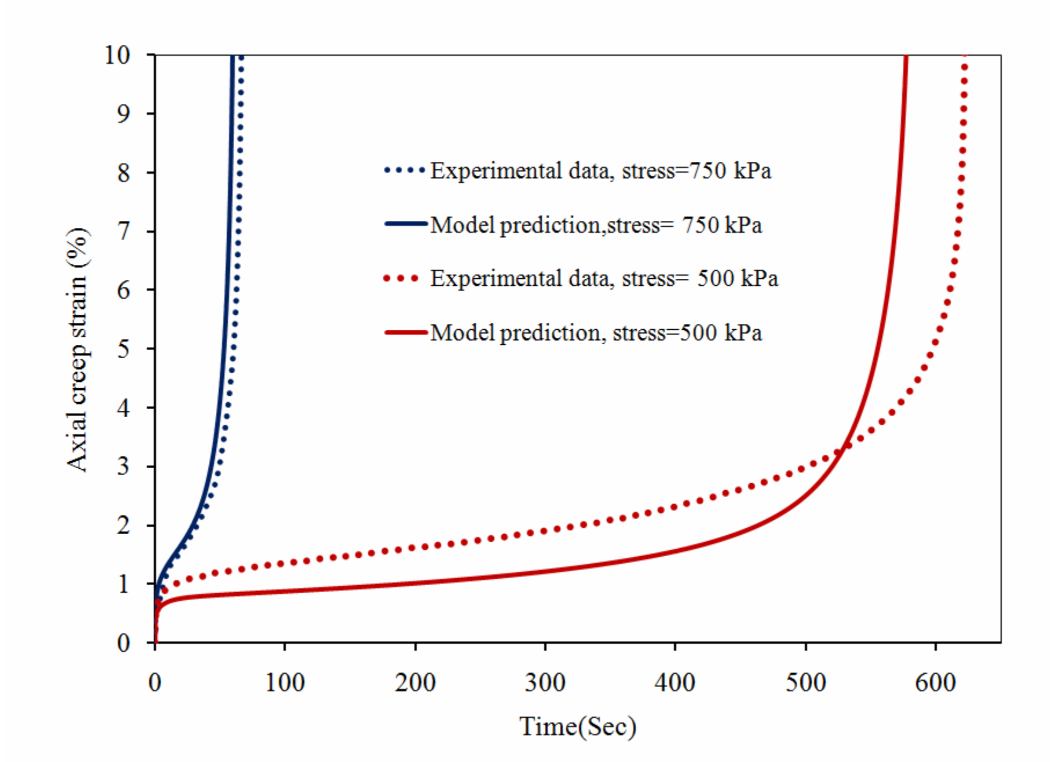
$T = 20^o C$

Creep test
Compression

Model Validation (Creep Test)

2-Model predictions agrees well with creep data at different temperatures and stress levels. Tertiary creep behavior is also captured.

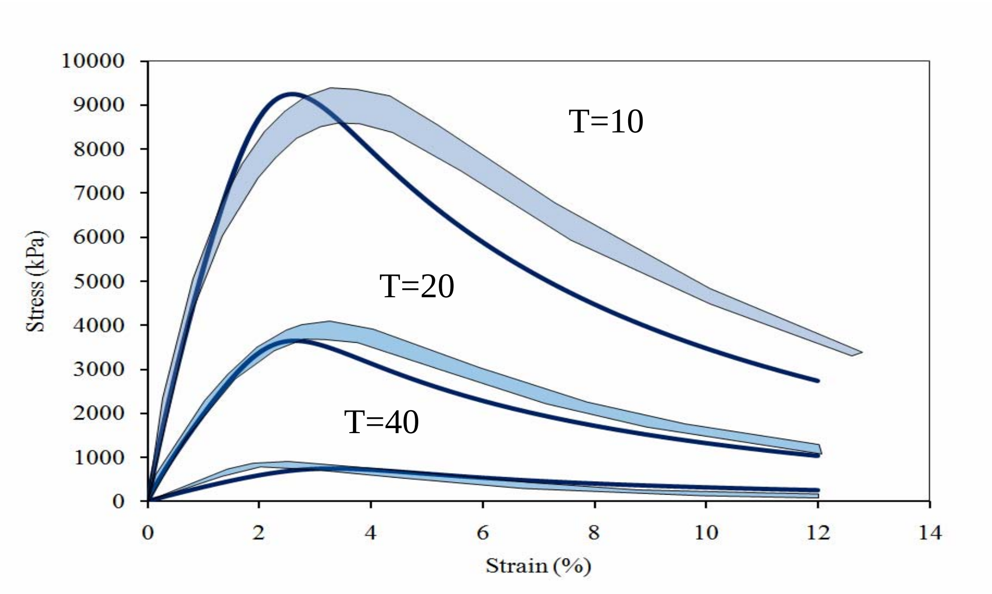
$$T = 40^o C$$

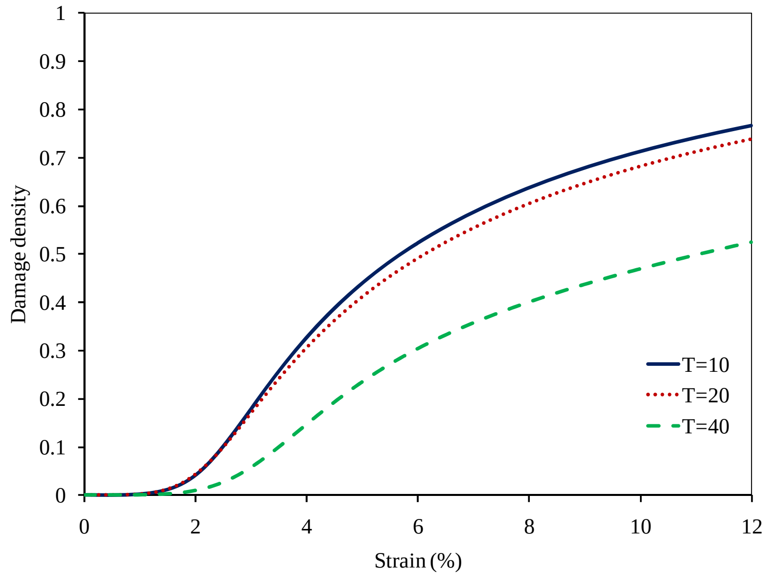


Creep test
Compression

Model Validation (Constant Strain Rate Test)

3-Model predicts temperature and rate-dependent behavior of asphalt mixes. Post peak behavior is captured well.

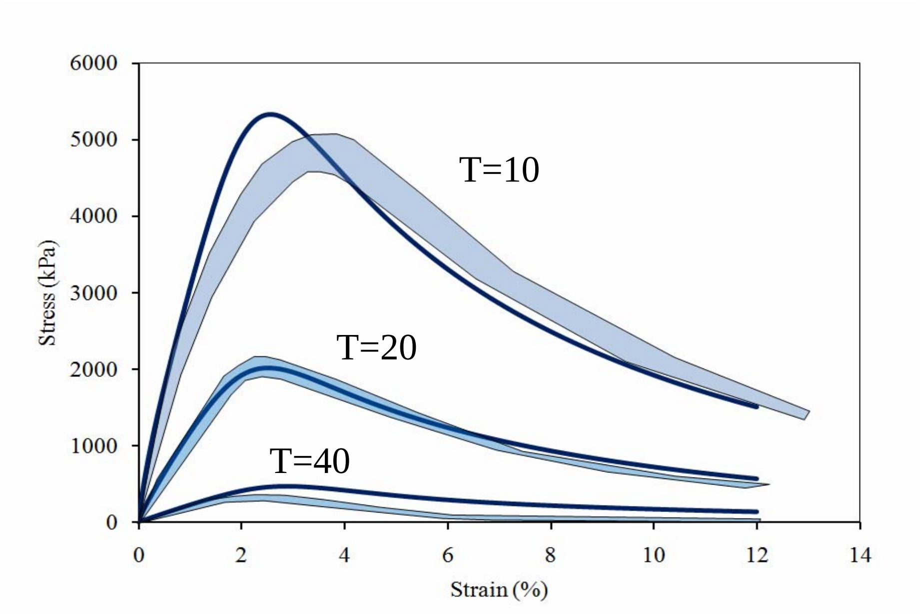


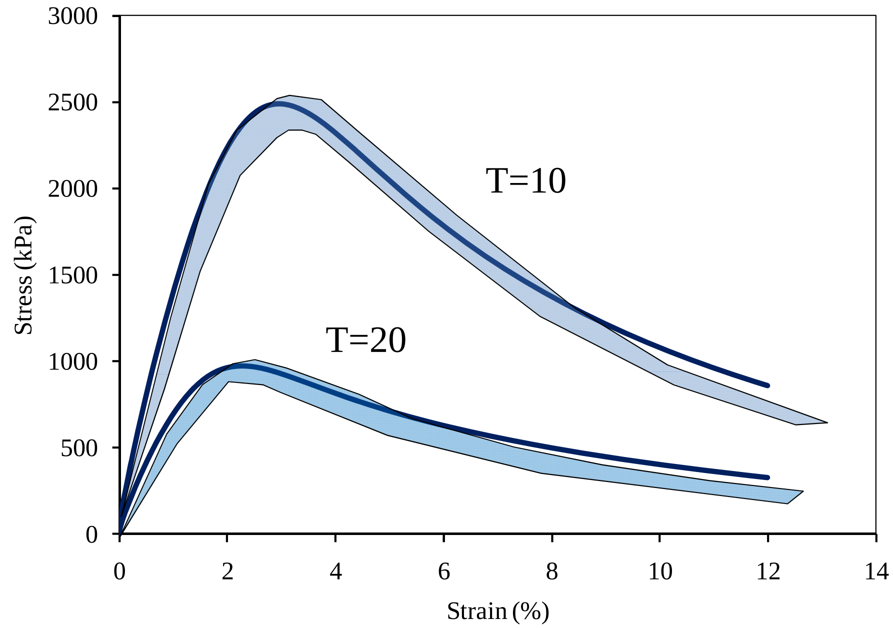


Constant strain rate test
Compression
Loading rate: 0.005/Sec

Model Validation (Constant Strain Rate Test)

3-Model predicts temperature and rate-dependent behavior of asphalt mixes. Post peak behavior is captured well.



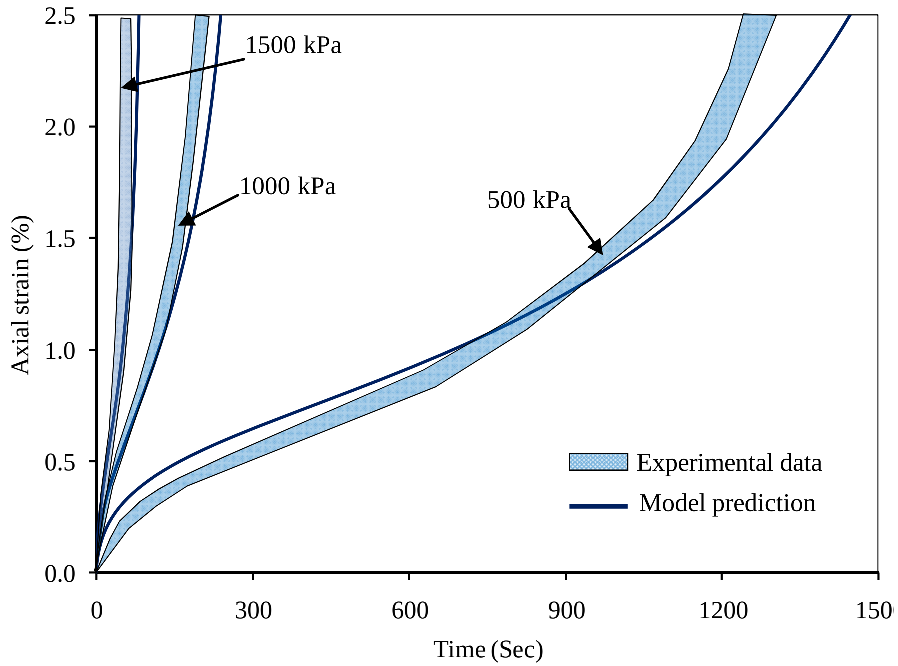


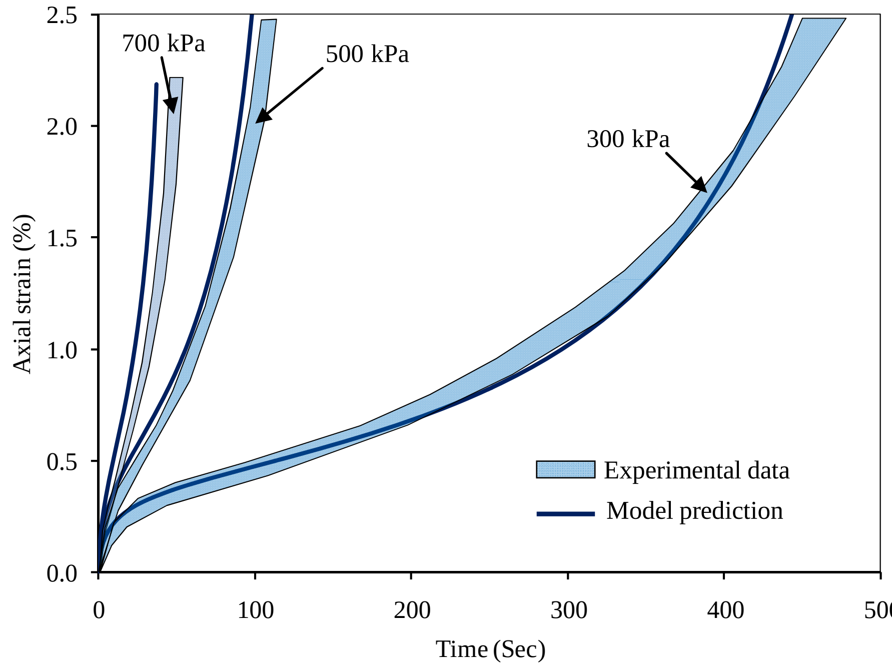
Constant strain rate test
Compression
Loading rate: 0.0005/Sec

Constant strain rate test
Compression
Loading rate: 0.00005/Sec

Model Validation in Tension (Creep Test)

4-Model predicts experimental data in tension.
Tertiary stage and time of failure are captured well.





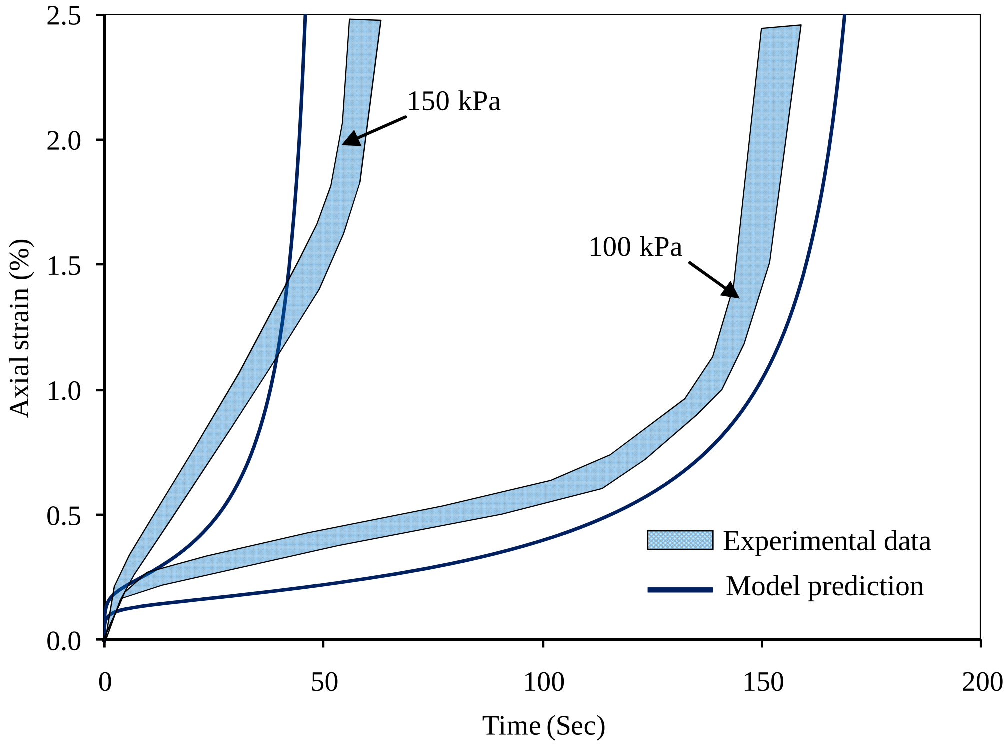
Creep test
Tension
Temperature: 10ºC

Creep test
Tension
Temperature: 20ºC

Model Validation in Tension (Creep Test)

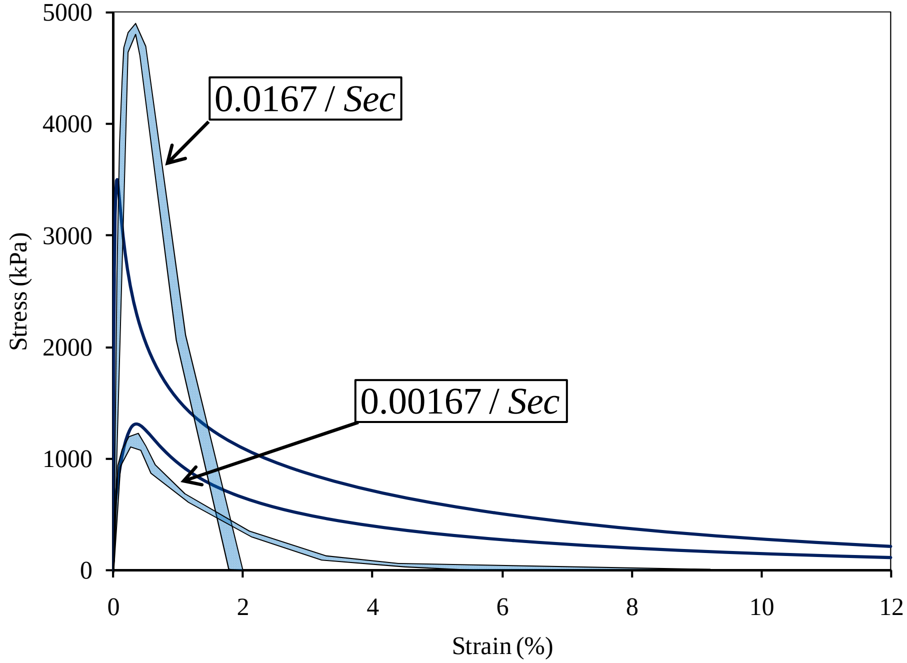
4-Model predicts experimental data in tension.
Tertiary stage and time of failure are captured well.

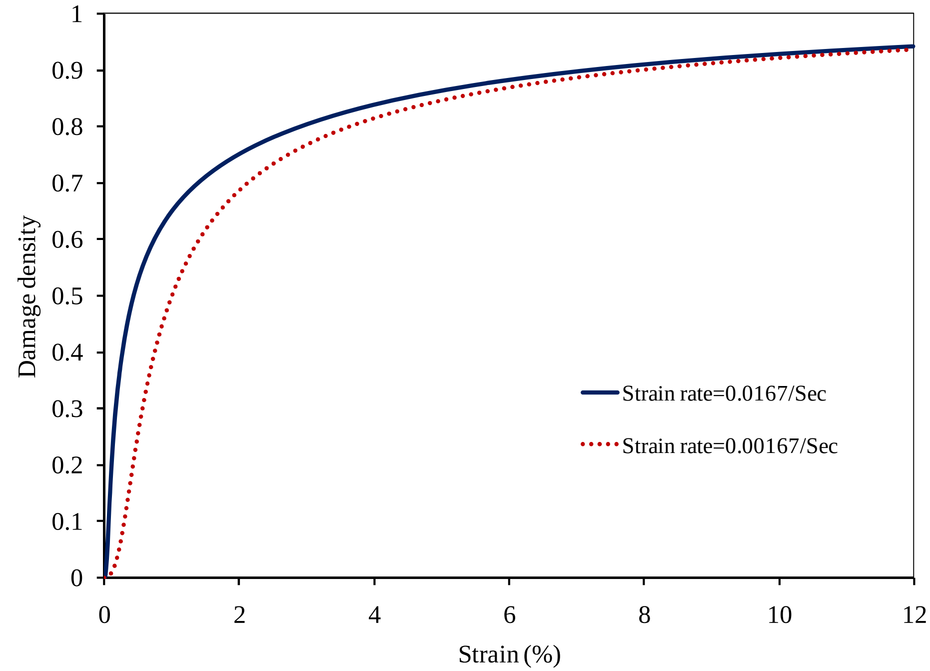
Creep test
Tension
Temperature: 35°C



Model Validation in Tension (Creep Test)

4-Model predicts experimental data in tension.





Constant strain rate test
Tension
Temperature: 20°C

Outline

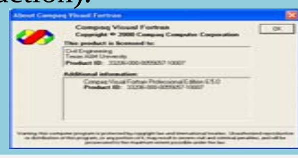
Implementation procedure

Implementation Procedure

Procedure to Run the Performance Prediction Continuum Damage Model

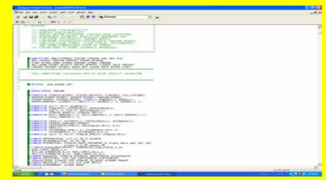
Fortran

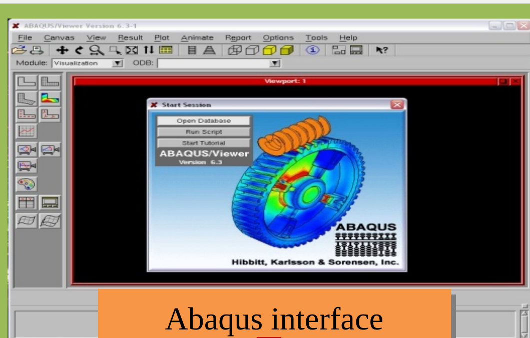
Fortran compiler is used to compile UMAT (i.e. translates programming commands into action).



UMAT

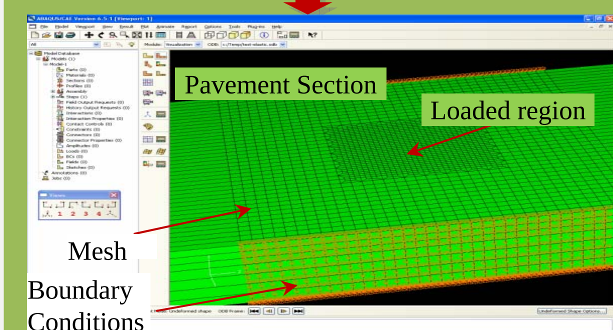
A Fortran code includes the Continuum Damage Model



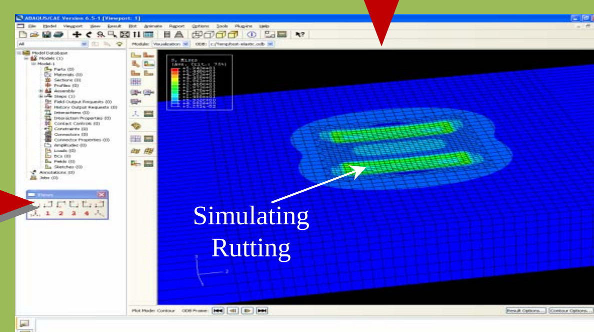


Abaqus interface

Abaqus calls UMAT to run the Continuum Damage Model and UMAT gives Abaqus the material response



Creating geometry, mesh, and applying loading



Running and viewing the simulation results

Outline

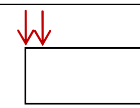
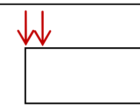
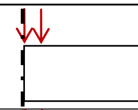
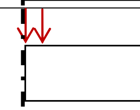
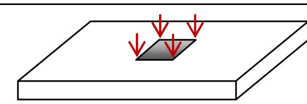
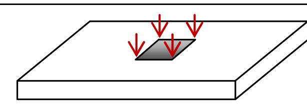
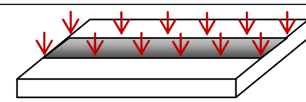
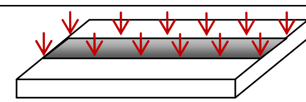
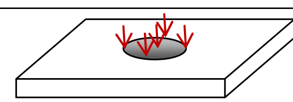
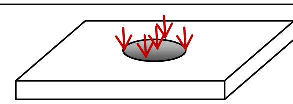
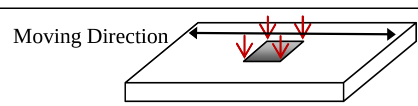
Application of the model for rutting performance simulation

Application for Simulation of Wheel Tracking Test

2D FE Model

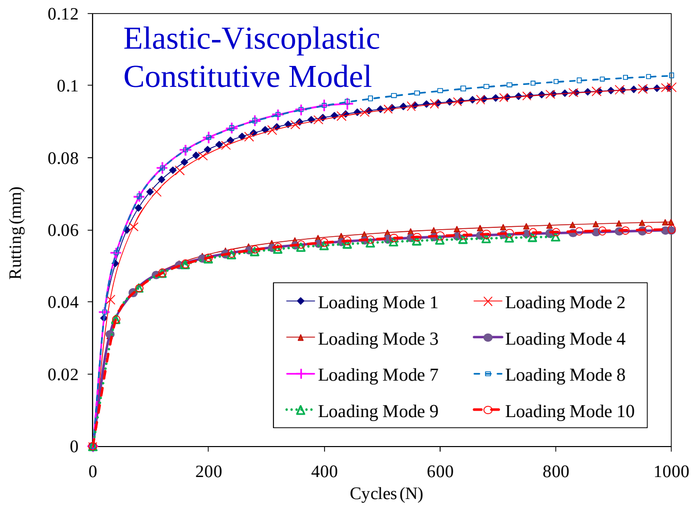
3D FE Model

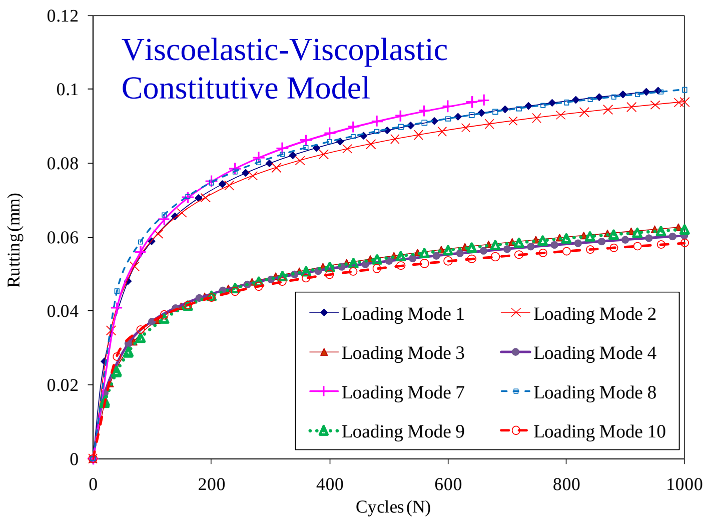
Application: Different Loading Cases

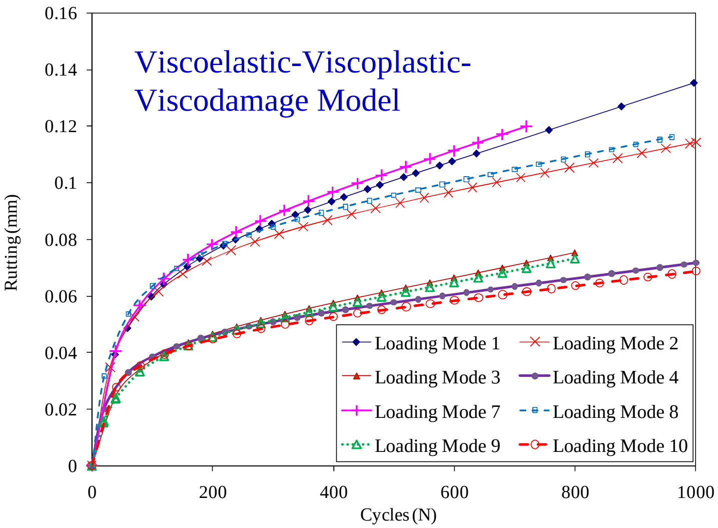
Mode	Loading approach	Loading Area	Schematic representation of loading modes
1 (2D)	Pulse loading (plane strain)	One wheel	
2 (2D)	Equivalent loading (plane strain)	One wheel	
3 (2D)	Pulse loading (axisymmetric)	One wheel	
4 (2D)	Equivalent loading (axisymmetric)	One wheel	
5 (3D)	Pulse loading	One wheel	
6 (3D)	Equivalent loading	One wheel	
7 (3D)	Pulse loading	Whole wheel path	
8 (3D)	Equivalent loading	Whole wheel path	
9 (3D)	Pulse loading	Circular loading area	
10 (3D)	Equivalent loading	Circular loading area	
11 (3D)	Moving loading	One wheel	

Application: Different Loading Modes and Constitutive Models

2D Rutting simulation results: Different constitutive models.

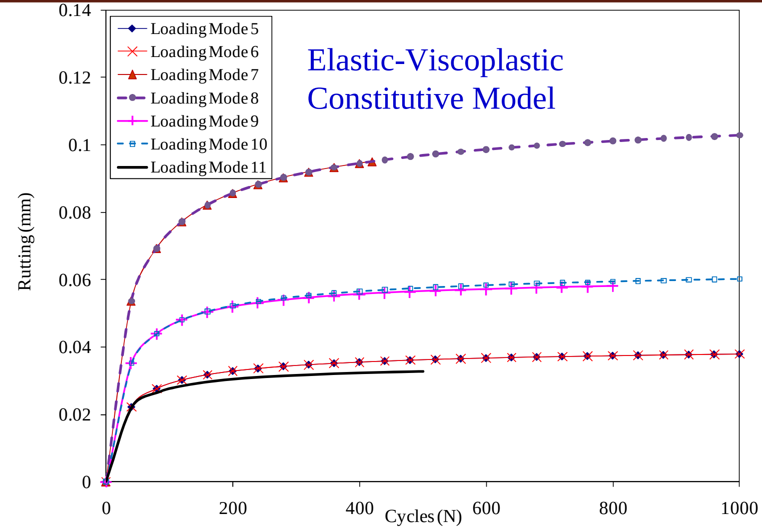


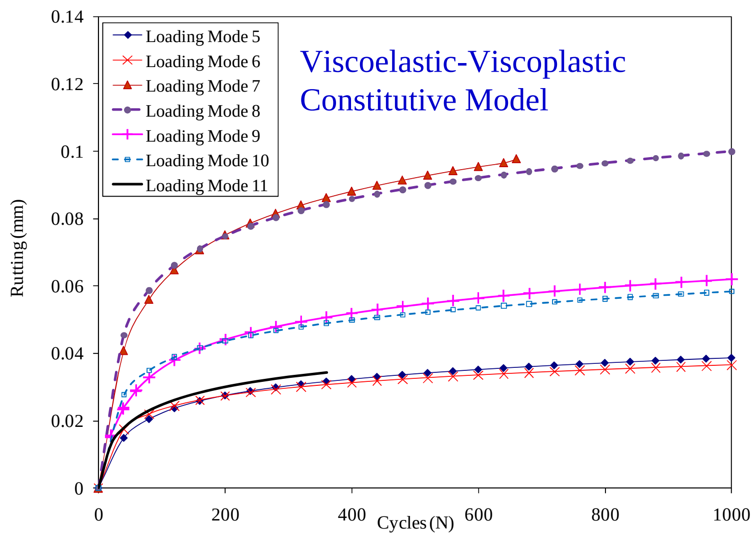


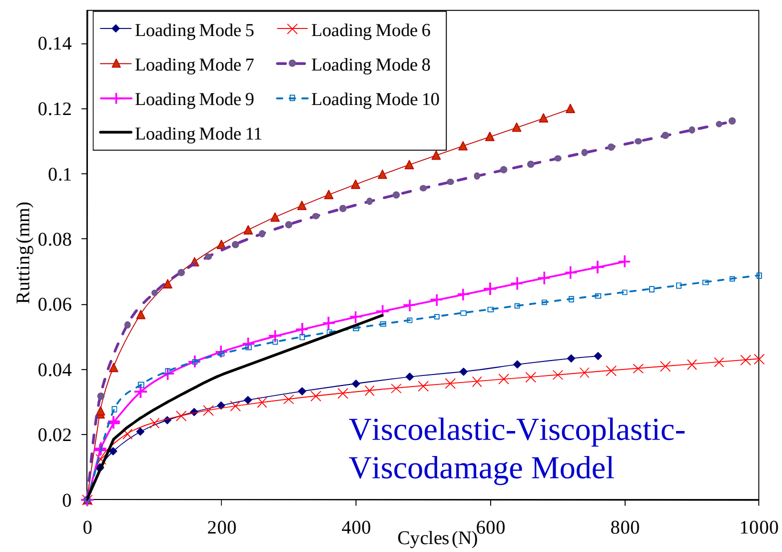


Application: Different Loading Modes and Constitutive Models

3D Rutting simulation results: Different constitutive models.







Application: Different Loading Modes and Constitutive Models

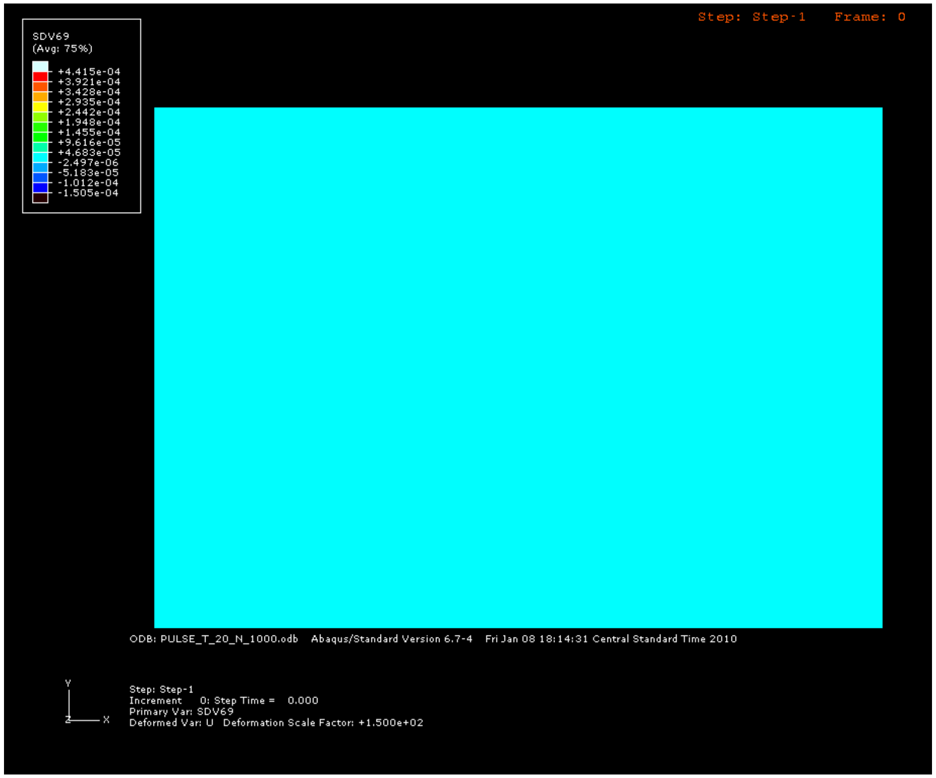
Simplified loading assumptions can be used when using elasto-viscoplastic model.

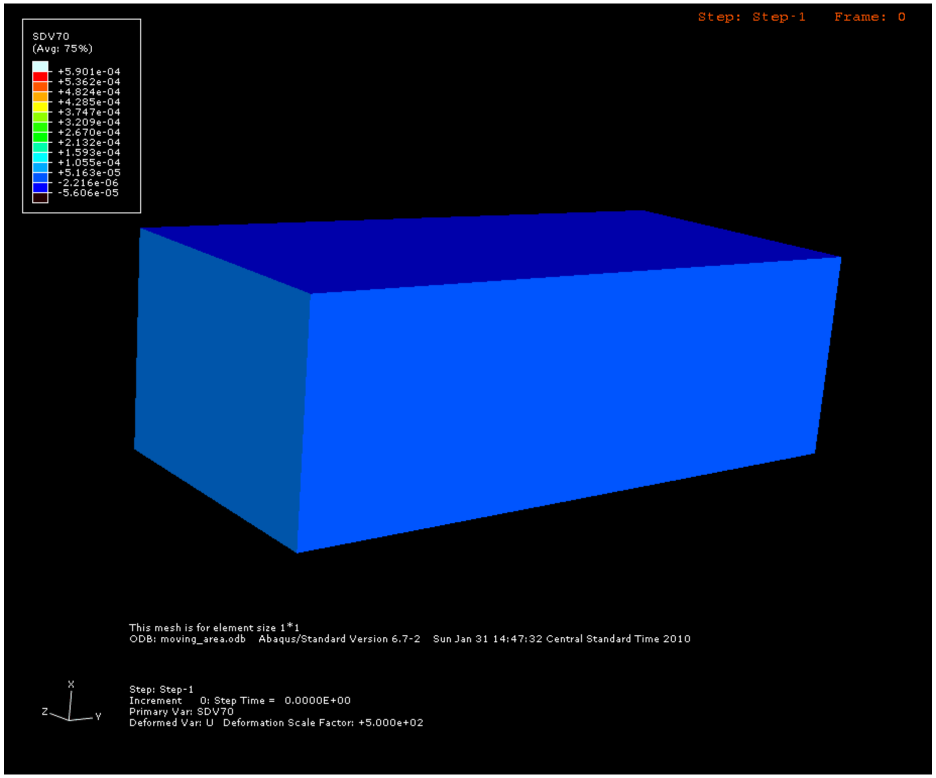
Simplified loading assumptions should be used carefully when viscoelastic response is significant.

Using simplified loading assumptions causes significant error when the damage level is significant.

Simulation Results

Viscoplastic strain



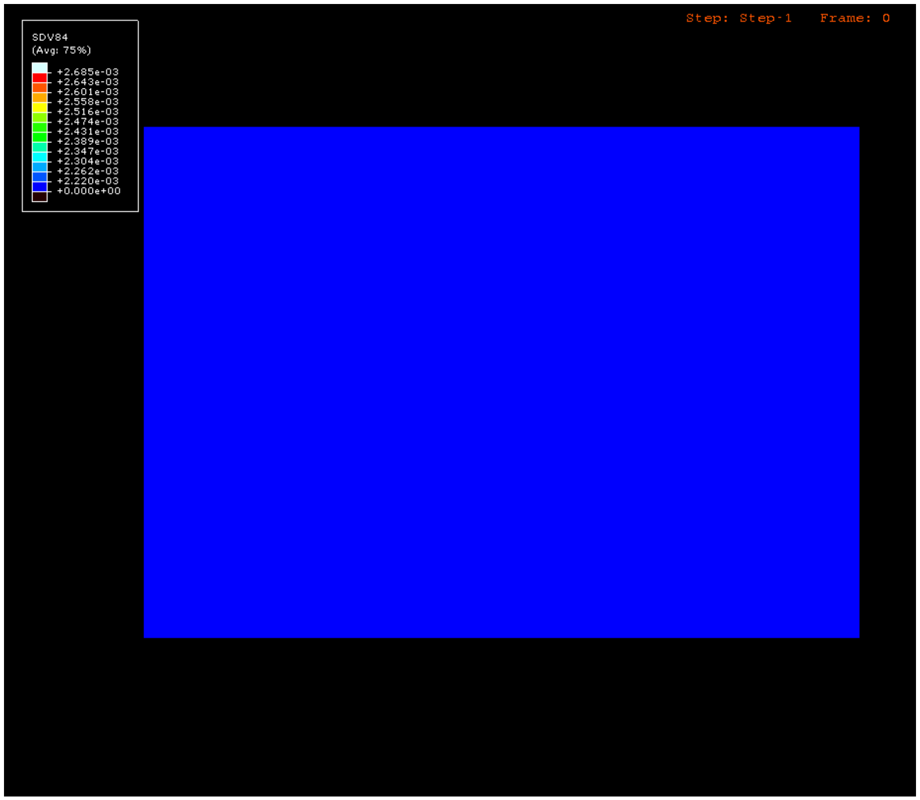


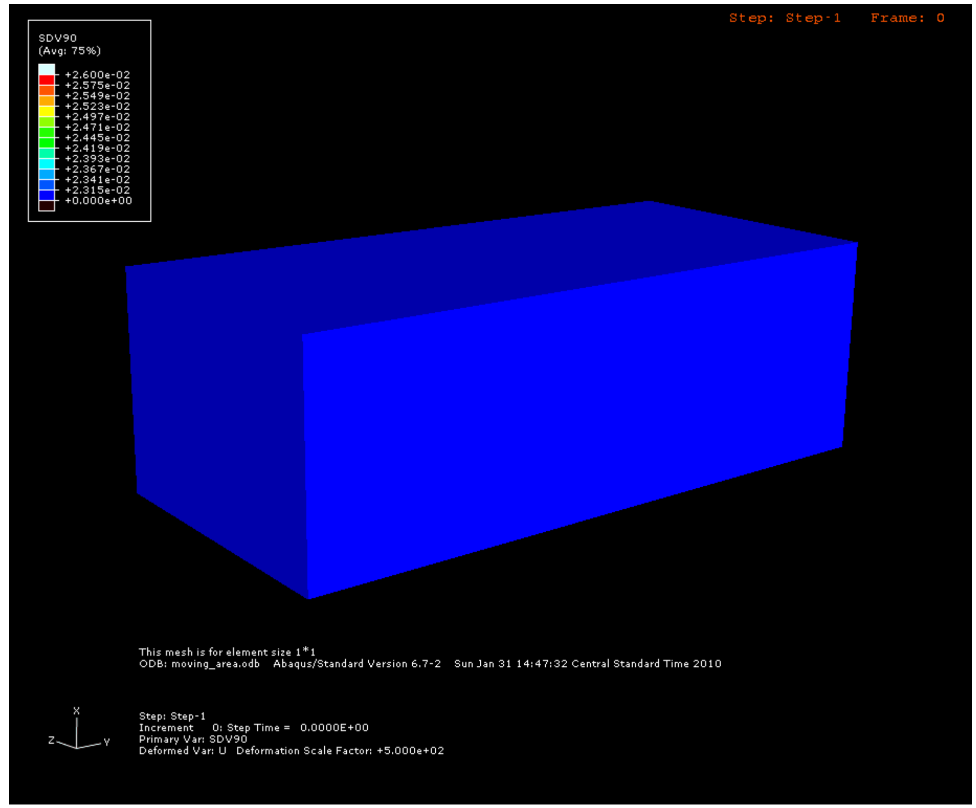
2D Results

3D Results

Simulation Results

Damage evolution

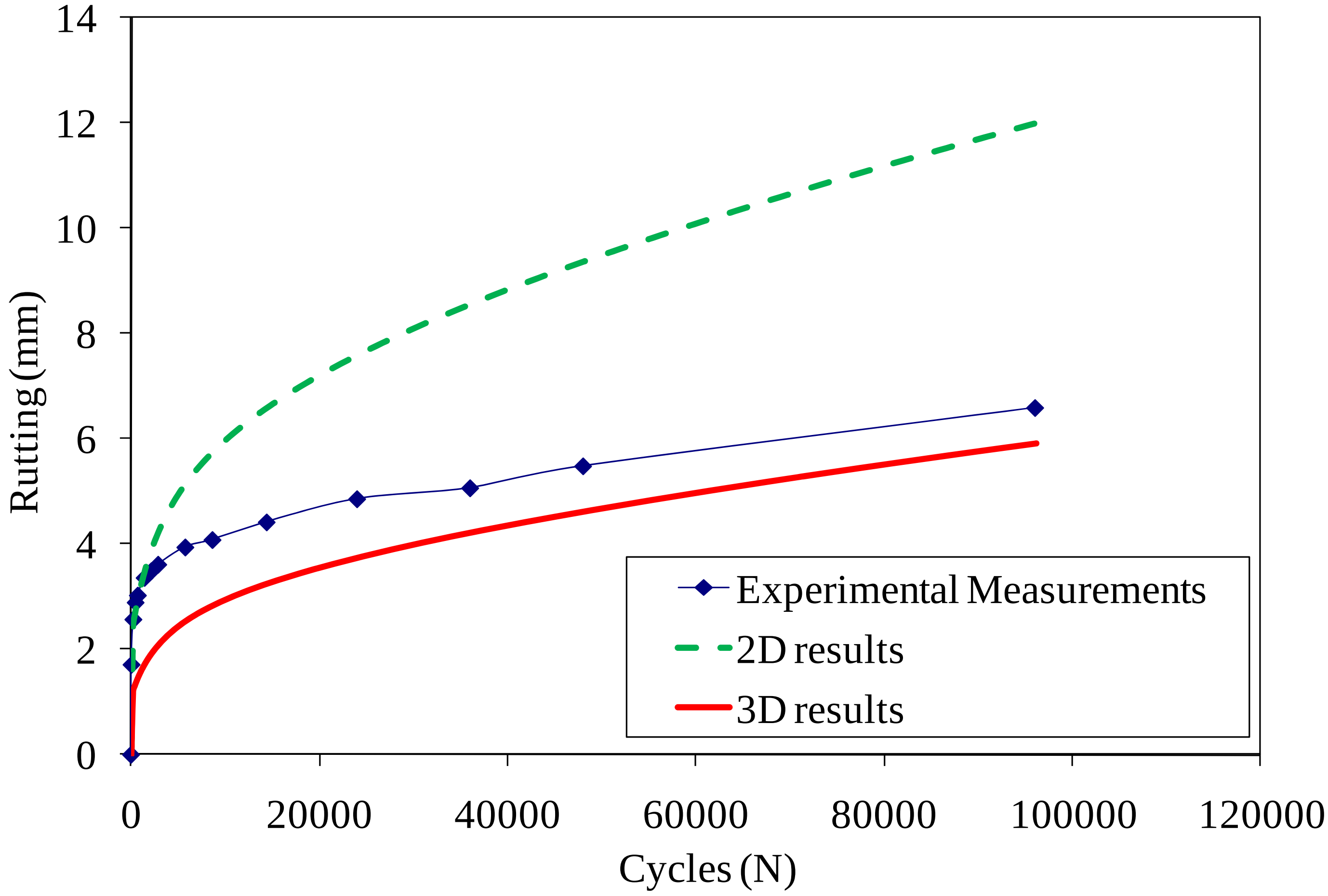




2D Results

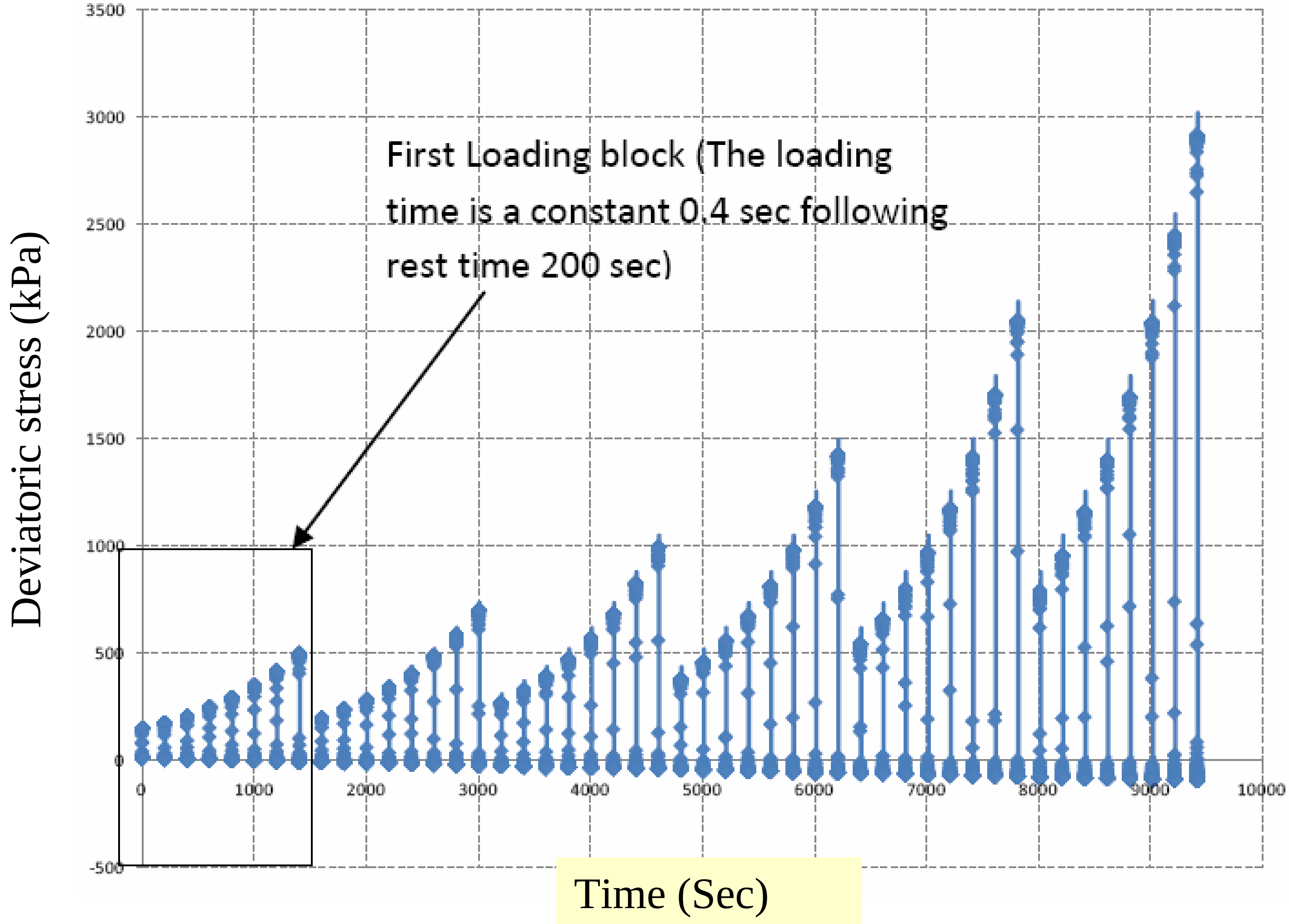
3D Results

Compare with Experimental Data

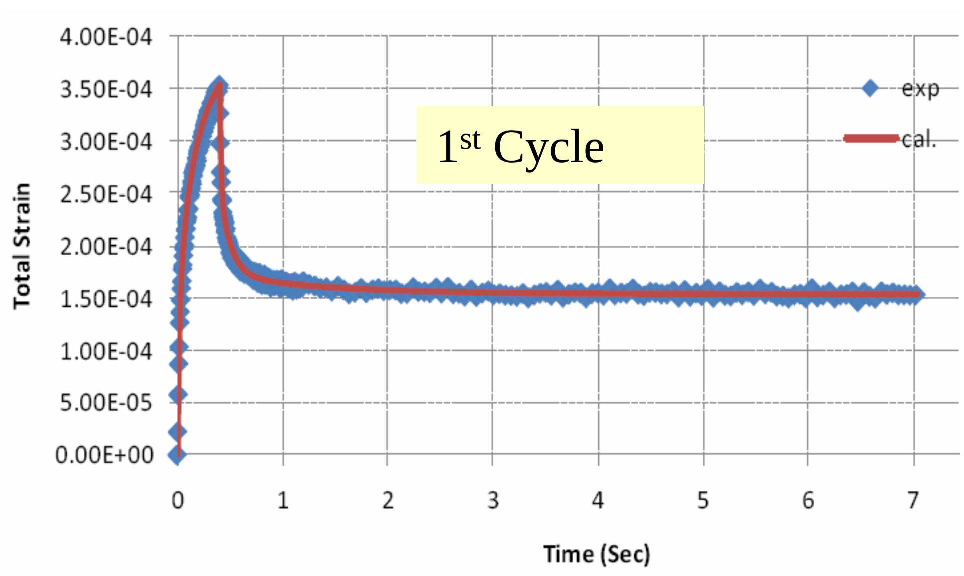


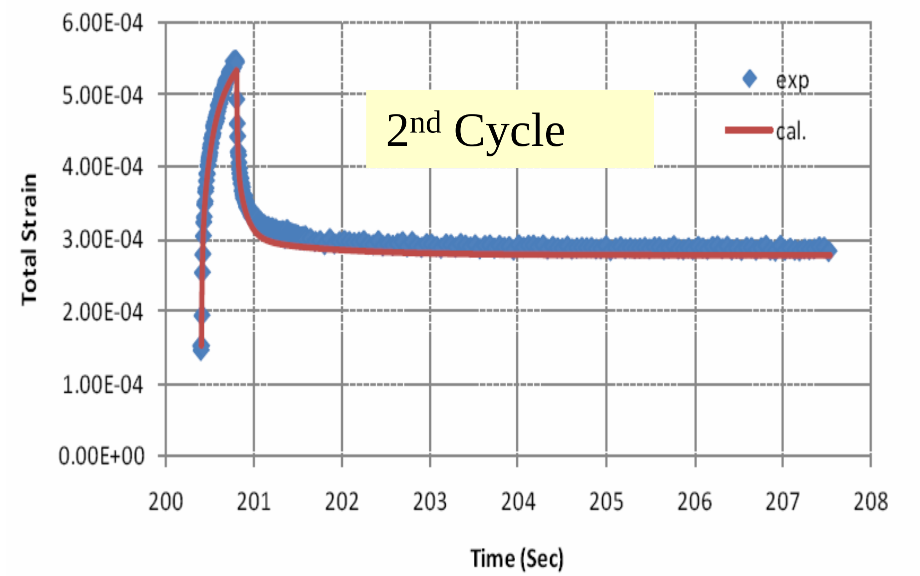
ALF Data-Variable Stress

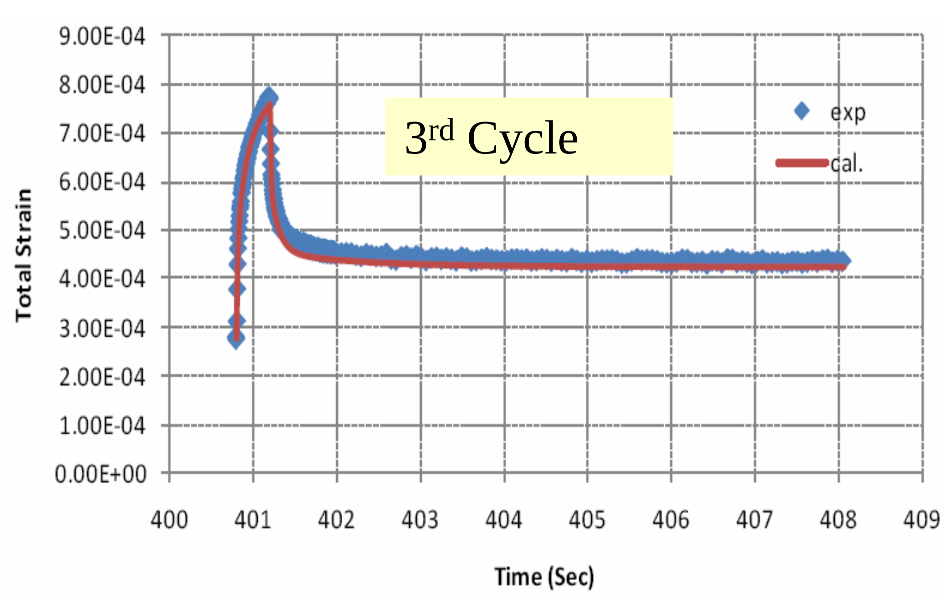
Applied stress (T=55ºC)

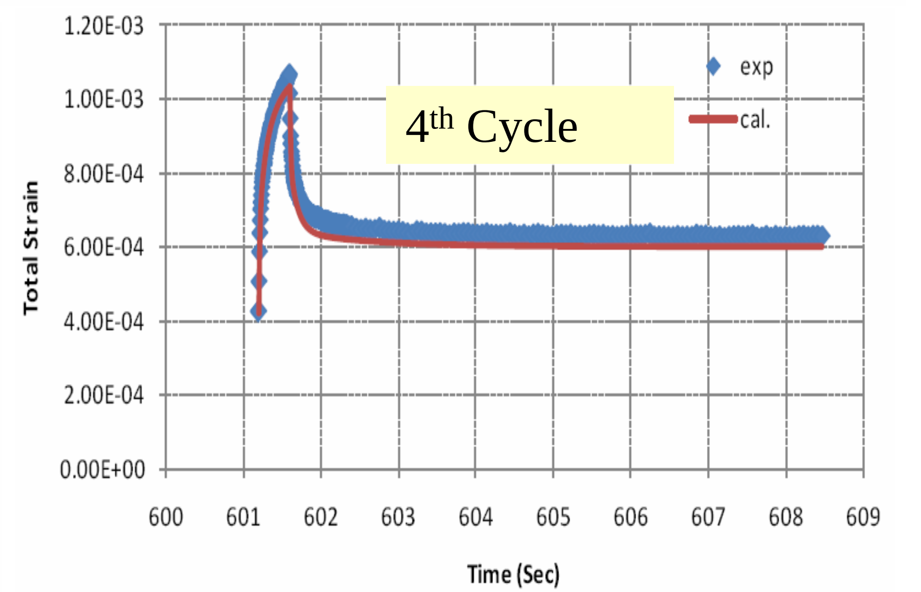


Model Validation: ALF Data (Strain Response)

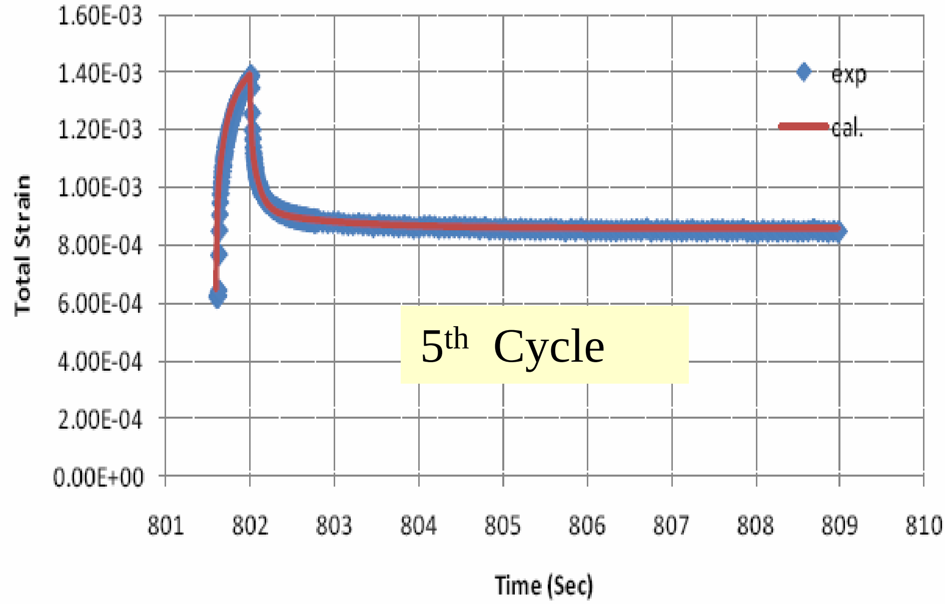


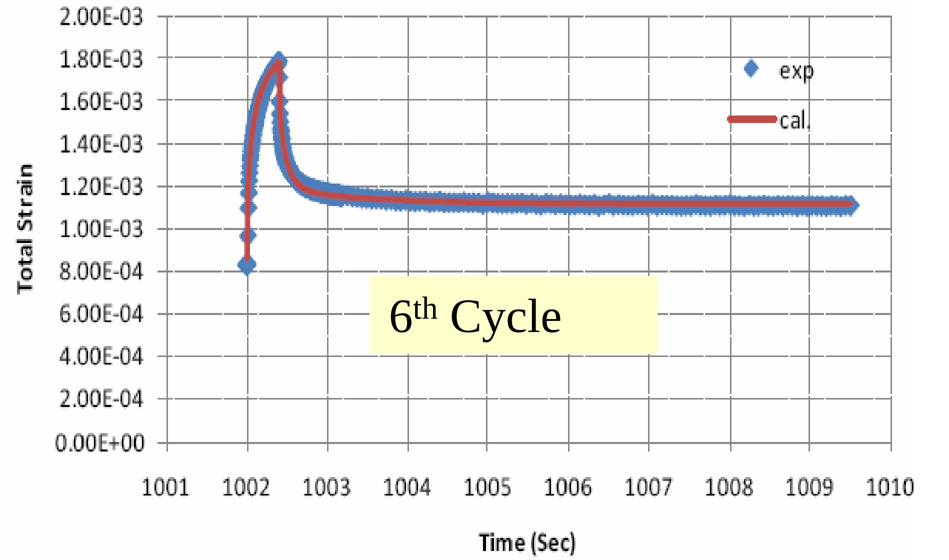


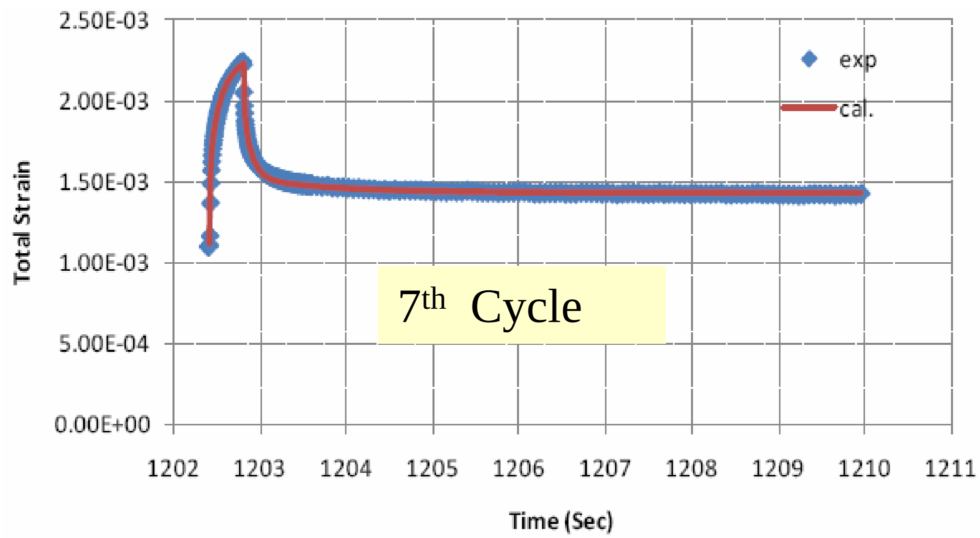


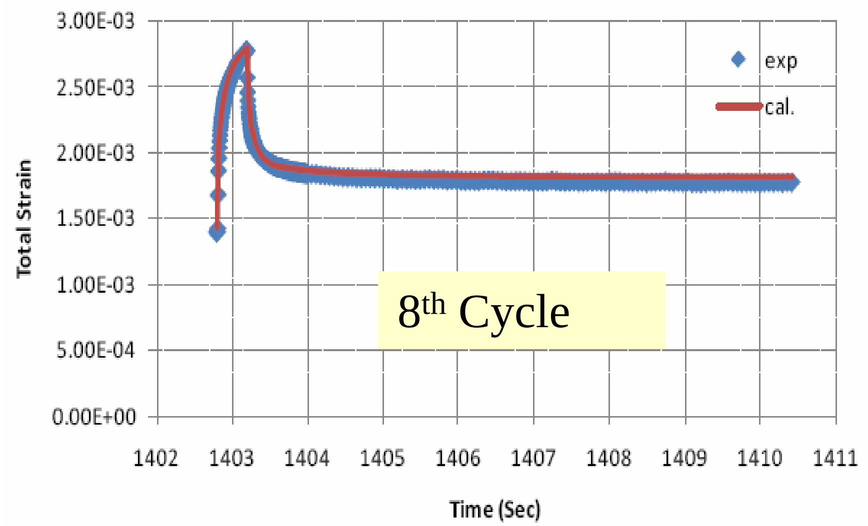


Model Validation: ALF Data (Strain Response)



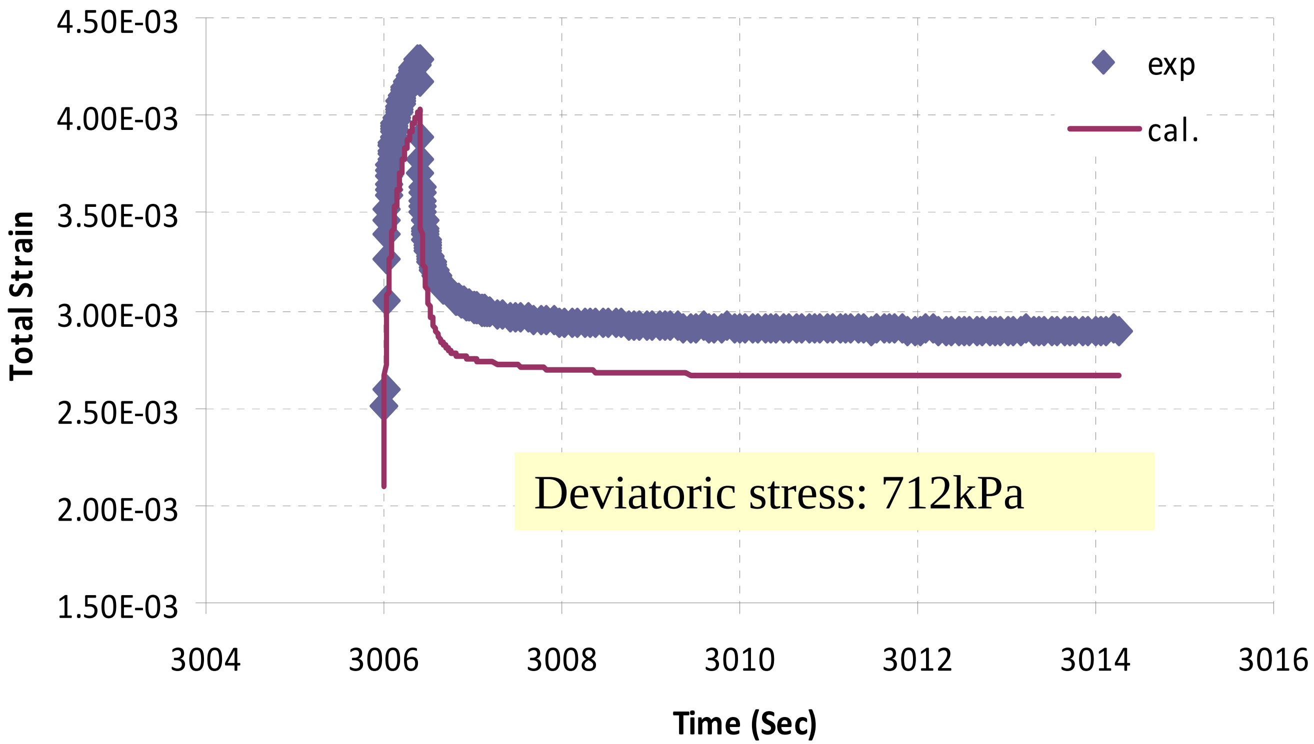






Model Validation: ALF Data (Strain Response)

Model predictions at large loading cycles

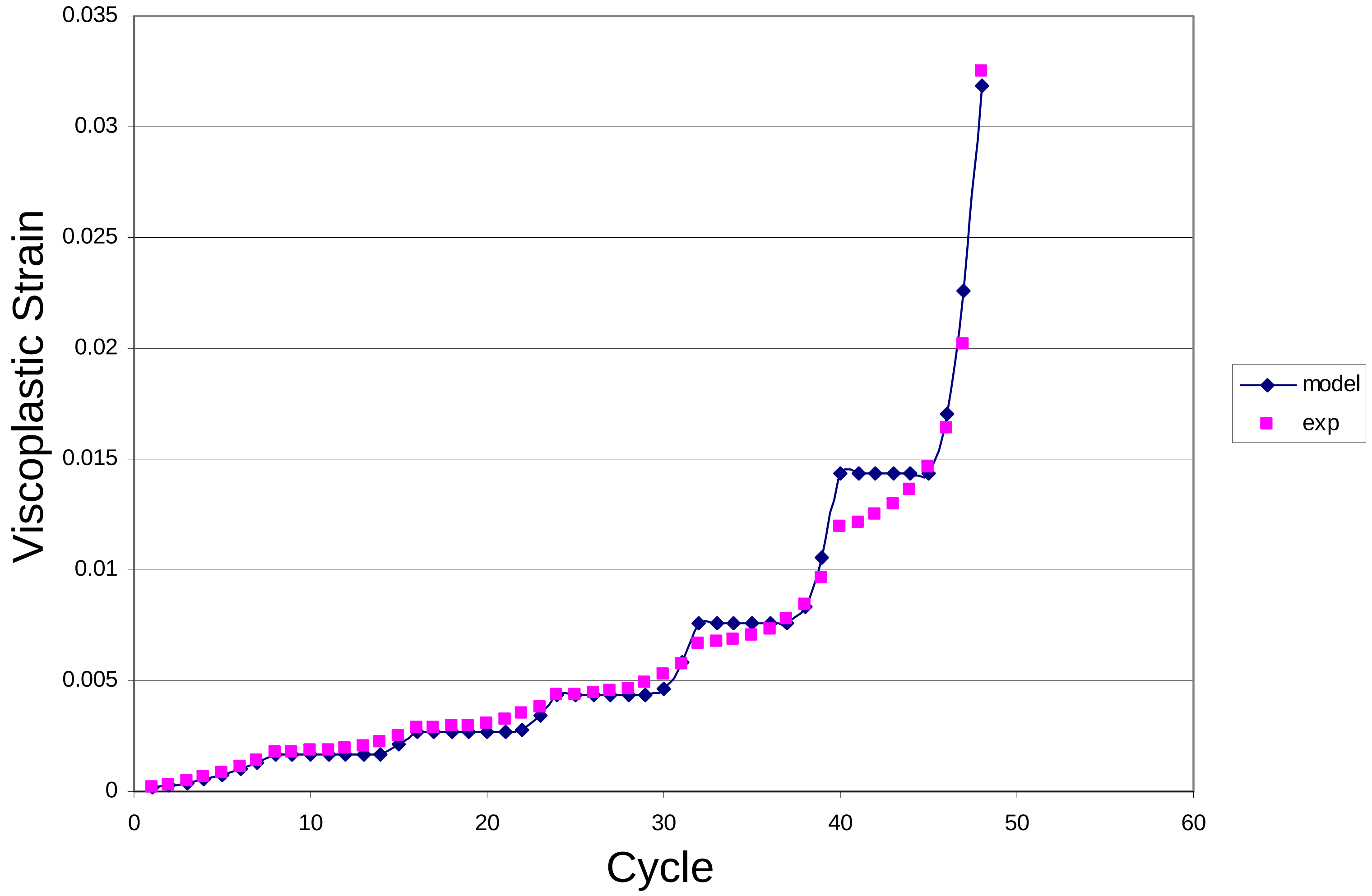


- At large loading cycles model predictions using VE-VP deviates from experimental measurements

- This deviation is due to damage and should be compensated using the damage model.

Model Validation: ALF Data (Strain Response)

Constant Stress-Variable Time Loading



Conclusions and Future Works

Conclusions:

❑ Proposed viscoelastic-viscoplastic-viscodamage model predicts rate-, time-, and temperature-dependent behavior of asphalt mixes in both tension and compression.

❑ Model can be used to predict performance simulations.

Challenges and future works:

❑ Including healing to the model.

❑ Including environmental effects such as aging and moisture induced damage to the model.

❑Validating the model over an extensive experimental measurements.

❑ Performing performance simulations in pavements.

THANK YOU

Questions?