Surface distress and the HVS

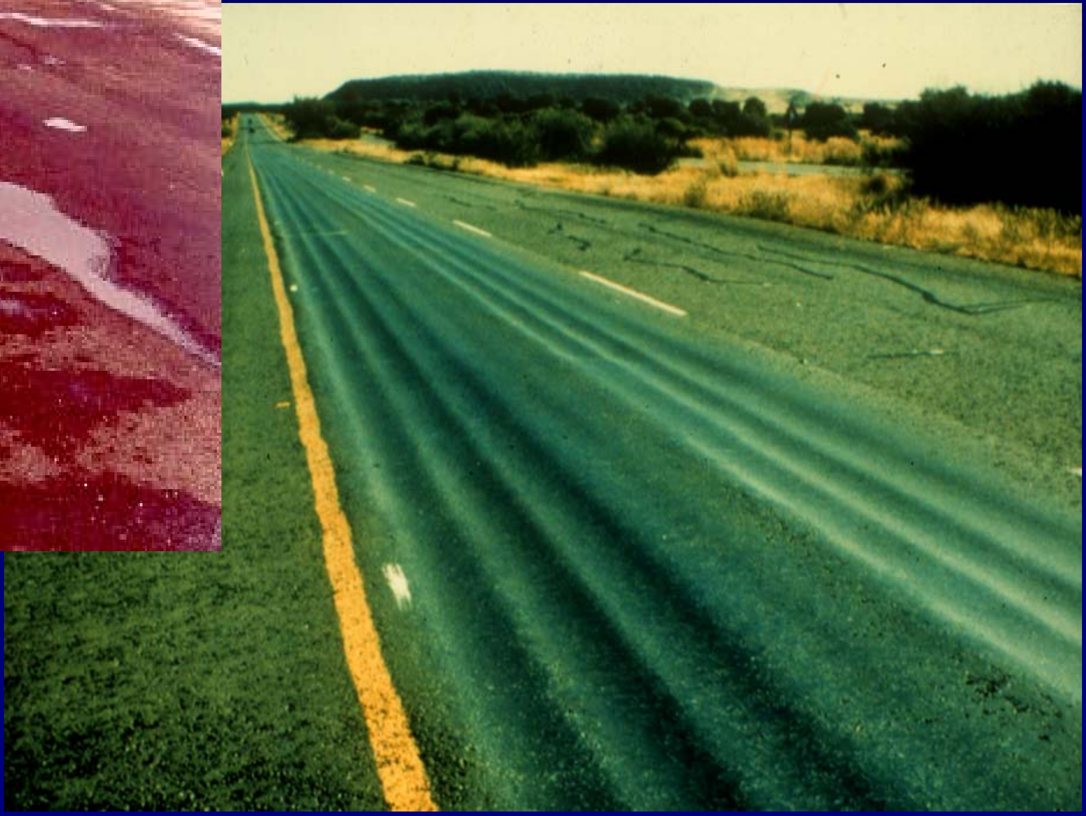
HVS Instrumentation Workshop
Florida
5 April 2003

CSIR TRANSPORTEK

Scope

- Surface distress
- Stress-in-motion (SIM)
  - Tire-contact stresses
- Asphalt concrete rutting
  - Constitutive model for AC rutting
    - » *Validation with the HVS*
  - Mix design procedure
    - » *Validation with the HVS*

Surfacing distress: Rutting



Surfacing distress

Flow

Shoving

Effects of surface distress: Safety

Surface distress: Fatigue cracking

Surface distress

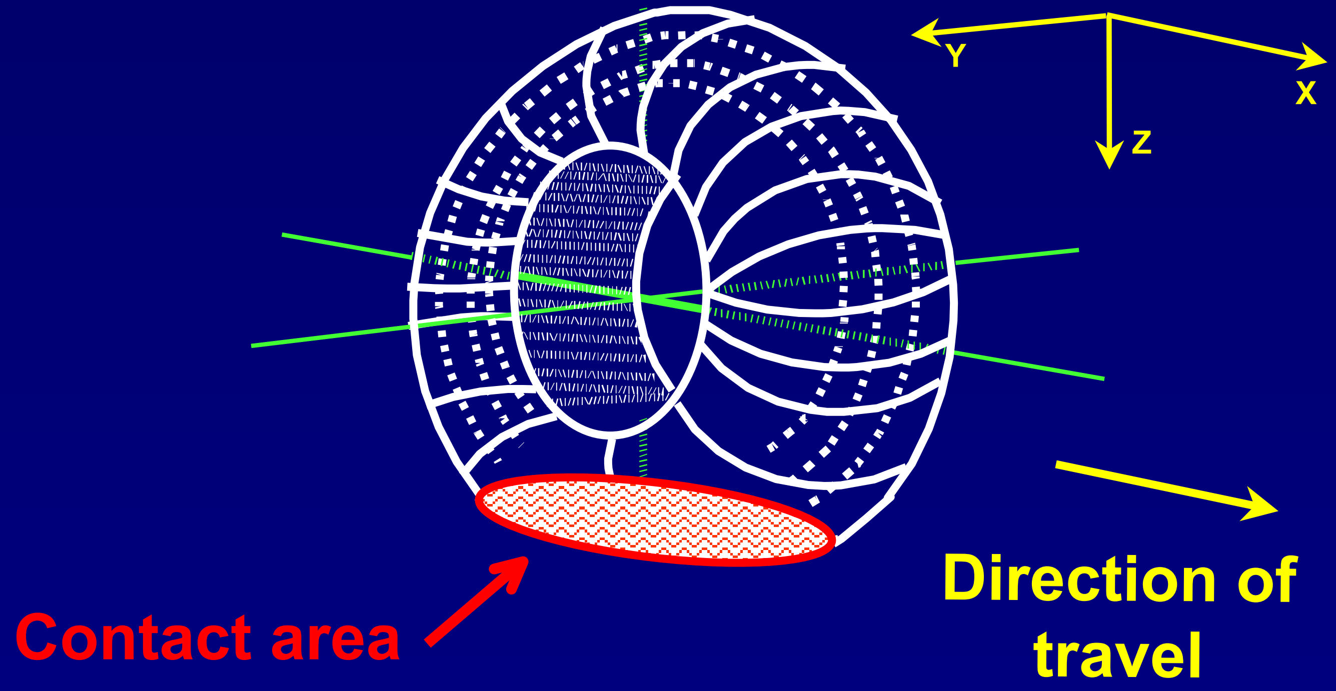
Surface distress

Potholes and patching

Surface distress

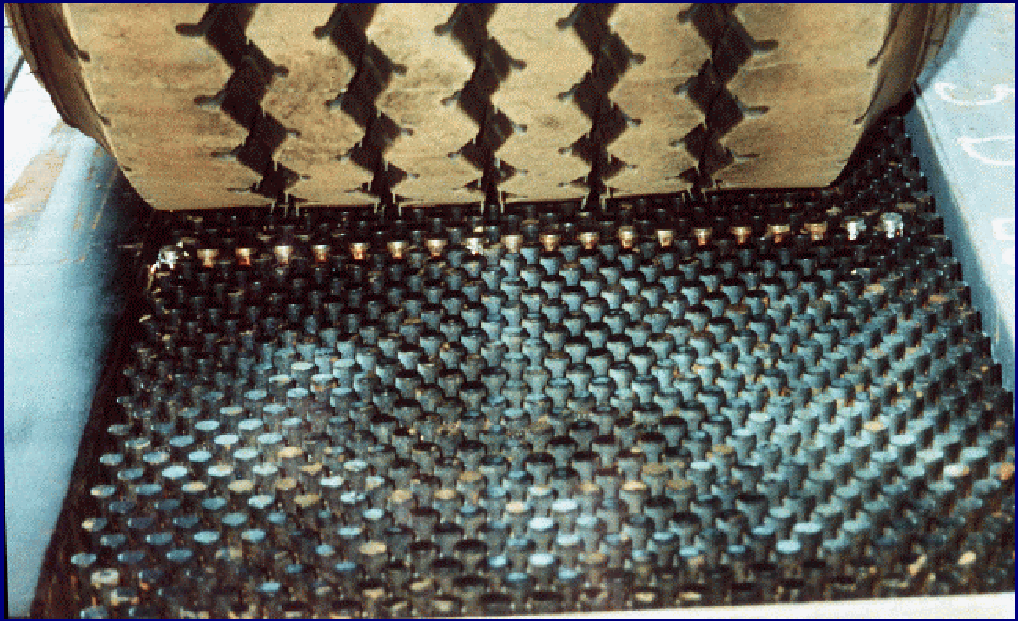
Surface distress

- Distress manifests in many different ways
- Contributor to almost all surface distress
  - Loading and tire-contact stress

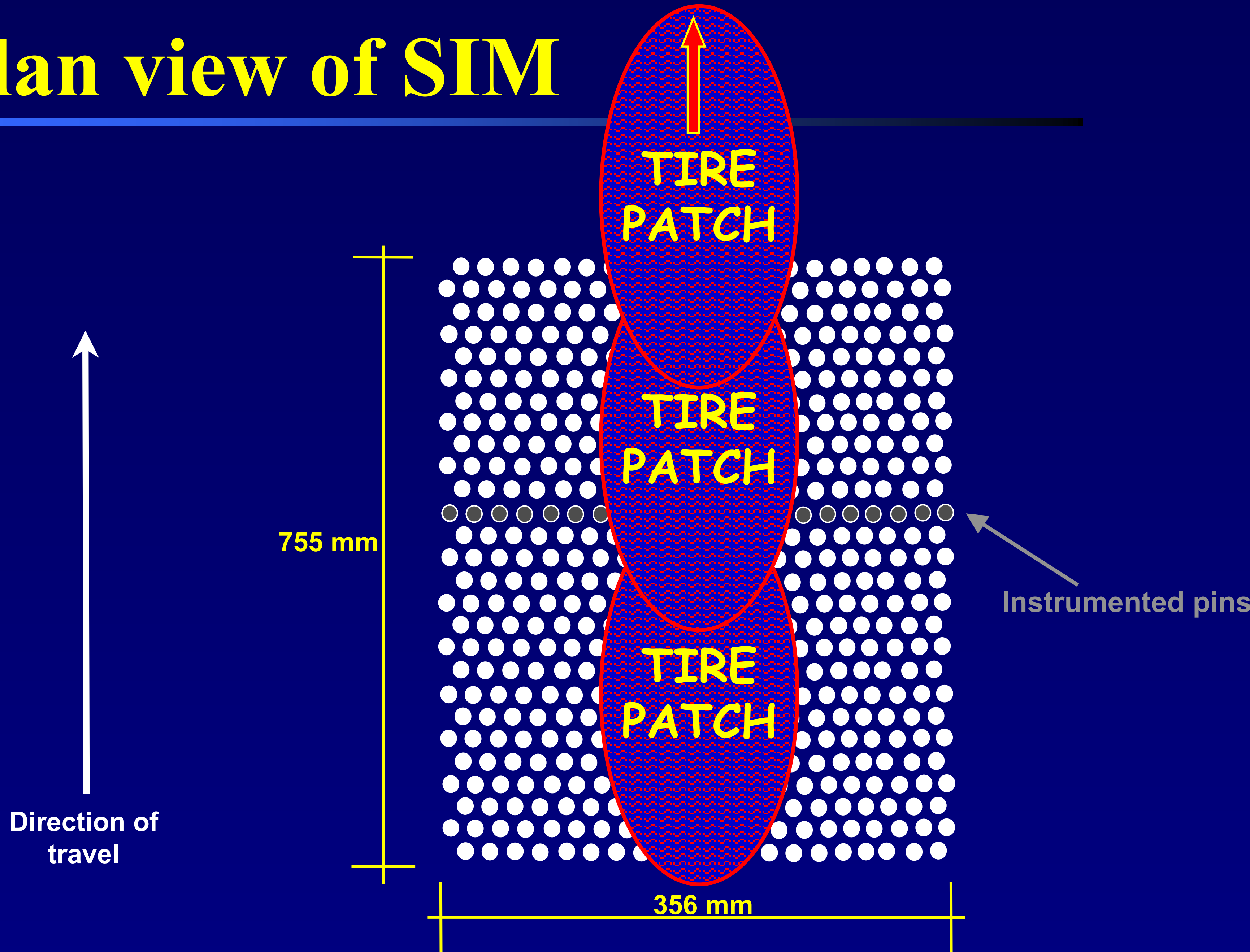


Stress-in-Motion Device (SIM)

Measurement of tire contact stresses



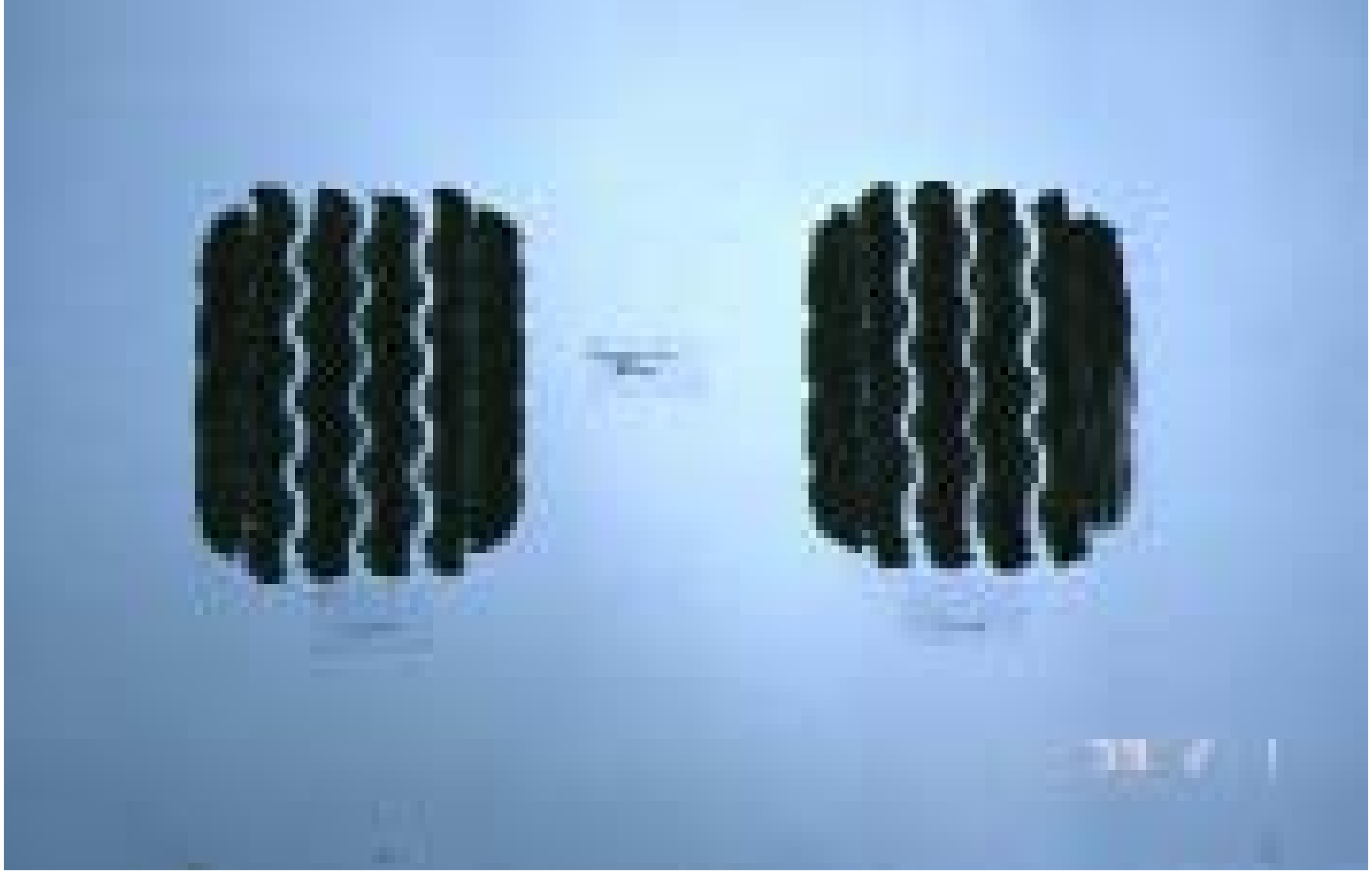
Plan view of SIM



HVS Tires: 11.00 – R22.5 Radial

HVS Footprint

- Dual tire at 30 kN and 420 kPa



HVS Footprint

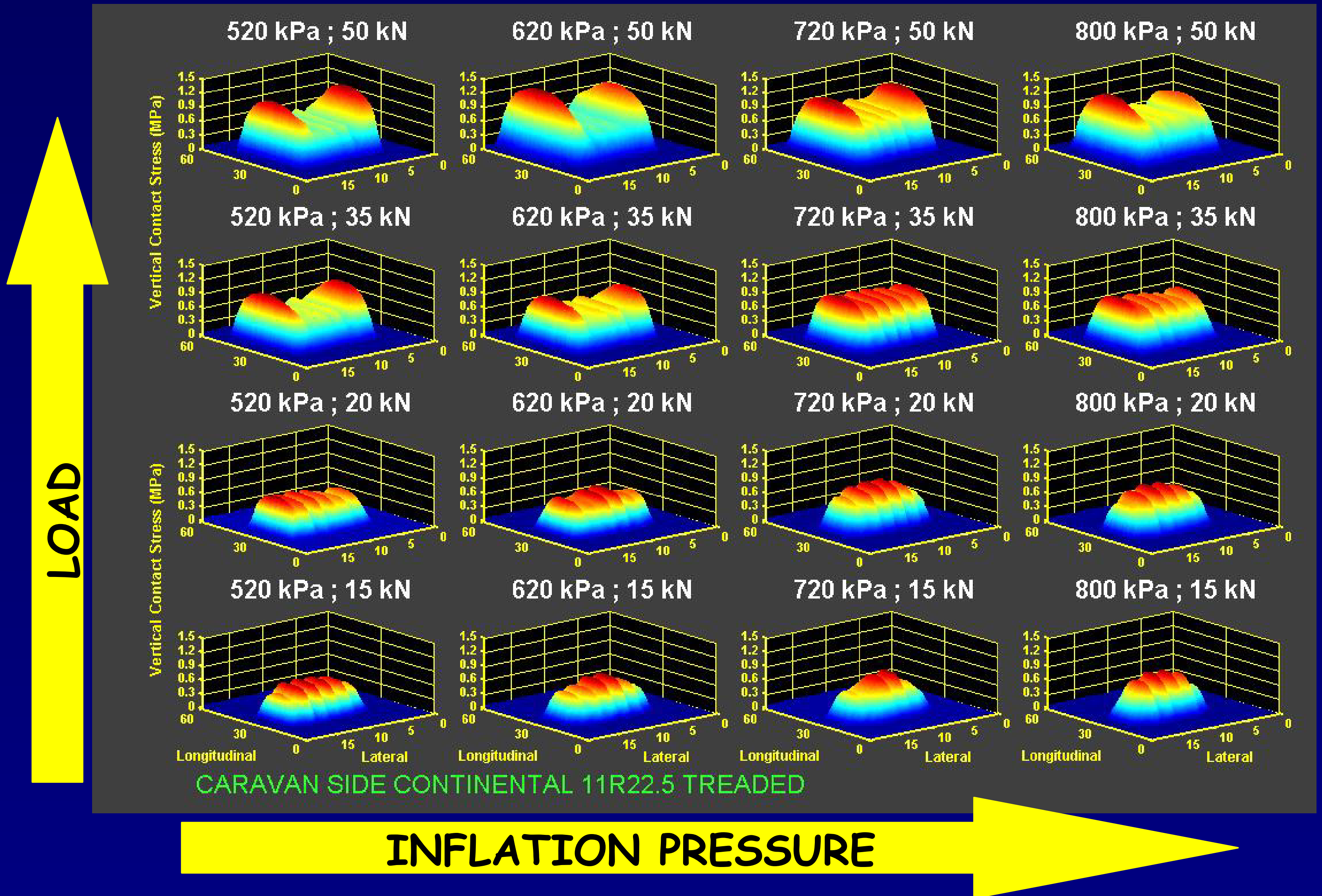
- Dual tire at 70 kN and 420 kPa

HVS Tires : 11.00 – R22.5 Radial

- High loading

Note the "bulging" of both tyres

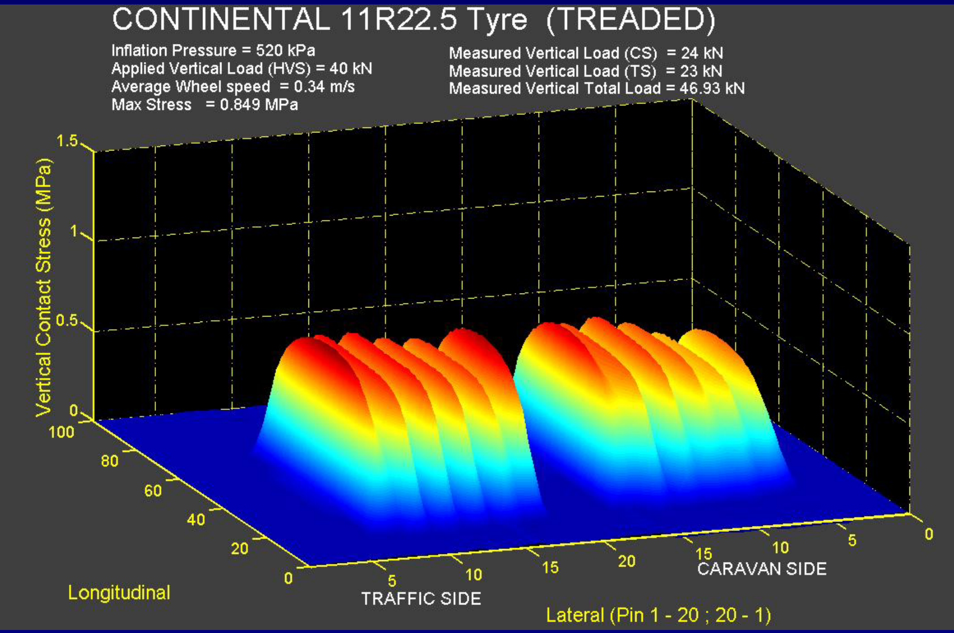
SIM measurements with HVS tire

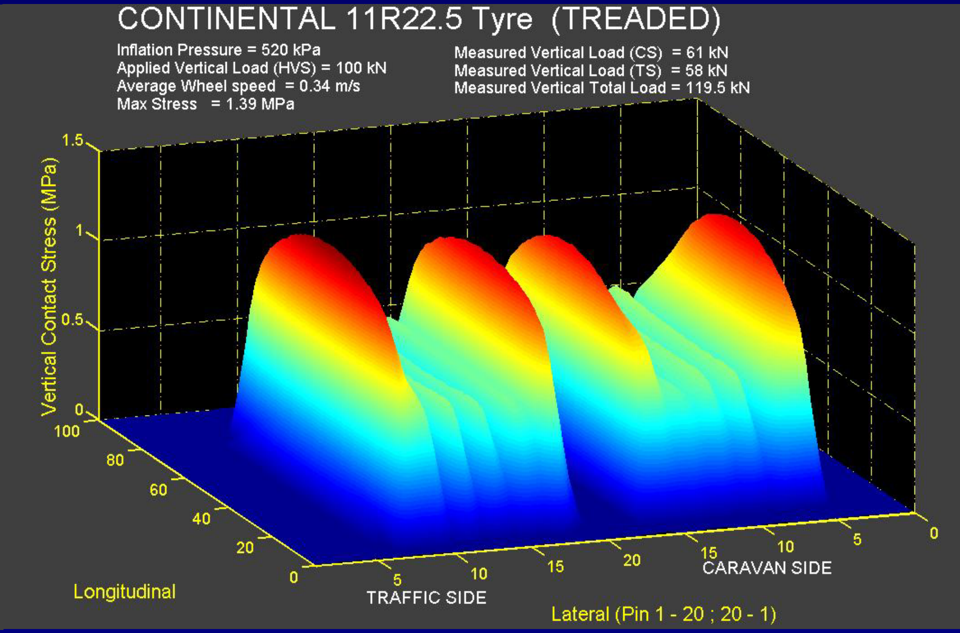


Effect of increase in load on contact stress

- Vertical stress
- 520 kPa
- 40 kN

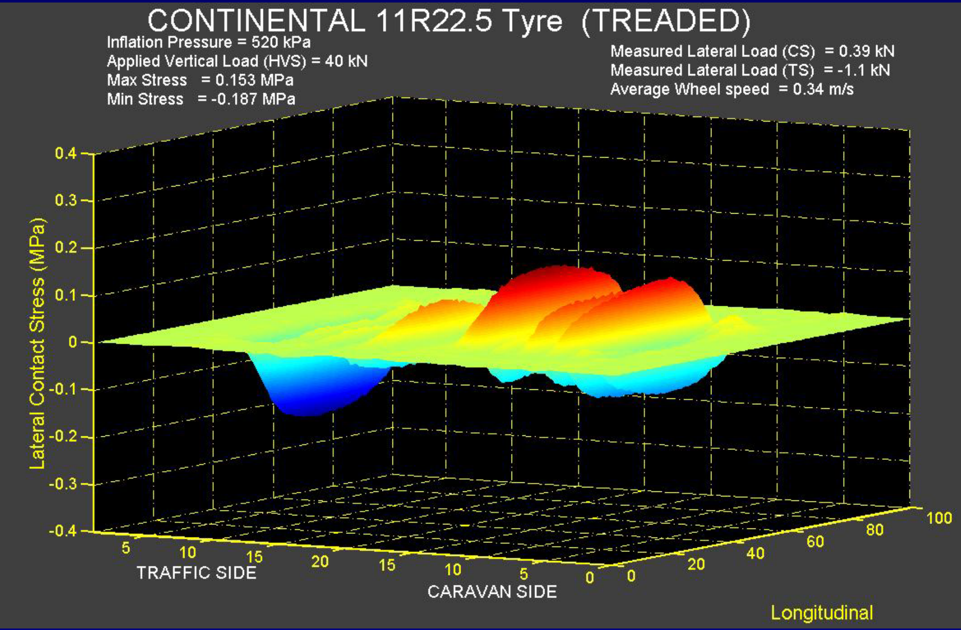
100 kN

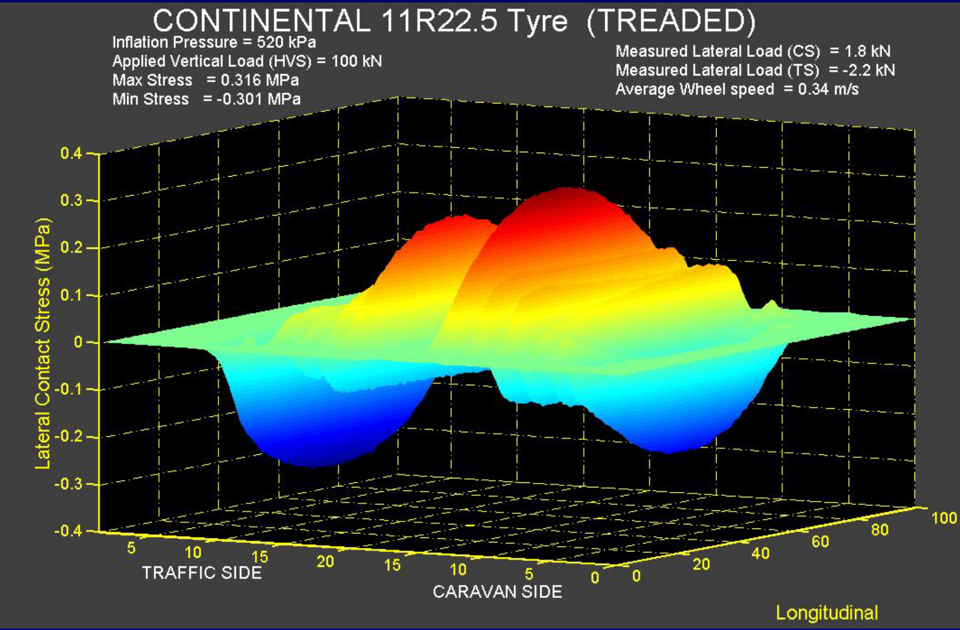




Effect of increase in load on contact stress

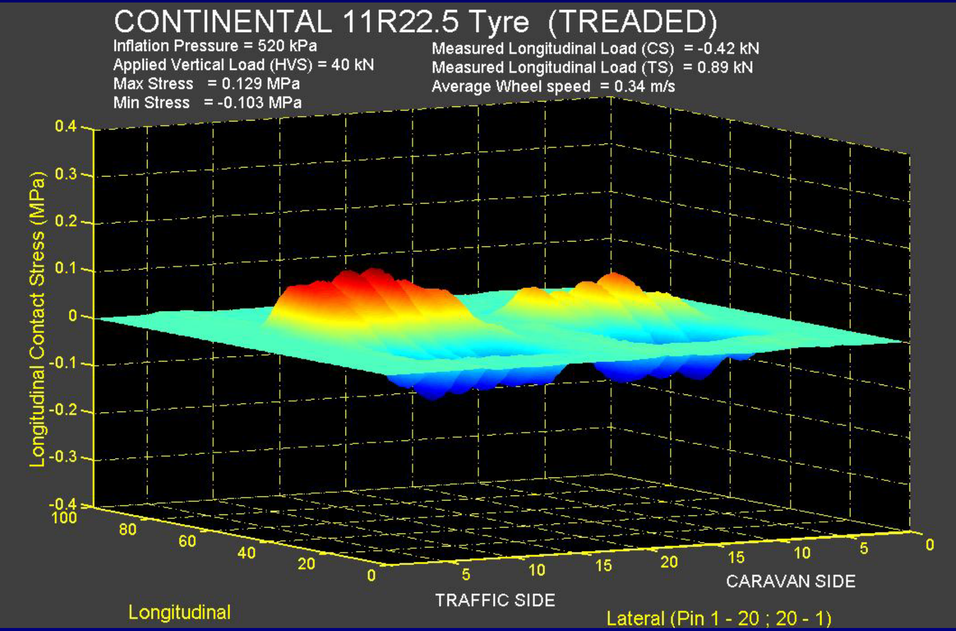
- Lateral stress
- 520 kPa
- 40 kN 100 kN

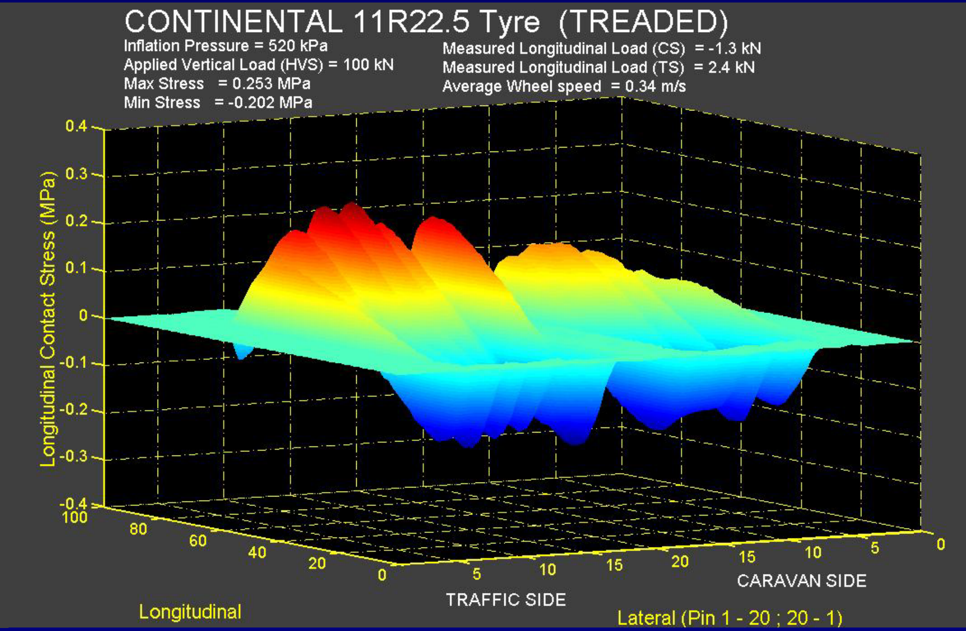




Effect of increase in load on contact stress

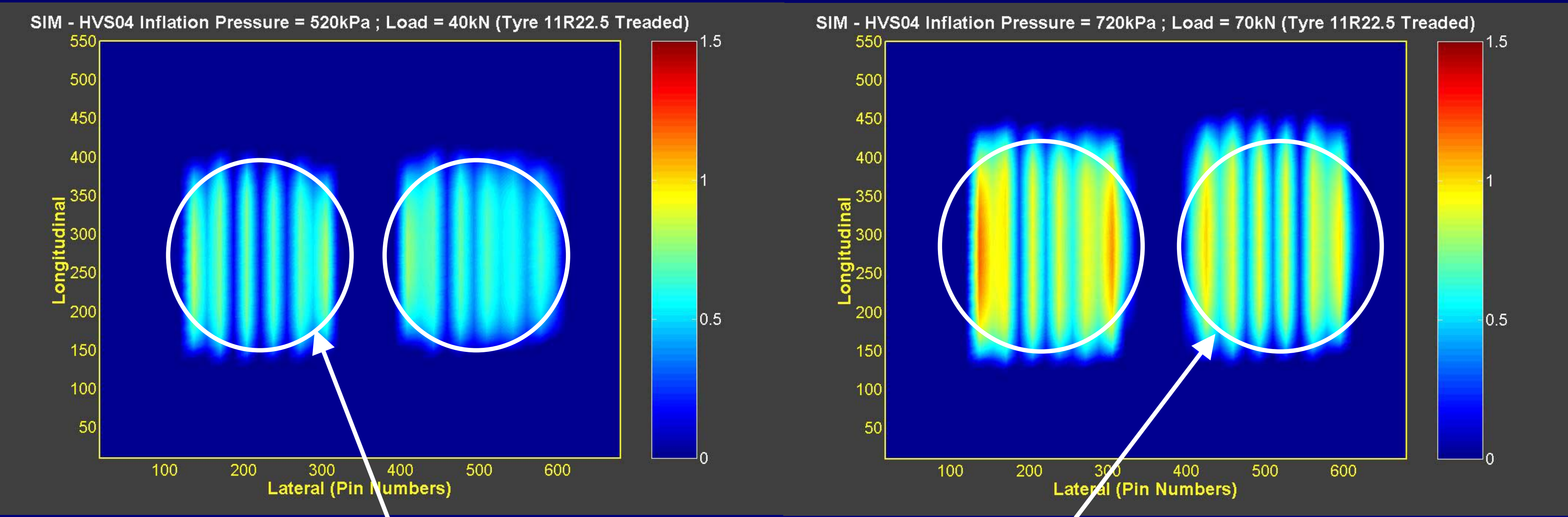
- Longitudinal stress
- 520 kPa
- 40 kN 100 kN





Effect of increase in load on contact area

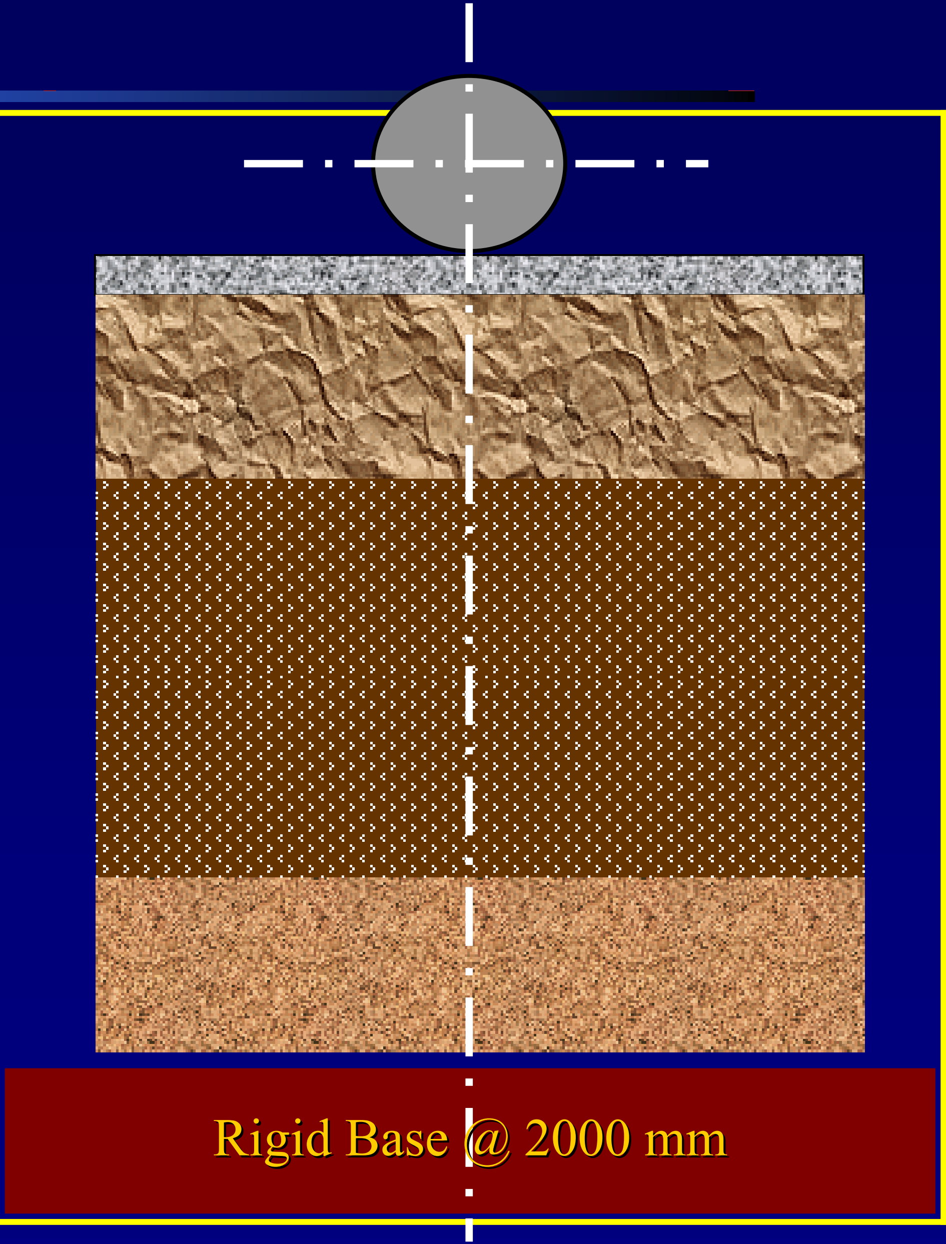
- 520 kPa
- 40 kN   100 kN



Current Design Assumption

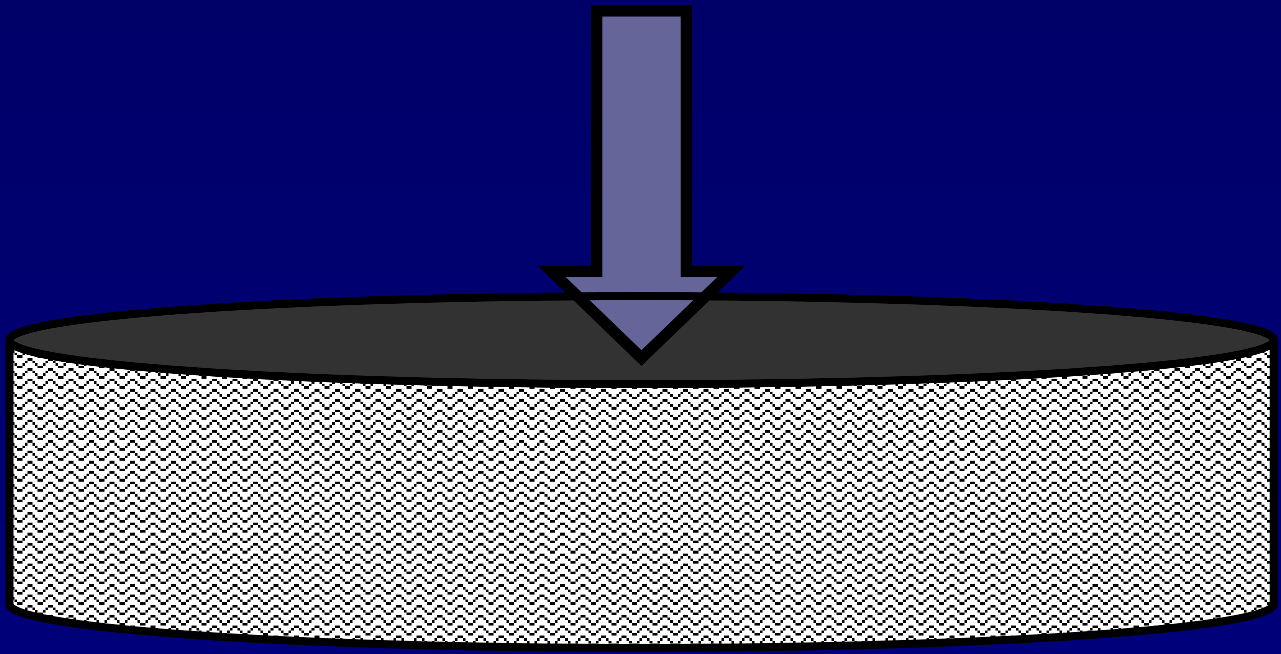
Modeled pavement structure: Linear elastic

Thin Asphalt Surfacing: 40 mm (E_1 = 5000 MPa, 1000, 200, ν_1= 0.44); (C = 2000 kPa, Φ = 43 deg, Yield = 1462 kPa, 585 kPa, 117 kPa)	
Crushed Stone Base: 150 mm (E_2 = 350 MPa, ν_2 = 0.35)	
Cementitious Subbase-1: 150 mm (E_3 = 1500 MPa, ν_3 = 0.35)	
Cementitious Subbase-2: 150 mm (E_4 = 1500 MPa, ν_4 = 0.35)	
Soil Subgrade:2000 mm (E_5 = 100 MPa, ν_5 = 0.35)	



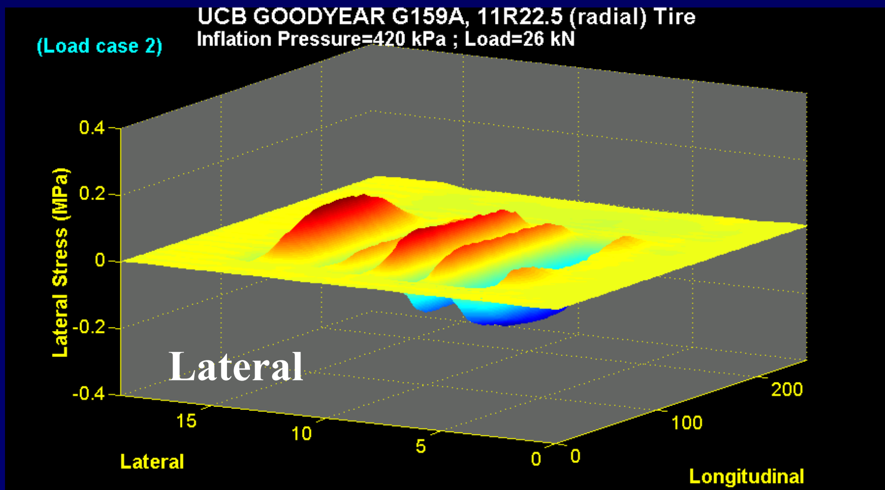
Load Case 1:
20 kN, 520 kPa

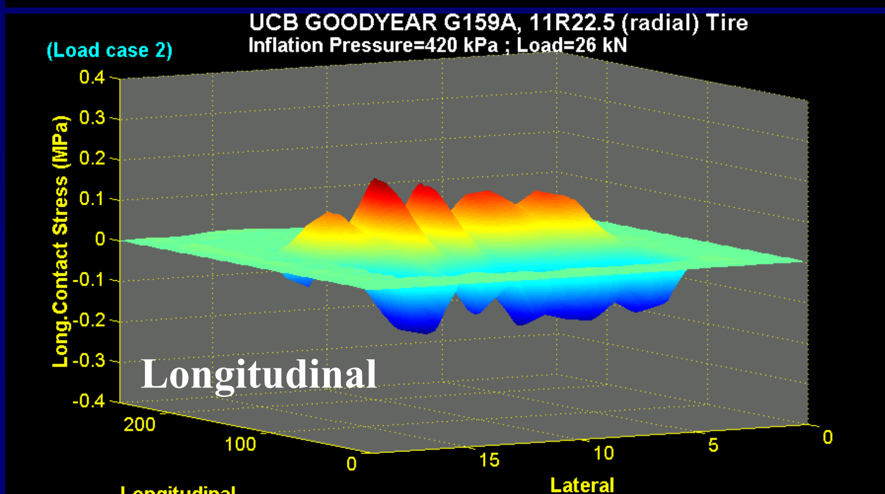
- Standard load case used for design
- Circular load

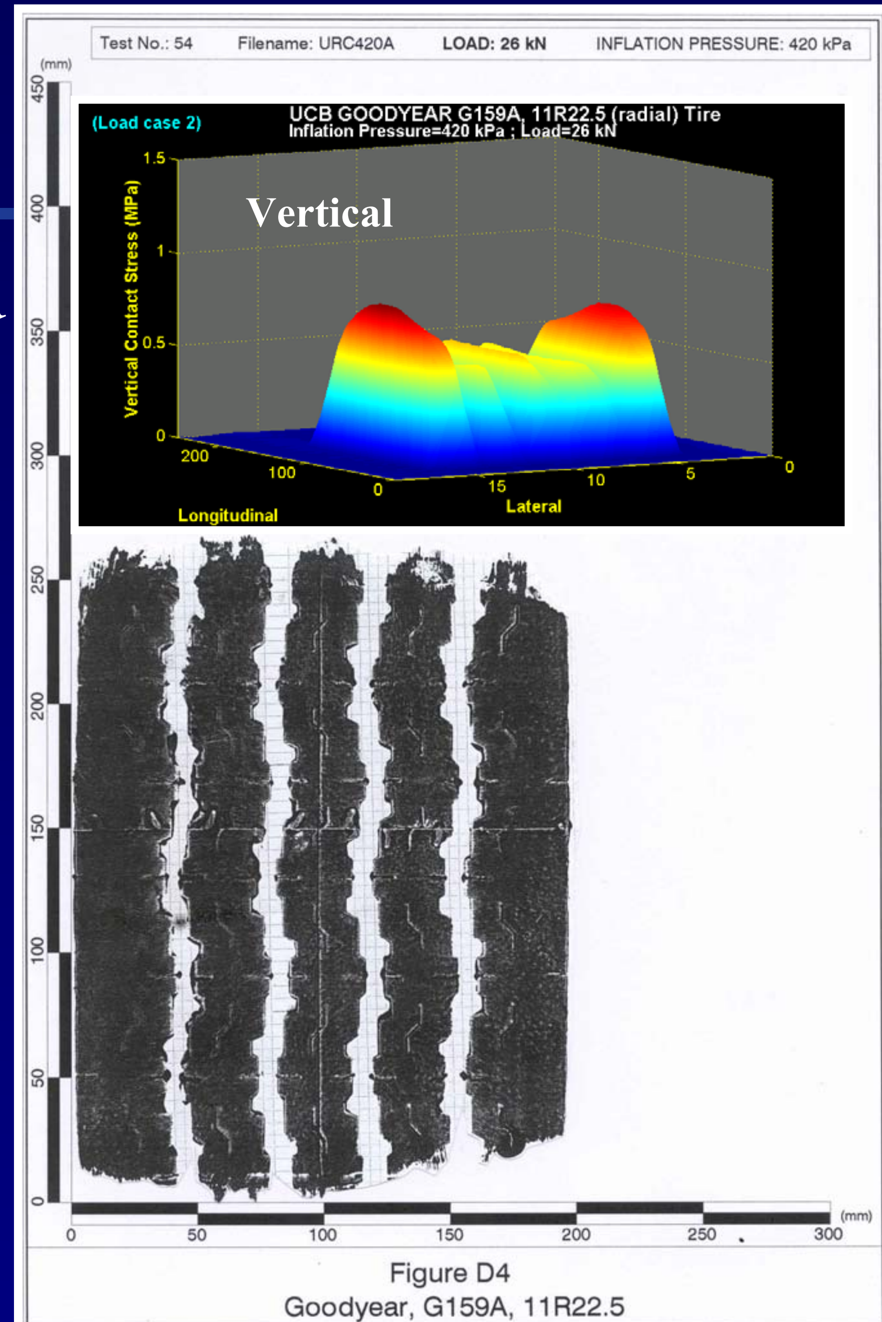


Load Case 2
26 kN, 420 kPa

- Overloaded, underinflated

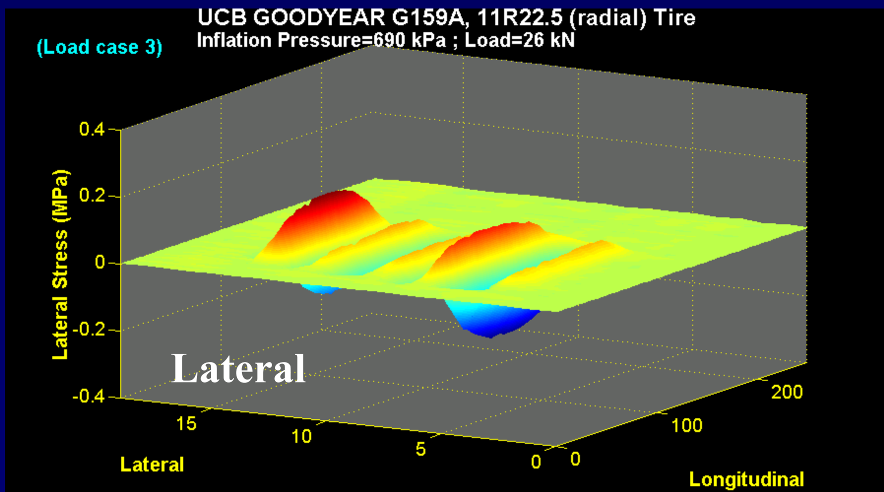


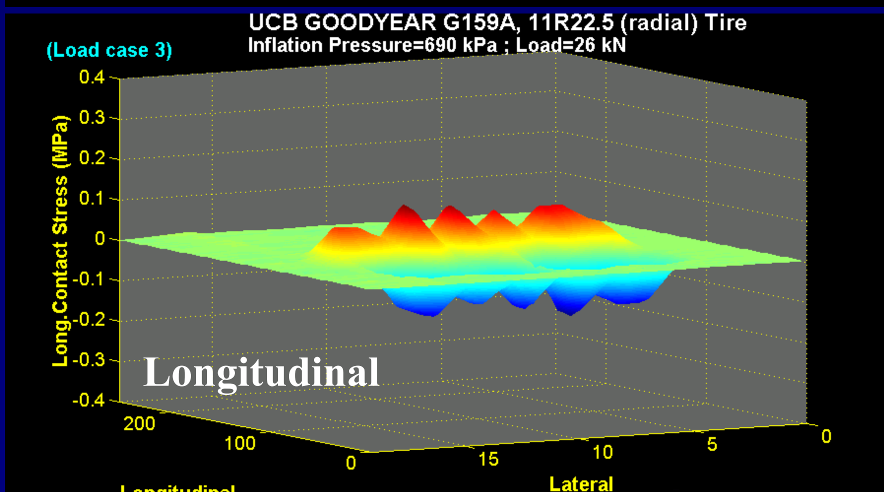




Load Case 3
26 kN, 690 kPa

- Rated load





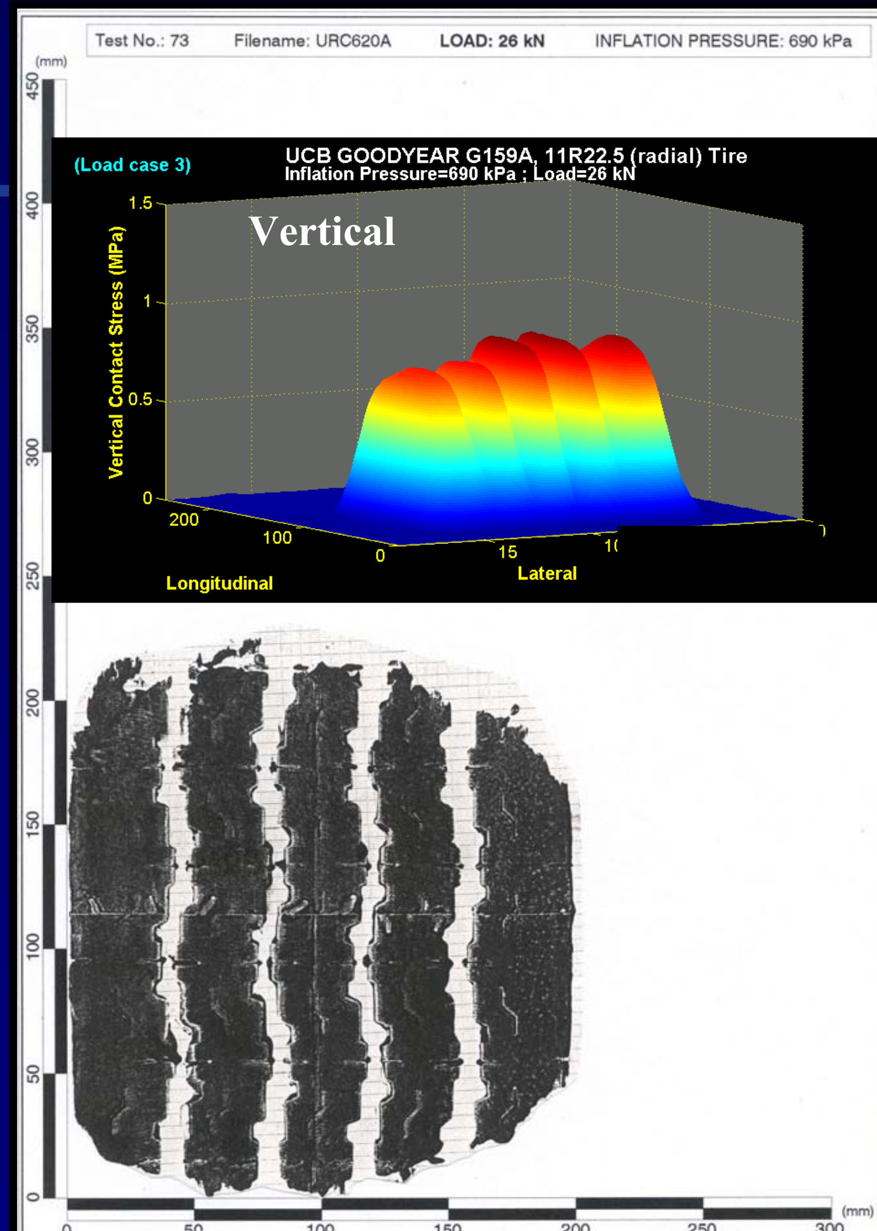
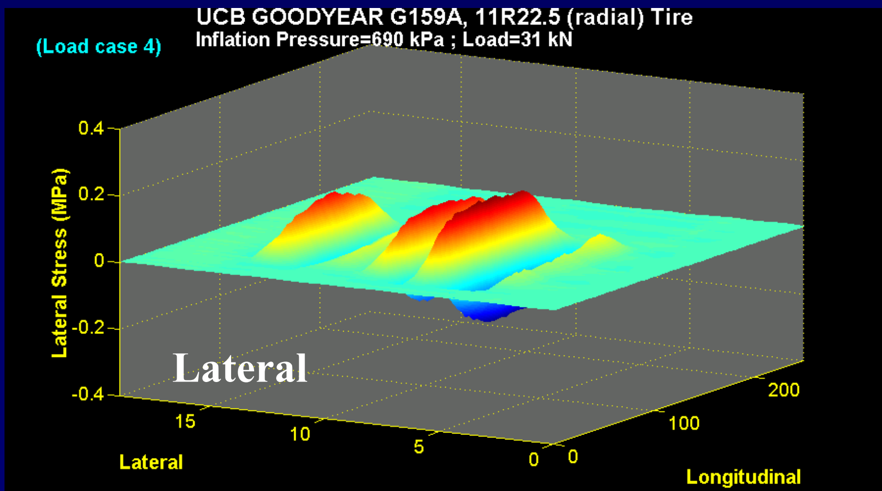
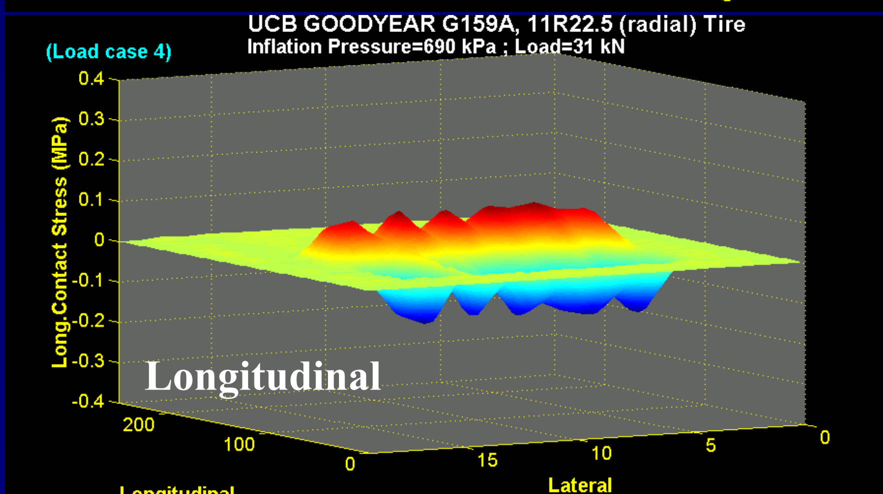


Figure D23
Goodyear, G159A, 11R22.5

Load Case 4
31 kN, 690 kPa

- Overloaded, overinflated





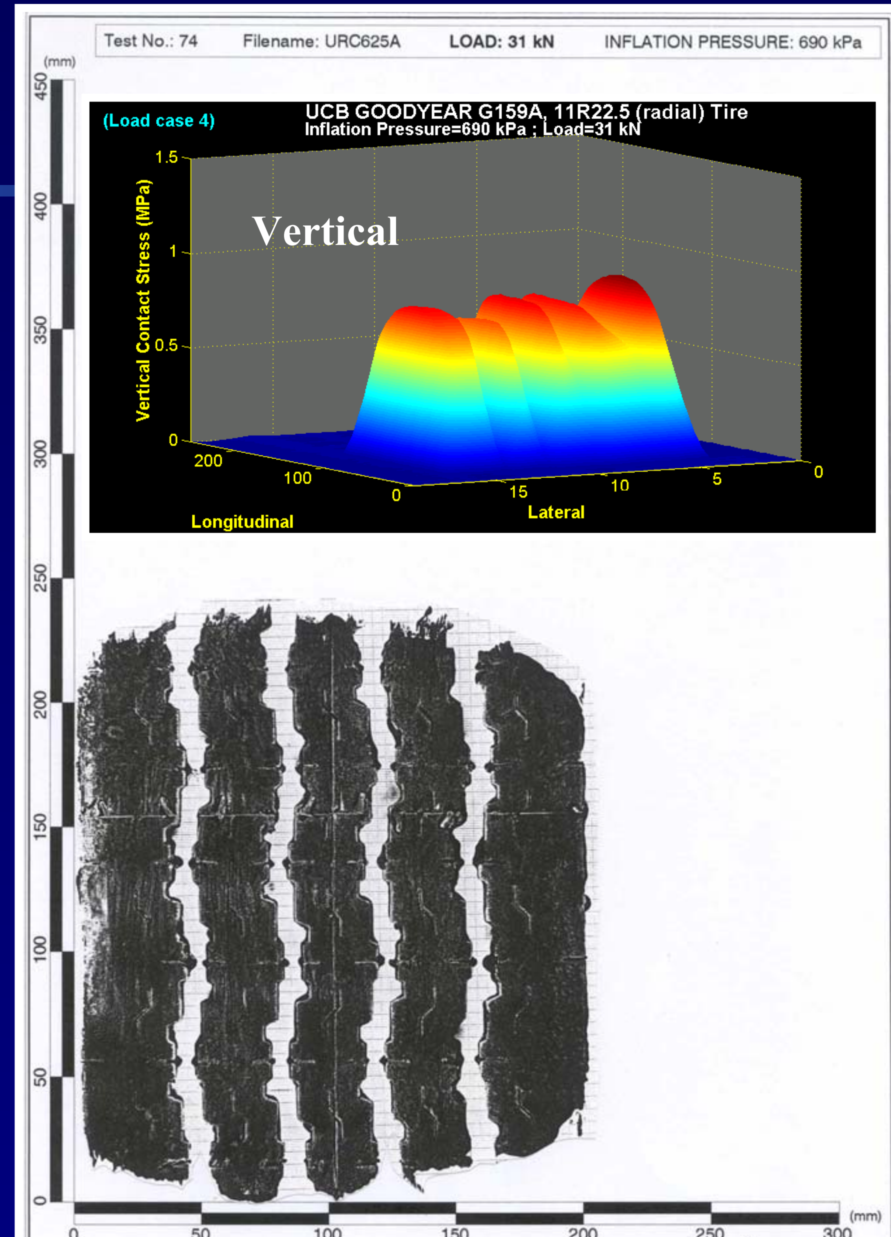
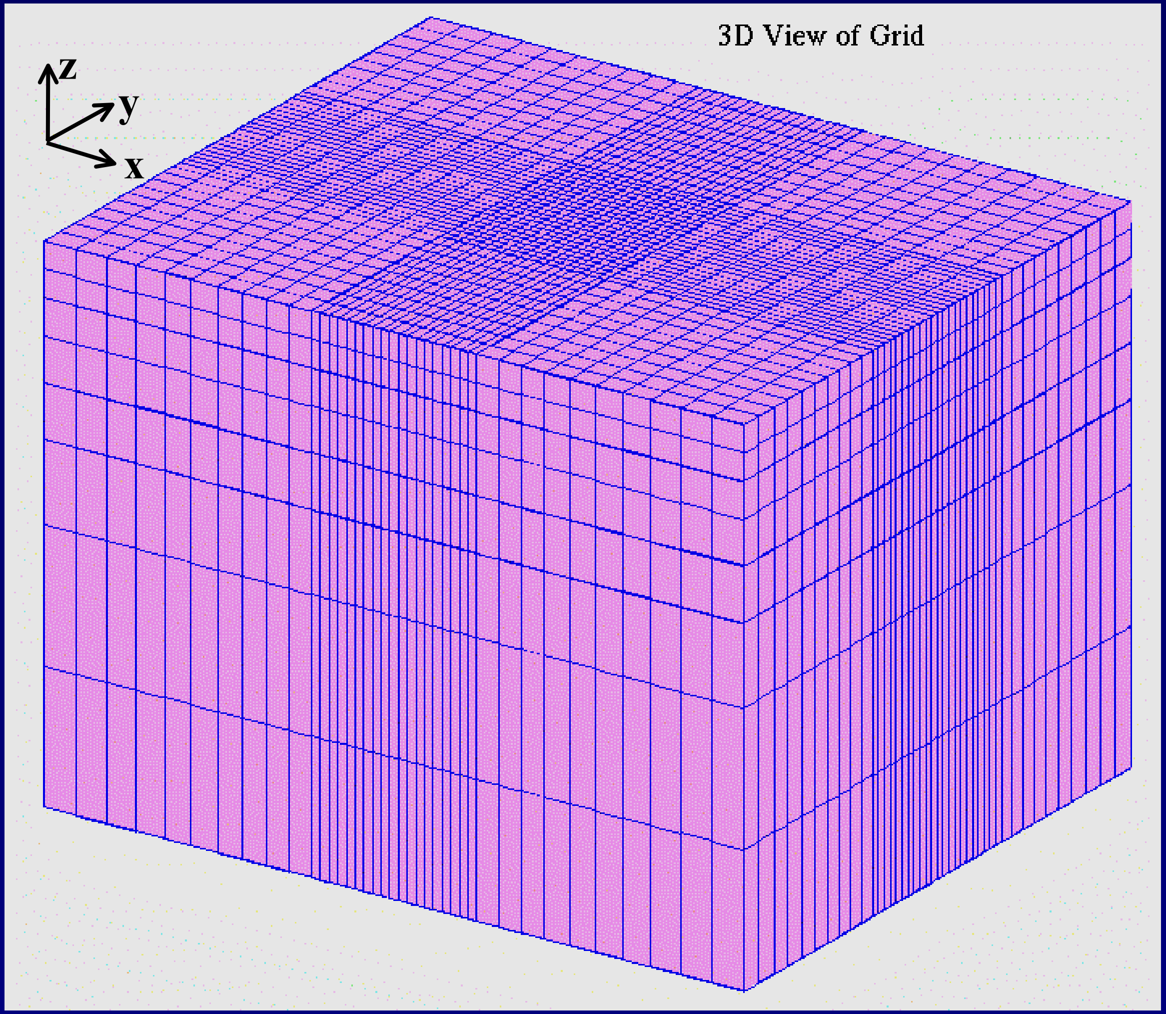


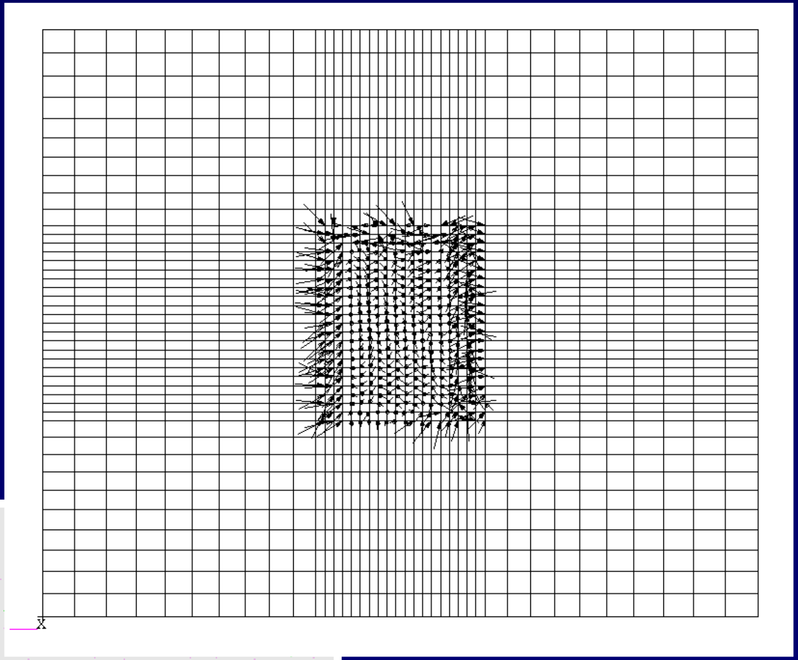
Figure D24
Goodyear, G159A, 11R22.5

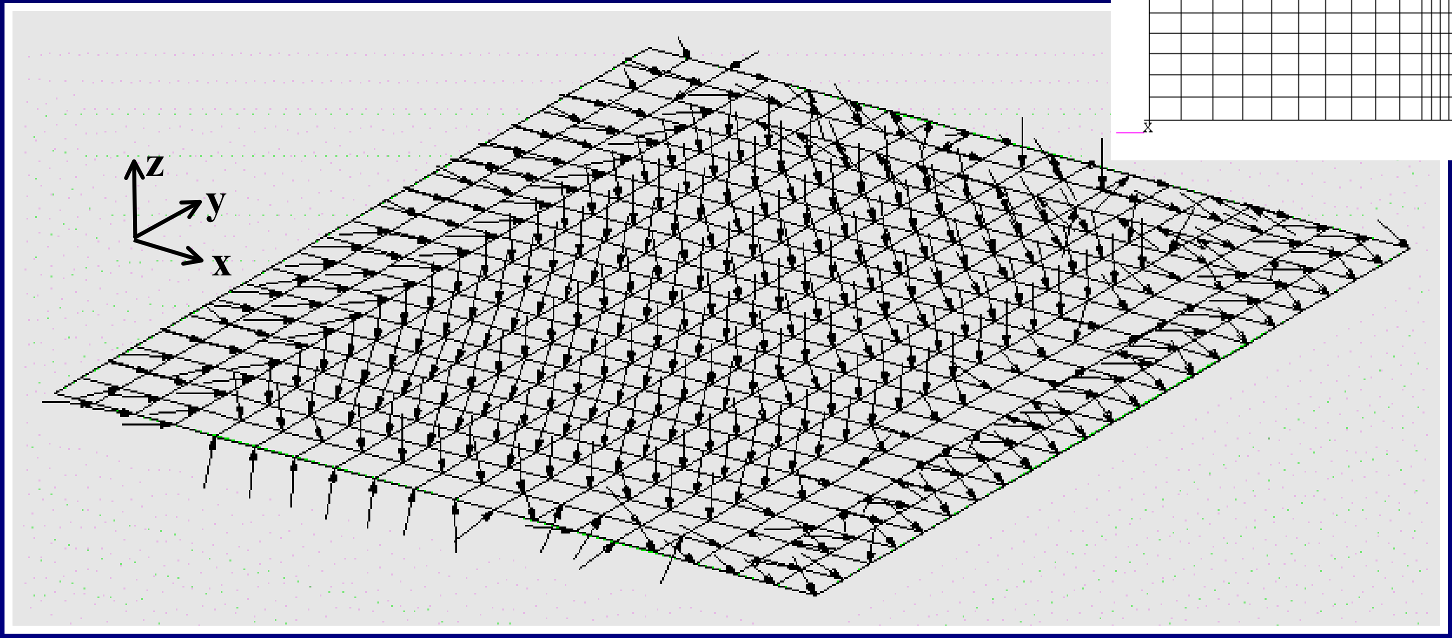
Finite element mesh



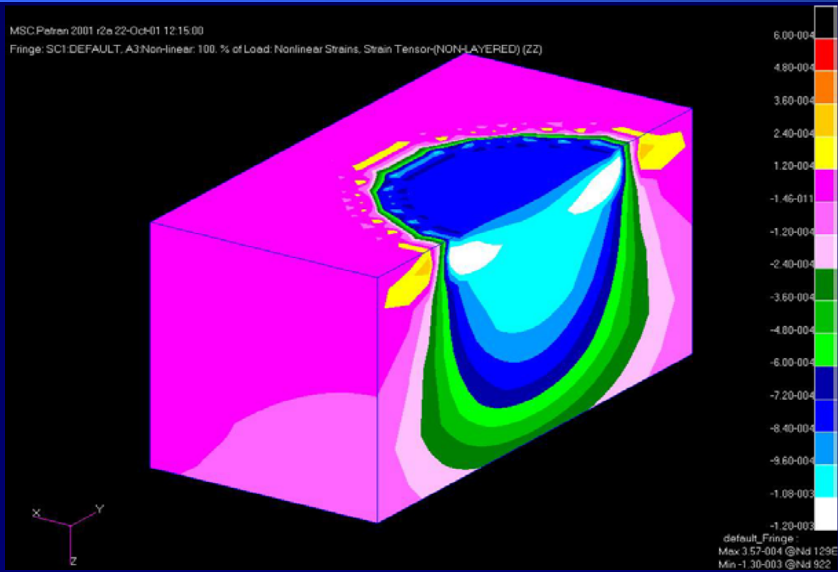
SIM Resultant forces for FEM

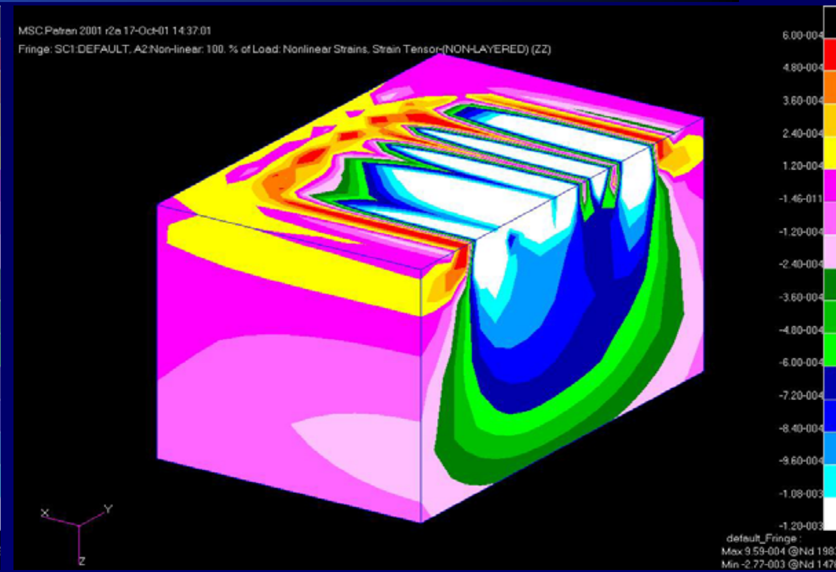
- SIM loading
  - Approximately 400 – 460 discrete forces on the nodes

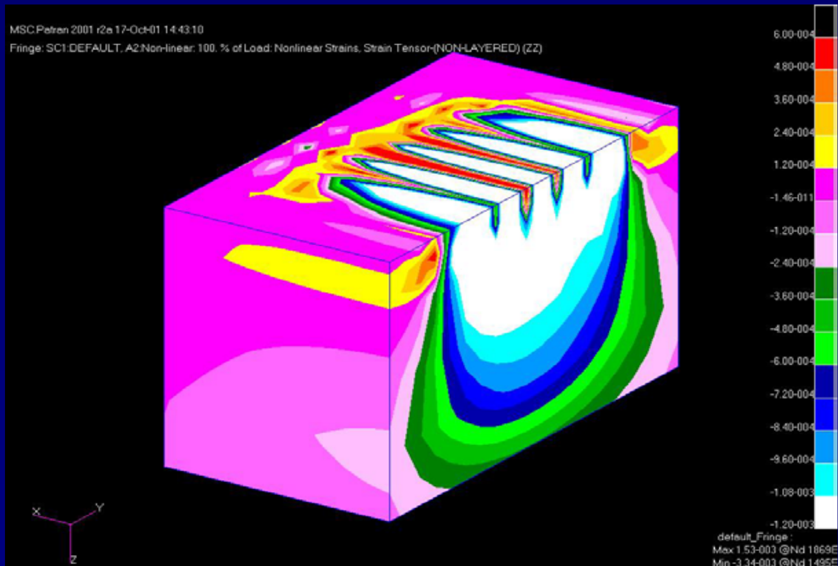


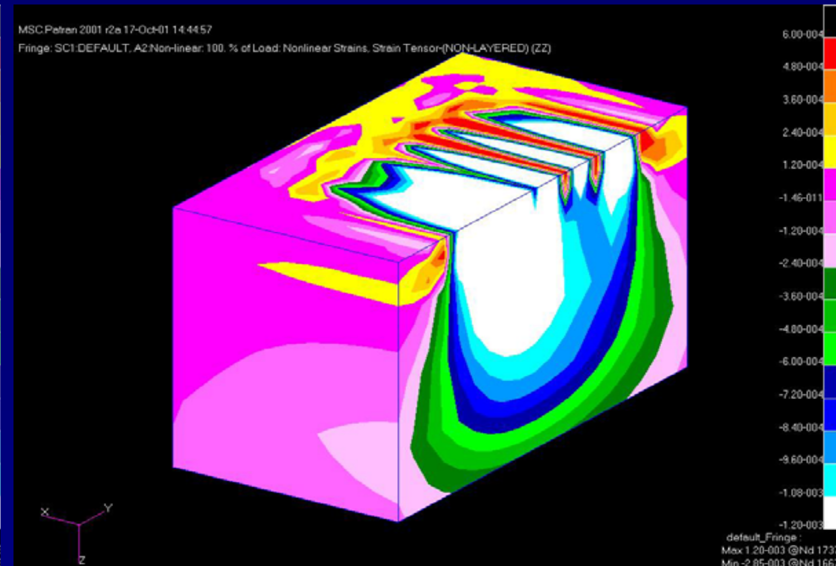


Vertical compressive strains: Hot case

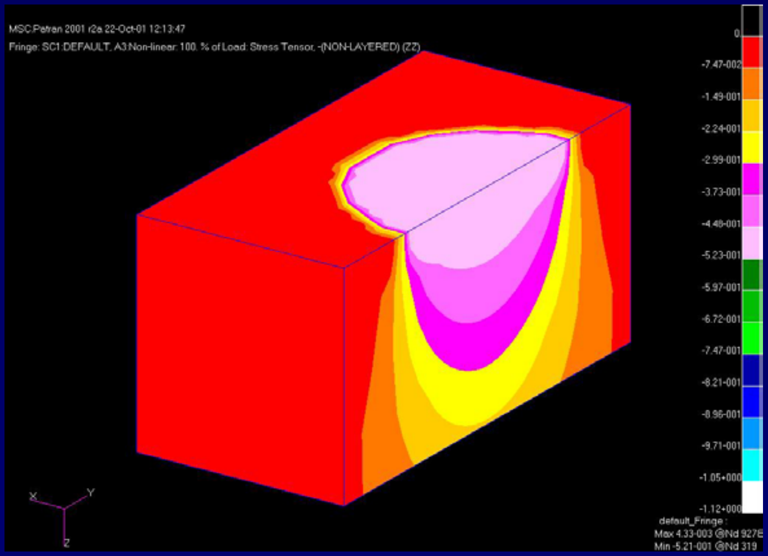


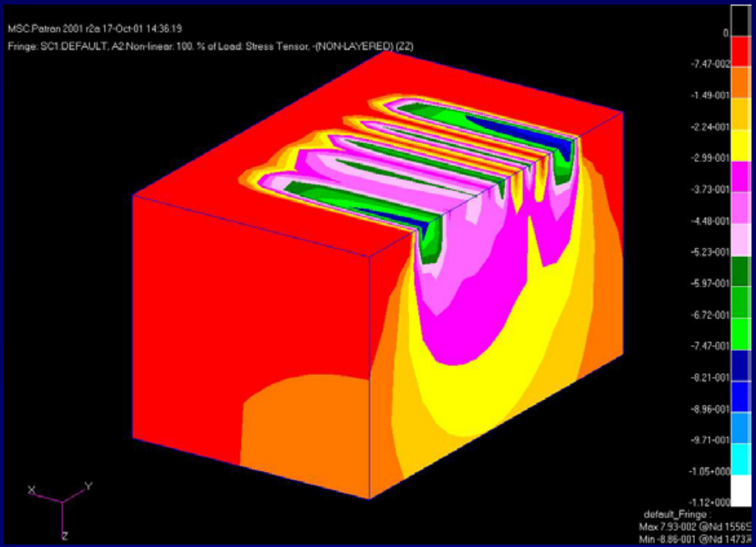


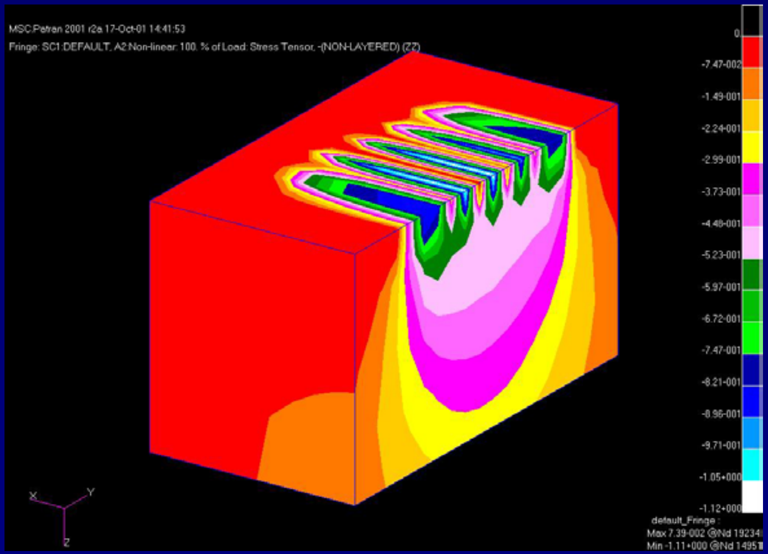


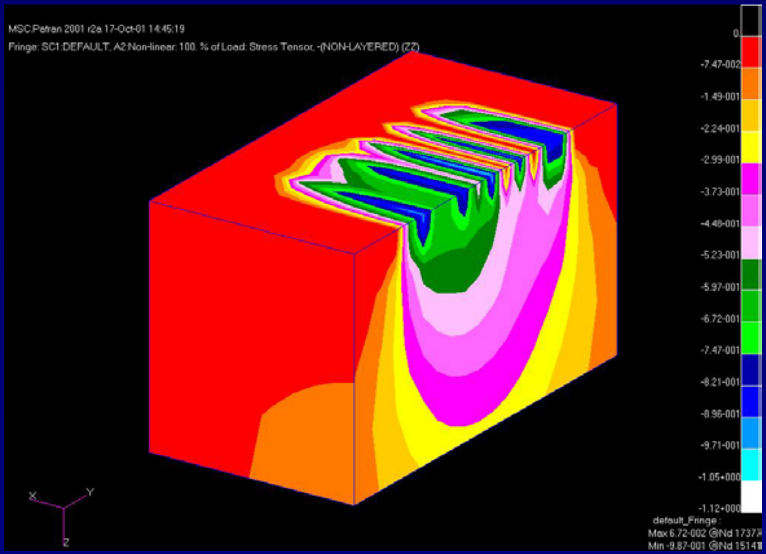


Vertical compressive stress: Hot case









SIM: Conclusions and recommendations

- Calculated stress and strain response reflects applied load
  - Shape and distribution of load are important
- More rational use of 3D tire-pavement contact stresses in the design and analyses of flexible pavements
  - Particularly for surface distress

Where are we?

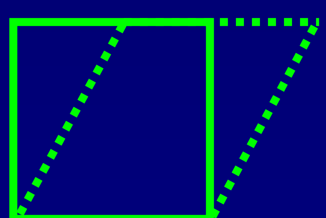
- Must use SIM in surface distress analysis
- Linear elasticity is not sufficient for rutting
  - Need a more advanced material model
- How can we use the HVS?

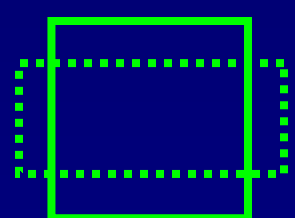
Constitutive model for asphalt concrete

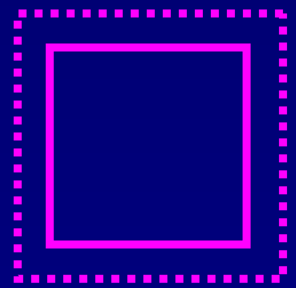
Nonlinear viscoelasticity

Nonlinear Viscoelasticity

- Nonlinearity in shear response
  - Temperature and strain dependant
- Linear viscoelastic for bulk response
  - Temperature dependant only

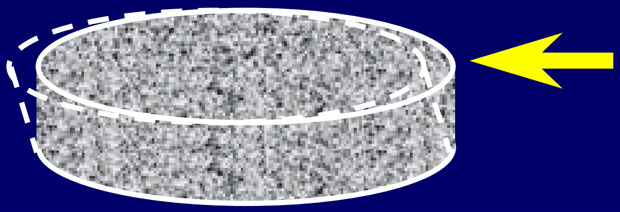




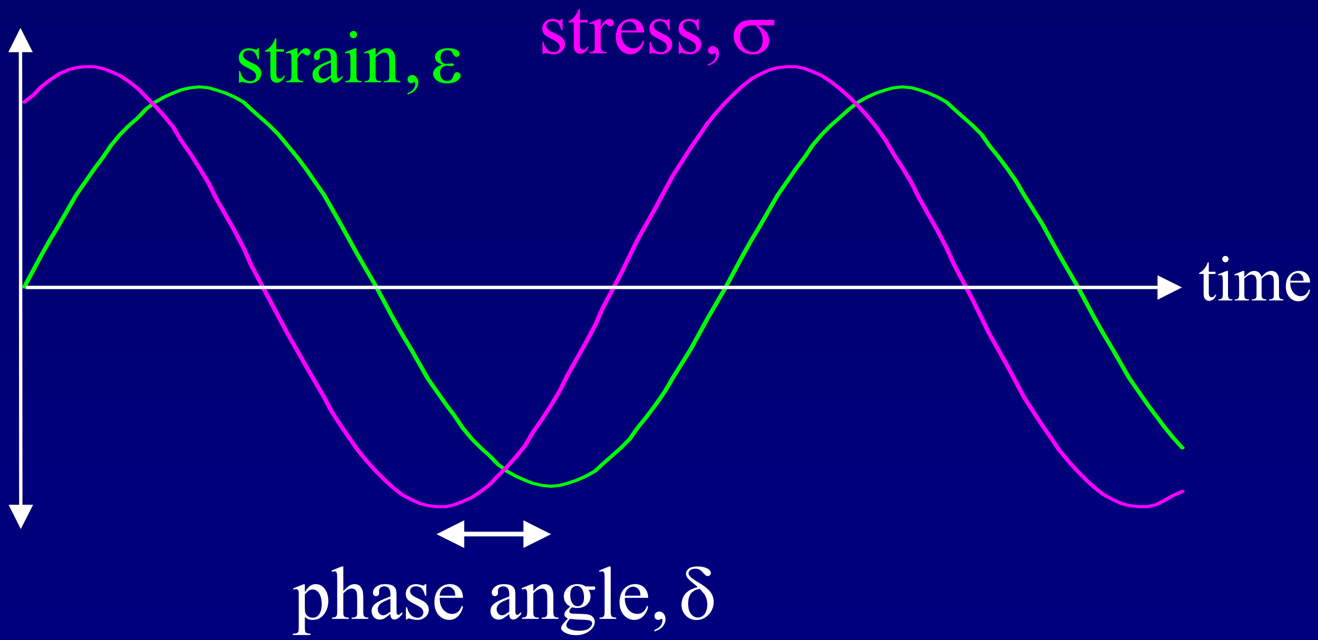


Lab testing for shear response

- Simple shear test at constant height



- Frequency sweep tests



$$G' = \frac{\sigma}{\varepsilon}\cos\delta$$

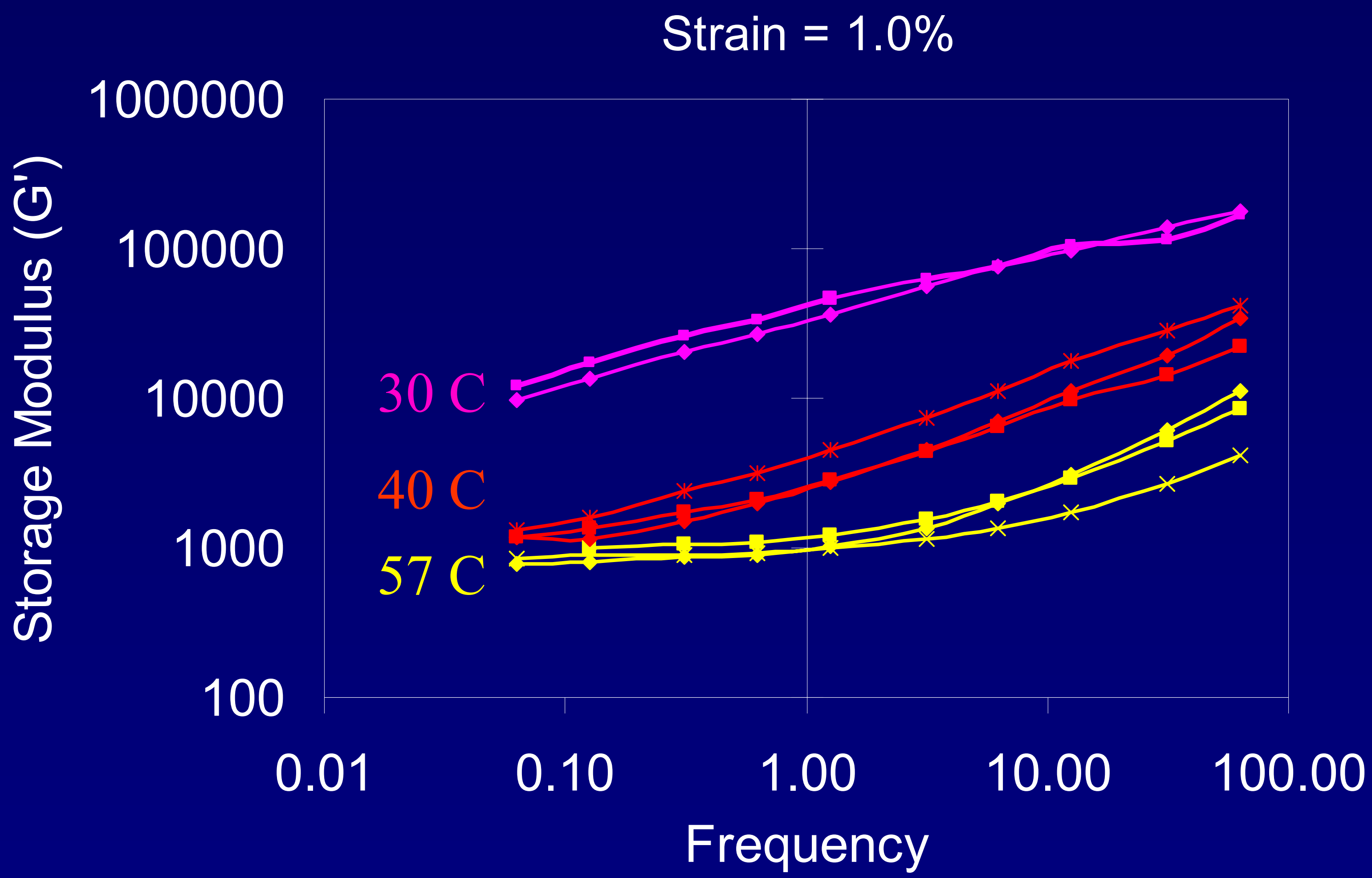
$$G'' = \frac{\sigma}{\varepsilon}\sin\delta$$

Laboratory testing

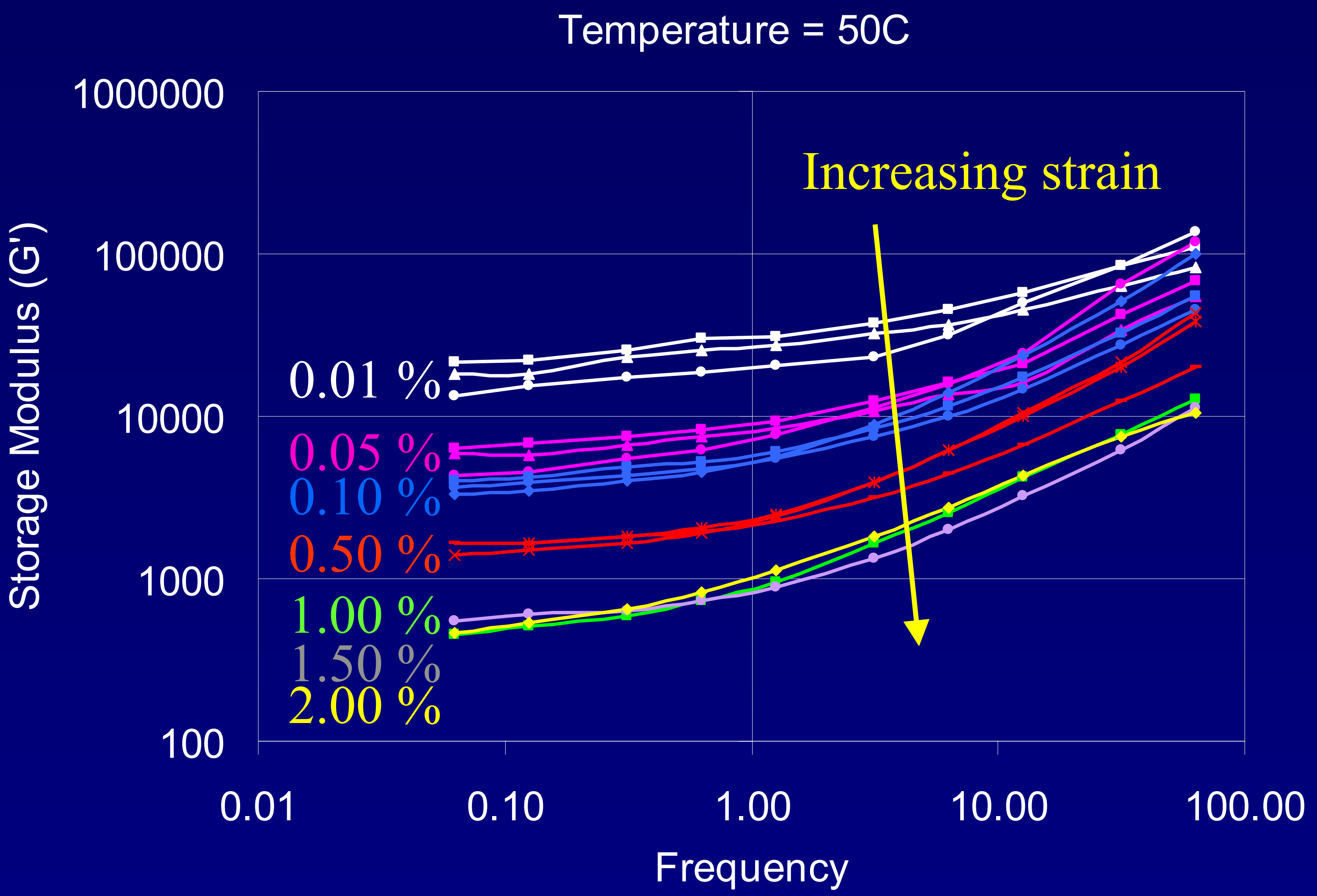
- Specimens cored from UC Berkeley HVS test pavement
  - Dense graded asphalt concrete – conventional binder
  - Asphalt rubber hot mix – gap graded
- Test Matrix

Temperature (°C)	Peak Strain Level (%) 0.01	0.05	0.10	0.50	1.00	1.50	2.00
20	X	X	X				
30	X	X	X	X	X		
40	X	X	X	X	X	X	
50	X	X	X	X	X	X	X
57/60	X	X	X	X	X	X	X

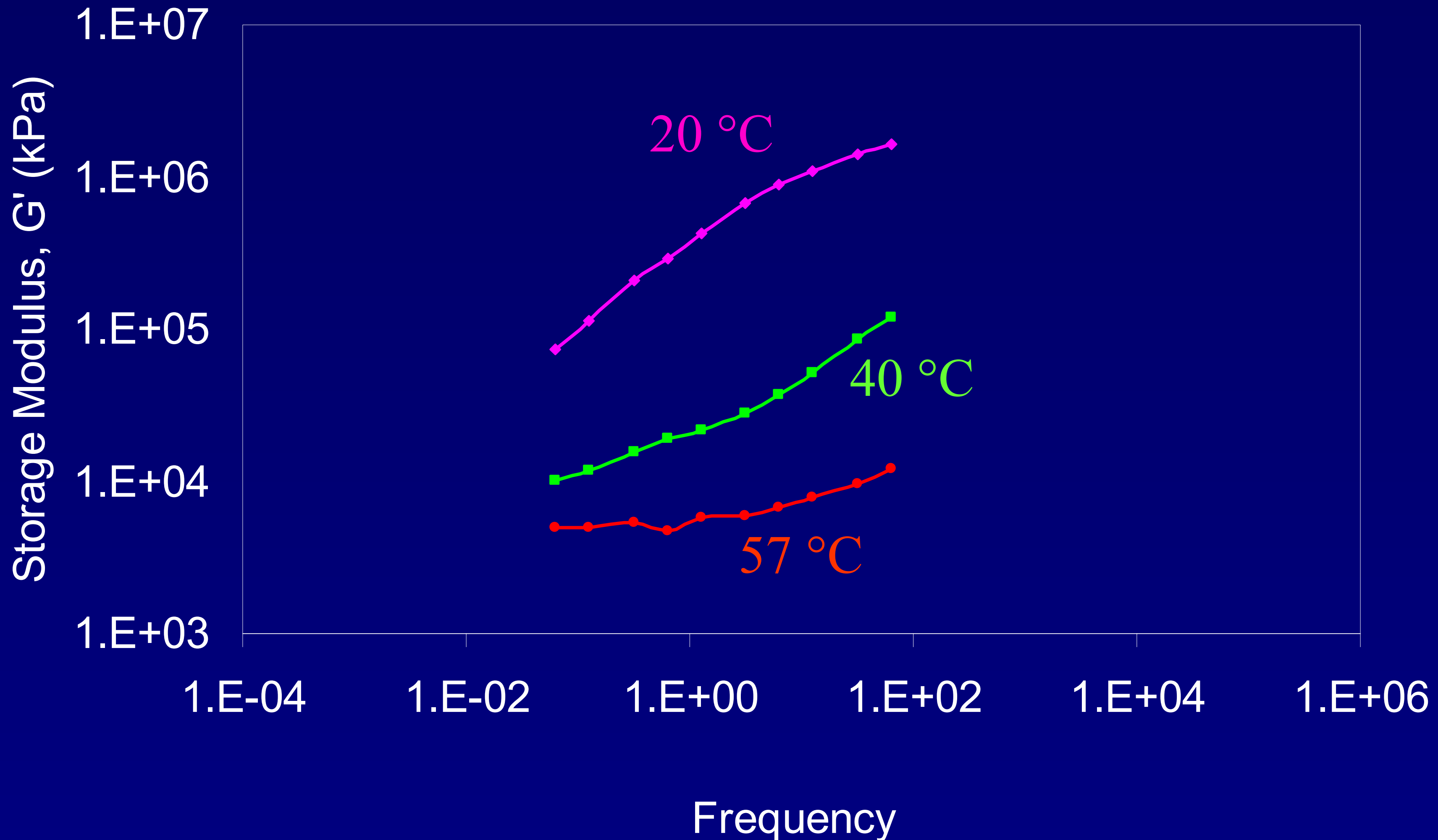
Laboratory test results



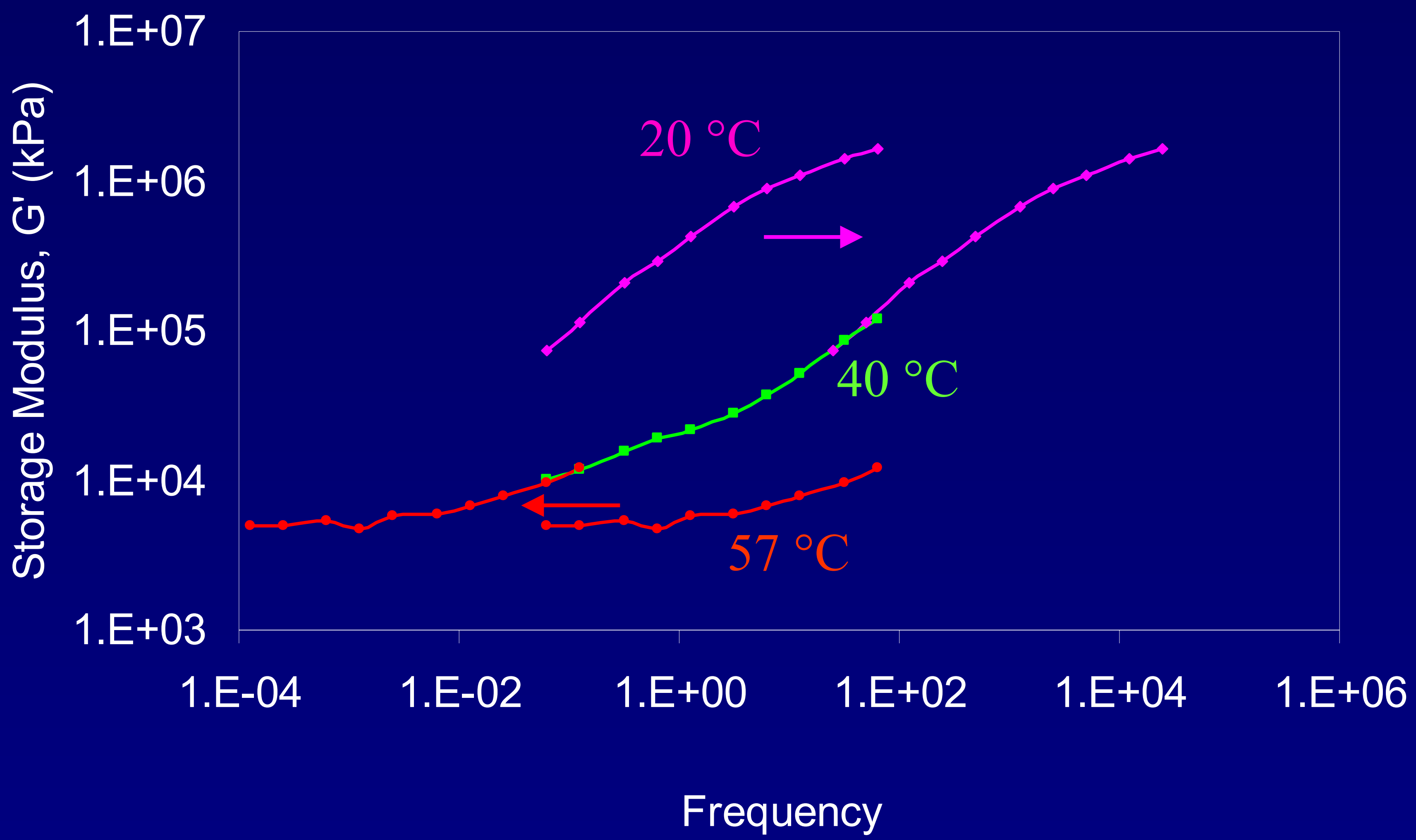
Laboratory test results



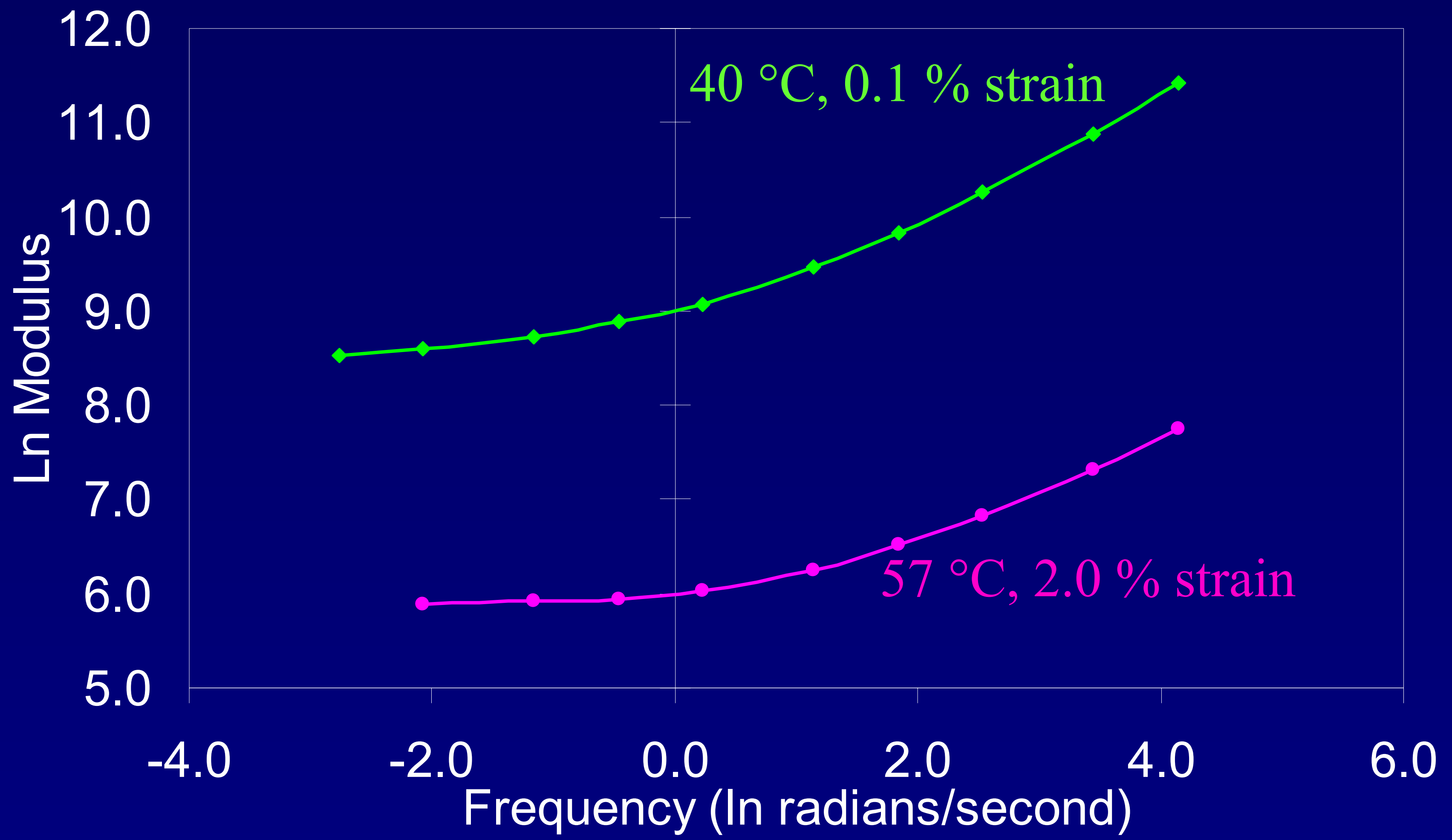
Time-temperature-superposition



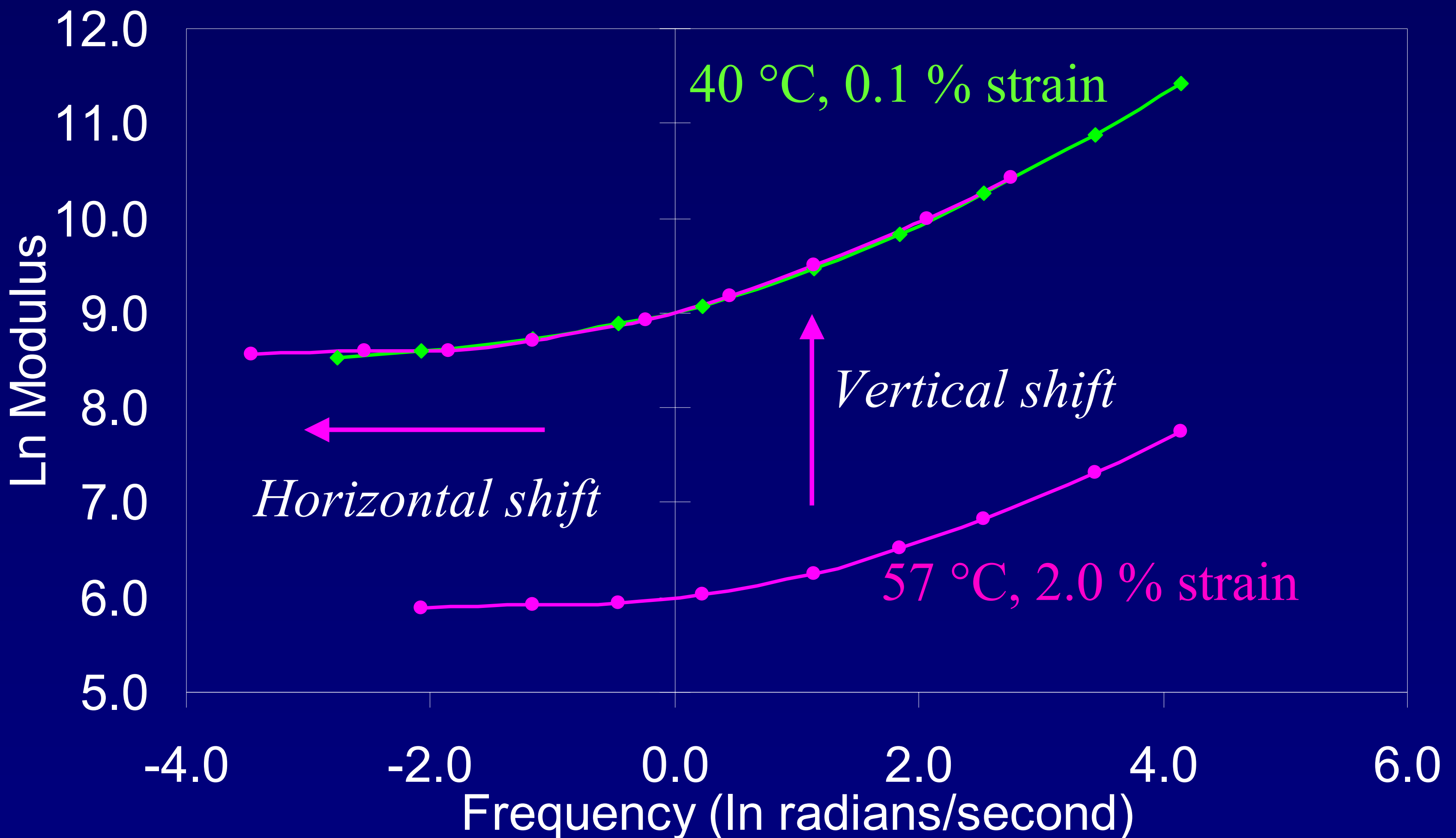
Time-temperature-superposition



Time-temperature-srain superposition

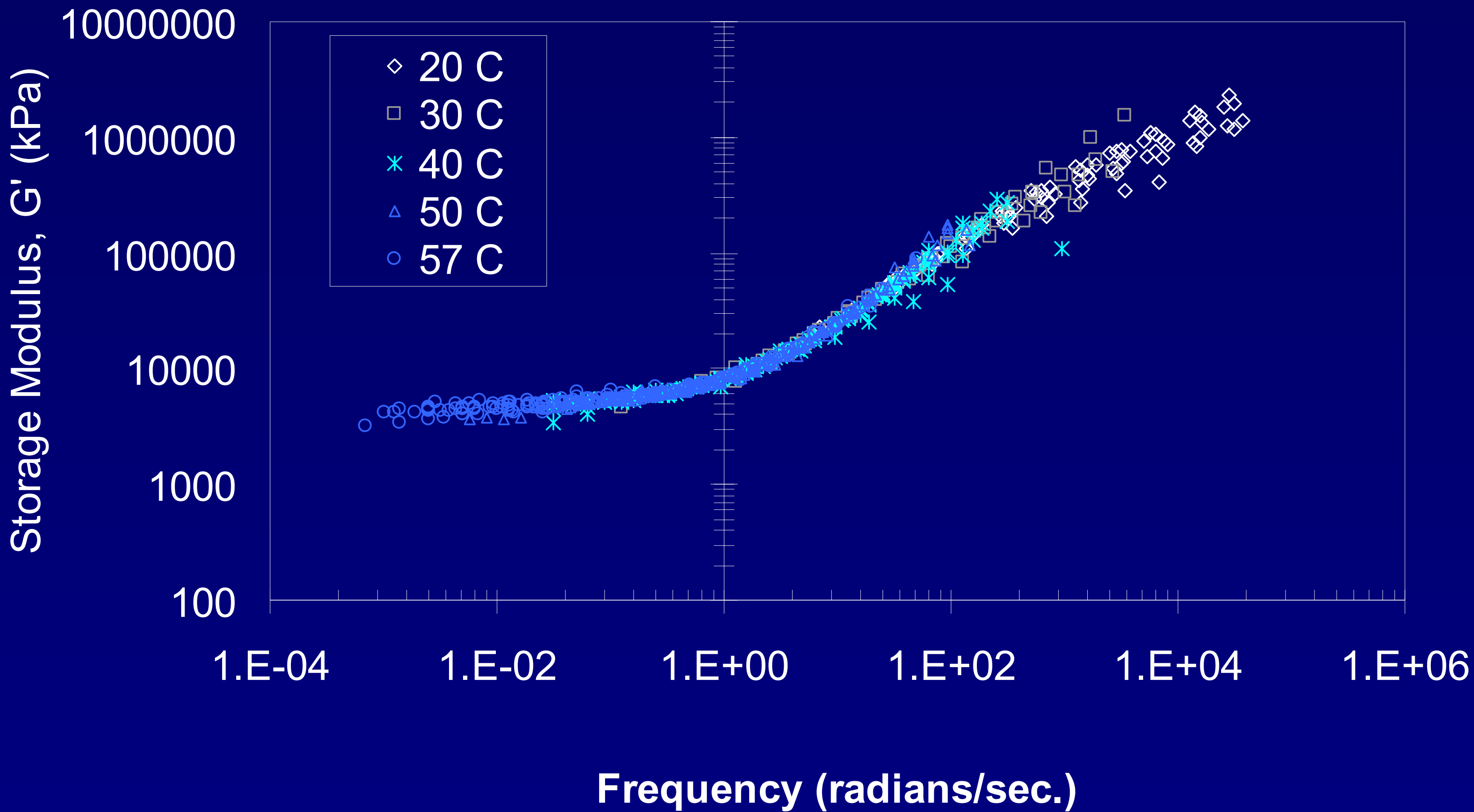


Time-temperature-strain superposition

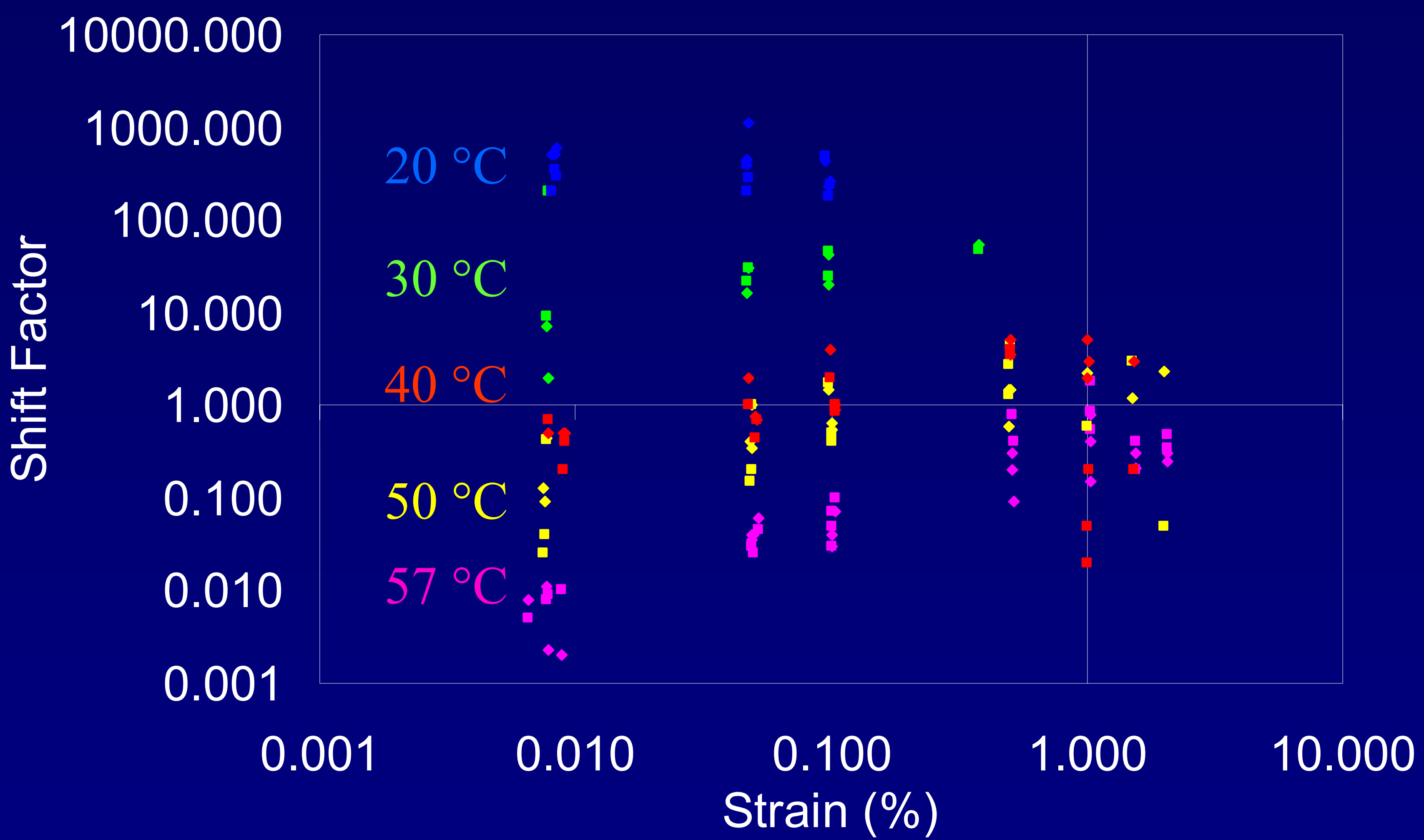


Reduced master curves

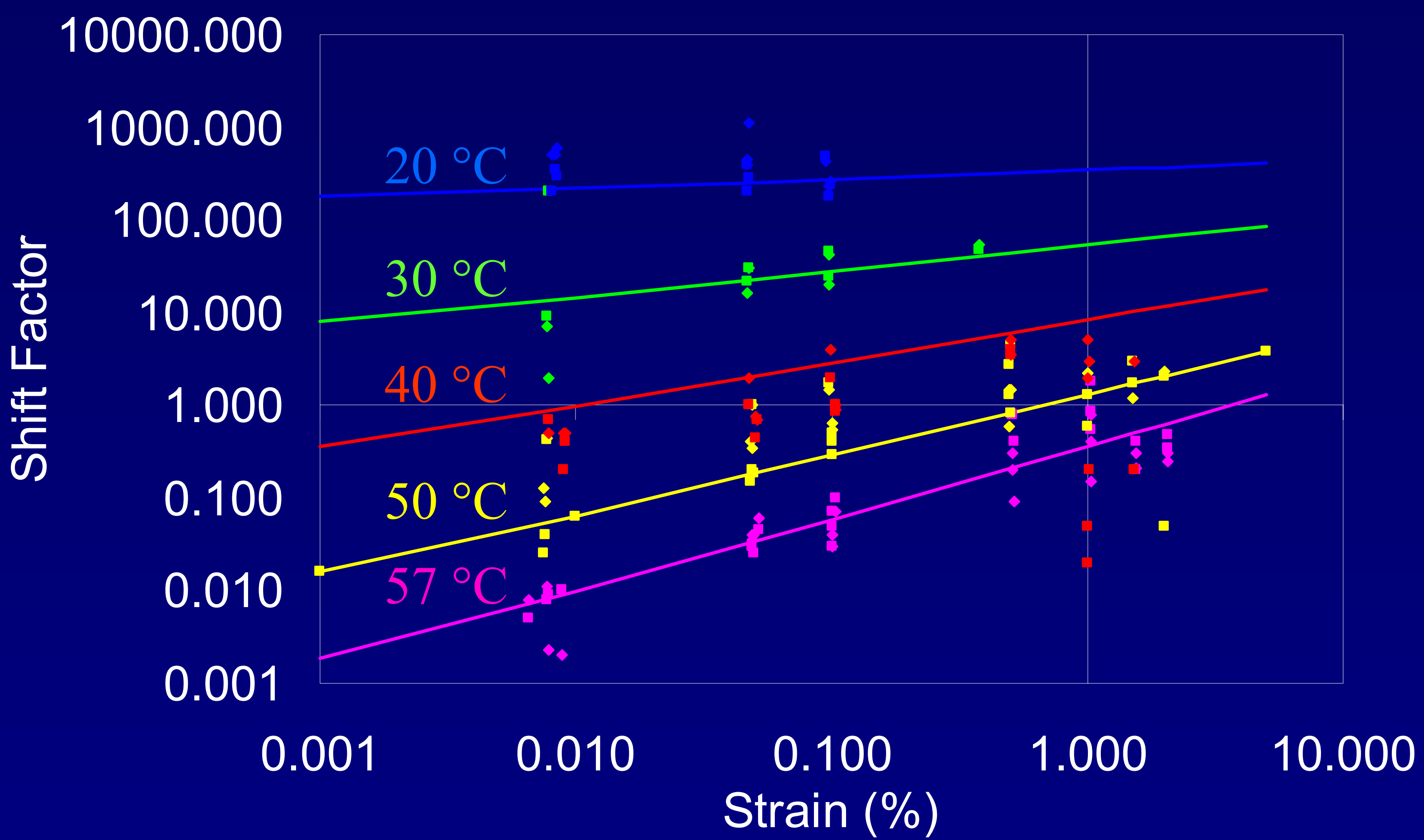
- 40 °C, 0.1 percent strain



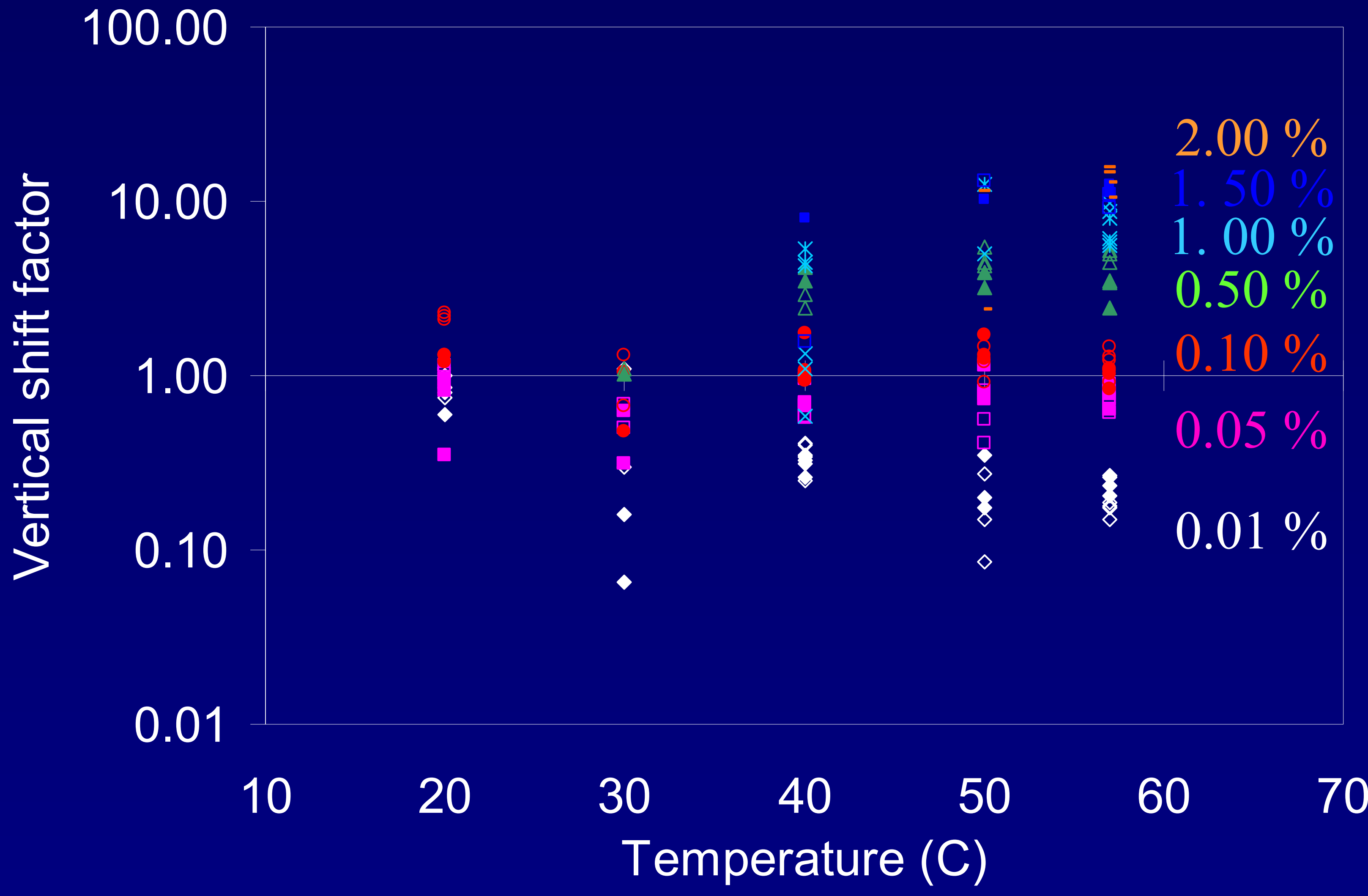
Horizontal shift factors



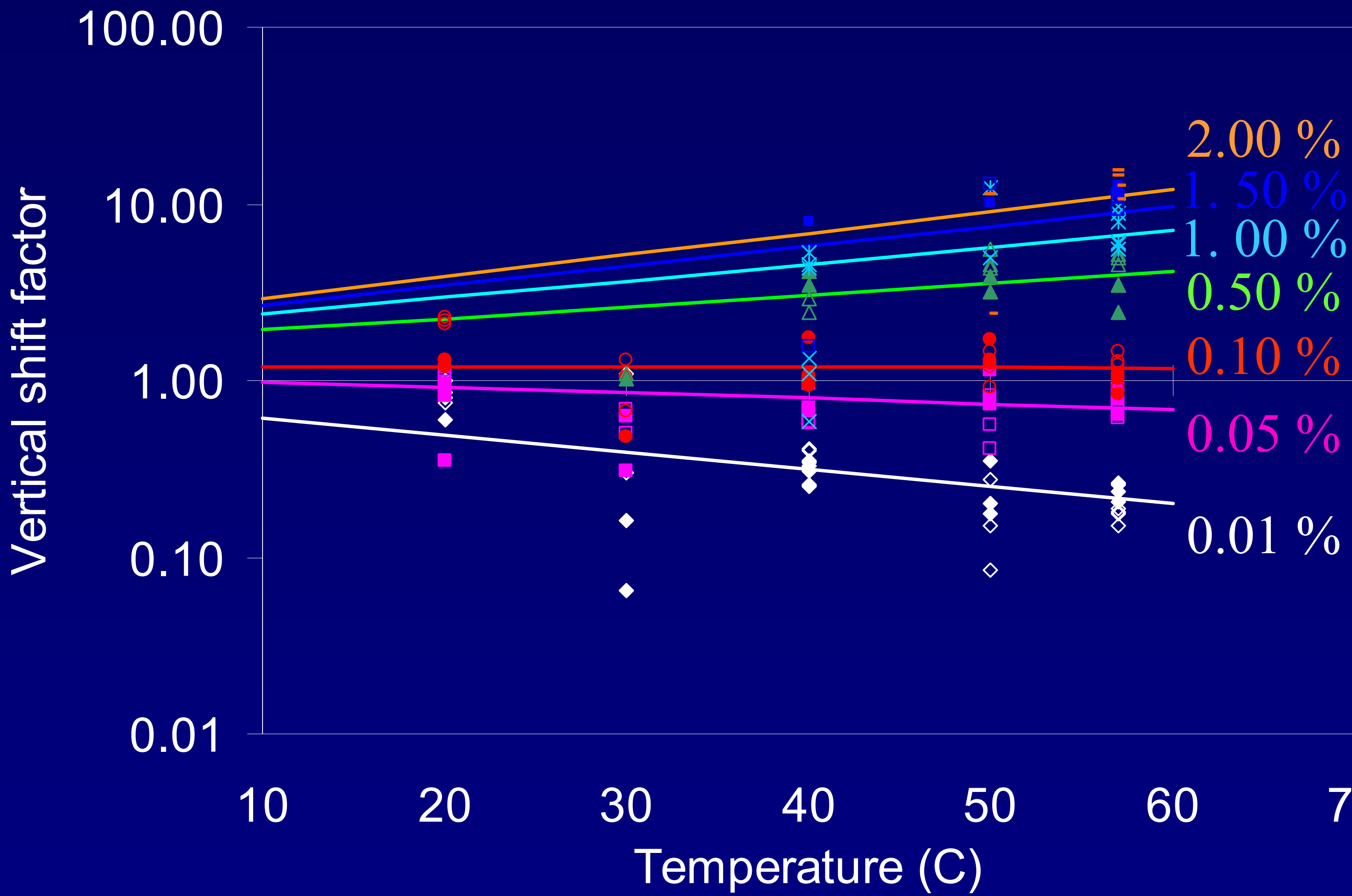
Horizontal shift factors



Vertical shift factors



Shift factors



Shift factor functions

- Shift factor = 1 for reference conditions
  - 40 °C and 0.1% strain
- Temperature term

$$\left(T - T_{ref}\right)$$

- Strain term

$$\log\left(\frac{x + \|\mathbf{e}\|}{x + \|\mathbf{e}_{ref}\|}\right)$$

$$\mathbf{e} = \text{deviatoric strain}$$

Shift factor functions

- Horizontal shift factor function

$$\log a_H = 0.4602 - 0.0989\left(T - T_{ref}\right) + 0.4731\left(\log\frac{10^{-6} + \|\mathbf{e}\|}{10^{-6} + \|\mathbf{e}_{ref}\|}\right) + 0.0187\left(T - T_{ref}\right)\left(\frac{10^{-6} + \|\mathbf{e}\|}{10^{-6} + \|\mathbf{e}_{ref}\|}\right)$$

- Vertical shift factor function

$$\log a_V = 0.0859 + 0.5848\left(\log\frac{10^{-6} + \|\mathbf{e}\|}{10^{-6} + \|\mathbf{e}_{ref}\|}\right) + 0.0097\left(T - T_{ref}\right)\left(\log\frac{10^{-6} + \|\mathbf{e}\|}{10^{-6} + \|\mathbf{e}_{ref}\|}\right)$$

Where:

$\|\mathbf{e}\|$ = norm of the deviatoric strain

$\|\mathbf{e}_{ref}\|$ = norm of the deviatoric reference strain

T = temperature

T_{ref} = reference temperature

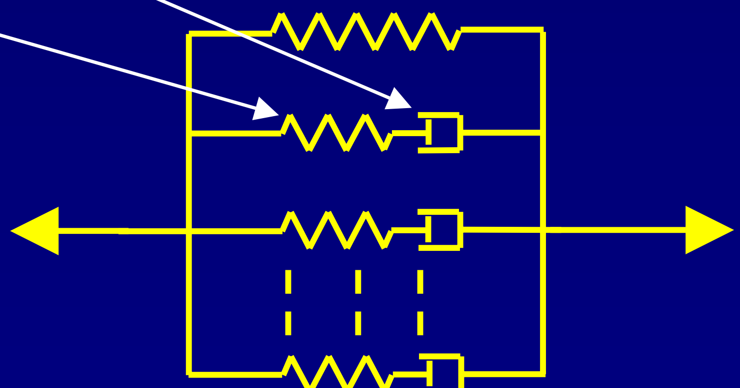
Linear viscoelastic constitution

- Deviatoric stress

$$\mathbf{s} = \int_{-\infty}^{t} 2 \underbrace{G(t-s)}_{\text{relaxation function}} \frac{d}{ds}\left[\mathbf{e}(s)\right] ds$$

- Relaxation function

$$G(t) = G_{\infty} + \sum_{i=1}^{m} G_i e^{-\frac{t}{\tau_i}}$$



Nonlinear viscoelasticity

- Linear viscoelasticity

$$s(t) = \int_{-\infty}^{t} 2\left[G_{\infty} + \sum_{i=1}^{m} G_i e^{-\frac{t}{\tau_i}}\right]\frac{d}{ds}\left[e(s)\right]ds$$

- Nonlinear viscoelasticity

$$s(t) = \int_{-\infty}^{t} 2\left[G_{\infty} + \sum_{i=1}^{m} G_i e^{-\frac{\xi(s,a_H)}{\tau_i}}\right]\frac{d}{ds}\left[\frac{e(s)}{a_V}\right]ds$$

Same as conventional horizontal temperature shift

Vertical shift

Implementation

- Algorithm
  - Calculate stress in time steps

$$\text{stress}_{t_{n+1}} = f\left(\text{strain}_{t_{n+1}}, \text{history}_{t_n}\right)$$

- Strain to calculate shift factors
  - Cannot use current strain
  - Maximum strain in time history, damage

Material properties

- Fit properties for relaxation function

$$G(t) = G_\infty + \sum_{i=1}^{m} G_i e^{-\frac{t}{\tau_i}}$$

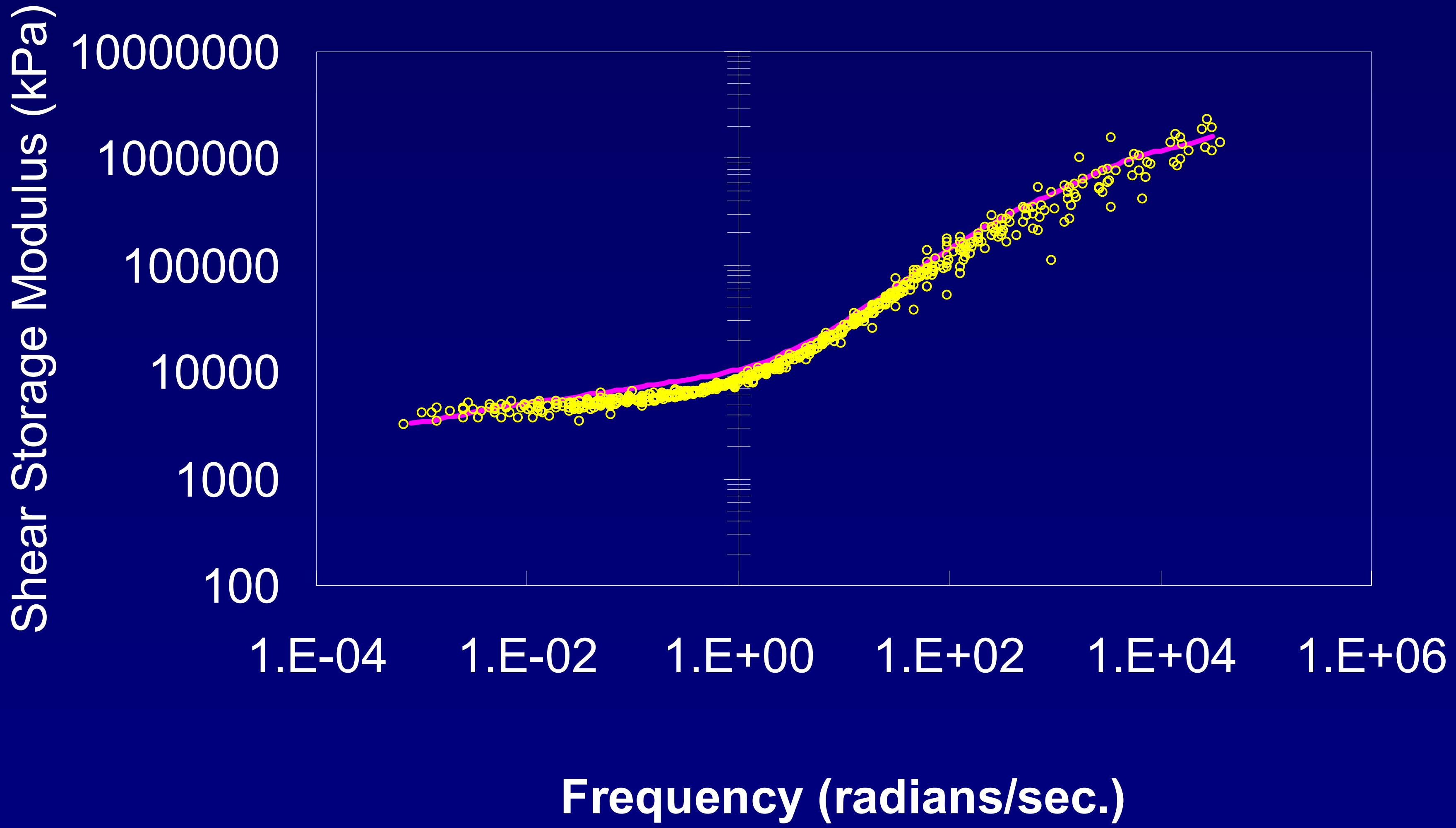
- Storage modulus and loss modulus master curves
  - Storage modulus

$$G' = G_\infty + \sum_{i=1}^{m} G_i \frac{(\omega\tau_i)^2}{1+(\omega\tau_i)^2}$$

  - Loss modulus

$$G'' = \sum_{i=1}^{m} G_i \frac{\omega\tau_i}{1+(\omega\tau_i)^2}$$

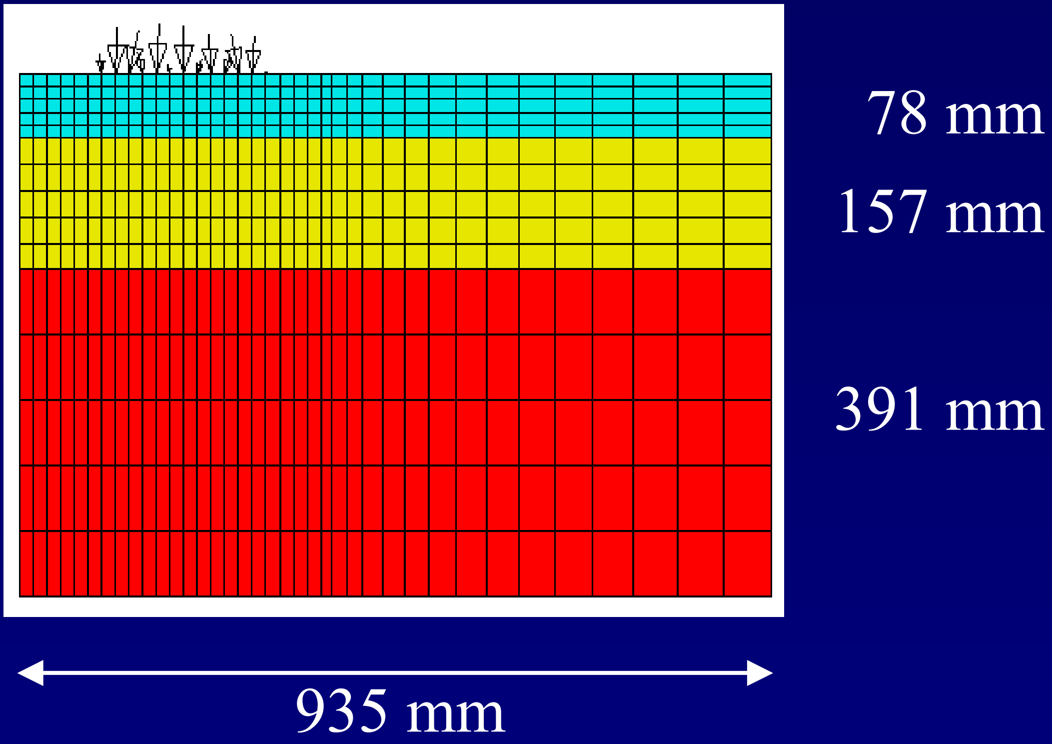
Fitted master curves



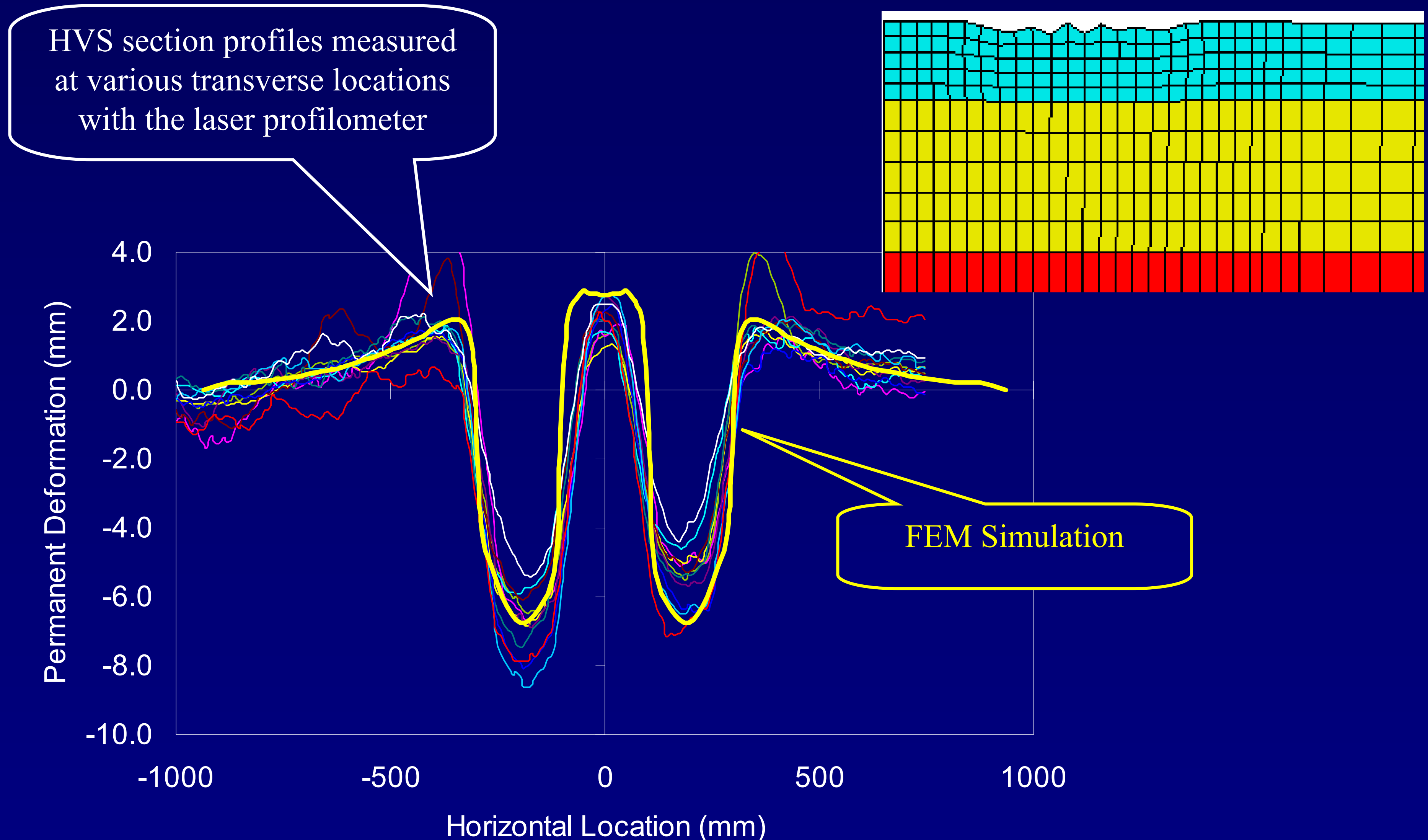
HVS rutting study (UC Berkeley)

Test section	Tire			Temperature at 50 mm depth (°C)	Overlay	
	Type	Pressure (kPa)	Load (kN)		Material	Thickness (mm)
505 RF	Dual bias	690	40	50	DGAC drained[1]	54
506 RF	Dual radial	720	40	50	DGAC undrained	78
507 RF	Wide-base single	760	40	50	ARHM undrained	76
508 RF	Wide-base single	760	40	50	ARHM undrained	73
509 RF	Dual radial	720	40	50	ARHM undrained	75
510 RF	Dual radial	720	40	50	ARHM undrained	35
511 RF	Wide-base single	760	40	50	ARHM undrained	35
512 RF	Wide-base single	760	40	40	DGAC drained	49
513 RF	Aircraft	1070	100	50	DGAC undrained	80

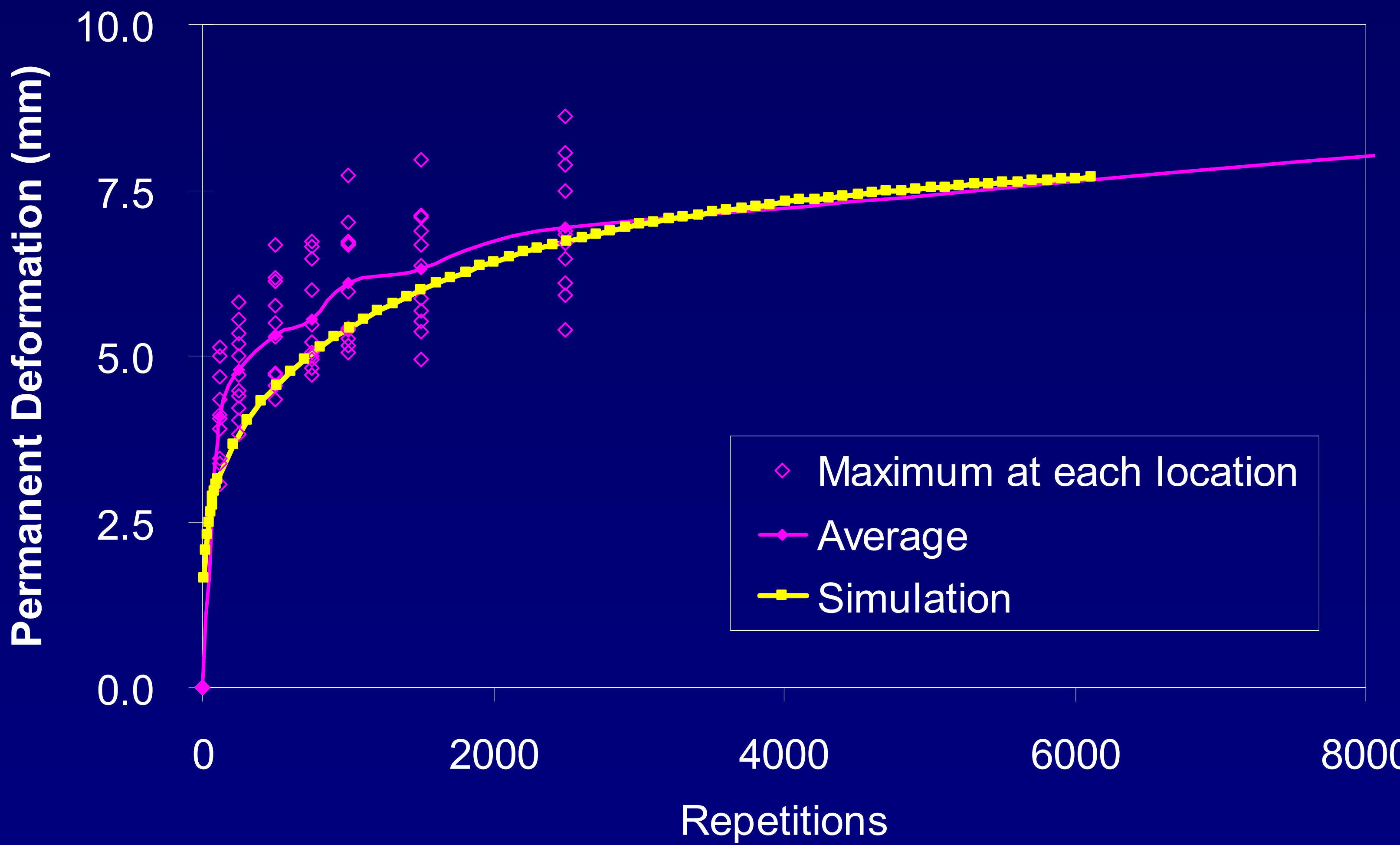
HVS rutting study



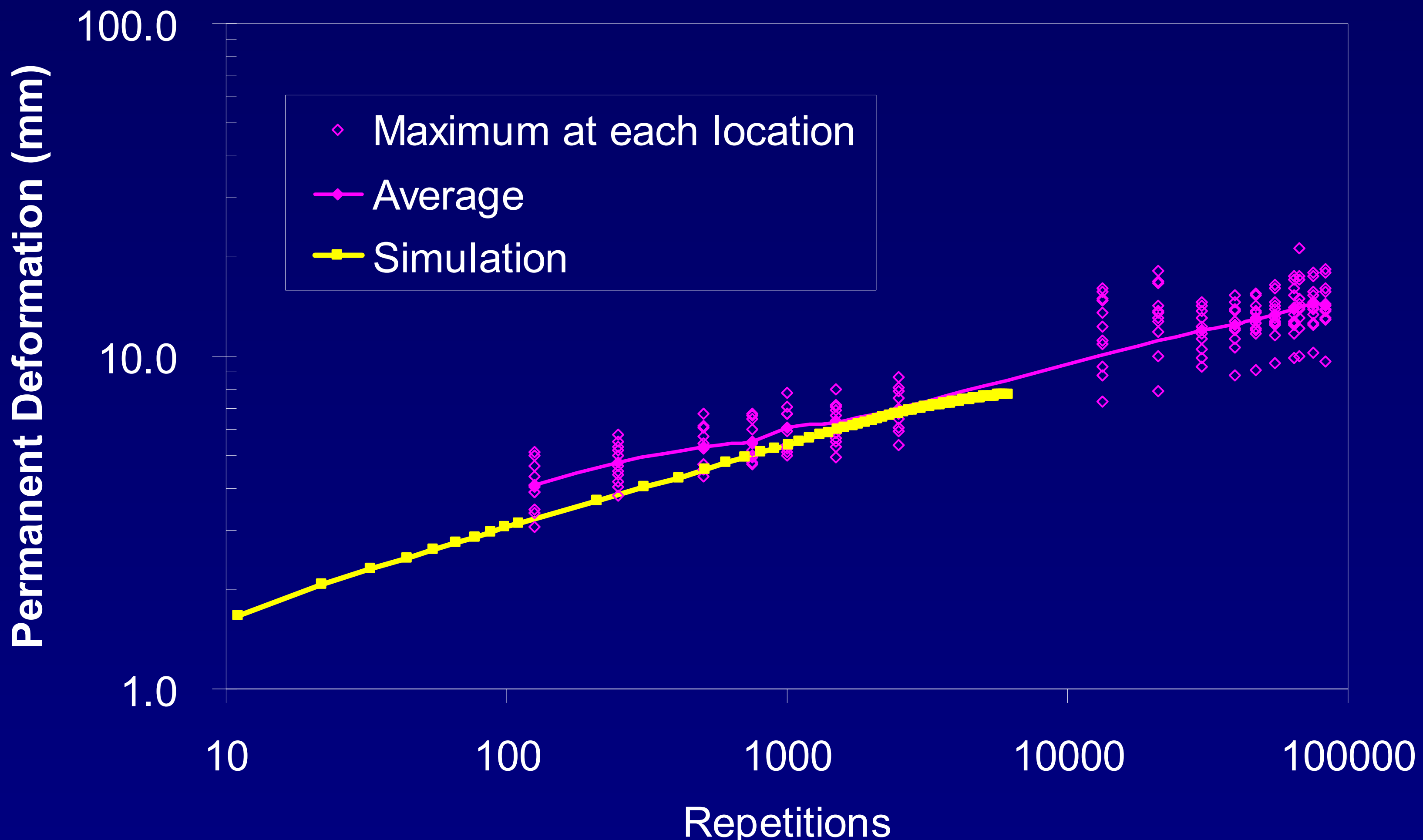
Rut profile


HVS section profiles measured at various transverse locations with the laser profilometer
FEM Simulation
Permanent Deformation (mm)
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-1000
-500
0
500
1000
Horizontal Location (mm)

Accumulation of rutting



Accumulation of rutting



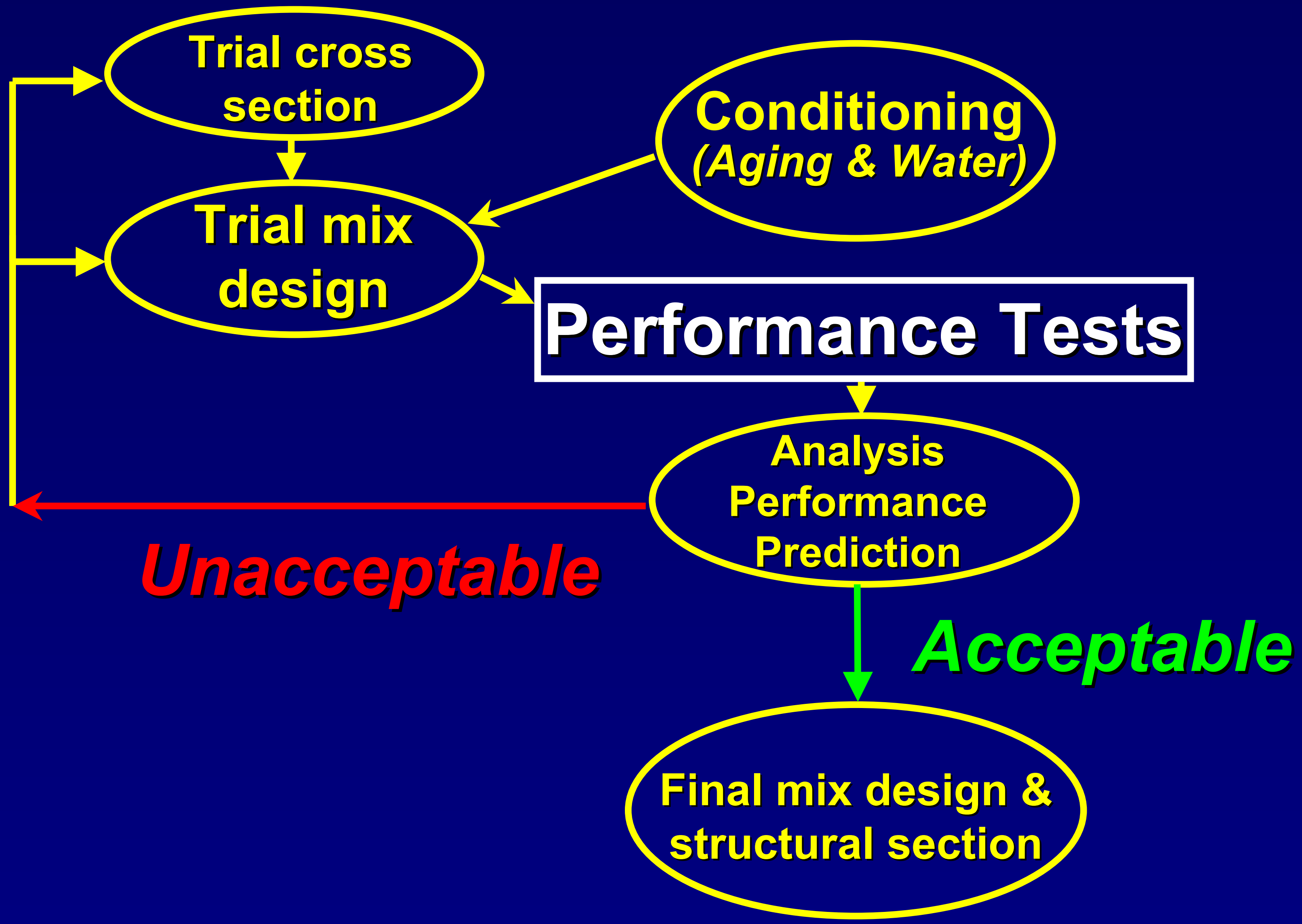
Summary

- HVS validated the nonlinear viscoelastic constitutive model
  - FEM predictions matched the HVS data well

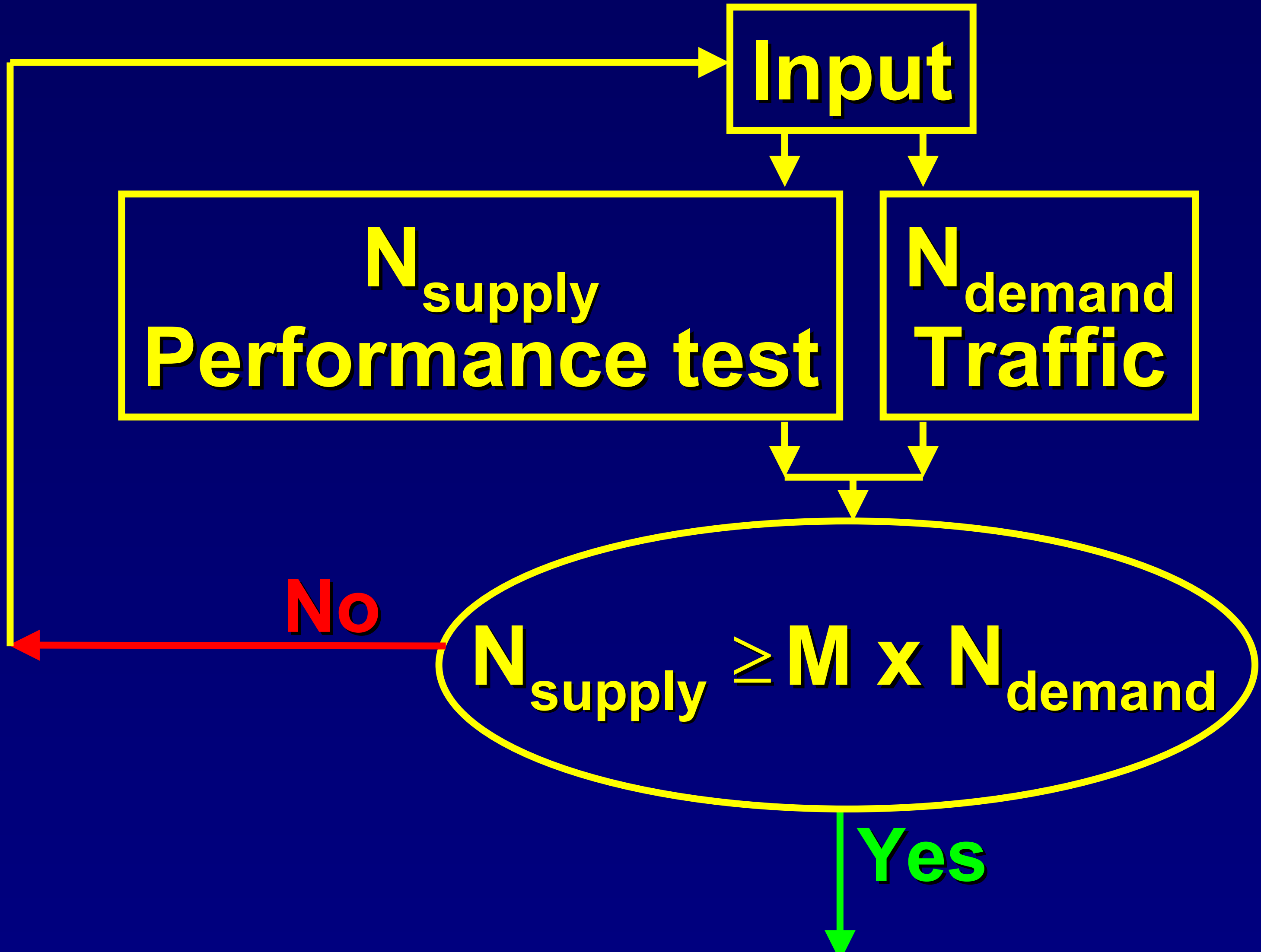
Mix design

Example

Design and analysis

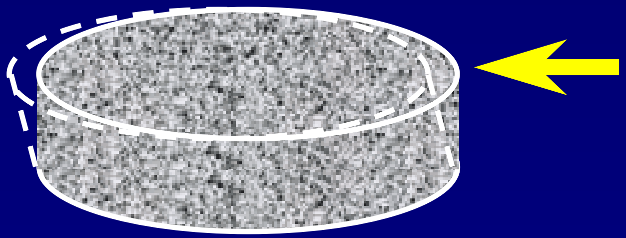


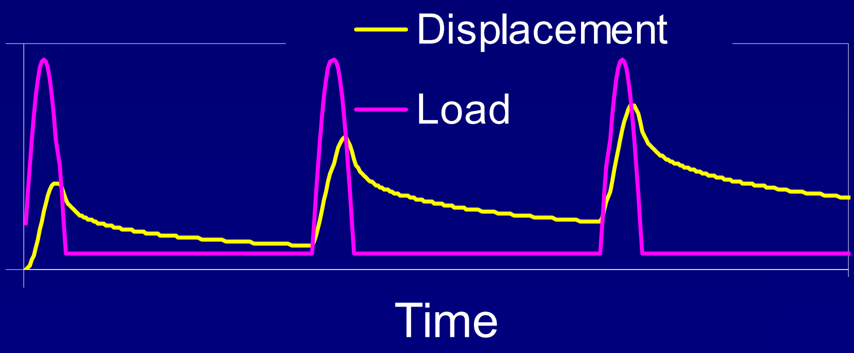
Mix design: Rutting



Performance test

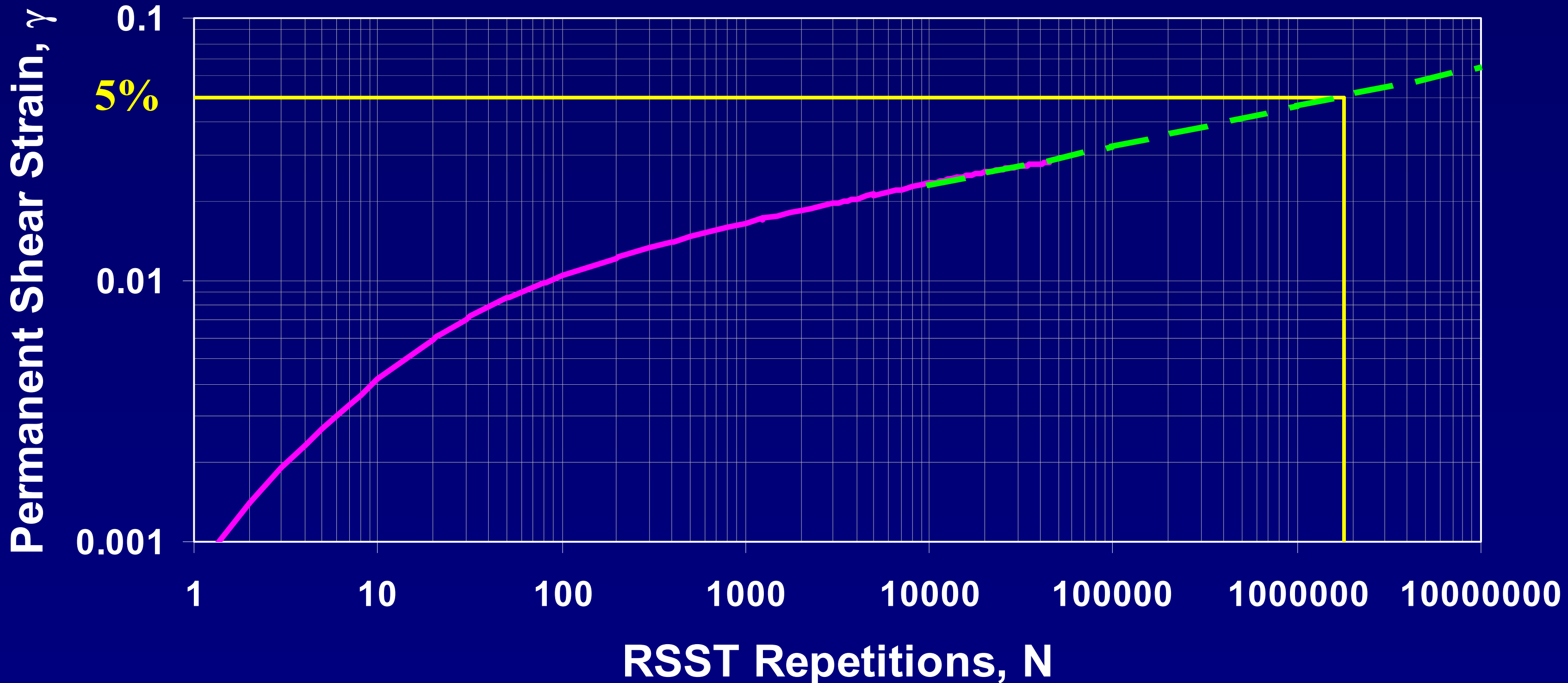
- Repeated simple shear test at constant height (RSST-CH)
- Critical temperature





Rutting: N_{supply}

- Simple shear test (RSST-CH)
  - specific value of shear strain, e.g., 5%.



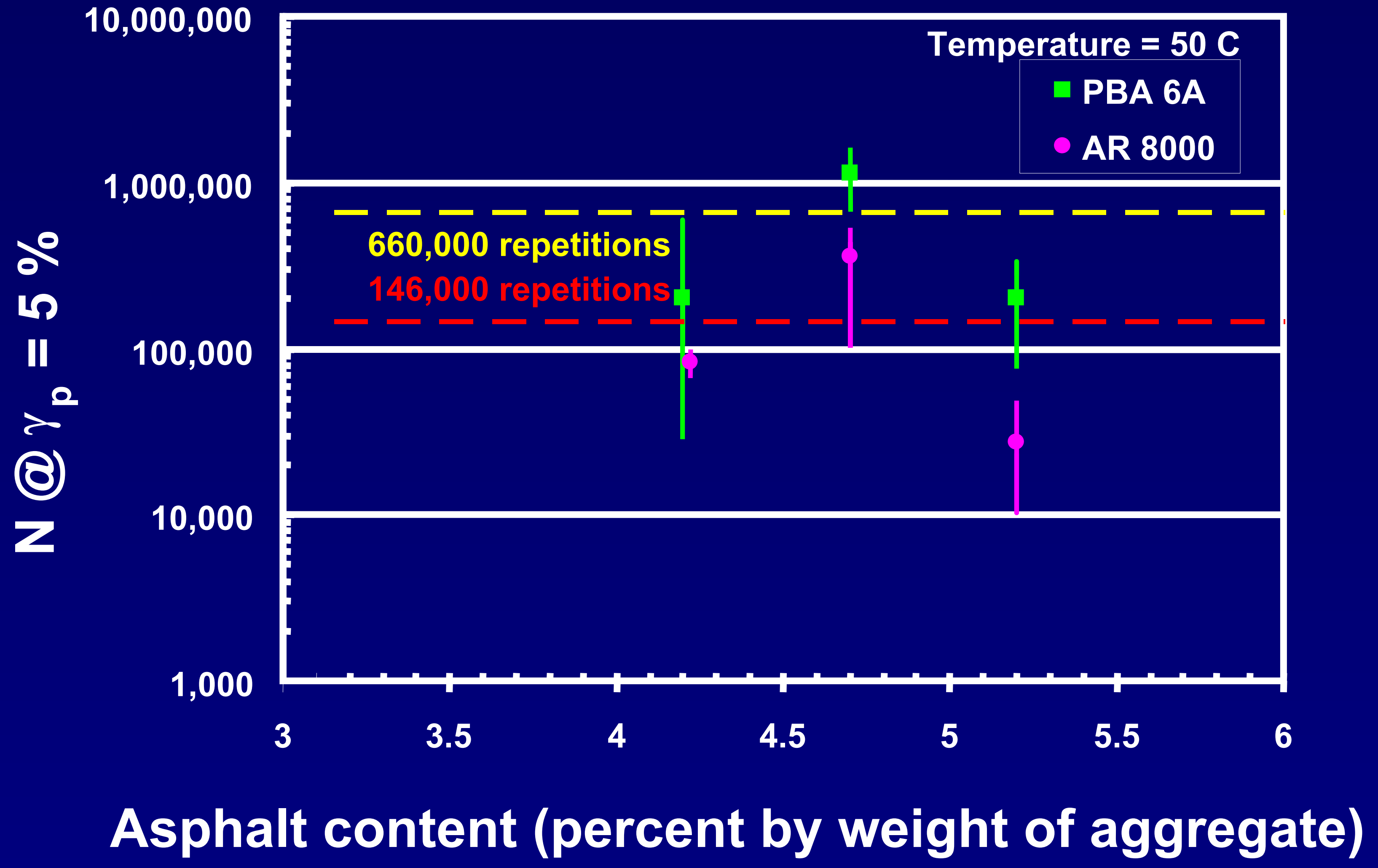
Rutting: N_{demand}

- N_{demand} =Design ESALs • TCF • SF
  - TCF = temperature conversion factor
  - SF = shift factor
- M = reliability multiplier
  - Laboratory test variance
  - Traffic variance

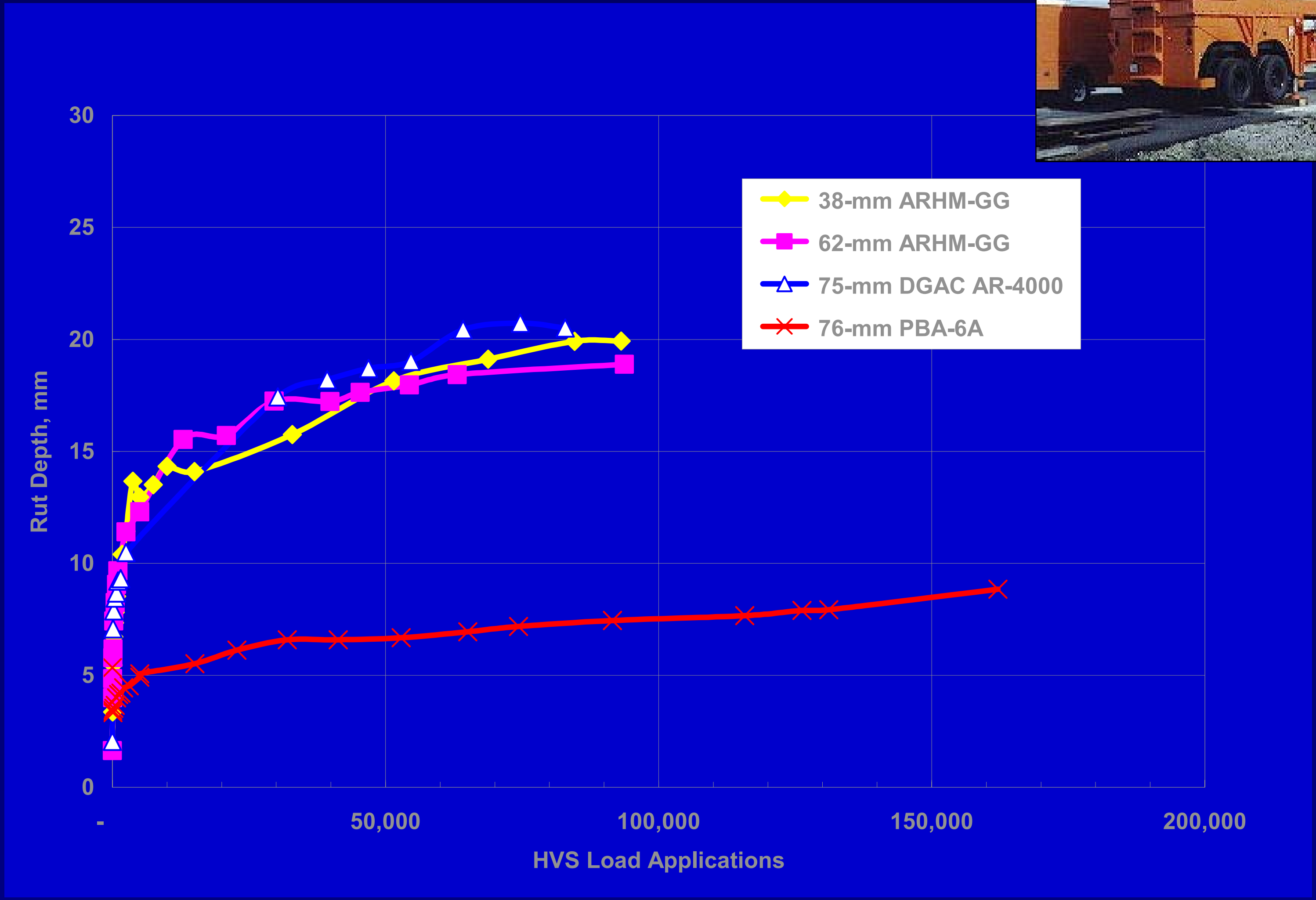
Mix design example

- I710, Long Beach, California
- Long-life (perpetual) pavement
- 2 Binders
  - AR 8000 (conventional binder)
  - PBA 6A (polymer modified)
    - *Less stiff than AR 8000*

Design binder content



CAL/APT evaluation

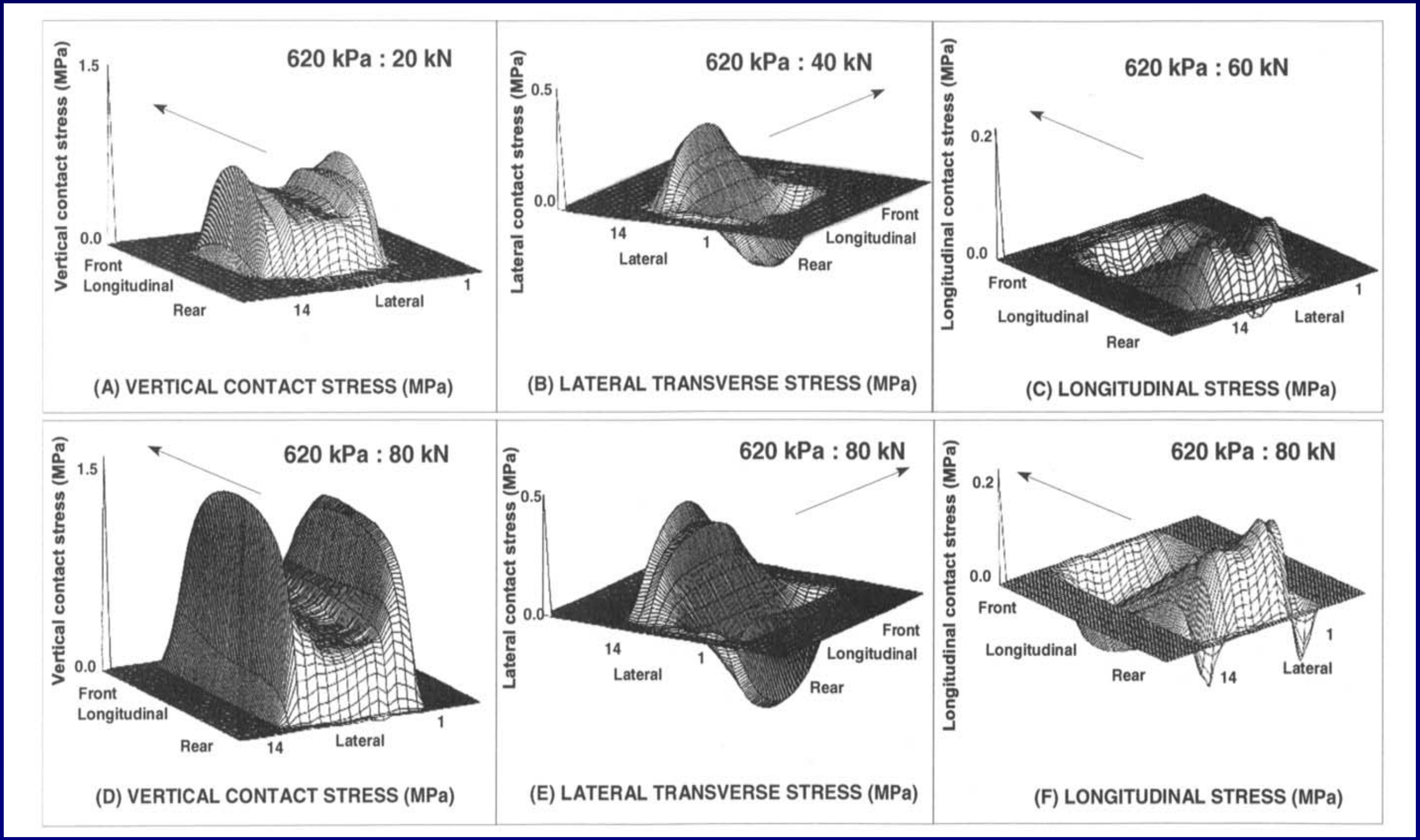


Summary

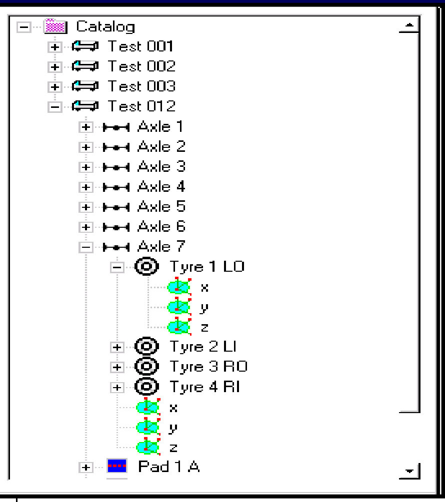
- Surface distress manifests in many different ways
- SIM key for analyses of surface distress
- AC rutting
  - HVS data used to successfully validate a nonlinear viscoelastic model
  - HVS data validated mix design of I 710

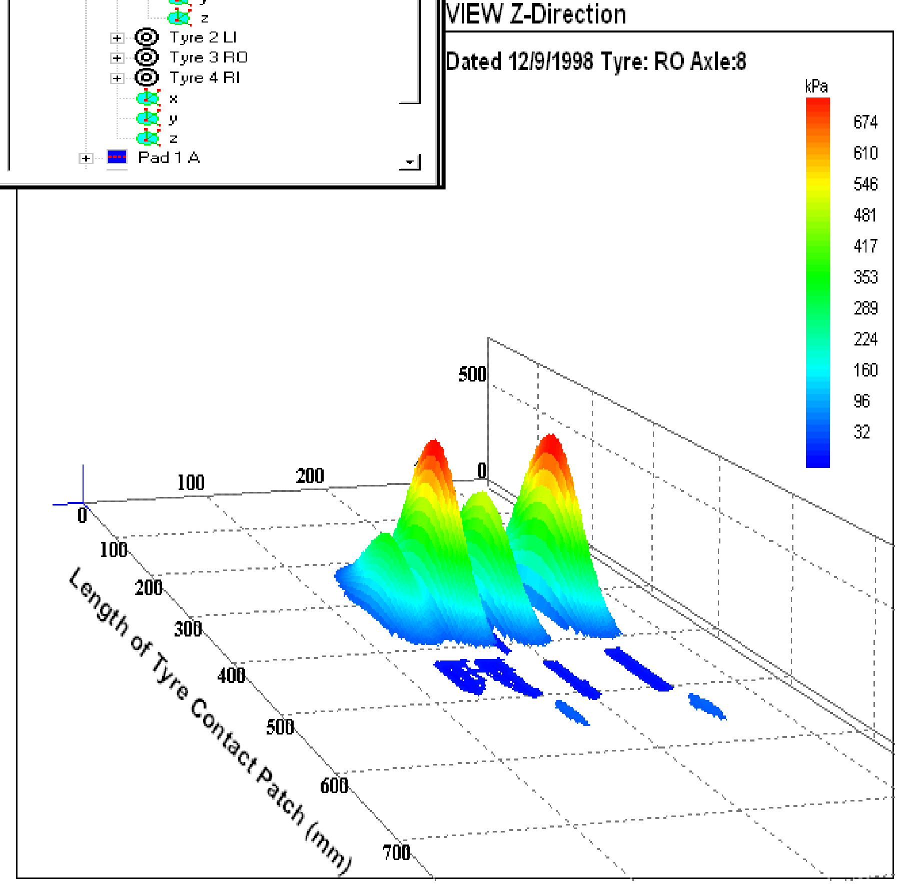
Questions??

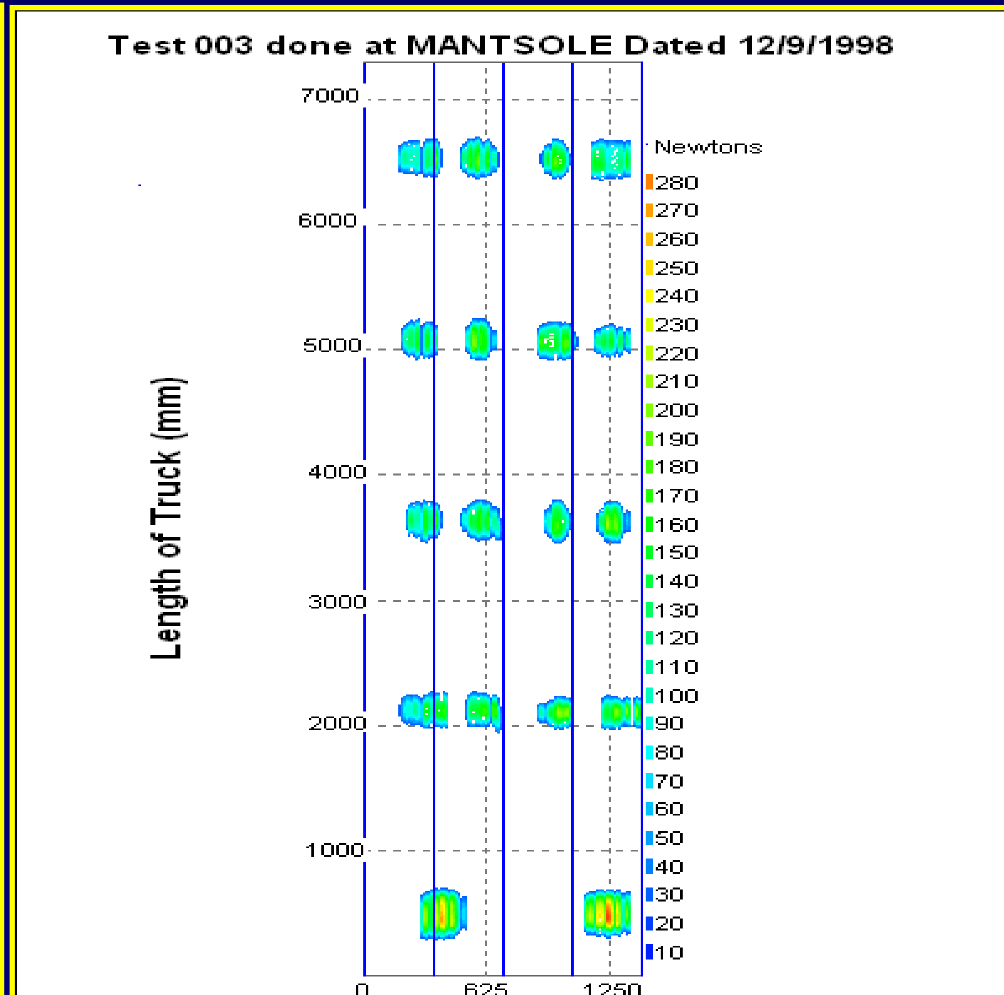
Contact stress (bald tire)



SIM DATA ORGANISATION :







Artificial Neural Networks (ANN) :

(ANN - FHWA/ PENN STATE)

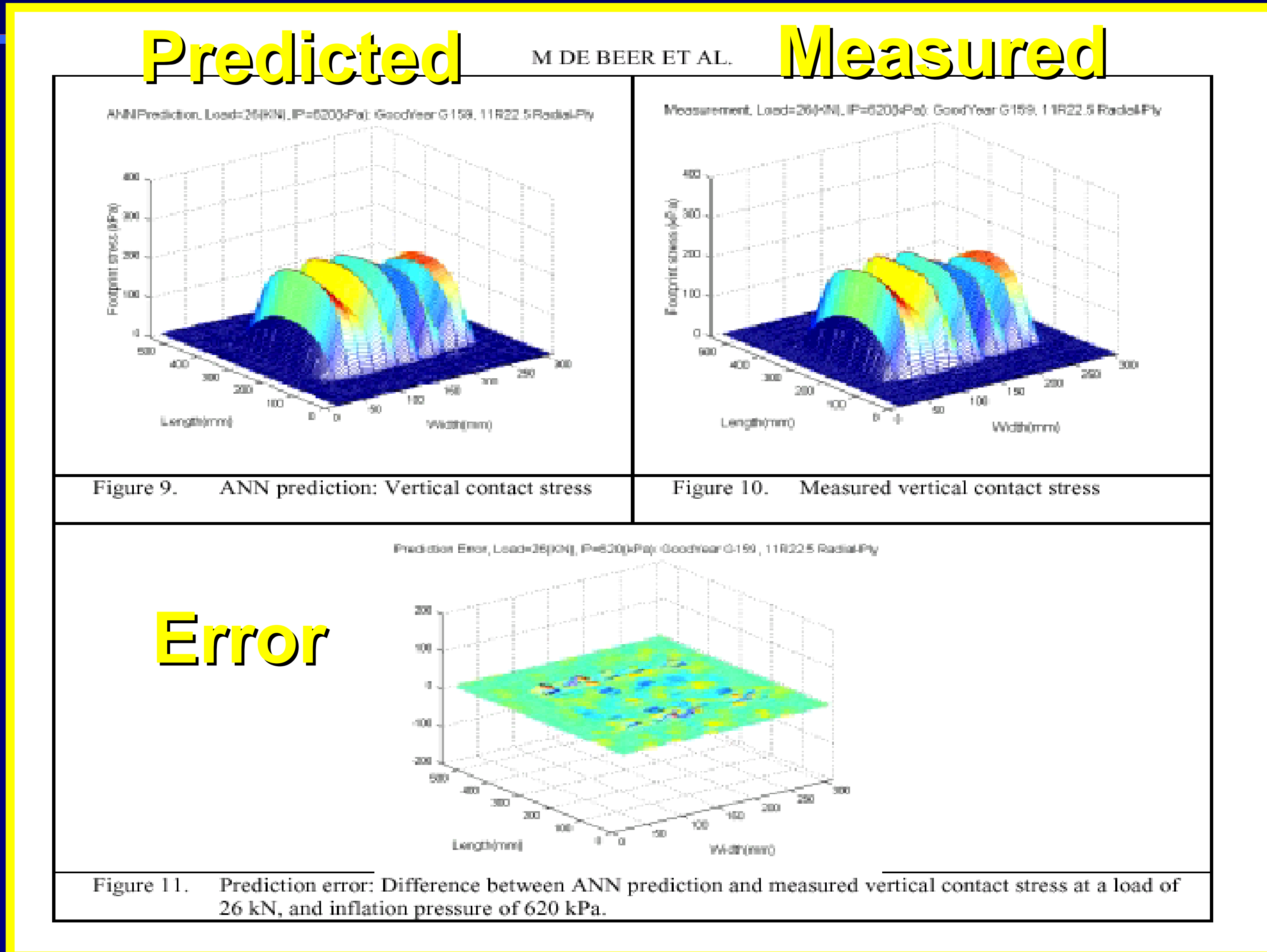
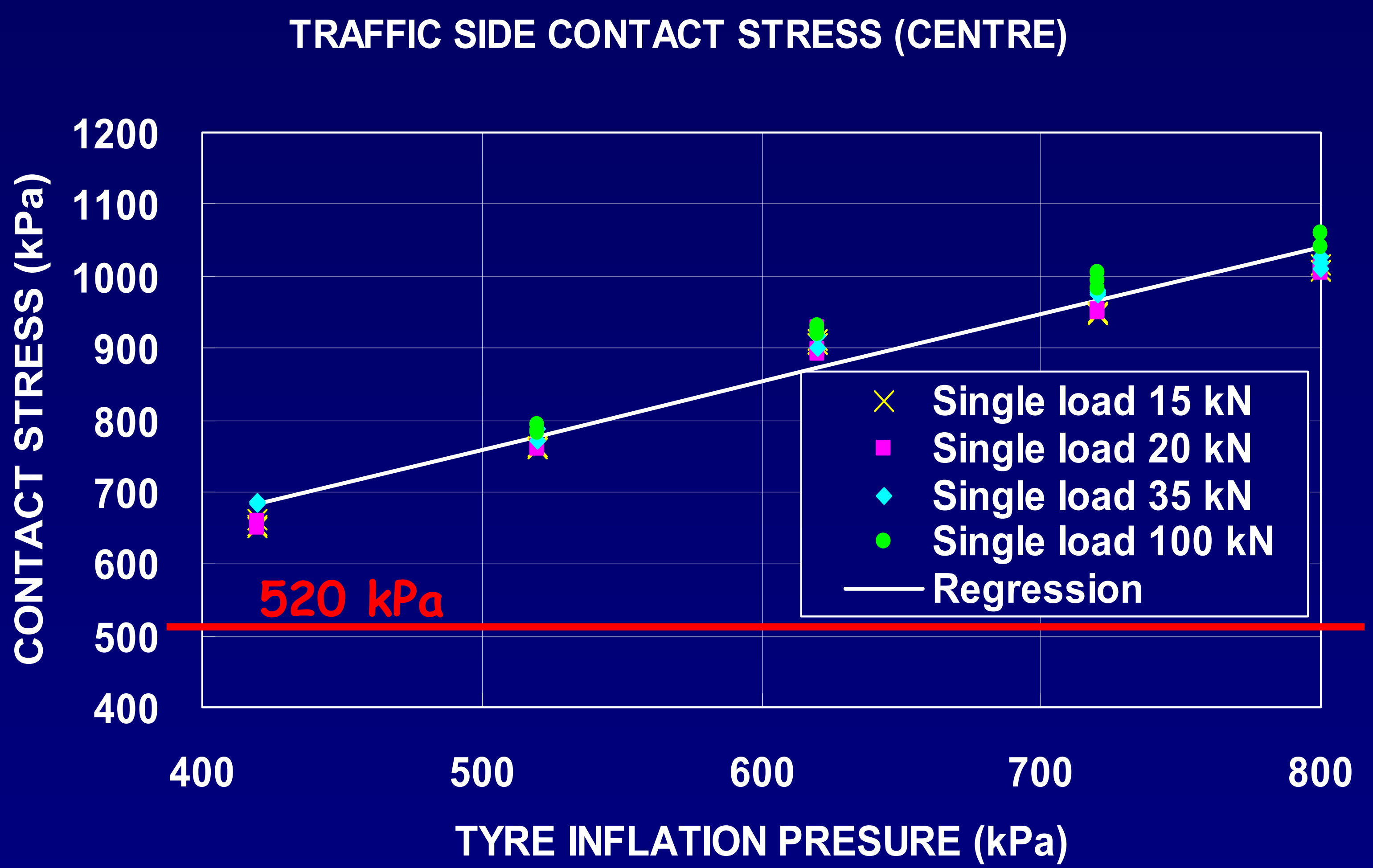


Figure 9. ANN prediction: Vertical contact stress

Figure 10. Measured vertical contact stress

Figure 11. Prediction error: Difference between ANN prediction and measured vertical contact stress at a load of 26 kN, and inflation pressure of 620 kPa.

Practical applications



Practical applications