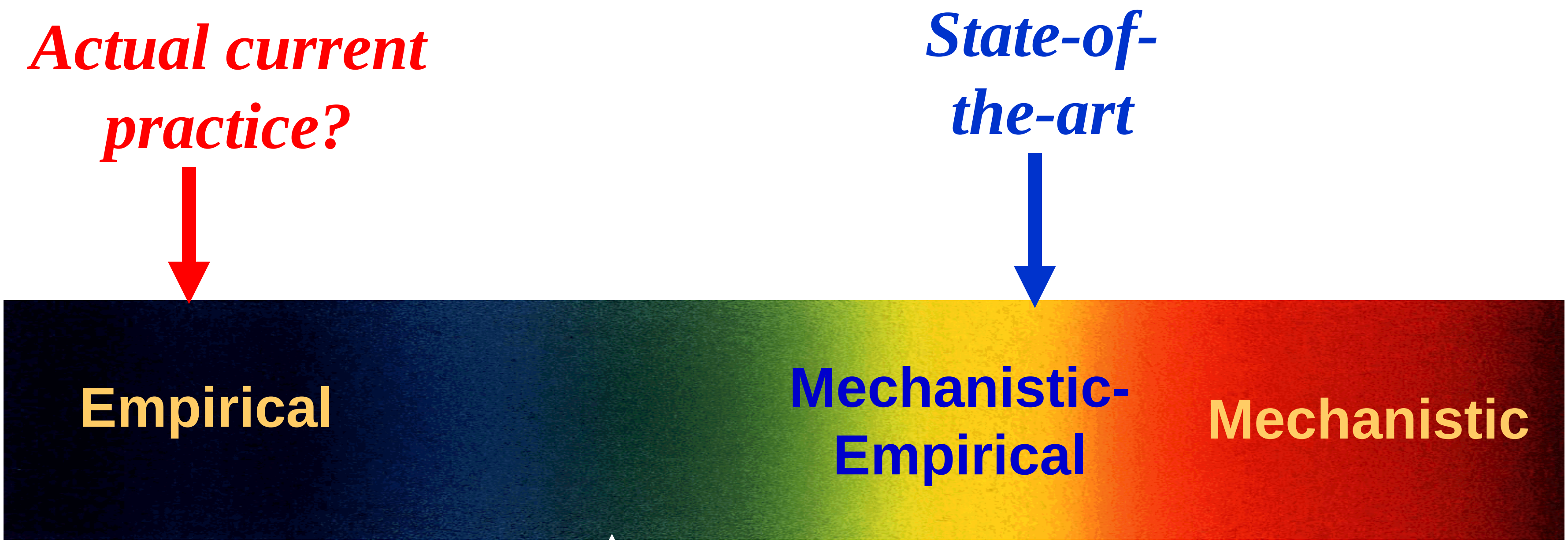
Modeling of Hot Mix Asphalt

Eyad Masad
Zachry Department of Civil Engineering
Texas A&M University

Workshop on Validation of Advanced Flexible Pavement Modeling with Accelerated Pavement Testing Data

87th TRB Annual Meeting

The Continuum of Development



Performance Prediction

Material Properties

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

Pavement Structure

- Thickness
- Sub grade type

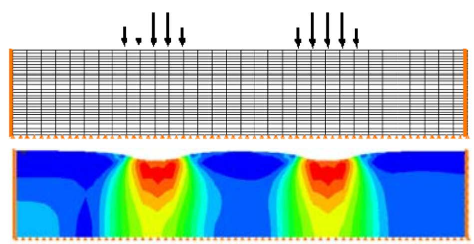
Environmental Factors

- Temperature
- Humidity differential
- Rainfall

Loading Conditions

- Type of loading
- Tire pavement interaction

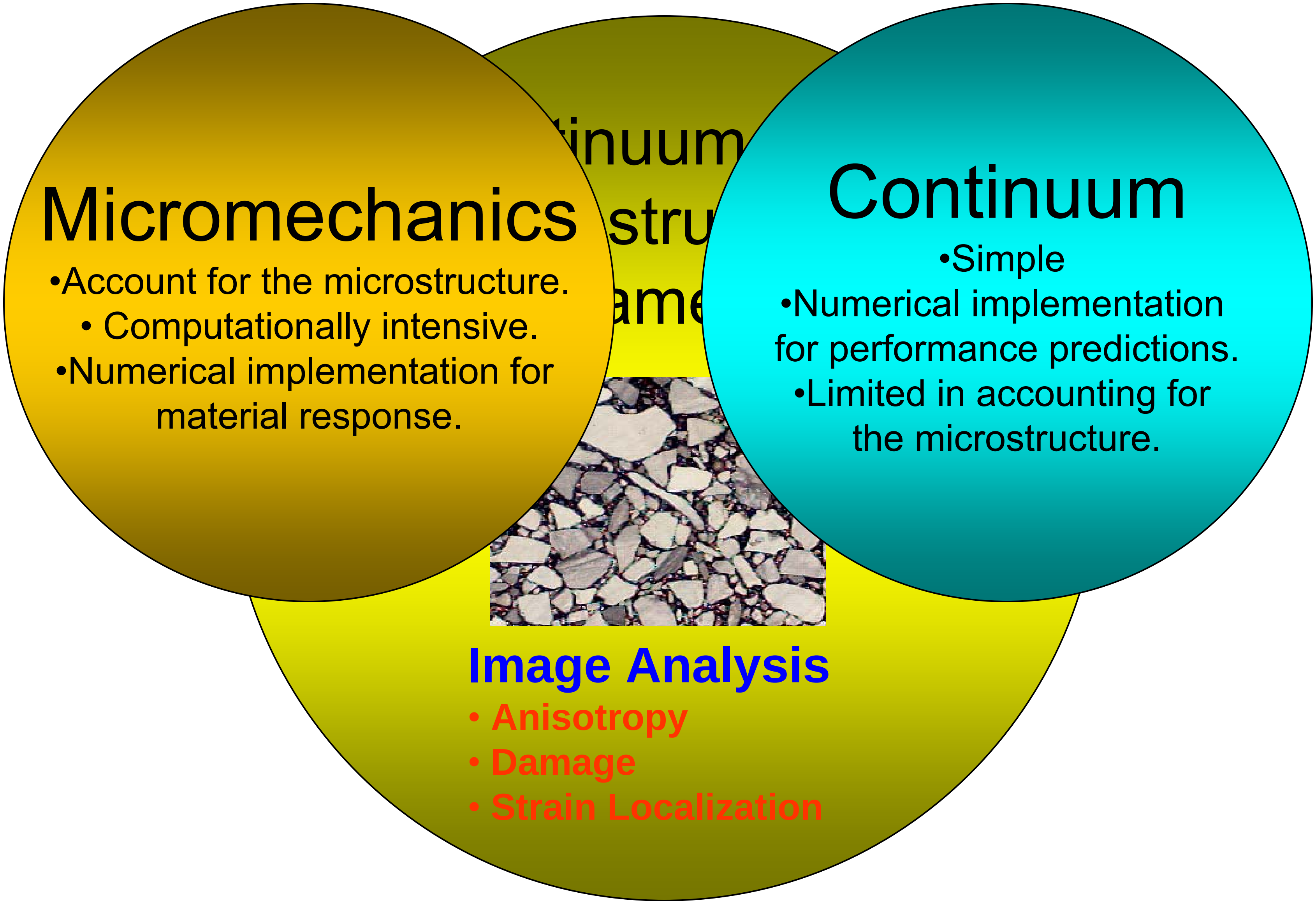
FEM Modeling



Calibration (minimize shift factor dependency)

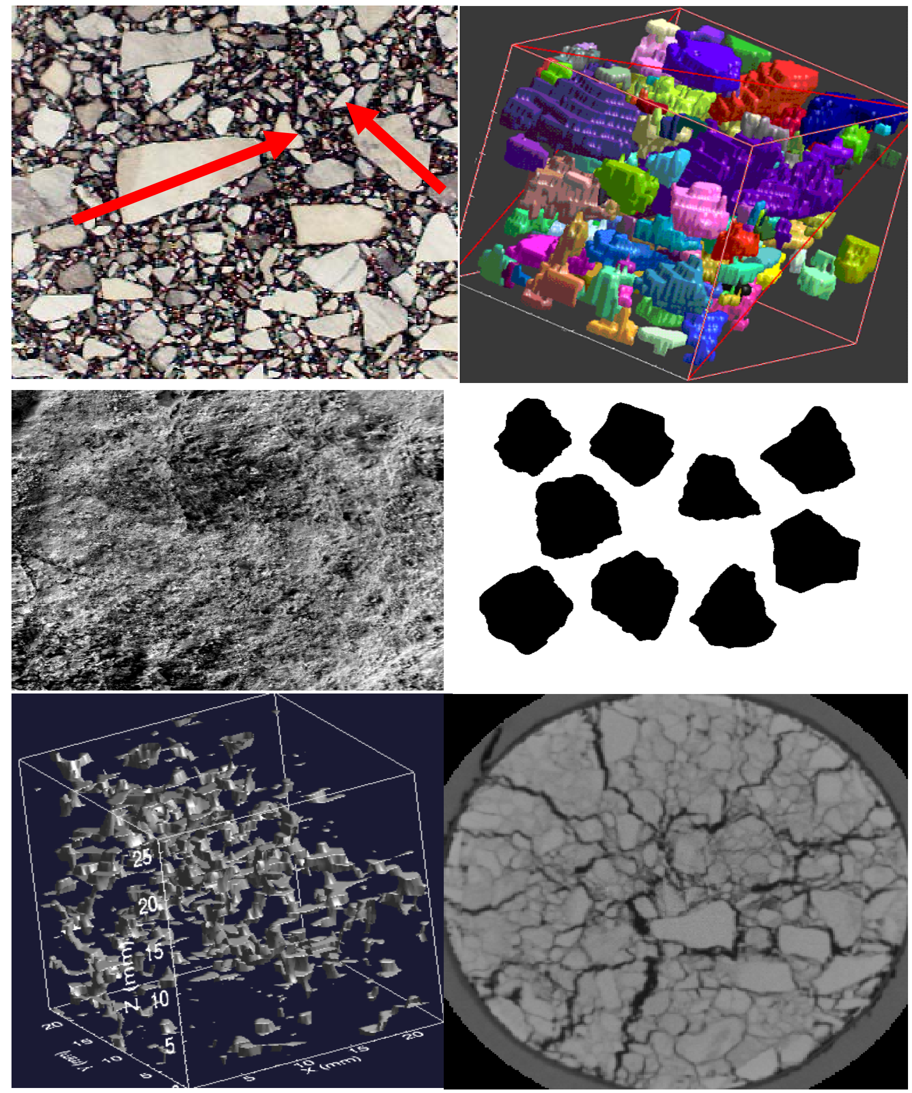
Prediction of material distress

Mechanistic Modeling Approaches



HMA Modeling Considerations

- Model accounts for:
  - Rate.
  - Temperature.
  - Anisotropy.
  - Heterogeneity.
  - Dilation/Contraction.
  - Confining pressure.
  - Damage.
  - Stress state.
- Model predicts:
  - Permanent deformation.
  - Fatigue cracking.
  - Low temperature cracking.



HMA Modeling Considerations

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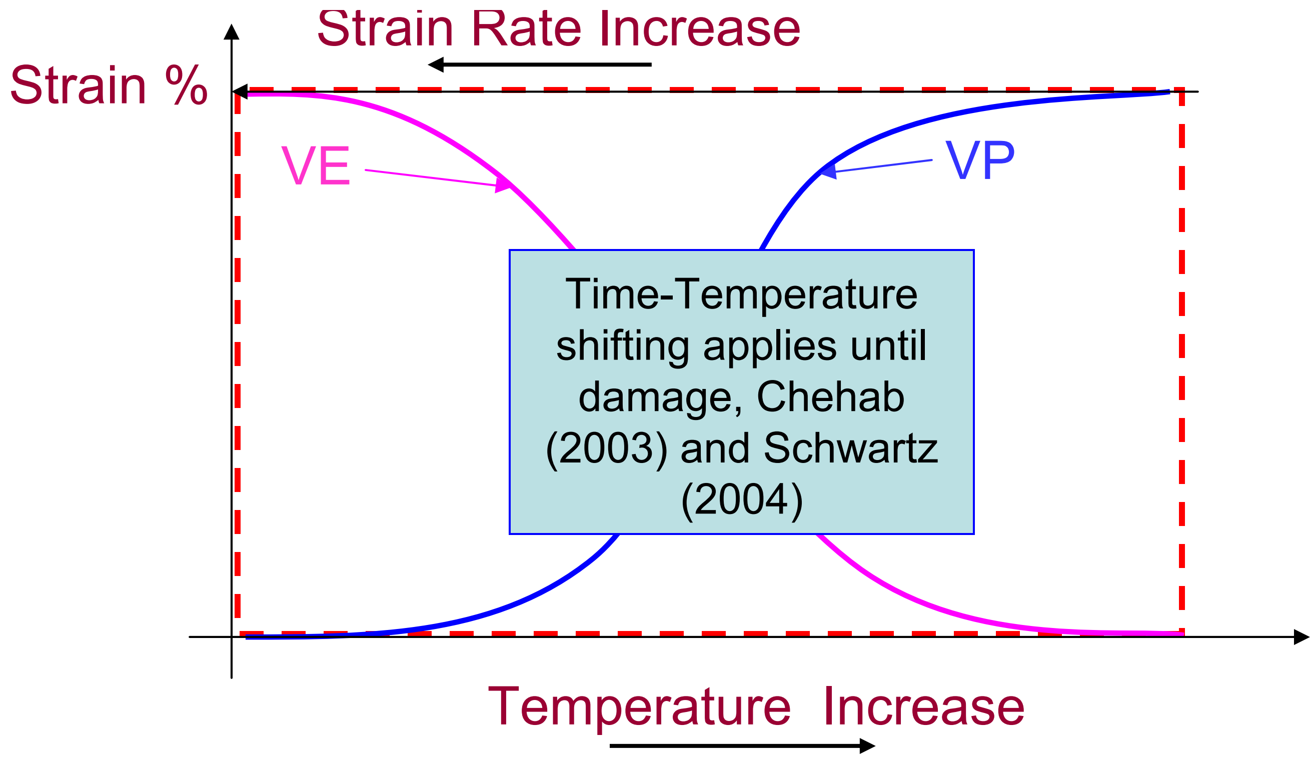


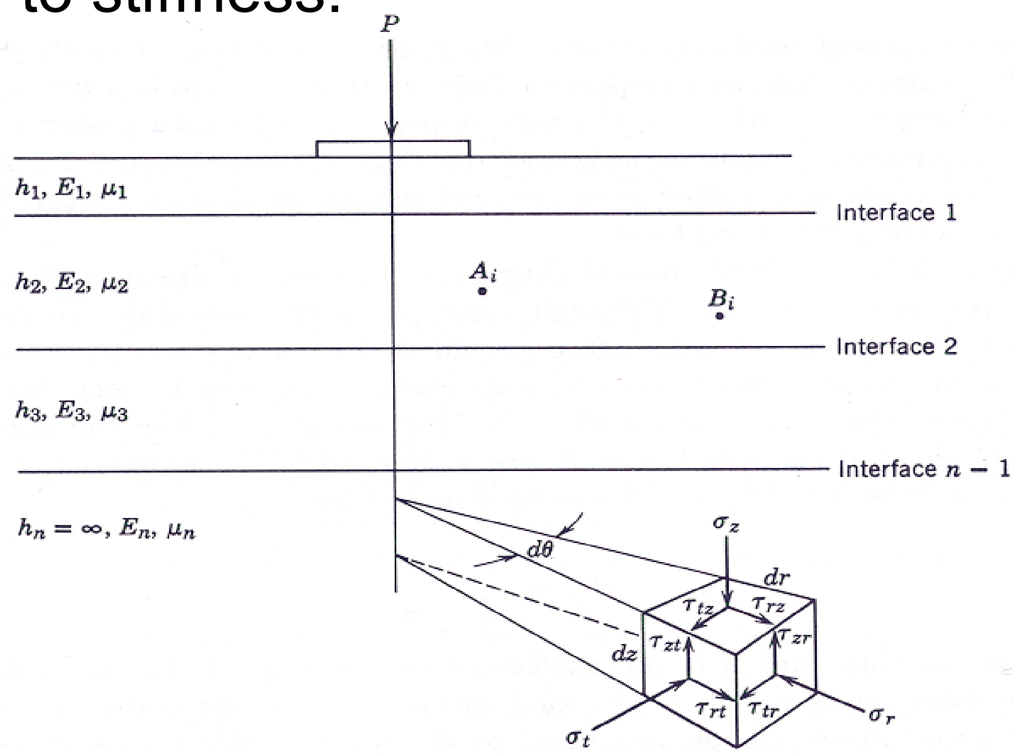
- Viscoplastic component:
  - Dilation and hydrostatic pressure
  - Work hardening
  - Damage
  - Healing
  - Anisotropy

- Viscoelastic component:
  - Nonlinear or stress dependent
  - Damage
  - Healing
  - Anisotropy

Continuum Models

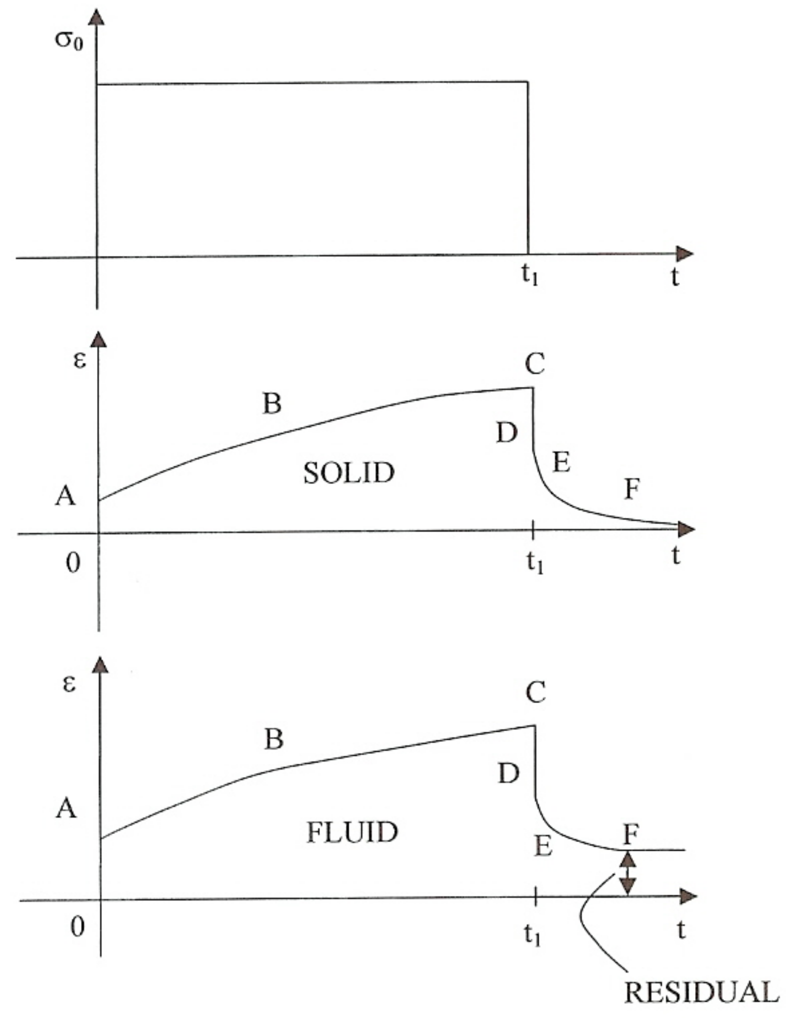
- **Elastic Models**
  - No failure mechanisms.
  - Predicts distresses using empirical “transfer functions”.
  - Relates distresses to stiffness.

$$N_f = \beta_3 k_1 \varepsilon_t^{-k_2} E^{-k_3}$$



Continuum Models

- **Classical Viscoelastic Models**
  - Temperature and time dependency.
  - Can be formulated to provide plastic deformation.
  - No failure mechanisms.



Objectives

- Develop a constitutive model for HMA that incorporates features of microstructure.
- Relate the model's parameters to aggregate characteristics.
- Implement the constitutive models in finite element to simulate permanent deformation.
- Study the effect of aggregate characteristics on mix performance.

Nonlinear Viscoelastic Model

- Shapery nonlinear Model:

$$\varepsilon(t) = g_o D_o \overline{\sigma} + g_1 \int_0^t \Delta D(\psi - \psi') \frac{d g_2 \overline{\sigma}}{d\tau} d\tau$$

$$\psi = \int_0^t dt' / a_{\overline{\sigma}}[\overline{\sigma}(t')] \; (a_{\overline{\sigma}} > 0)$$

$$\psi' = \psi(\tau) = \int_0^\tau dt' / a_{\overline{\sigma}}[\overline{\sigma}(t')]$$

ψ :is the reduced time (effective time)

- For the case of constant load it reduces to:

$$D_n = \frac{\varepsilon(t)}{\overline{\sigma}} = g_0 D_0 + g_1 g_2 \Delta D \left(\frac{t}{a_{\overline{\sigma}}} \right)$$

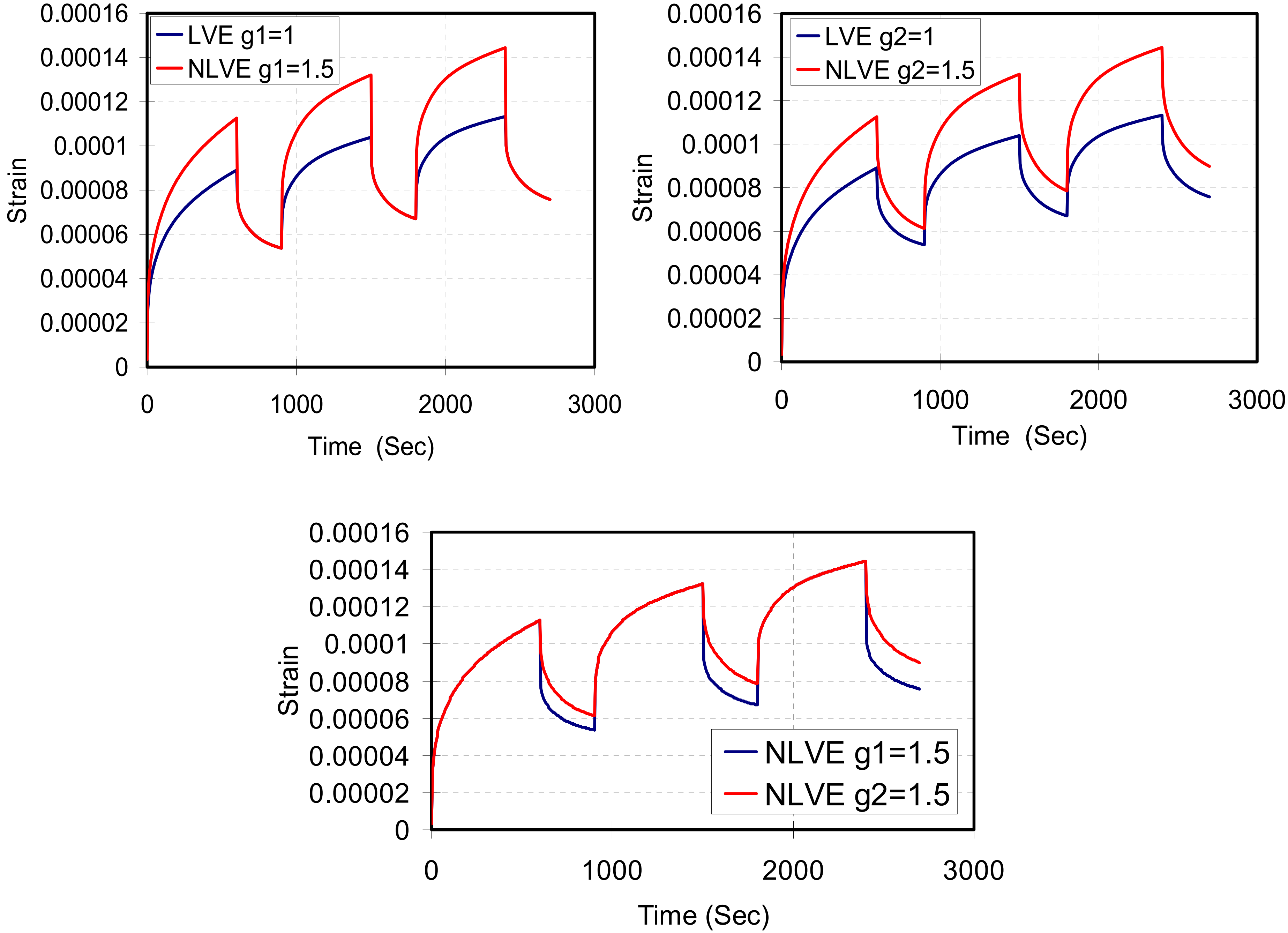
D_n :Nonlinear Creep Compliance

g_o :Nonlinear instantaneous elastic compliance

g_1 :Transient compliance nonlinearity effect parameter

g_2 :Load rate effect parameter

$a_{\overline{\sigma}}$:Time scaling factor


LVE g1=1
NLVE g1=1.5
Strain
Time (Sec)
LVE g2=1
NLVE g2=1.5
Strain
Time (Sec)
NLVE g1=1.5
NLVE g2=1.5
Strain
Time (Sec)

Viscoplastic Model

$$\dot{\varepsilon}_{ij}^{vp} = \Gamma \cdot < \phi(f) > \cdot \frac{\partial g}{\partial \sigma_{ij}}$$

$$f = F(I_1, J_2, J_3, \Delta, \xi) - \kappa$$

$$< \phi(f) > = \begin{bmatrix} 0 & f \le 0 \\ f^N & f > 0 \end{bmatrix}$$

I_1	1st invariant of the stress tensor
J_2	2nd invariant of deviatoric stress tensor
J_3	3rd Invariant of deviatoric stress tensor
k	Hardening parameter
Δ	Anisotropy Parameter
ξ	Damage Parameter

Extended Drucker-Prager Yield Surf

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

- Dilation and confinement

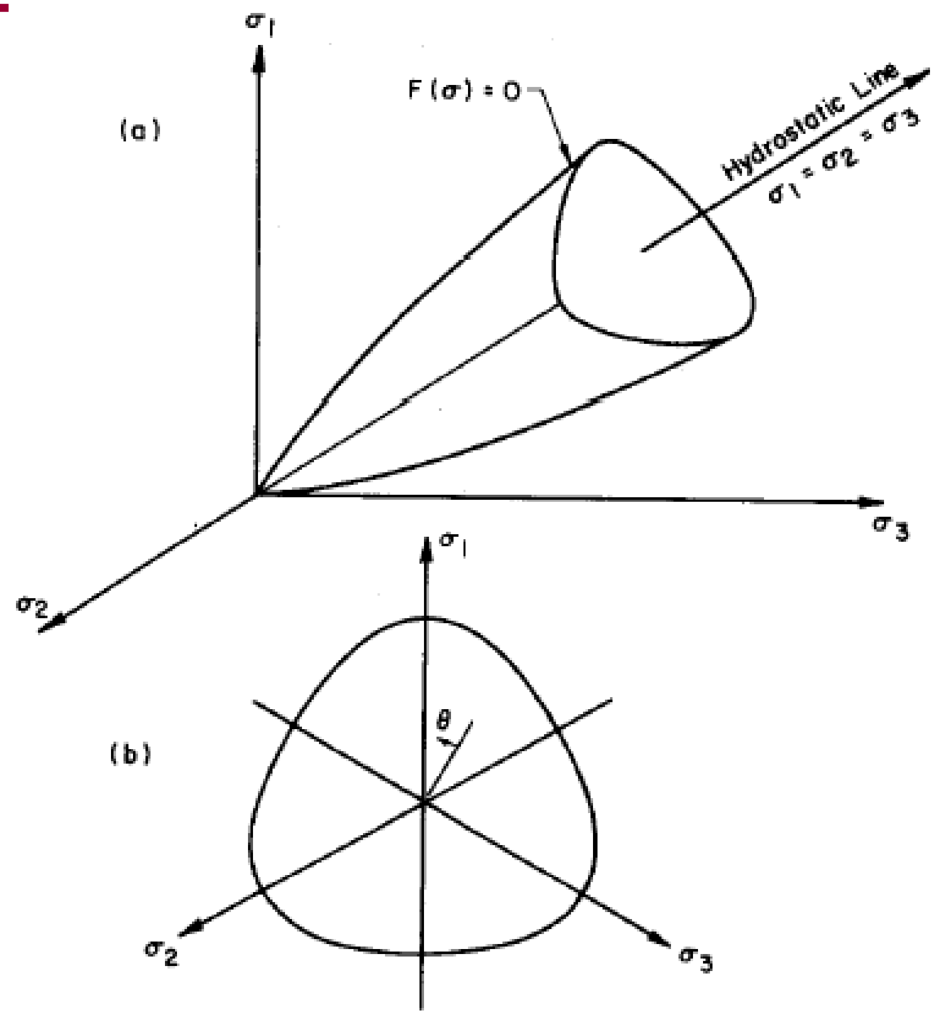
$$I_1 = \frac{1}{3}\,\mathrm{trace}\,(\sigma) = \frac{1}{3}\sigma_{ii}$$

- Shear, and stress path

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

- Hardening/softening

$$\kappa = \kappa_0 + \kappa_1\left[1 - \exp(-\kappa_2 \cdot \varepsilon_{vp})\right]$$



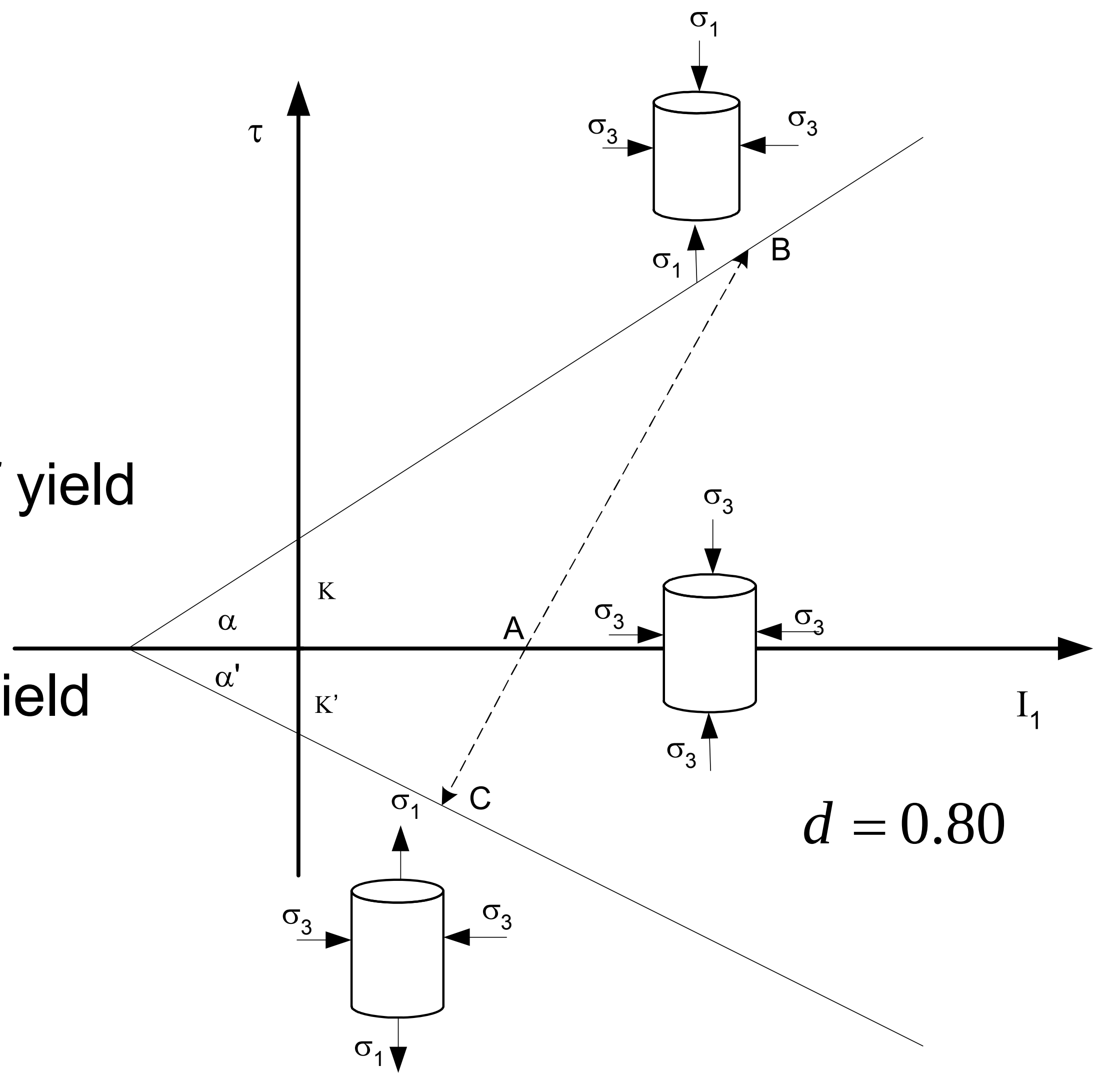
Stress State Influence

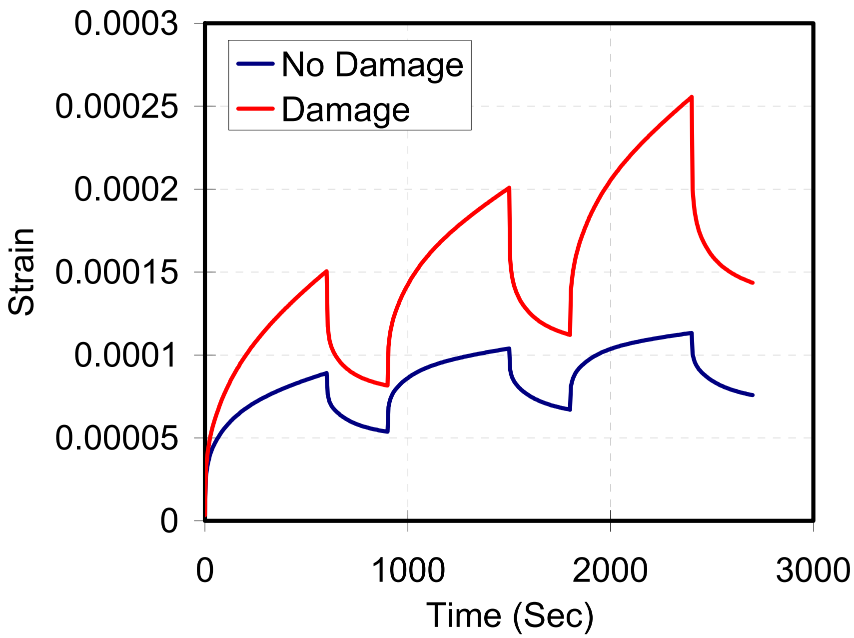
$$d = \frac{\sigma_y^{Tension}}{\sigma_y^{Compression}}$$

- Represents the sensitivity of yield behavior to confinement

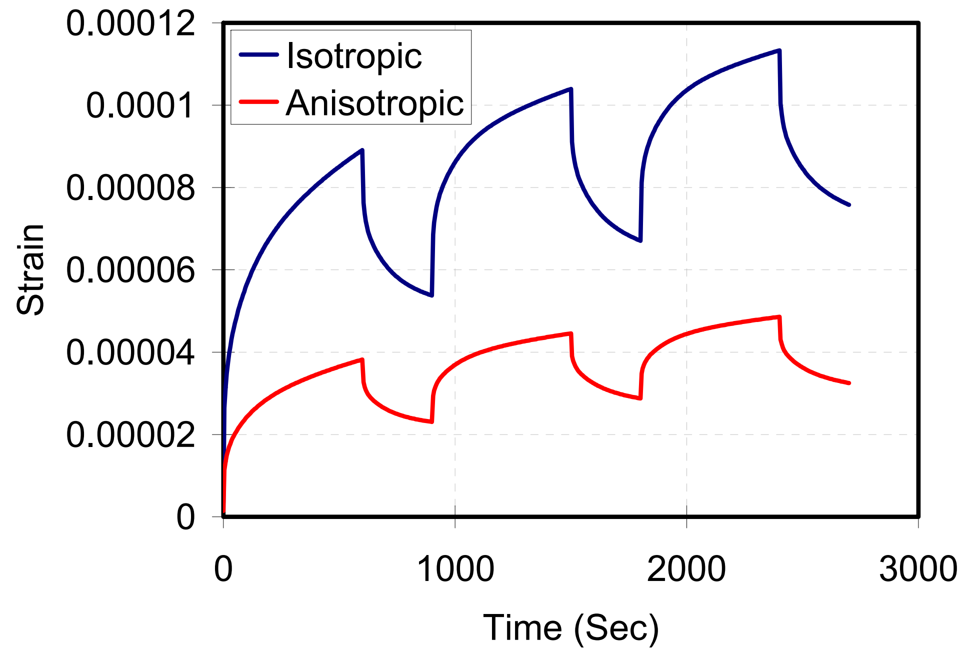
- To ensure convexity of the yield surface

$$0.80 \leq d \leq 1.00$$

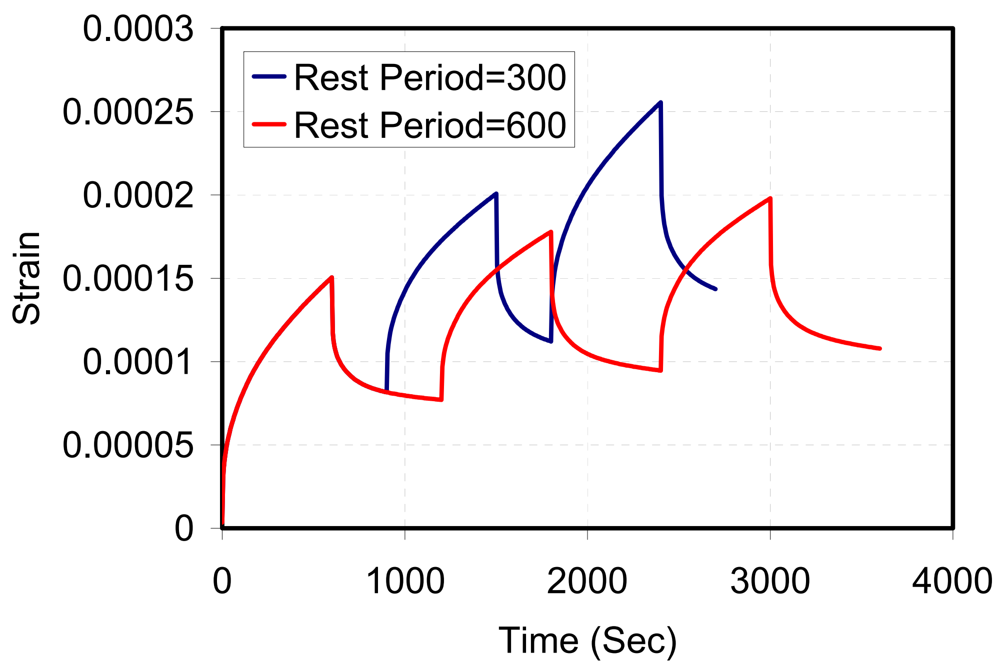




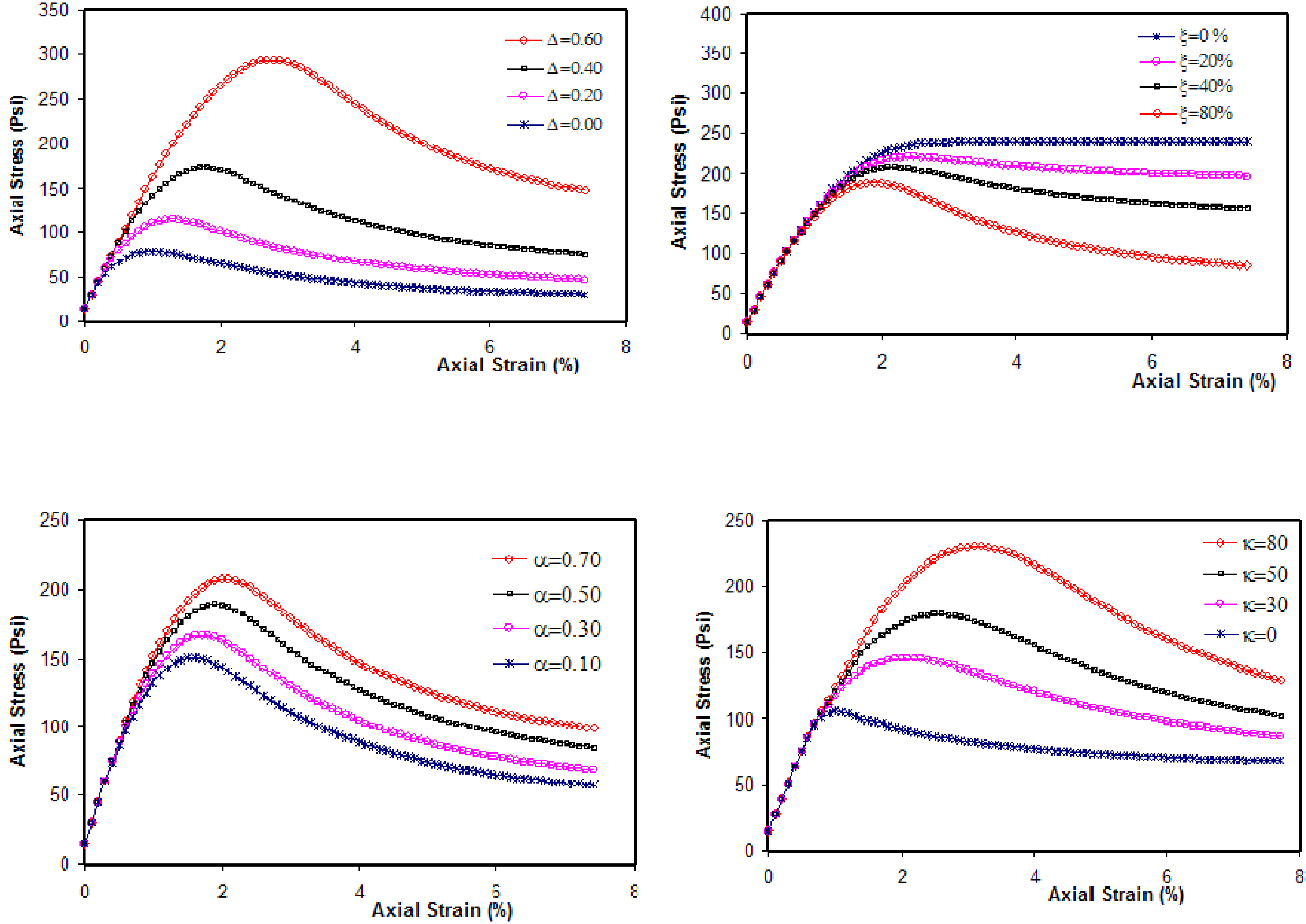
No Damage
Damage
Strain
Time (Sec)
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
0
1000
2000
3000



Isotropic
Anisotropic
Strain
Time (Sec)
0.00012
0.0001
0.00008
0.00006
0.00004
0.00002
0
0
1000
2000
3000



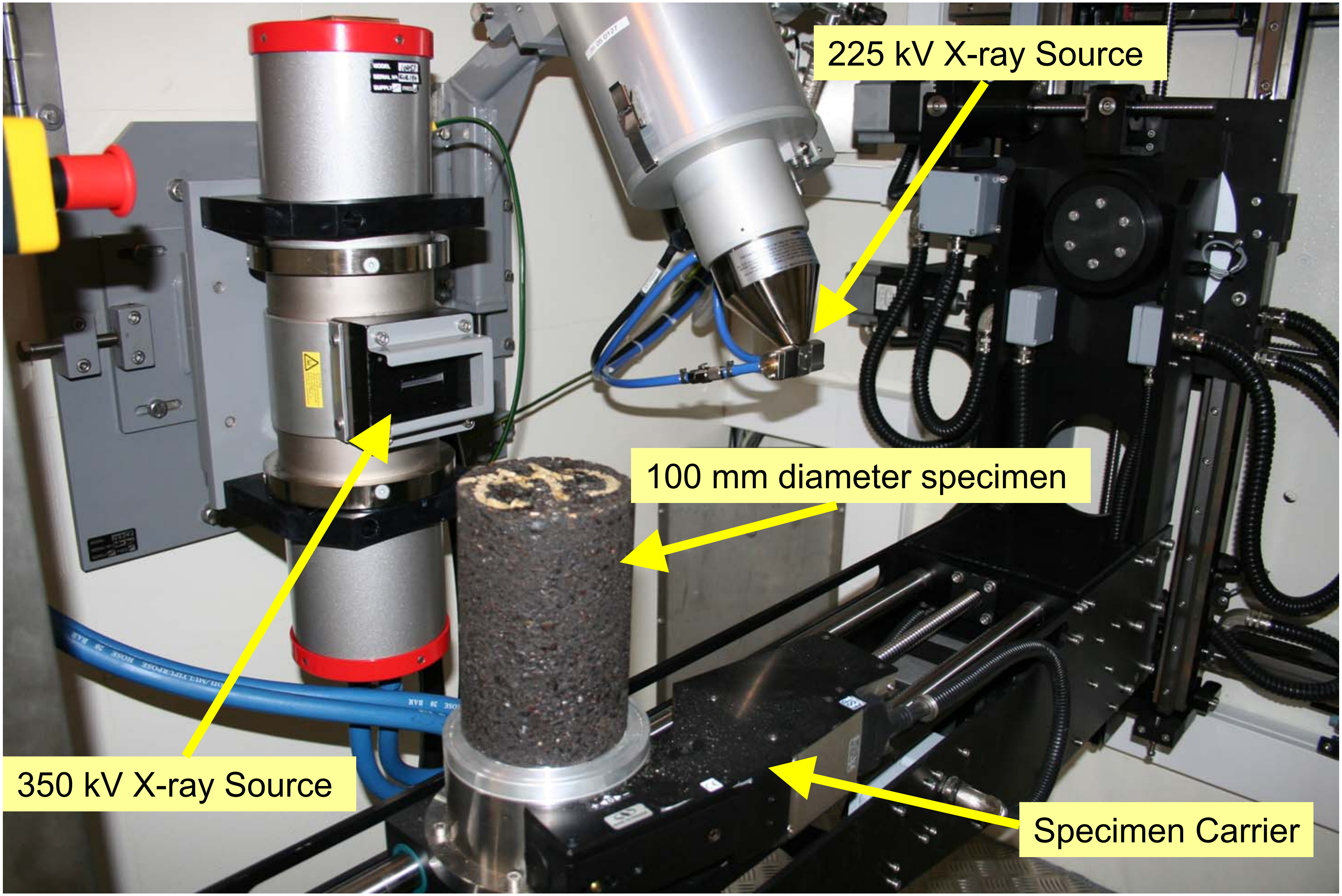
Rest Period=300
Rest Period=600
Strain
Time (Sec)
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
0
1000
2000
3000
4000


Axial Stress (Psi)
Axial Strain (%)
Δ=0.60
Δ=0.40
Δ=0.20
Δ=0.00
ξ=0 %
ξ=20%
ξ=40%
ξ=80%
α=0.70
α=0.50
α=0.30
α=0.10
κ=80
κ=50
κ=30
κ=0

Experimental Validation

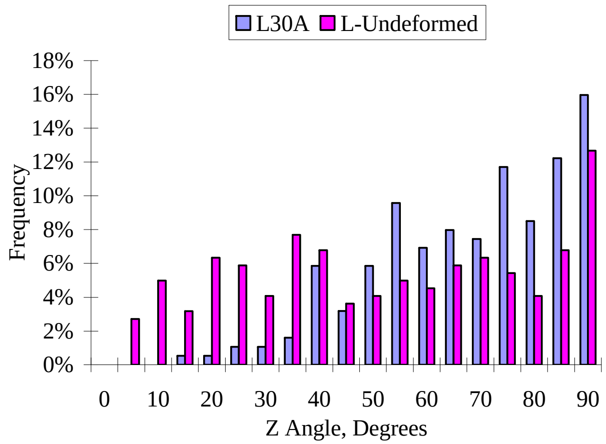
- 4 inch HMA Specimens.
- 3 aggregate types:
  - Gravel,
  - Limestone, and
  - Granite
- 7% target percent air void.

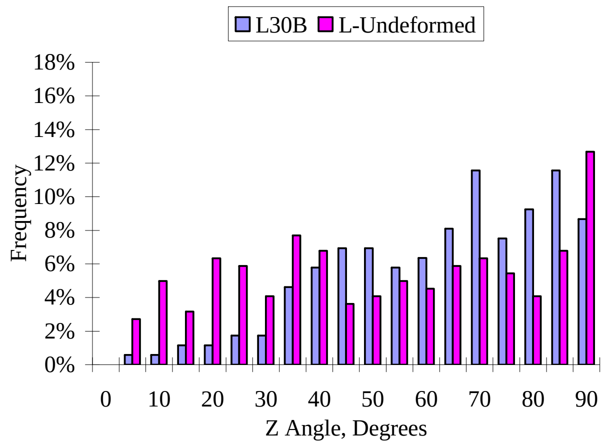
Microstructure Analysis

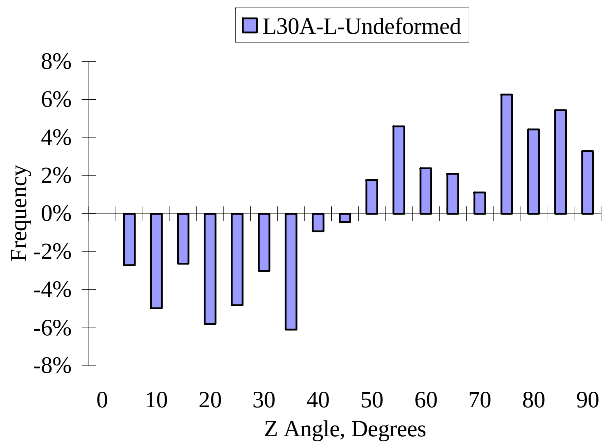


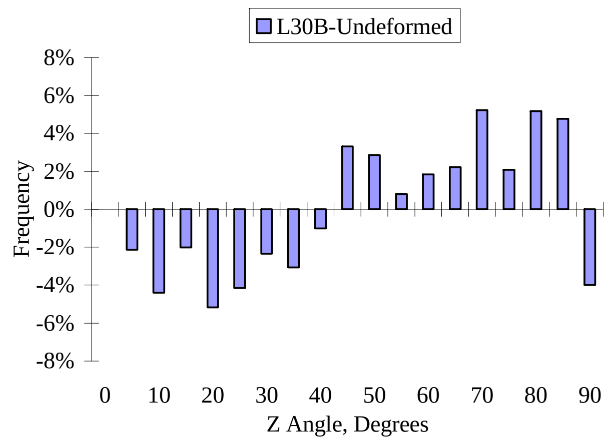
Anisotropy

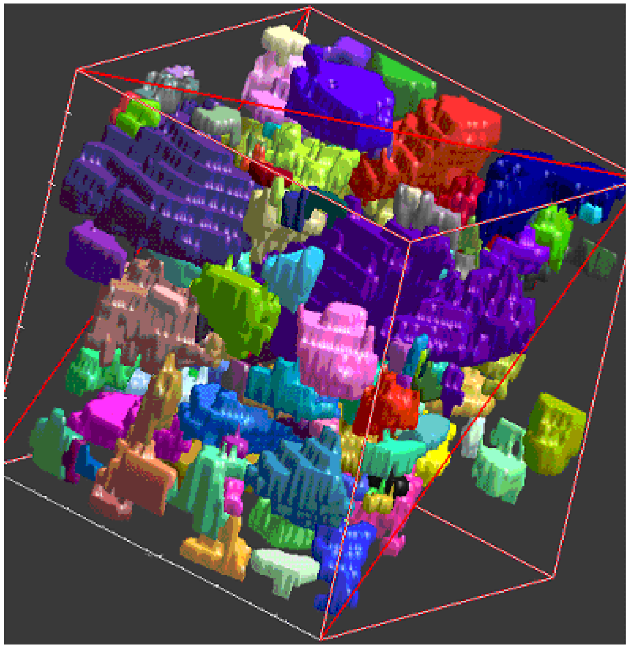
$$\overline{\sigma}_{ij} = \frac{3}{2}\left[\sigma_{ik}F_{kj} + F_{ik}\sigma_{kj}\right]$$









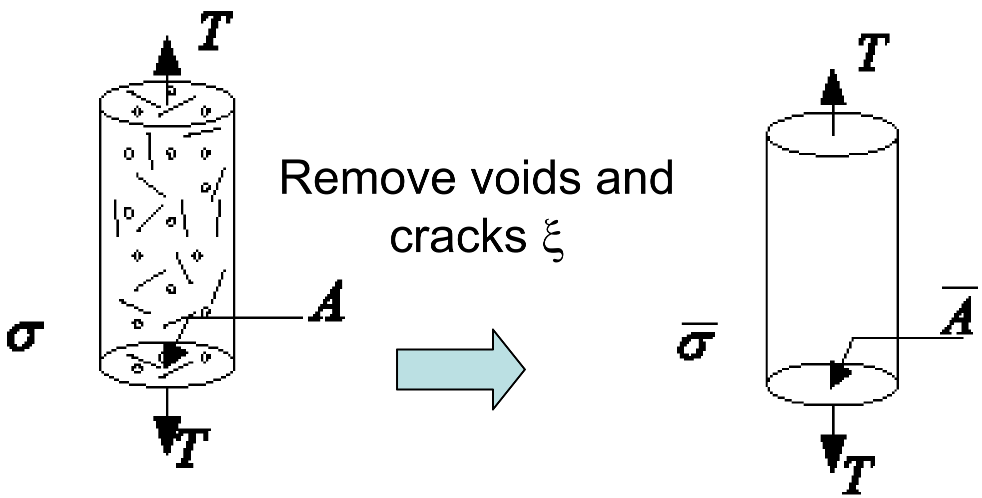


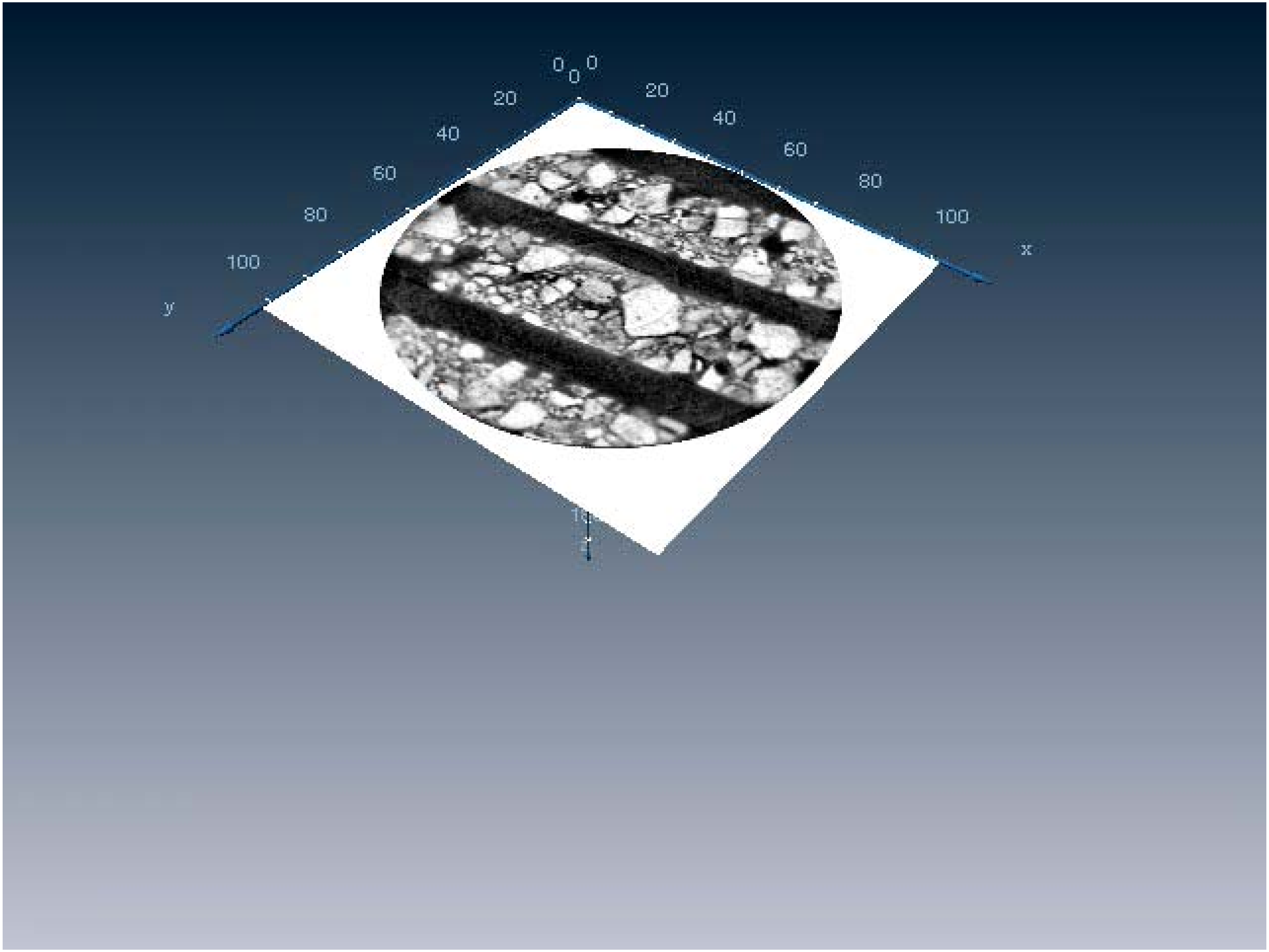
Damage

- Defects in the form of cracks and air voids

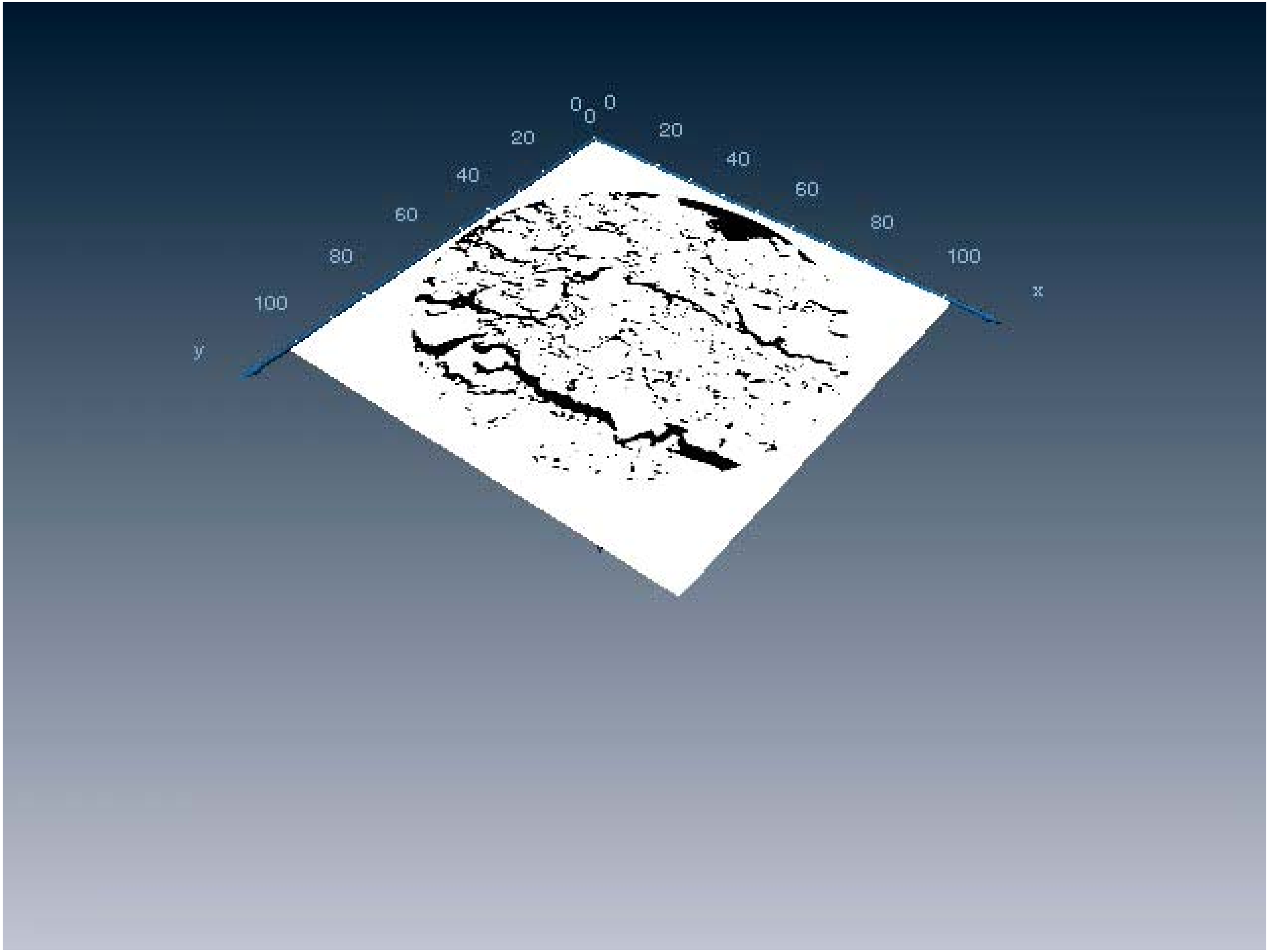
$$0 \leq \xi \leq 1$$

$$\overline{\sigma}_e = \frac{\sigma}{1-\xi}$$



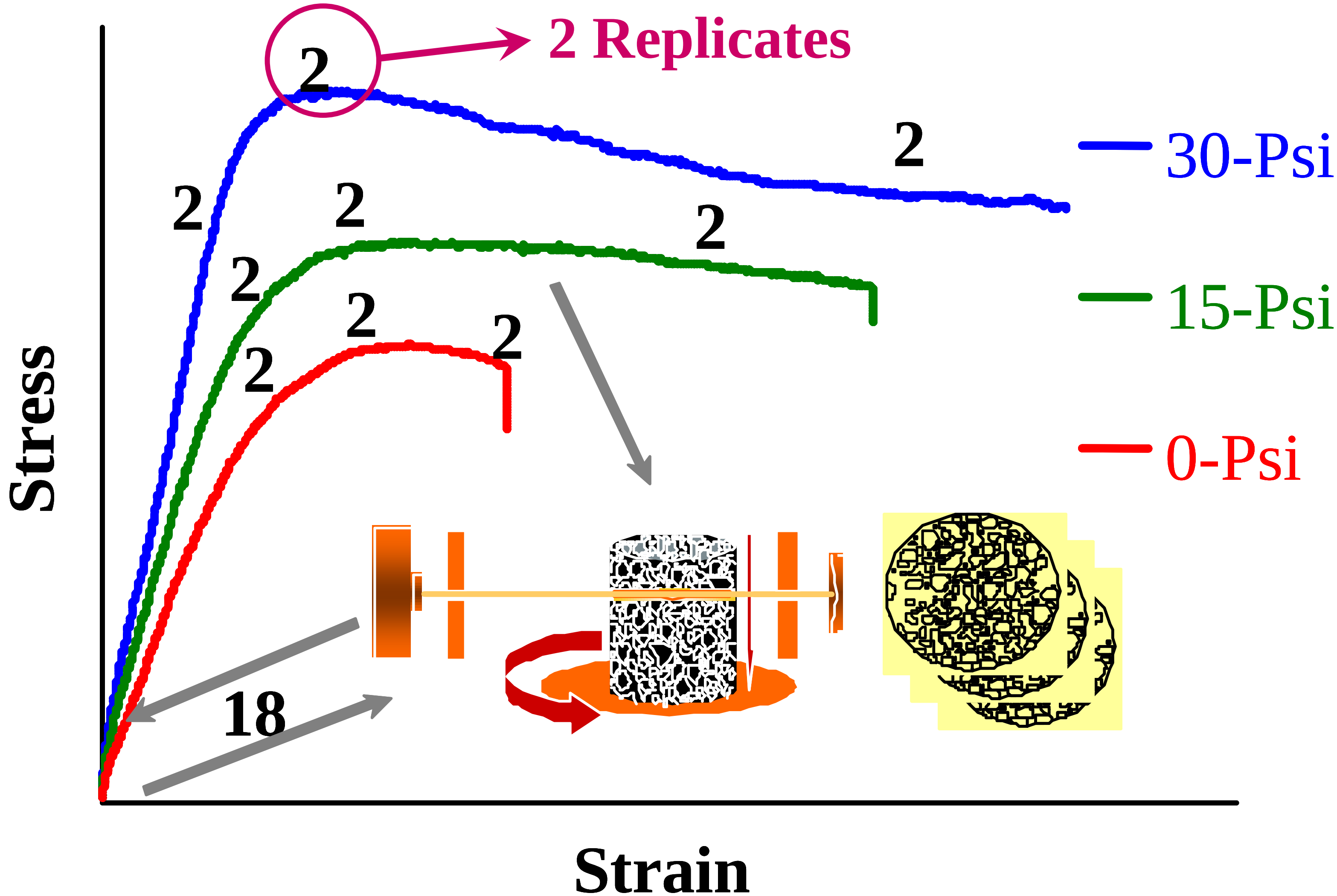


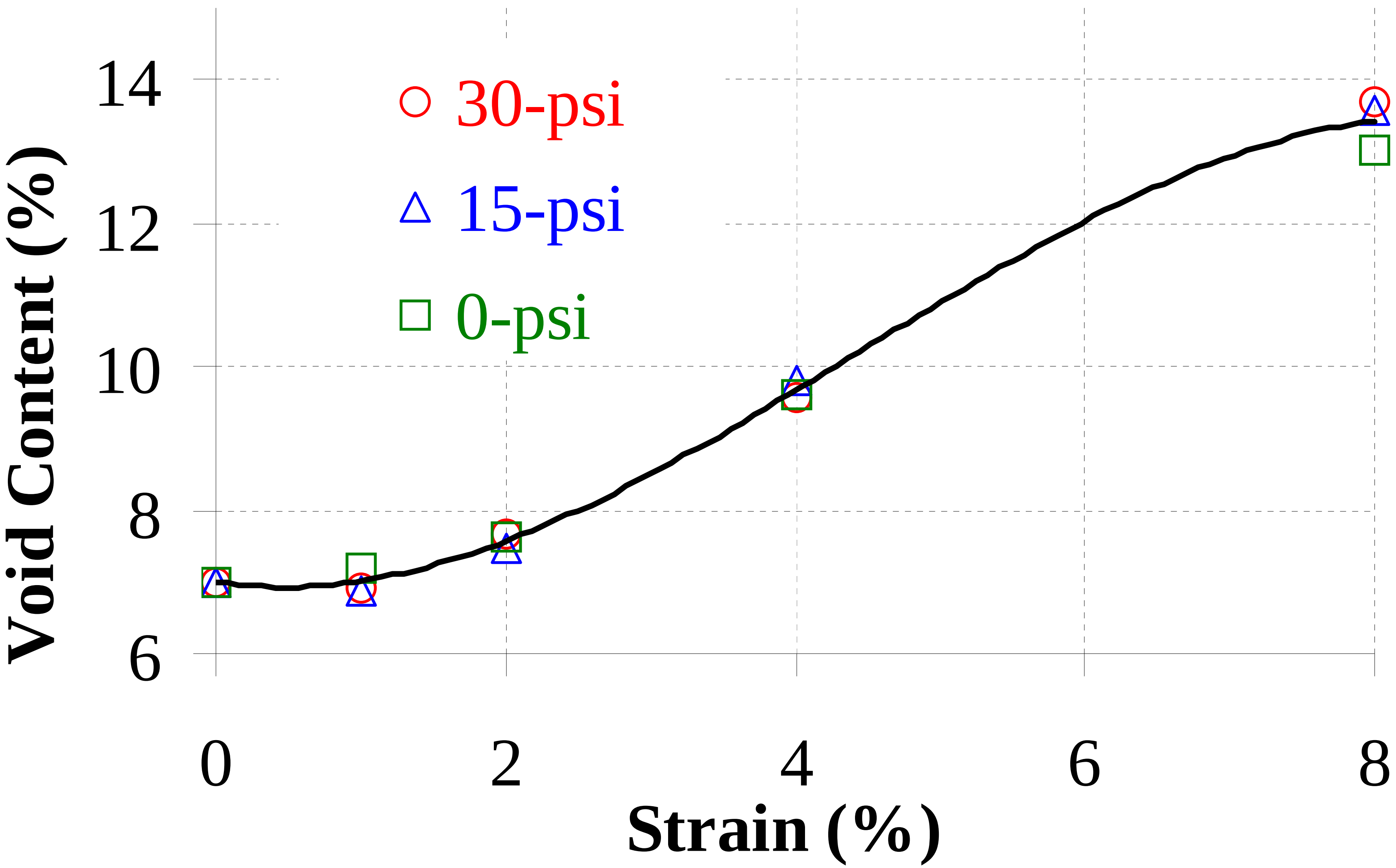
0
0
0
20
40
60
80
100
x
20
40
60
80
100
y



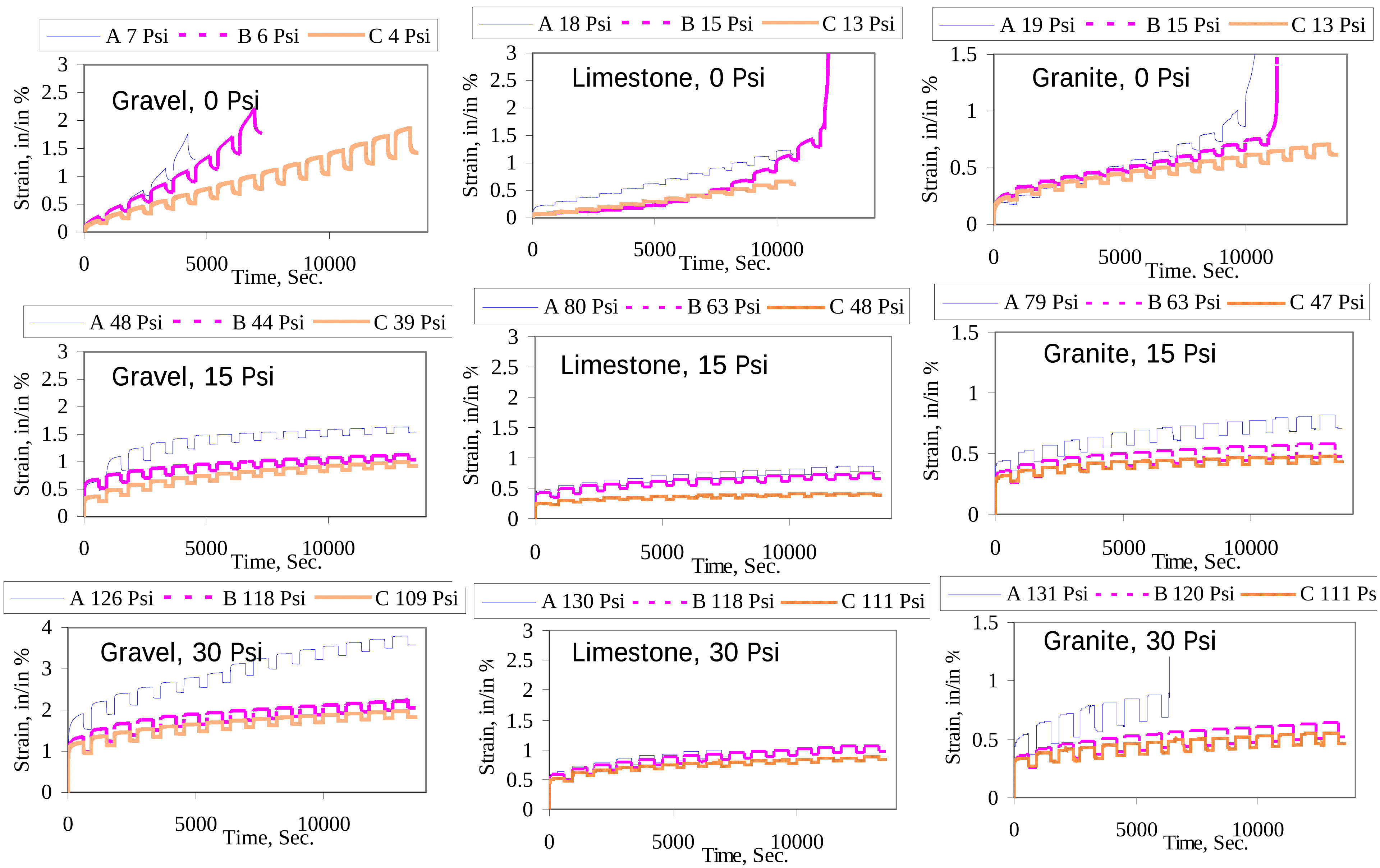
0
0
0
20
40
60
80
100
x
20
40
60
80
100
y

Damage Experiment

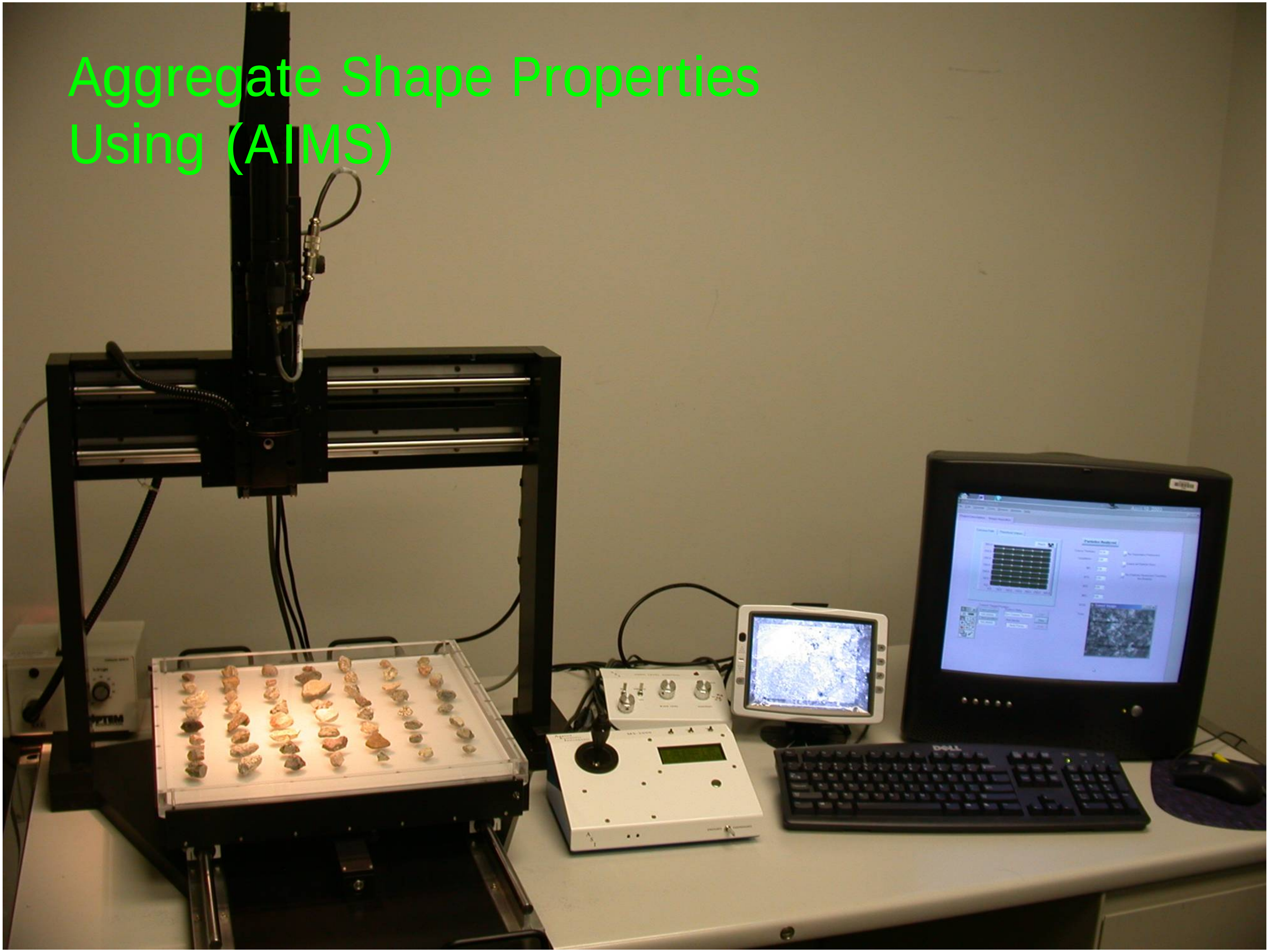


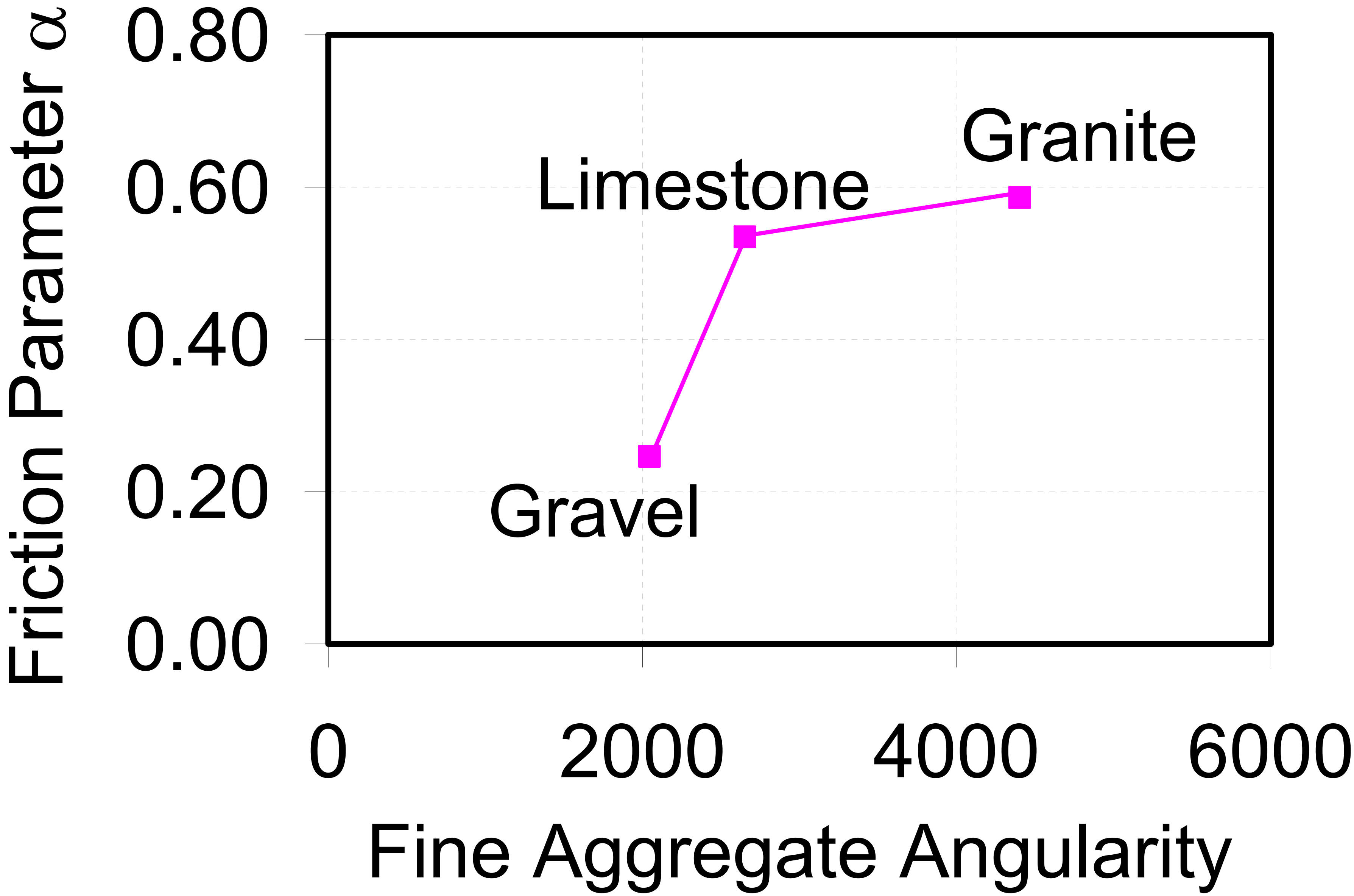

30-psi
15-psi
0-psi
Void Content (%)
Strain (%)
14
12
10
8
6
0
2
4
6
8

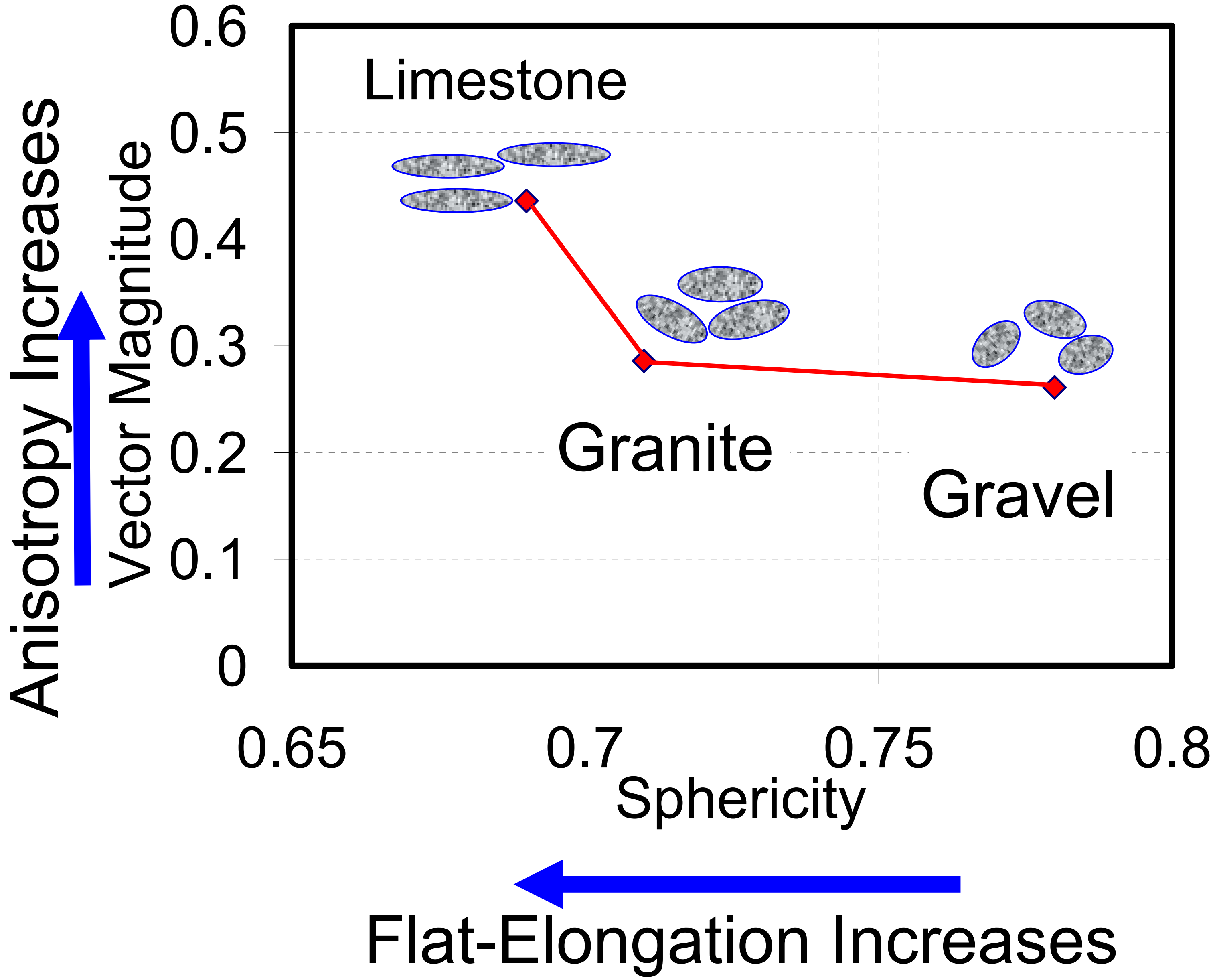
Repeated Creep Tests



Aggregate Shape Properties Using (AIMS)

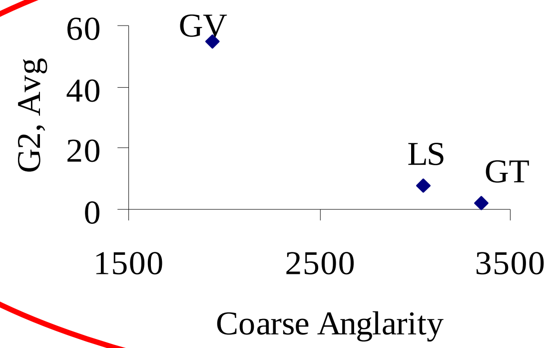


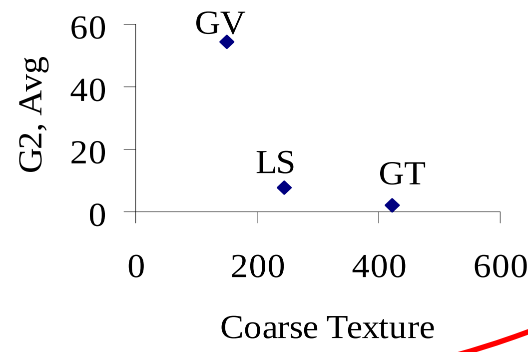

Friction Parameter α
0.80
0.60
0.40
0.20
0.00
Granite
Limestone
Gravel
0
2000
4000
6000
Fine Aggregate Angularity



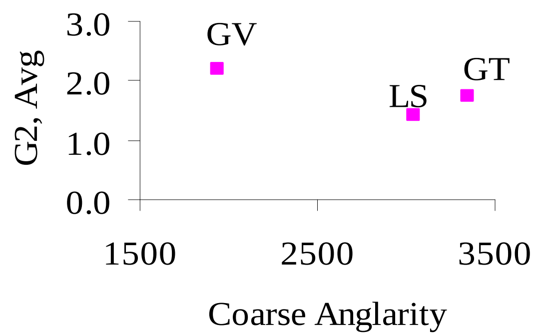
Anisotropy Increases
Vector Magnitude
0.6
0.5
0.4
0.3
0.2
0.1
0
Limestone
Granite
Gravel
0.65
0.7
0.75
0.8
Sphericity
Flat-Elongation Increases

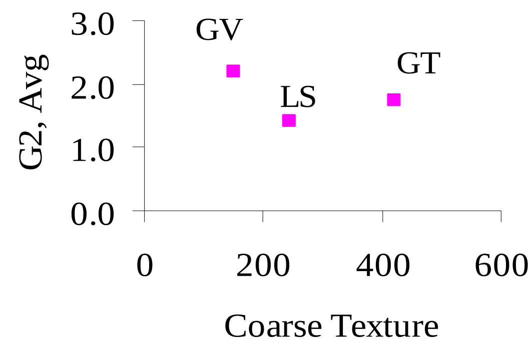
0 psi



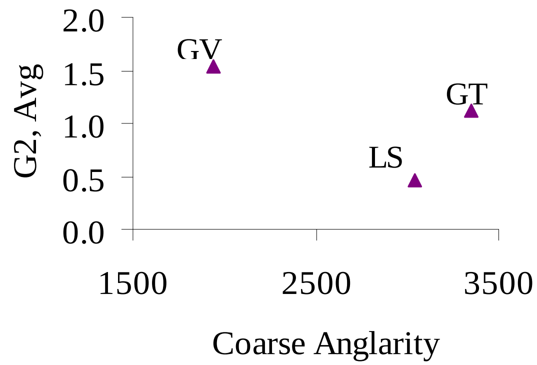


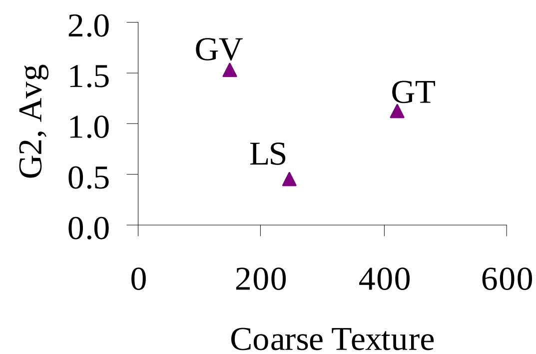
15 psi



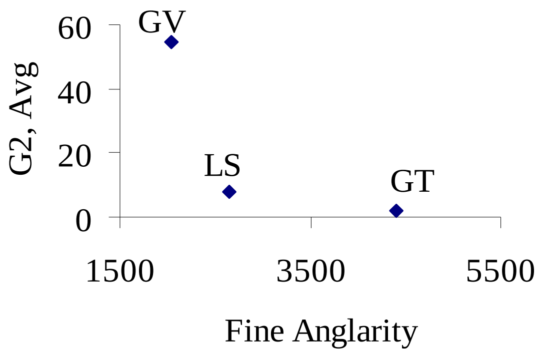


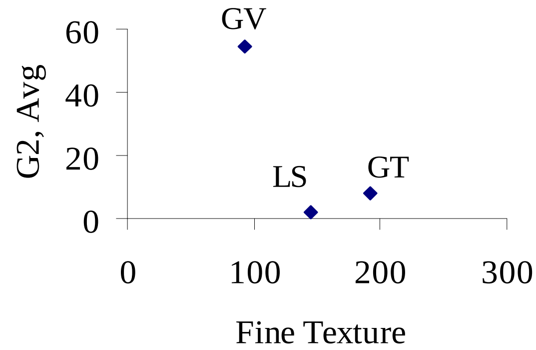
30 psi



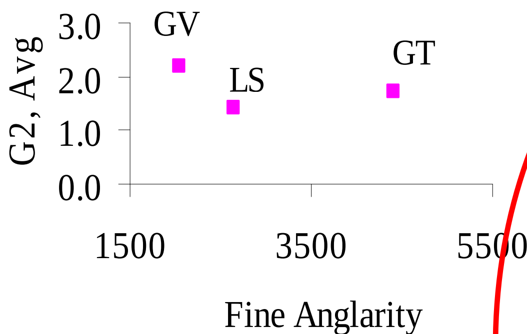


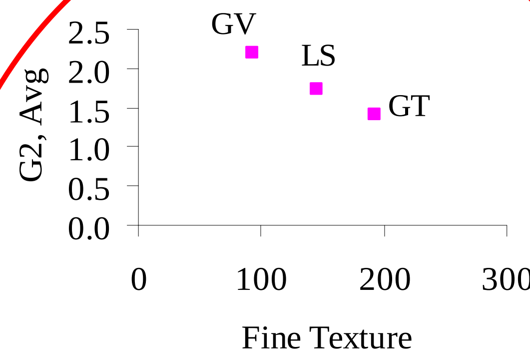
0 psi



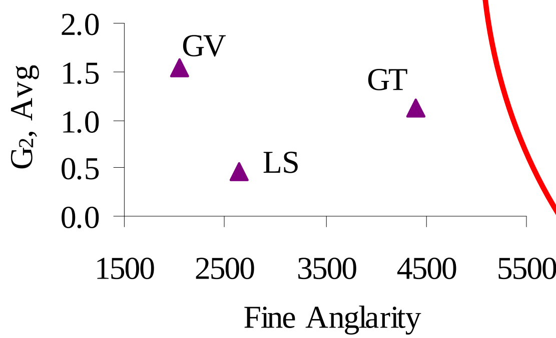


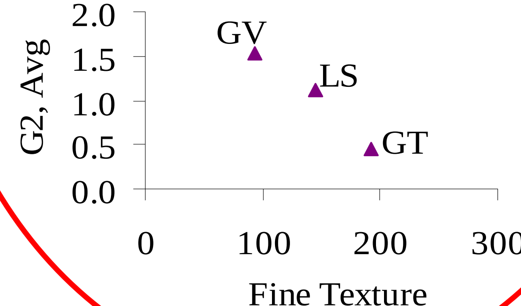
15 psi



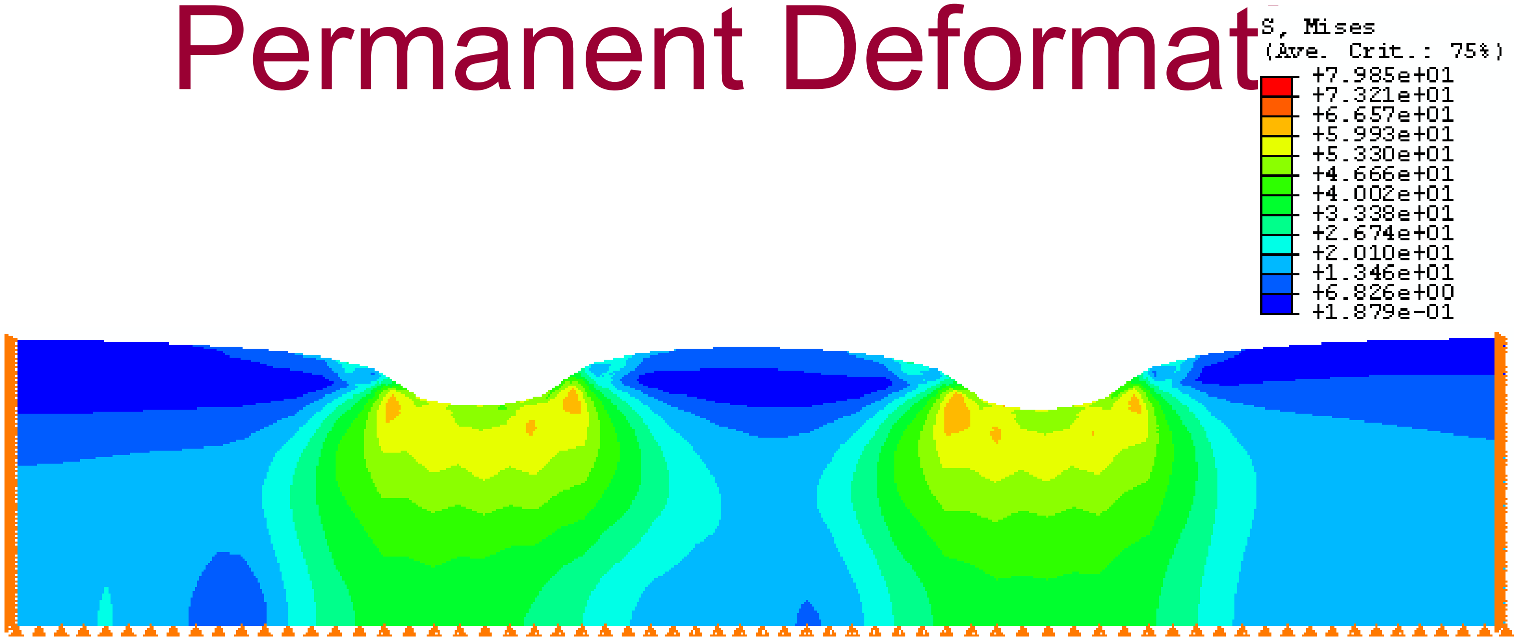


30 psi

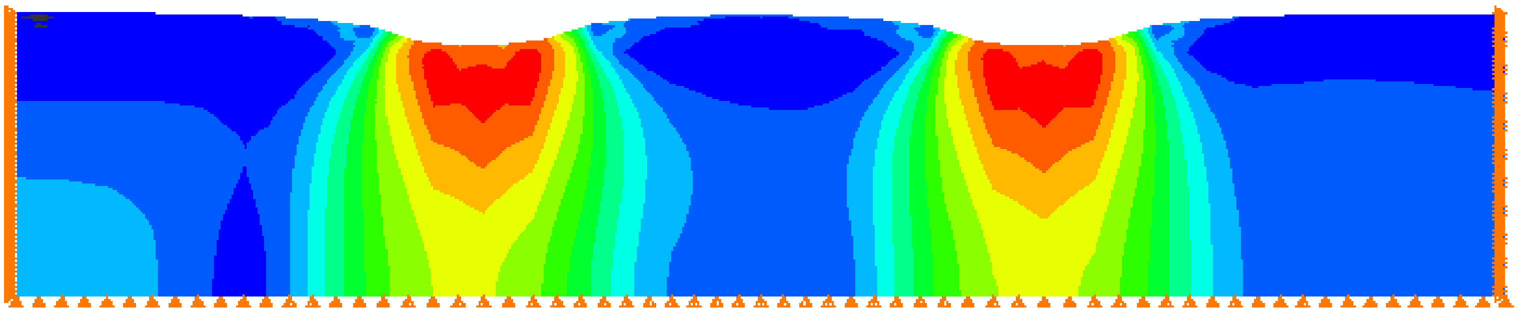




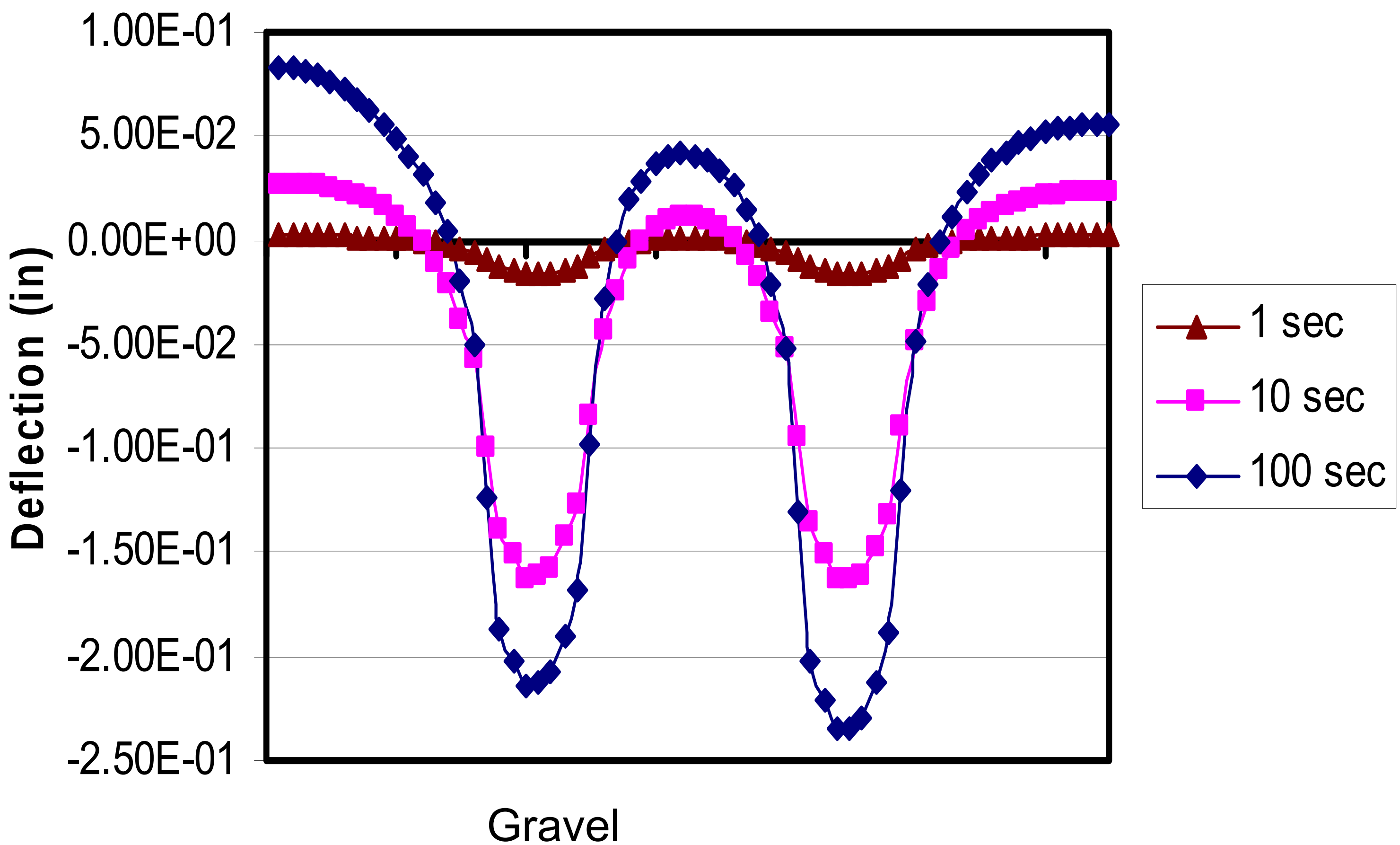
Effect of Anisotropy on Permanent Deformat



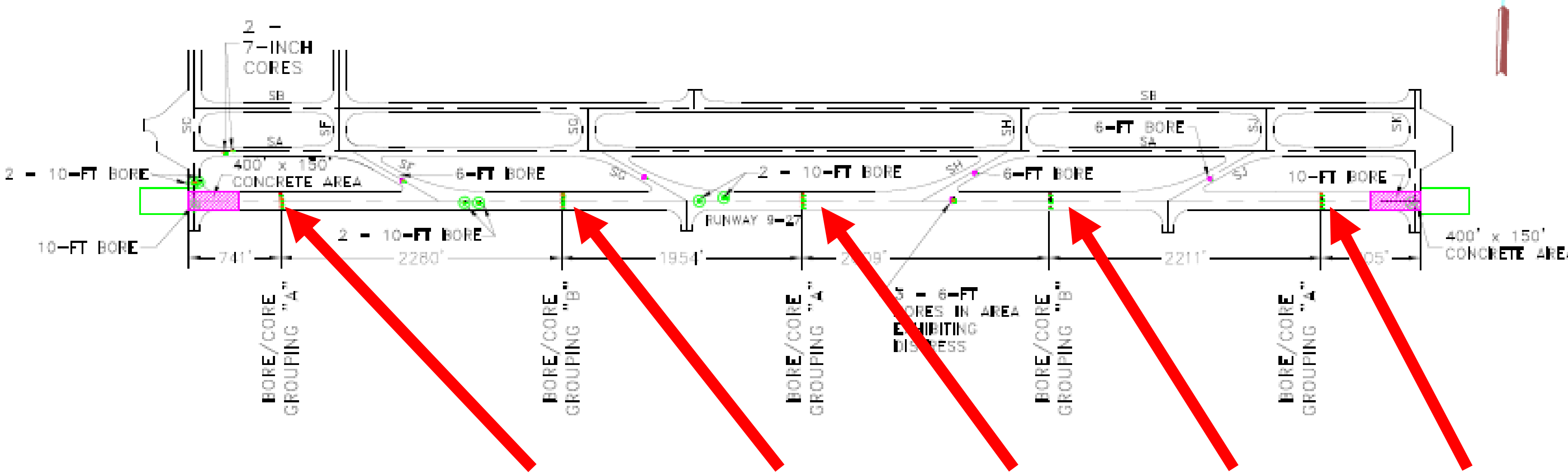
a) Isotropic layer (Δ =0)



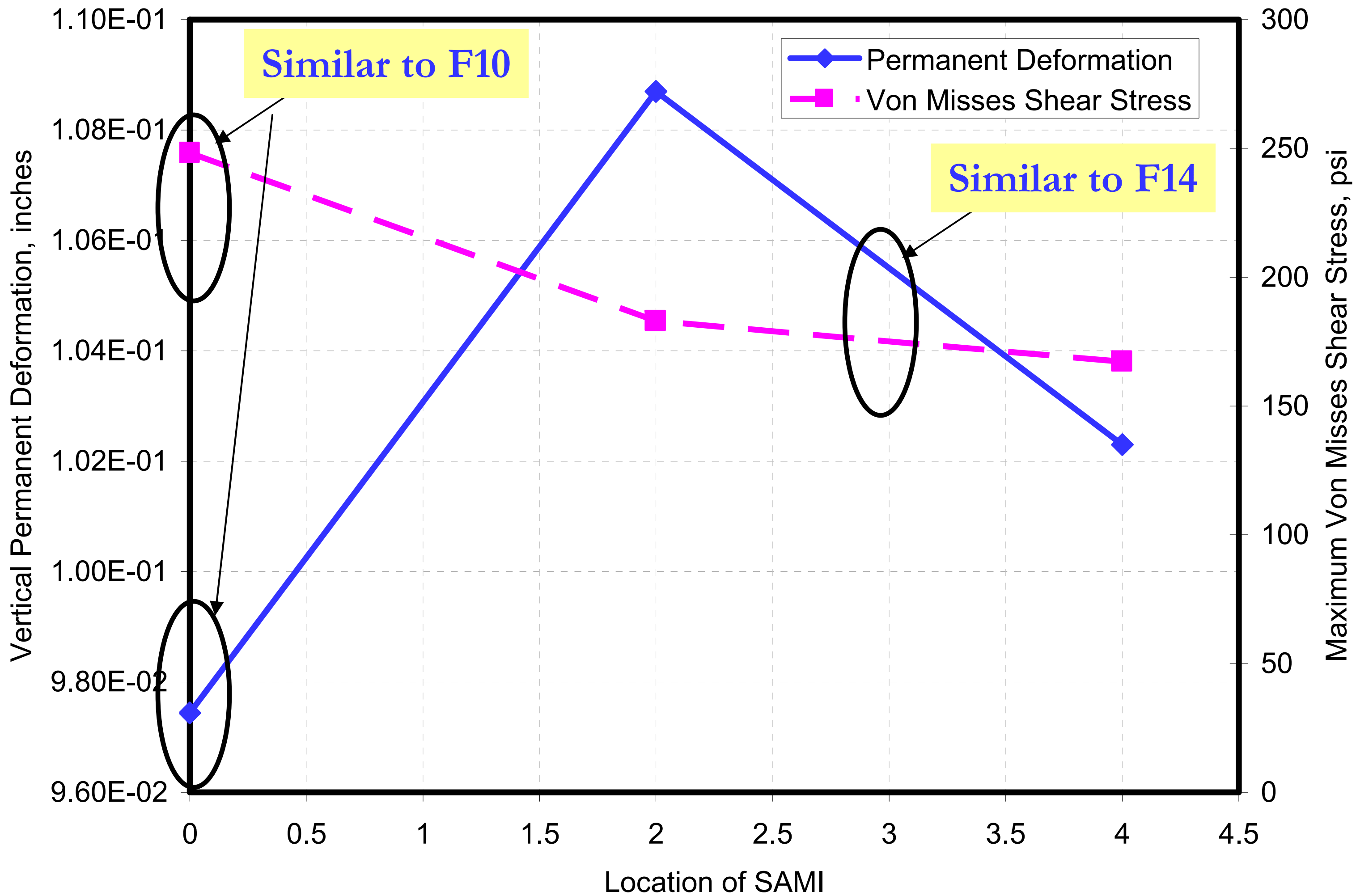
b) Anisotropic layer (Δ =30 percent)


1.00E-01
5.00E-02
0.00E+00
-5.00E-02
-1.00E-01
-1.50E-01
-2.00E-01
-2.50E-01
Deflection (in)
Gravel
1 sec
10 sec
100 sec

HAS Rehabilitation of Rwy 9-27



Item	Group A	Group B	Group C	Group D	Group E
Depth of AC	5½" – 6 5/8 "	6½" – 8 5/8"	8 ½" – 9"	7 5/8" – 10 ¼"	6 ¼' – 9"
Thickness of SAMI	¼" – ½"	½" – ¾"	1/8" – ¾"	¼" – ¾"	1/8" – 7/8"
Depth of Surface AC	3" – 5 3/8"	3 3/8" – 5"	5 ¾" – 6 1/8"	5 ¼" – 6"	3 5/8" – 6 3/8"



No SAMI Layer: High shear stresses at the surface and small permanent deformation.
Low depth SAMI Layer: Lower shear stresses and higher permanent deformation.
SAMI at more than 4 inches depth gives small shear stress and small permanent deformation.

In Summary

- Challenges:
  - Extensive experimental program (rate, temp., confinement, stress path..).
  - Long computational time to account for repeated loading.
  - Material variability.
  - Material heterogeneity.
- Opportunities:
  - Develop database or catalog of material properties and model parameters.
  - Simulate model predictions based on variability of material properties.
  - Incorporate realistic loading conditions.