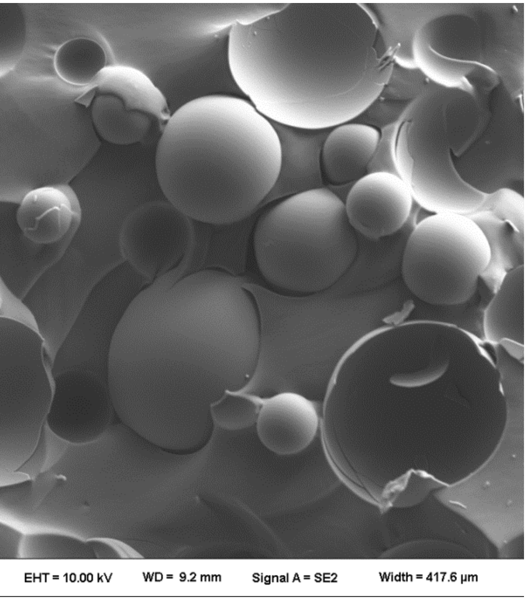
SEM 2015 Annual Conference and Exposition on Experimental and Applied Mechanics

SAND2015-4432C

Mechanical Behavior and Damage Mechanisms of Encapsulant-filled Elastomers



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6/4/2015

What is GMB-filled Sylgard®?

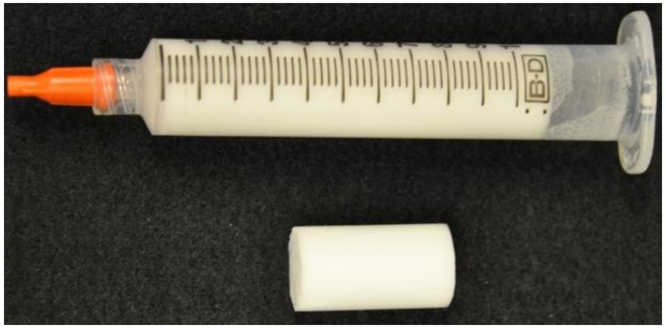
- **Syntactic foam**
  - **Sylgard silicone elastomer: Dimethylvinylated and trimethylated silica**
  - **Glass micro-balloons: Hollow spheres of soda-lime borosilicate glass**
- **Used in potting materials to protect components against corrosion, shock, etc.**
- **Glass micro-balloons added for many reasons**
  - **Increase stiffness**
  - **Lower thermal expansion coefficient.**
  - **Decrease density**
  - **Lower cure shrinkage**

	Pure Sylgard	Sylgard GMB (undamaged)
Coefficient of Thermal Expansion (ppm/C)	270	185
Young's Modulus (MPa)	1.84	13
Bulk Modulus (MPa)	920	71
Glass Transition Temperature (°C)	-60	-45

Sylgard® 184/A16 GMB composition

Sylgard composition

- 100 pbw Sylgard 184 base resin
- 10 pbw Sylgard 184 curing agent
- 10 pbw 3M A16 glass microballoons
- 10 pbw silicone accelerator
- Cured 16 hours at **21°C.**

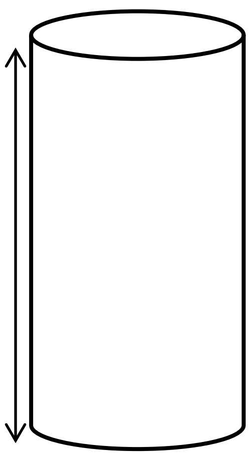


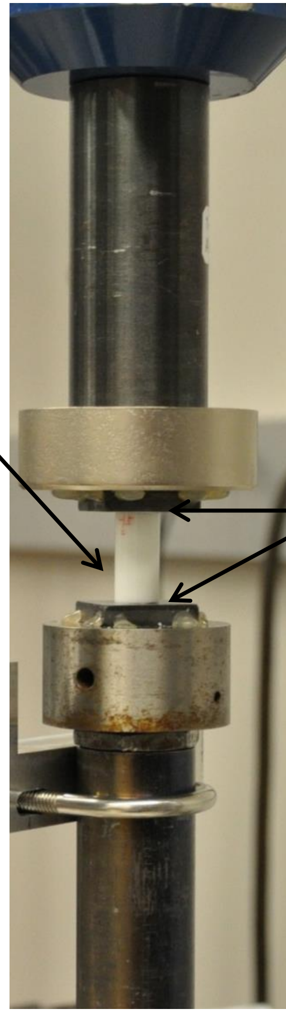
Sylgard® 184

3M A16 Glass Microballoons:

- Target crush strength (90% survival): 500 psi, 3.45 MPa
- True Density: 0.16 g/cc
- Average particle size: 70 µm
- Particle size range: 35–115 µm

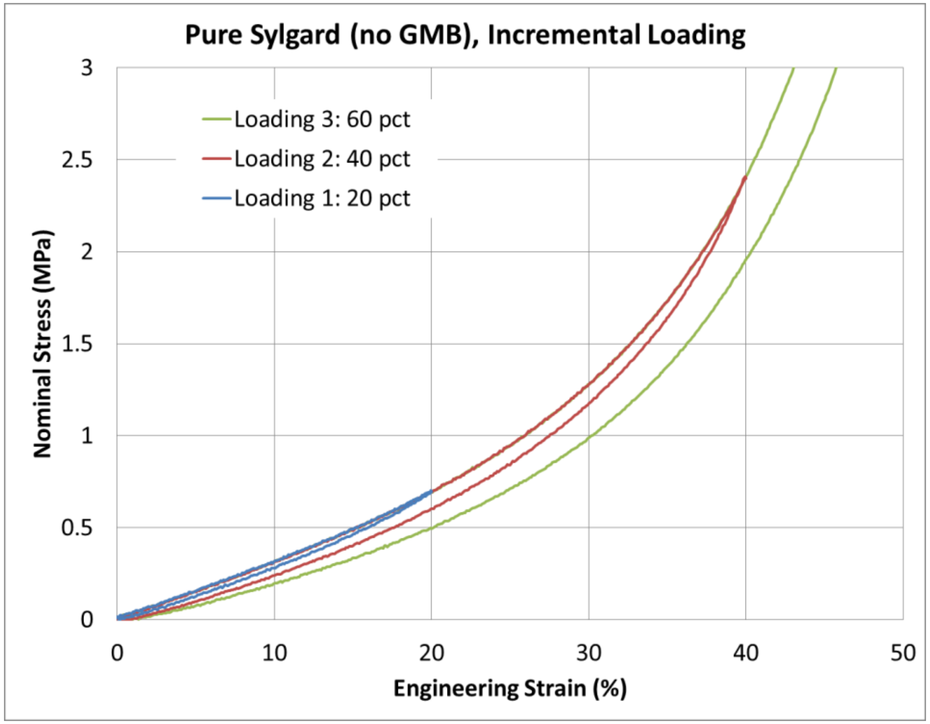
Experimental Setup



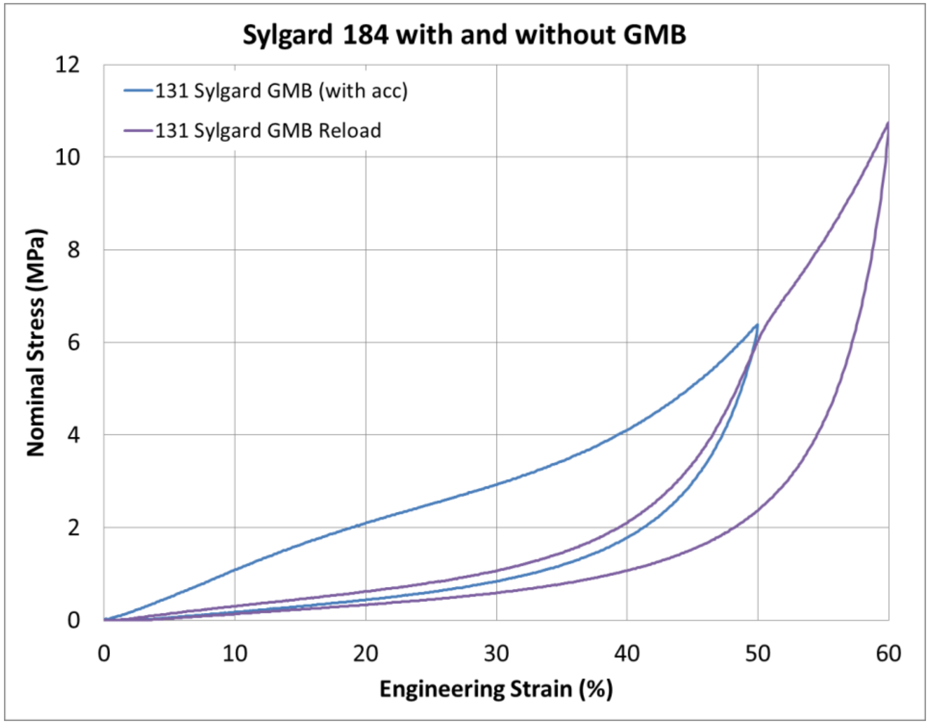


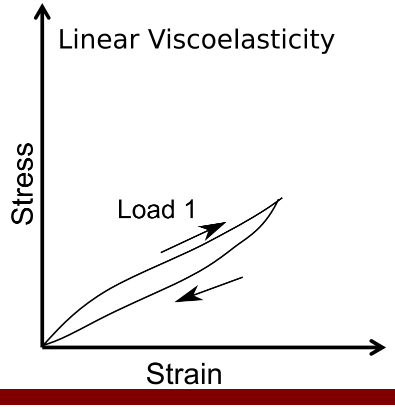
Hysteresis in stress-strain curves

Pure Sylgard can be loaded repeatedly with no damage (minor hysteresis).

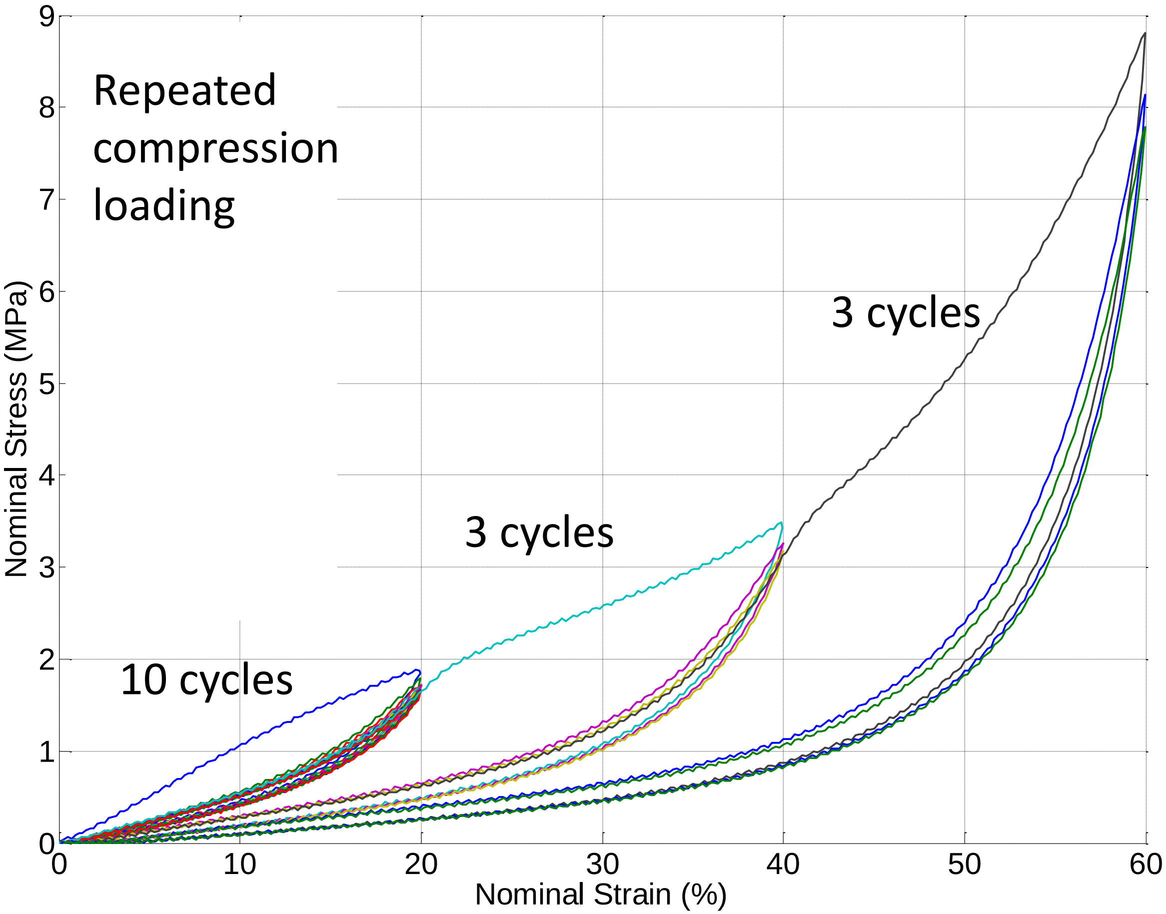


Sylgard-GMB exhibits the Mullins effect





No damage occurs until previous peak-load is achieved.



Damage Mechanisms in Syntactic Foams

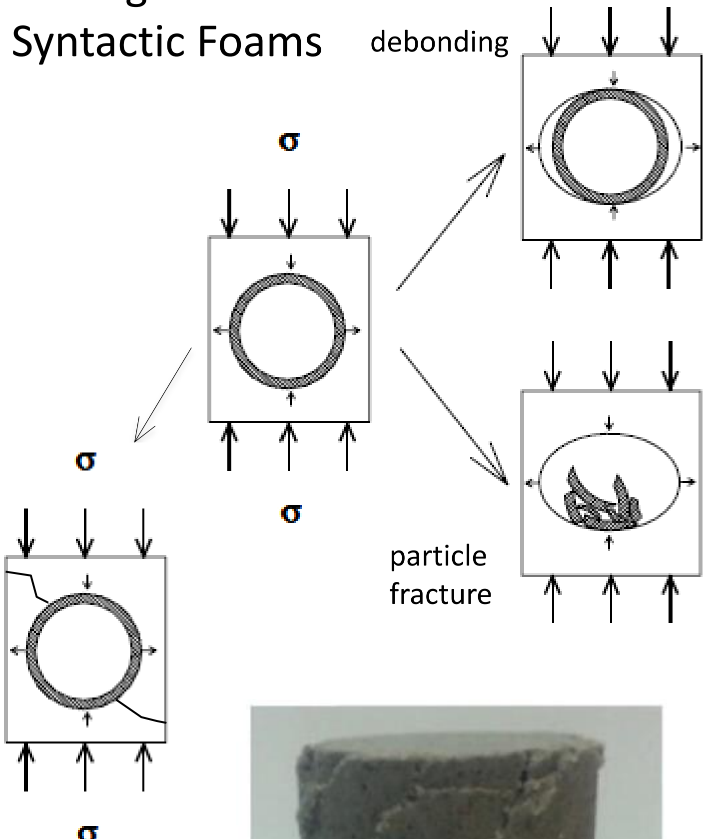


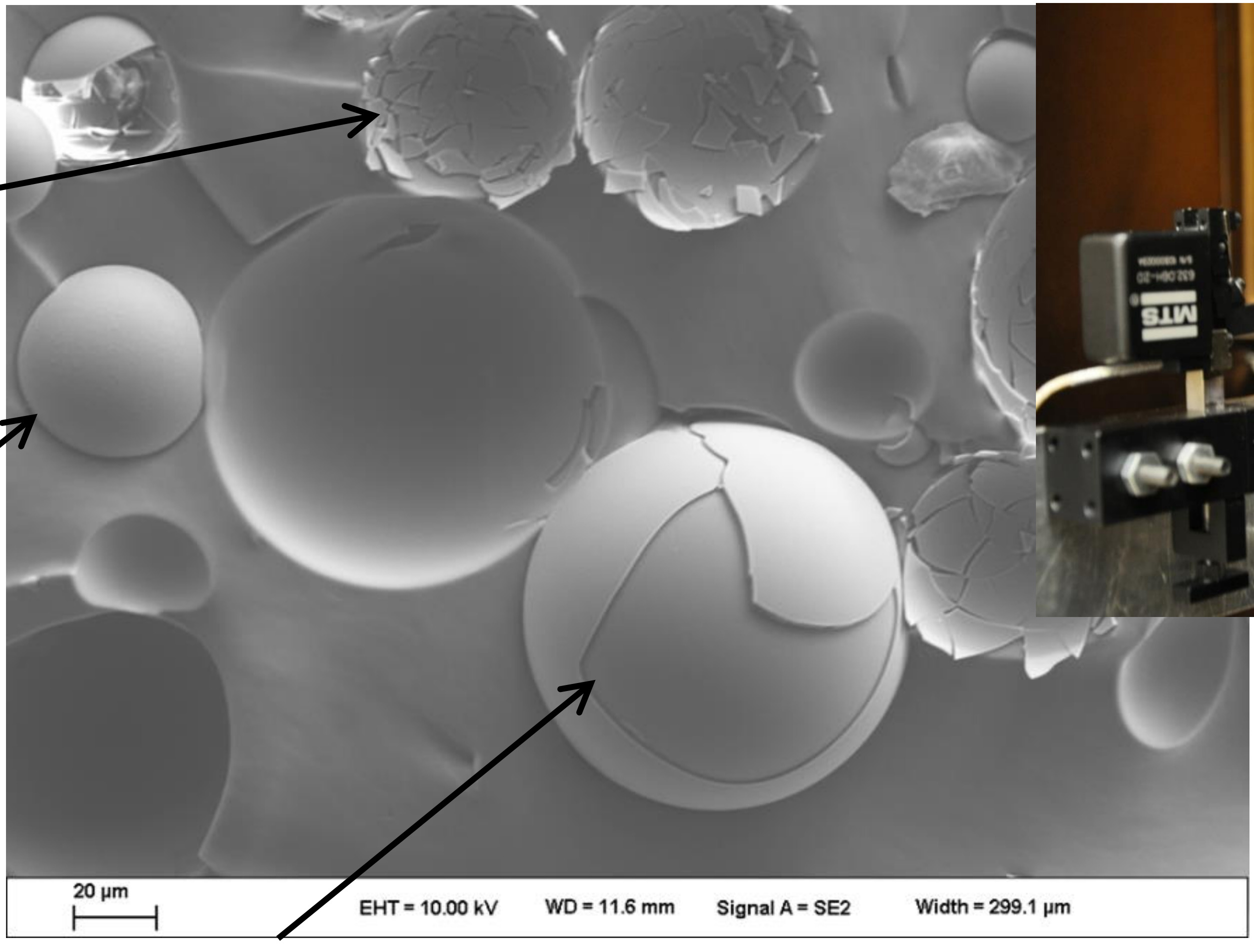
Figure 7. Shear cracks formed during plateau region on syntactic foam.

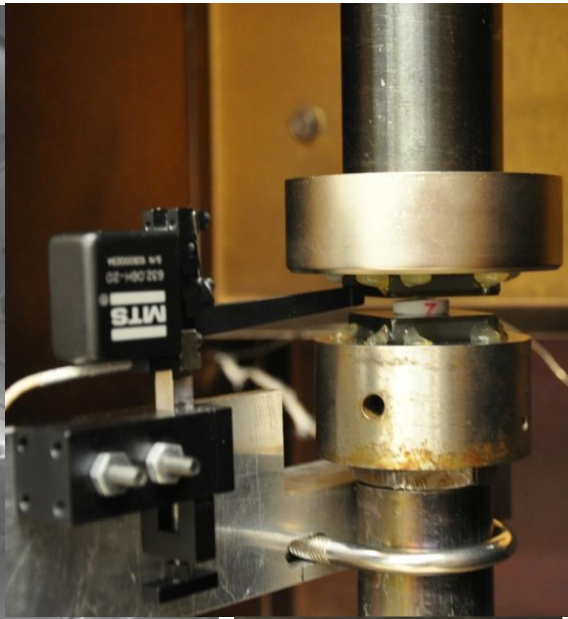
Taken after Gupta Dissertation 2003

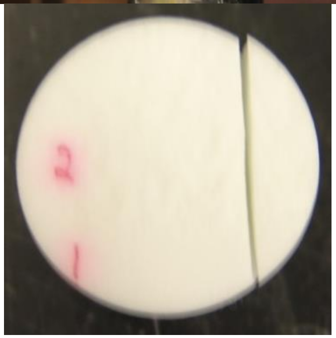
SEM images after loading provide insight

After compressive loading a thin disk (inner surface from tearing apart after loading)

Shattered GMBs indicate fracture during loading



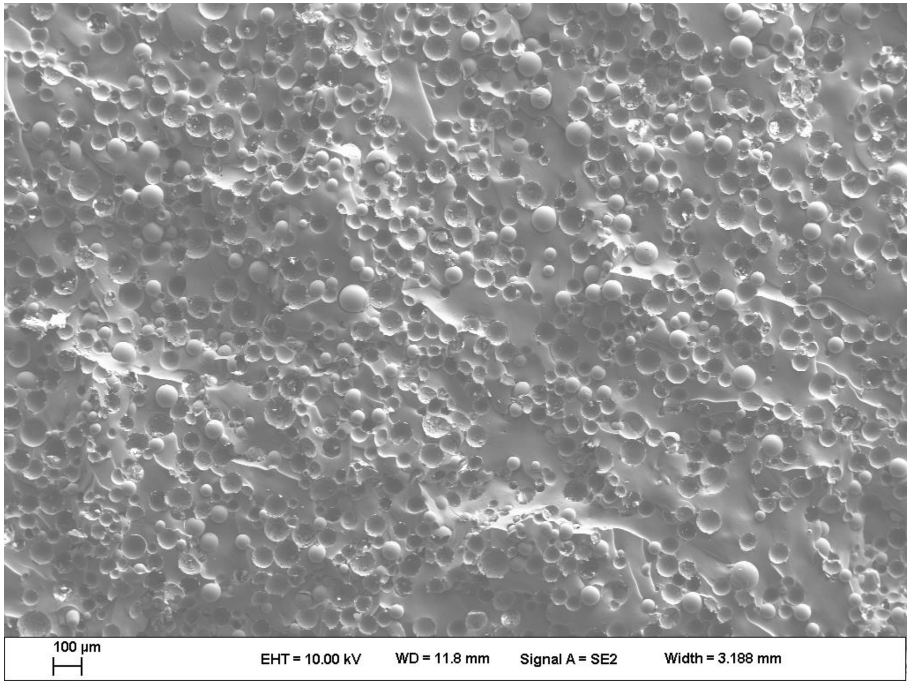


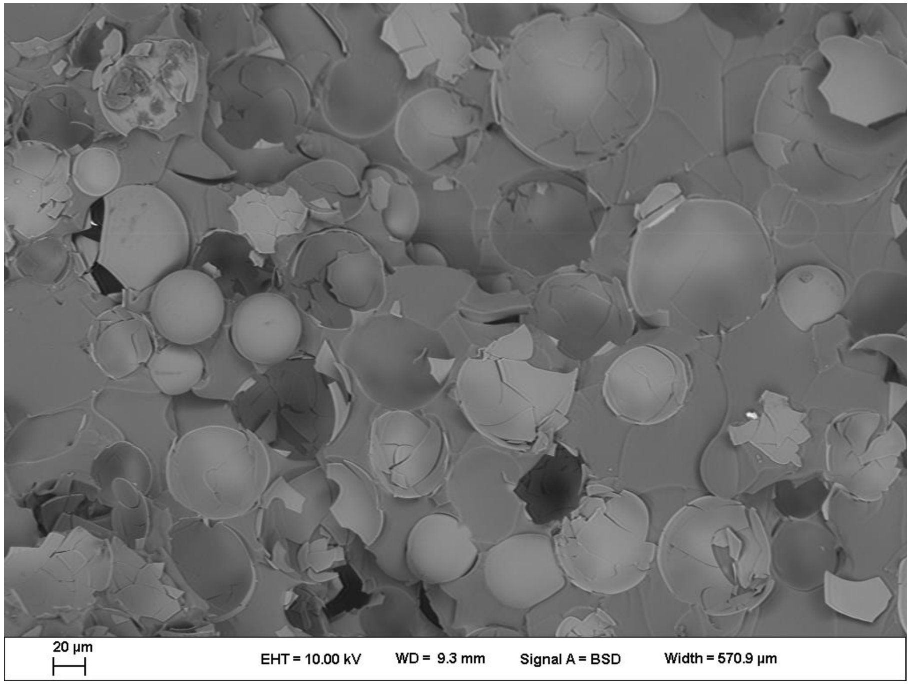


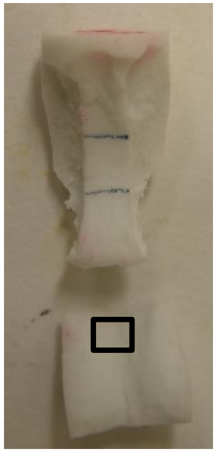
Intact GMBs indicate delamination

“Hard-boiled egg” structure indicates this GMB was broken before gel point. Sylgard flowed into GMB void.

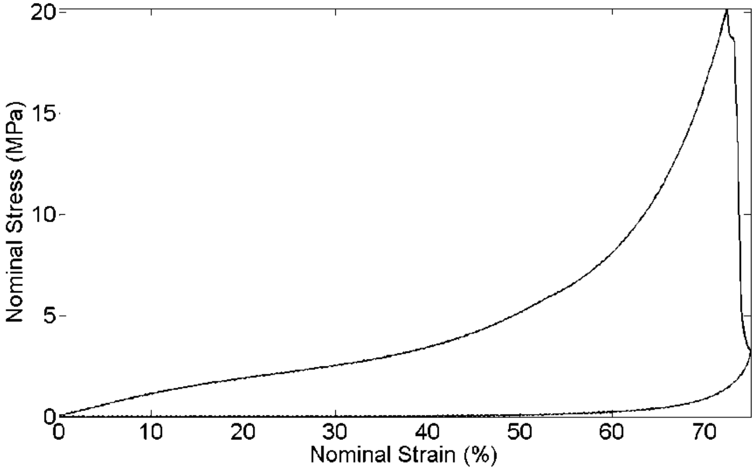
Internal fracture surface from loading specimen to compressive limit.





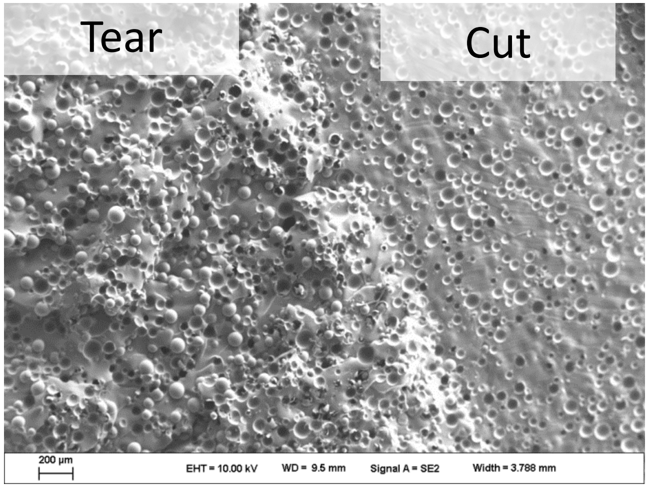


- **Undulating fracture surface**
- **Most GMBs broken**
- **Some GMBs intact**

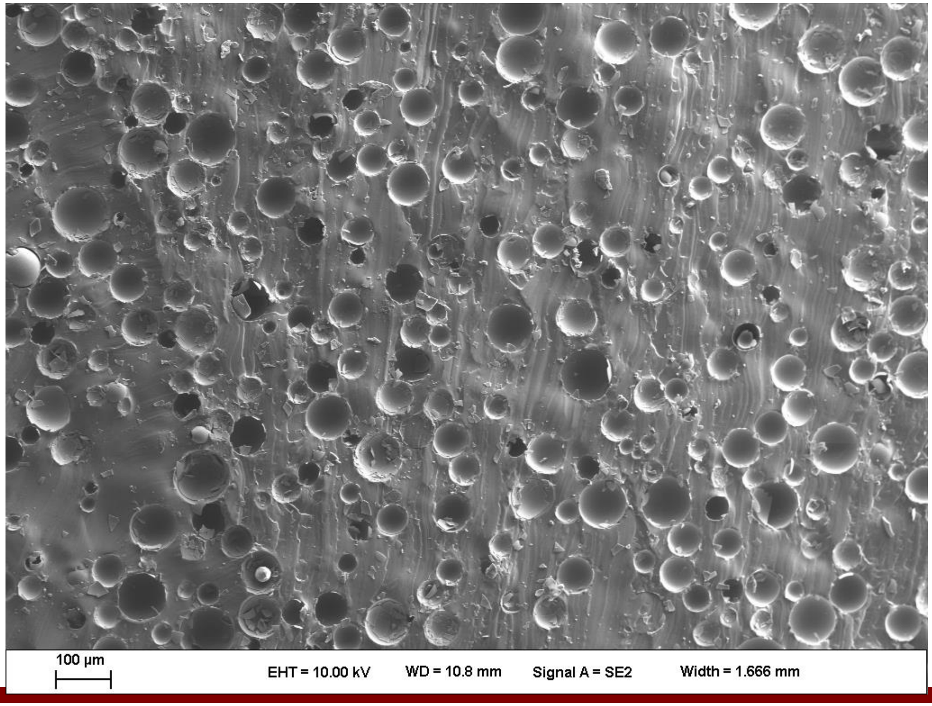


Imaging fracture surfaces depends strongly on specimen preparation.

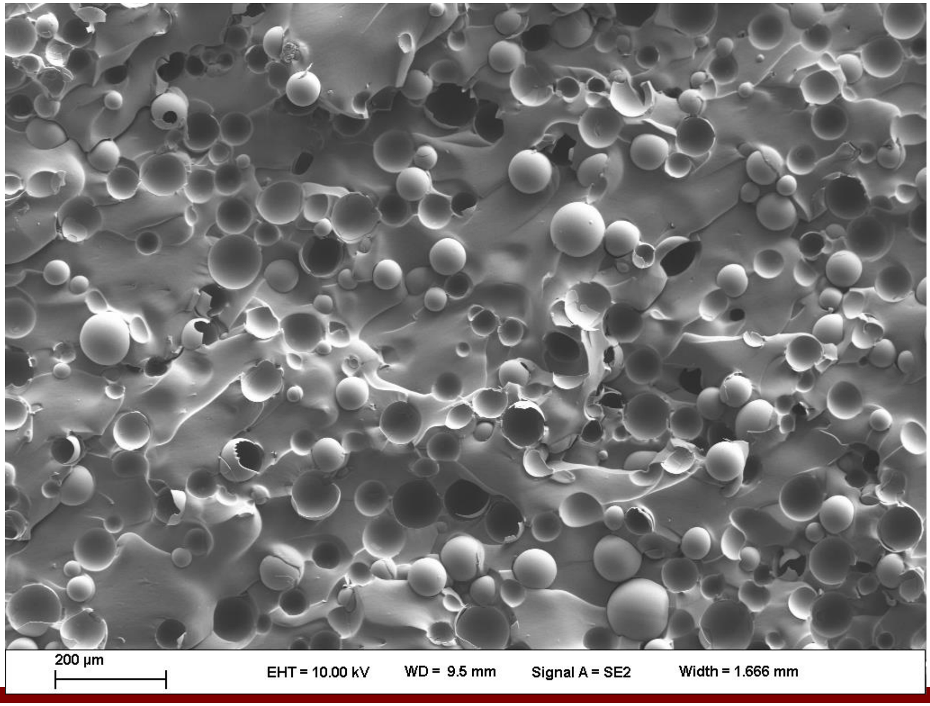
- **Neither specimen experienced compressive loading before fracture.**
- **Tearing fracture shows some signs of delamination and GMB fracture.**
- **Cutting with a razor blade fractures all GMBs in path.**



Cut surface

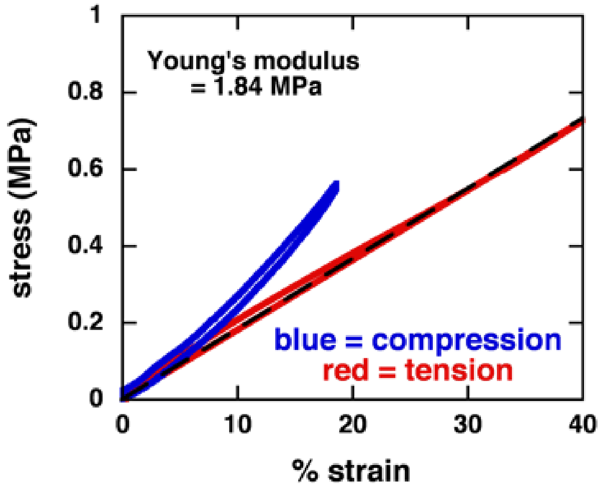


Tensile fractured surface

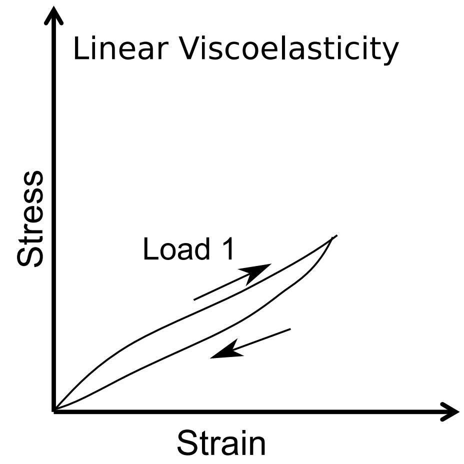


Typical Qualitative Macroscale Response of Filled Rubbery Thermosets Under Cyclic Loading

Elastic Response

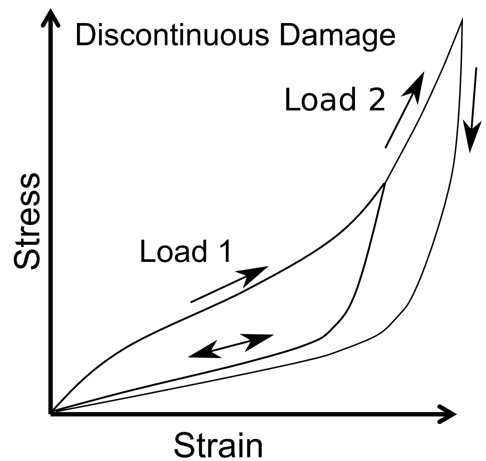


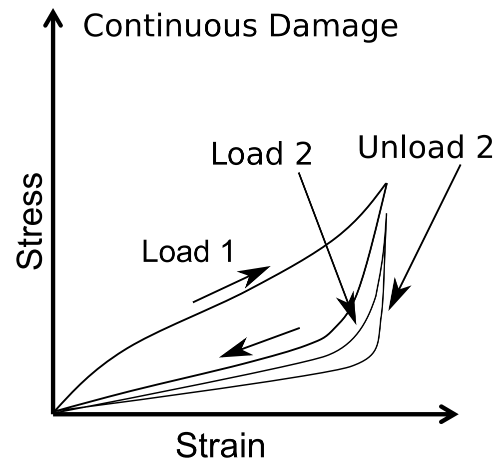
Legacy Sylgard 184



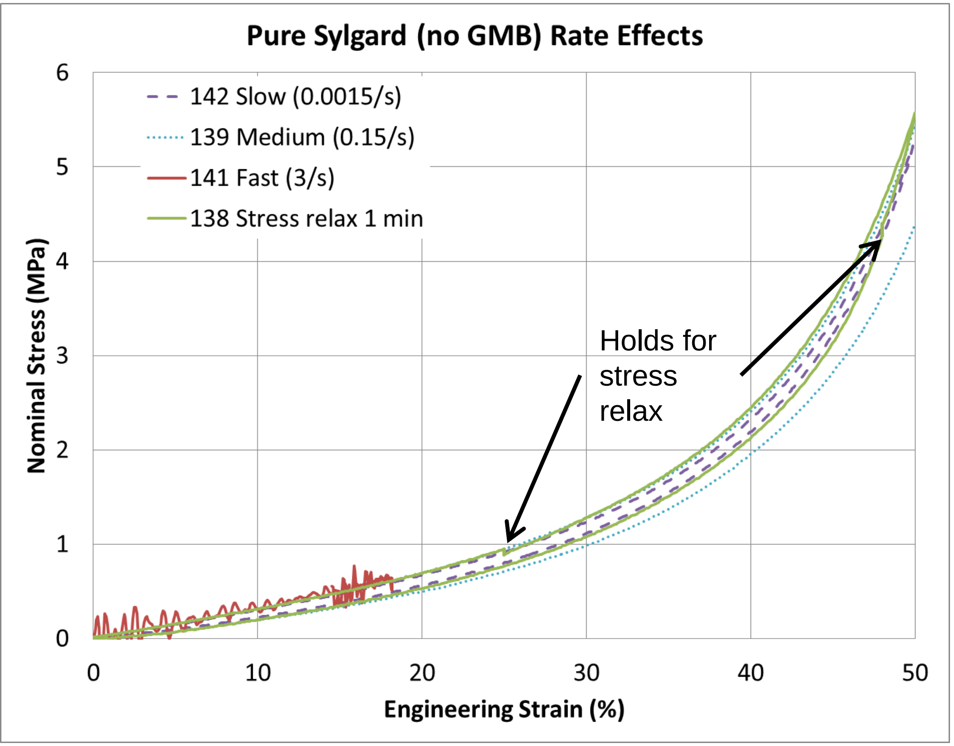
Damage types

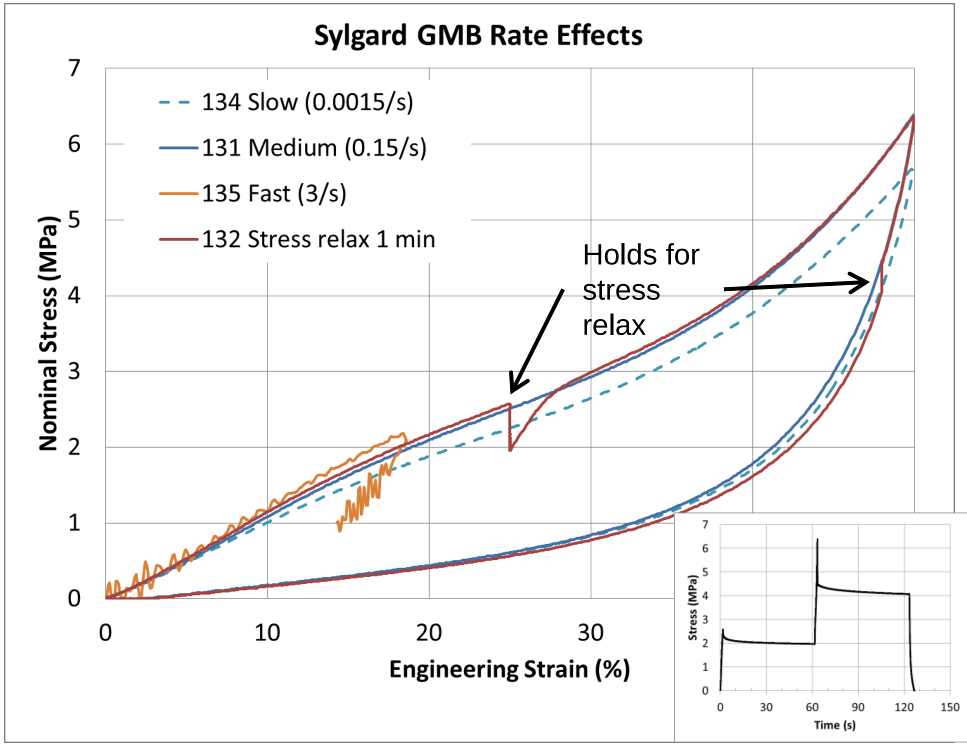
	Continuous	Discontinuous
Volumetric		
Isochoric		





Time dependence in pure Sylgard vs Sylgard-GMB





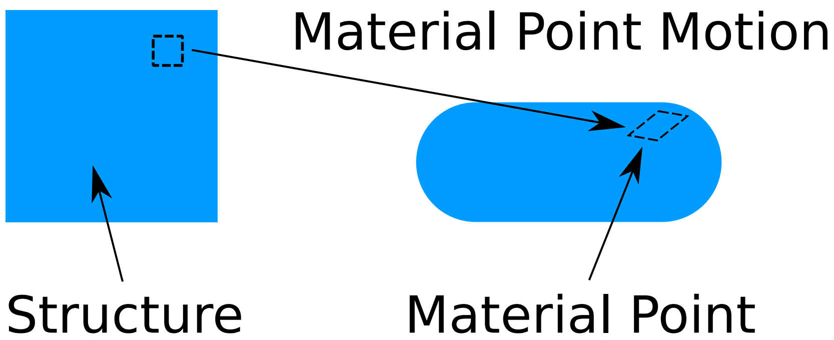
- Pure Sylgard has no measurable rate dependence. Rate effects are related to GMBs.
- Stress relax test had a 1 minute hold at 25% on loading and 48% on unloading. Pure Sylgard showed little stress relaxation.

- Sylgard/GMB has some rate dependence, particularly at slower speeds.
- Stress relax test had a 1 minute hold at 25% on loading and 48% on unloading. Sylgard GMB exhibits significant stress relaxation.

Phenomenological Macroscale Constitutive Model: Hyperelastic Yeoh Model With Discontinuous, Continuous Damage of Both Shear (Isochoric) and Volumetric Deformation

O.H. Yeoh. Rubber Chemistry and Technology, 63 (1990)

Kinematics of the structure and a material point



Deformation Gradient

$$\boldsymbol{F} = \frac{\partial \boldsymbol{x}}{\partial \boldsymbol{X}} = \boldsymbol{x}\nabla_X, \qquad J = \det(\boldsymbol{F}) > 0$$

Jacobian of the Motion

Isochoric Deformation Tensors

$$\overline{\boldsymbol{F}} = J^{-\frac{1}{3}}\boldsymbol{F}, \quad \overline{\boldsymbol{b}} = \overline{\boldsymbol{F}}\overline{\boldsymbol{F}}^T = J^{-\frac{2}{3}}\boldsymbol{F}\boldsymbol{F}^T = J^{-\frac{2}{3}}\boldsymbol{b}.$$

First Invariant of the Isochoric *b*

$$\overline{I}_1 = \operatorname{trace}\overline{\boldsymbol{b}}.$$

Strain Energy Per Unit Current Volume

- Isotropic function of isochoric and volumetric deformation invariants
- Kachanov-style scalar damage in 4 damage variables
- Temperature dependence only through thermal expansion

$$\psi\left(\overline{I}_1, J, T, d^d_{iso}, d^c_{iso}, d^d_{vol}, d^c_{vol}\right) = \left(1 - d^d_{iso} - d^c_{iso}\right)\psi_{iso}\left[\overline{I}_1\right] + \left(1 - d^d_{vol} - d^c_{vol}\right)\psi_{vol}\left[J\right],$$

$$\psi_{iso}\left[\overline{I}_1\right] = \frac{1}{2}\left(\mu_1\left(\overline{I}_1 - 3\right) + \mu_2\left(\overline{I}_1 - 3\right)^2 + \mu_3\left(\overline{I}_1 - 3\right)^3\right),$$

$$\psi_{vol}\left[J\right] = \frac{\kappa}{\beta^2}\left(\beta^2 J\alpha\Delta T + \beta\log[J] + J^{-\beta} - 1\right).$$

Phenomenological Macroscale Constitutive Model: Hyperelastic Yeoh Model With Discontinuous, Continuous Damage of Both Shear (Isochoric) and Volumetric Deformation

Non-Linear Shear Response

$$\mu_{eff} = \mu_1 + 2\mu_2\left(\overline{I}_1 - 3\right) + 3\mu_3\left(\overline{I}_1 - 3\right)^2$$

Infinitesimal Shear Modulus

Lockup Behavior

Kirchoff Stress

$$\boldsymbol{\tau} = 2\boldsymbol{b}\frac{\partial\psi}{\partial\boldsymbol{b}} = 2\frac{\partial\psi}{\partial\boldsymbol{b}}\boldsymbol{b} = \boldsymbol{\tau_{iso}} + \boldsymbol{\tau_{vol}},$$

$$\boldsymbol{\tau_{iso}} = 2\mu_{eff}\left(1 - d^d_{iso} - d^c_{iso}\right)\left(\overline{\boldsymbol{b}} - \frac{\overline{I}_1}{3}\mathbf{1}\right) = \left(1 - d^d_{iso} - d^c_{iso}\right)\boldsymbol{\tau^0_{iso}},$$

$$\boldsymbol{\tau_{vol}} = \frac{\kappa}{2}\left(1 - d^d_{vol} - d^c_{vol}\right)\left(2J\alpha\Delta T + J^2 - 1\right)\mathbf{1} = \left(1 - d^d_{vol} - d^c_{vol}\right)\boldsymbol{\tau^0_{vol}},$$

Discontinuous Damage Evolution

Maximum Strain Energy Densities

$$d^d_{iso} = d^{dMAX}_{iso}\left(1 - \exp\left(-\frac{\mathrm{MAX}[\psi_{iso}\left[\overline{I}_1\right]]}{d^{dSAT}_{iso}}\right)\right),$$

$$d^d_{vol} = d^{dMAX}_{vol}\left(1 - \exp\left(-\frac{\mathrm{MAX}[\psi_{vol}\left[J[t]\right]]}{d^{dSAT}_{vol}}\right)\right)$$

Continuous Damage Evolution

$$d^c_{iso} = d^{cMAX}_{iso}\left(1 - \exp\left(-\frac{\beta_{iso}[t]}{d^{cSAT}_{iso}}\right)\right)$$

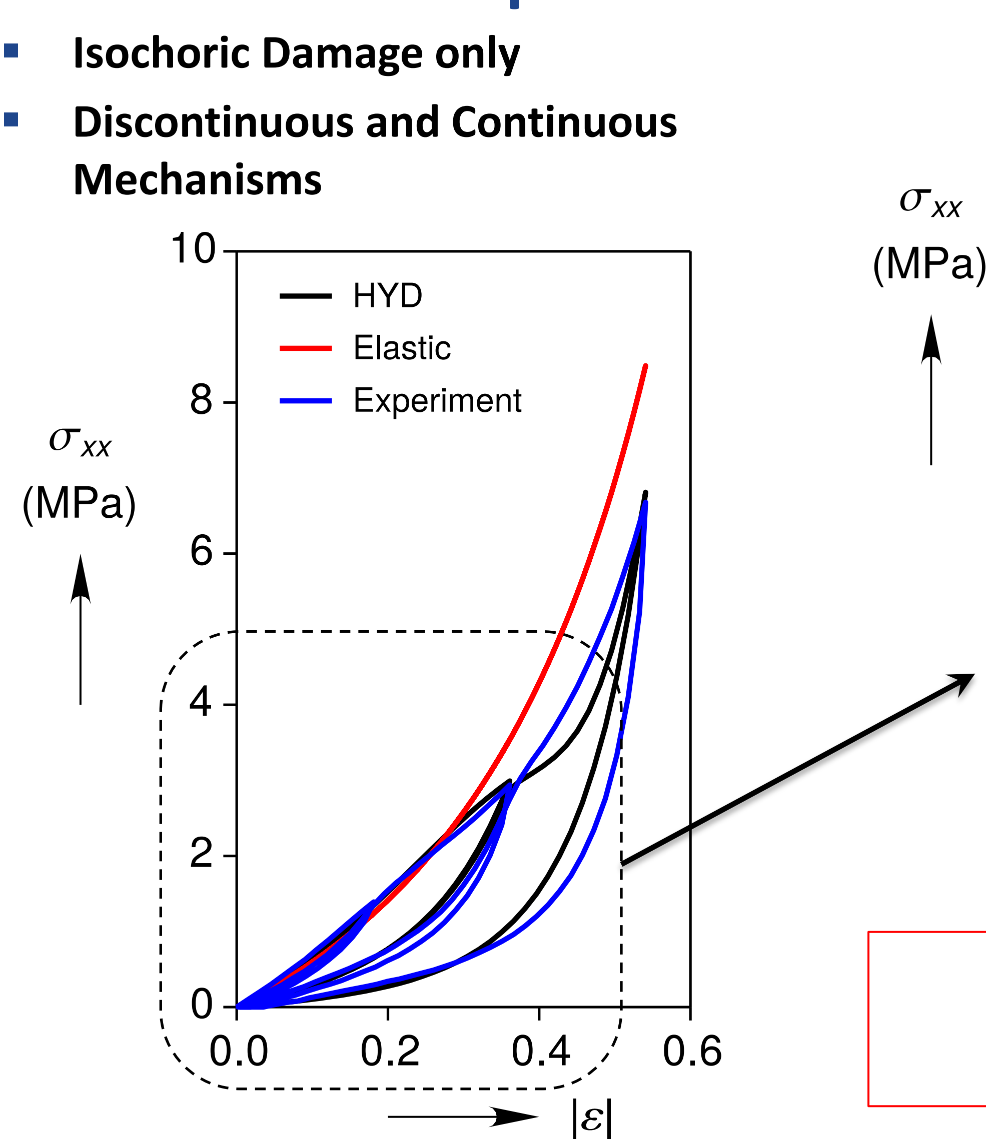
$$d^c_{vol} = d^{cMAX}_{vol}\left(1 - \exp\left(-\frac{\beta_{vol}[t]}{d^{cSAT}_{vol}}\right)\right)$$

Integrated Power Density

$$\beta_{iso,\,(vol)}[t] = \int_0^t |\dot{\psi}_{iso,\,(vol)}|dt'$$

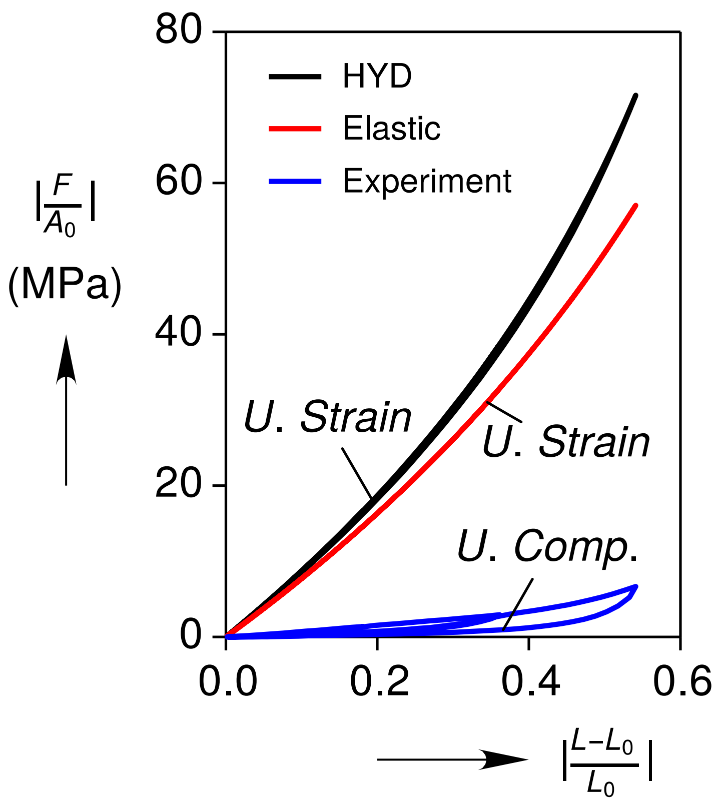
Elastic and Damage Model Calibrations to Uniaxial Compression Data

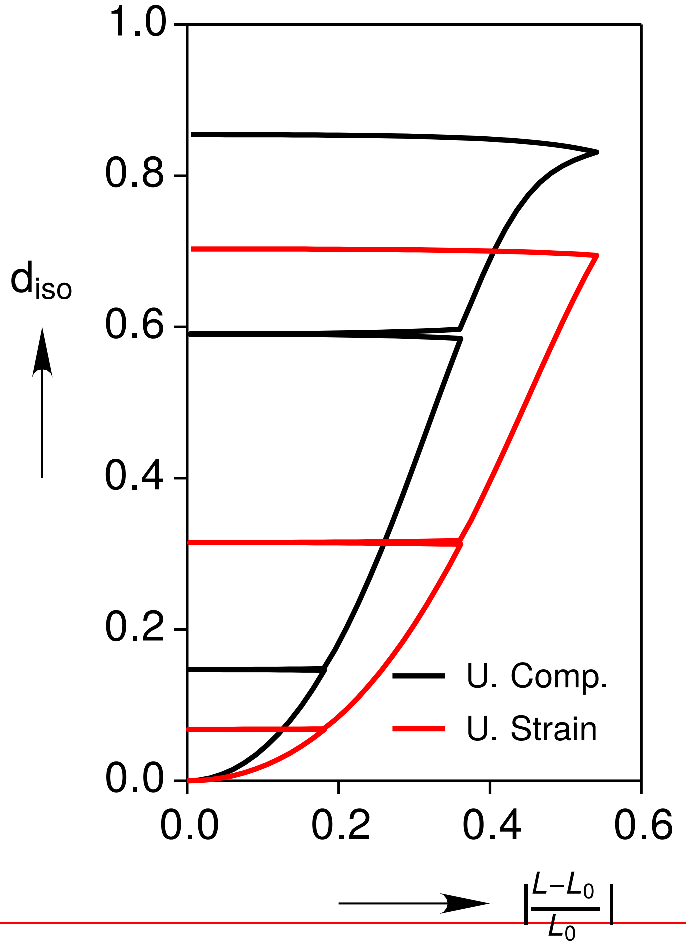
- **Isochoric Damage only**
- **Discontinuous and Continuous Mechanisms**



HYD model reasonably fits the uniaxial compression data

The Importance of the Boundary Value Problem (BVP): Uniaxial Compression vs. Uniaxial Strain





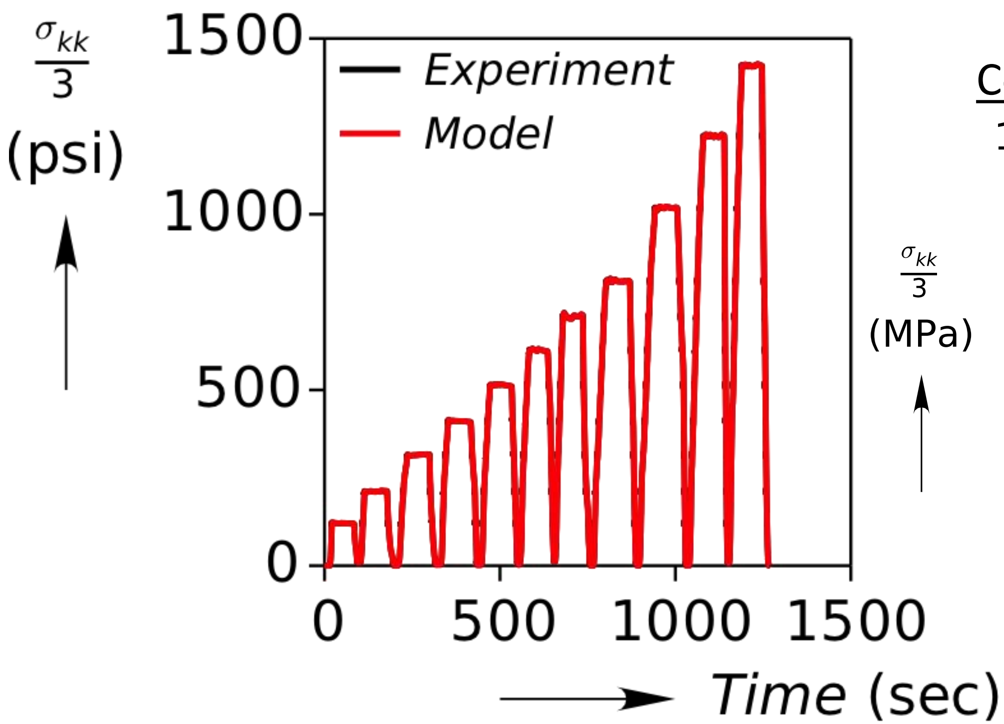
Although both BVPs similarly damage syglard GMB, isochoric damage contributes very little to the uniaxial strain response

<u>Volumetric damage may not be negligible</u>

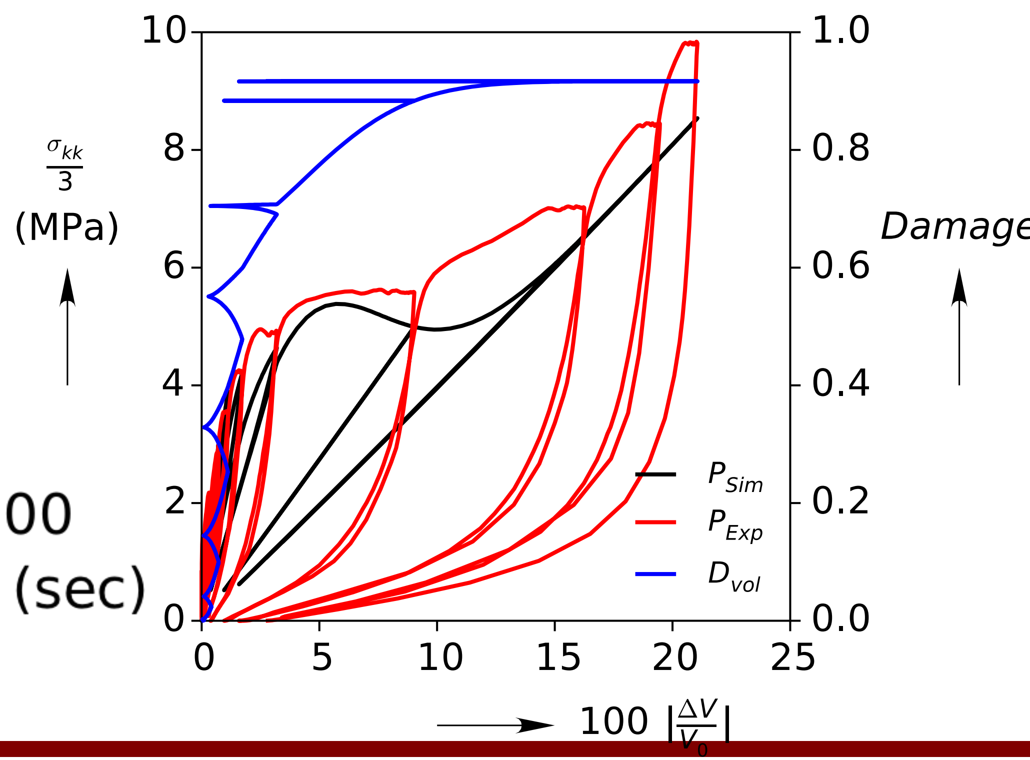
Model Performance Under Cyclic Hydrostatic Pressurization is Incorrect

Data is Time Dependent → No Time Dependence in the Model

Apply Pressure/Measure Volume Strain



Compared Pressure-Volume Response



Future work

- **Micromechanics model development**
- **Supporting experiments**
  - **In situ deformation**
    - **Microscope**
    - **CT scanning**
    - **Digital image correlation (DIC) or digital volume correlation (DVC).**
  - **Constrained compression**

In situ synchrotron CT compression of GMB-filled Sylgard.

Patterson et. Al, Microsc. Microanal. 20 (suppl 3), 2014

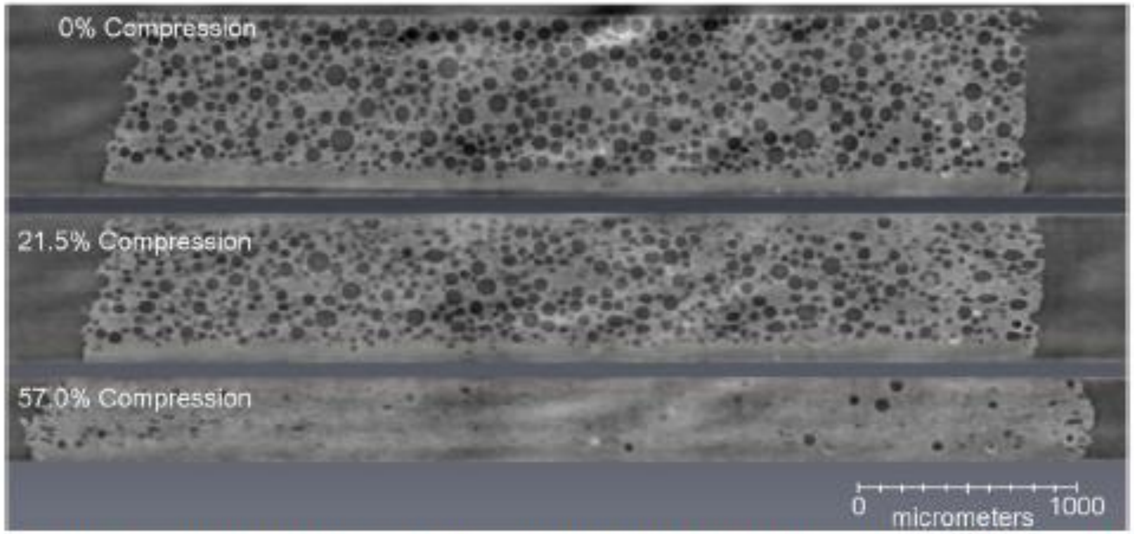
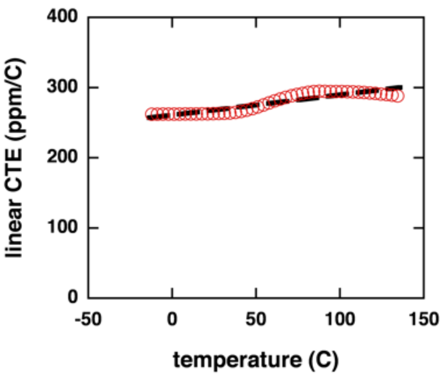


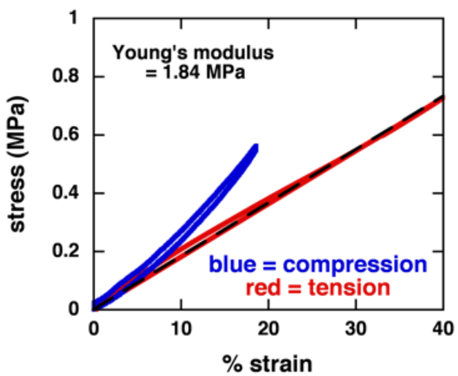
Figure 3: Compression of syntactic Sylgard foam with 100 µm hollow glass beads. Sample is nearly incompressible with a high Poisson ratio.

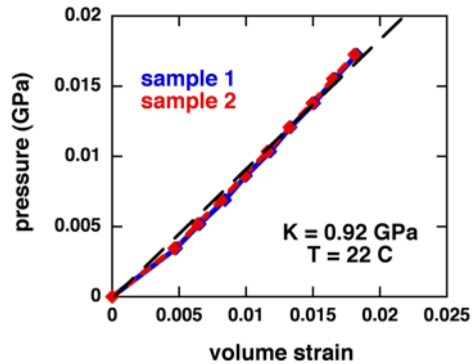
Bonus Slides

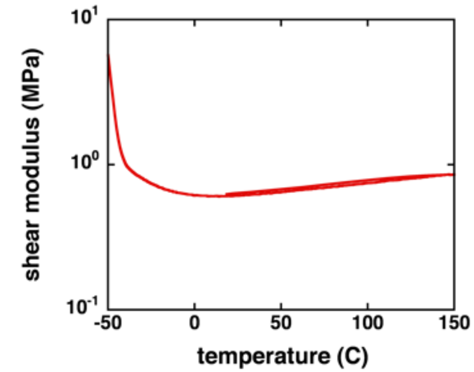
Basic Mechanical Properties

Pure Sylgard









Sylgard GMB