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Ablaos

Asphalt Binder
Large Amplitude Oscillatory Shear

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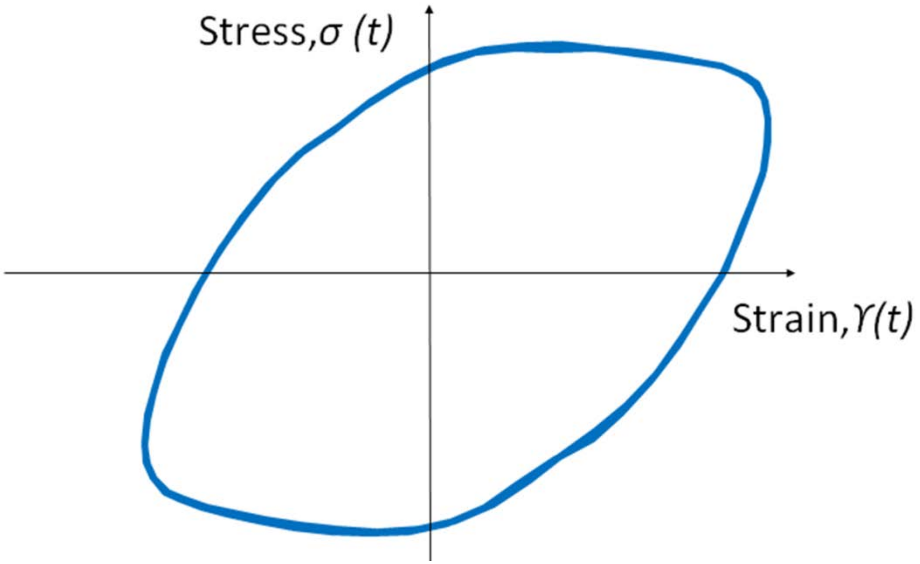

Binder ETG
Baton Rouge, LA
Sept. 16, 2014

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Outline

- Linear Viscoelasticity
- Large Amplitude Oscillatory Shear (LAOS)
- Linear Amplitude Sweep (LAS) test method
- Analysis - LAS strain sweep using the first harmonic Fourier coefficients G_1' *(ω), G_1'' (ω)*
- Analysis of a LAS strain sweep using LAOS
- LAOS test and Pipkin diagrams
- Unresolved issues with the nonlinear data (torque and angle)
- Summary

Linear Viscoelasticity (strain control)

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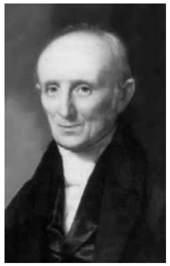
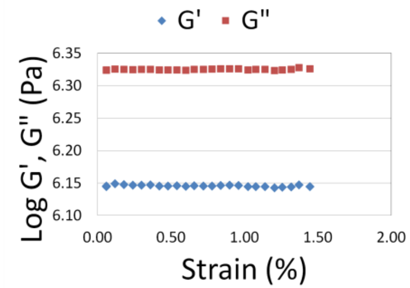
Nathaniel Bowditch (1773-1838) American mathematician

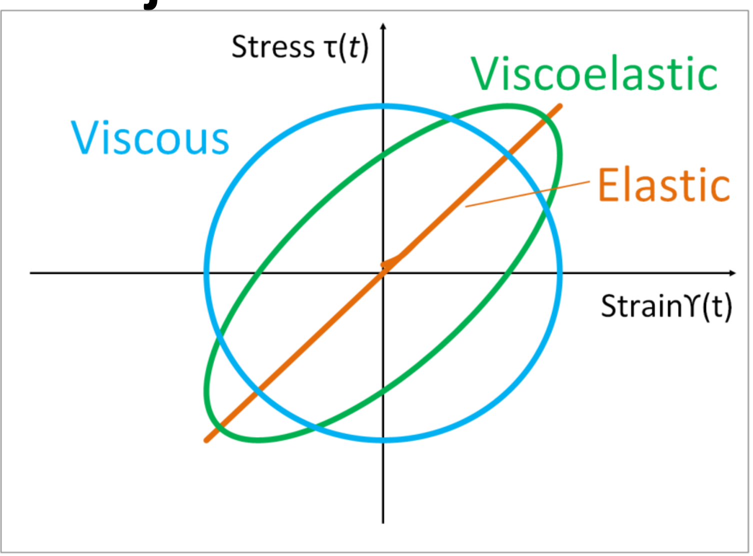


- At small strain amplitudes the response is linear



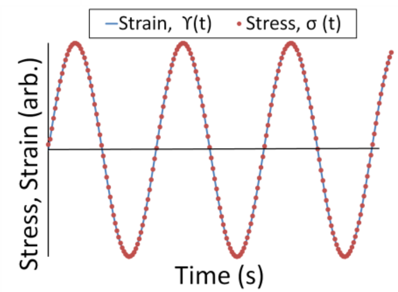
Jules Antoine Lissajous (1822-1880)French Mathematician

Lissajous – Bowditch Curves



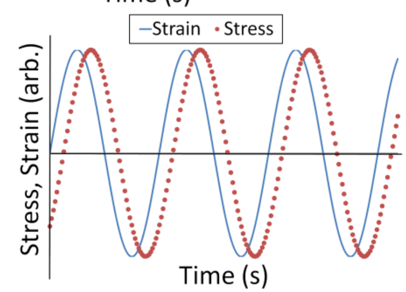
Elastic dominated

$\delta \rightarrow 0°$



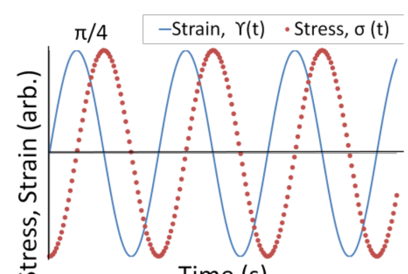
Viscoelastic

$0° < \delta < 90°$



Viscous dominated

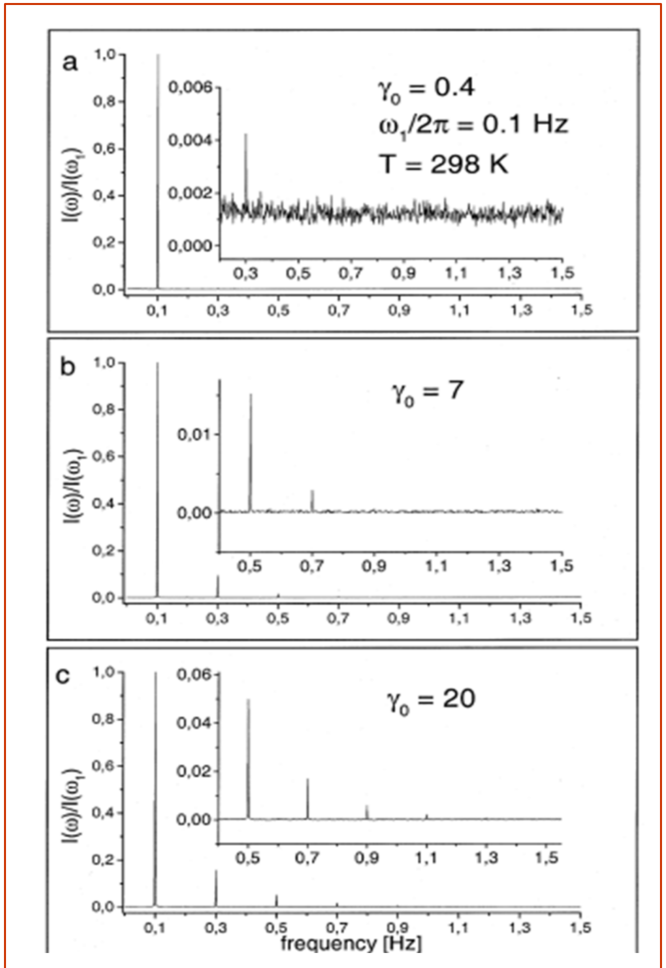
$\delta \rightarrow 90°$

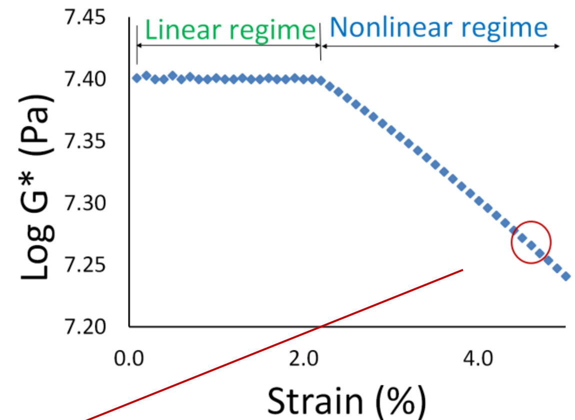


The imposed strain takes the form $\gamma(t) = \gamma_o \sin \omega t$ which results in an oscillatory shear stress $\sigma(t) = \sigma_o \sin(\omega t + \delta)$

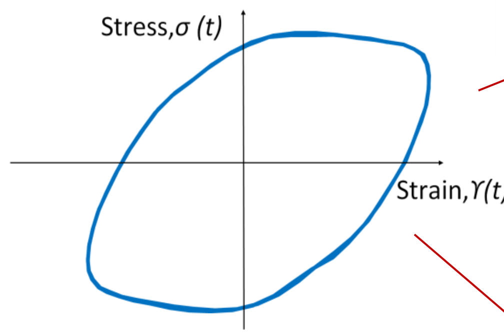
LAOS

- Normalized intensities and the number of higher harmonic contributions with increasing strain amplitude

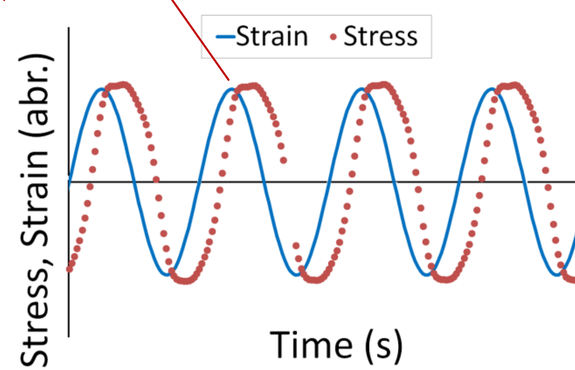




Lissajous curve



- Stress sine wave is distorted



Wilhelm, M., Macromol. Mater. Eng. 2002, 287, No. 2

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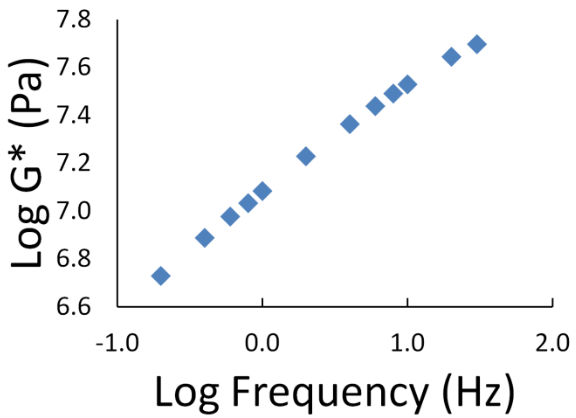
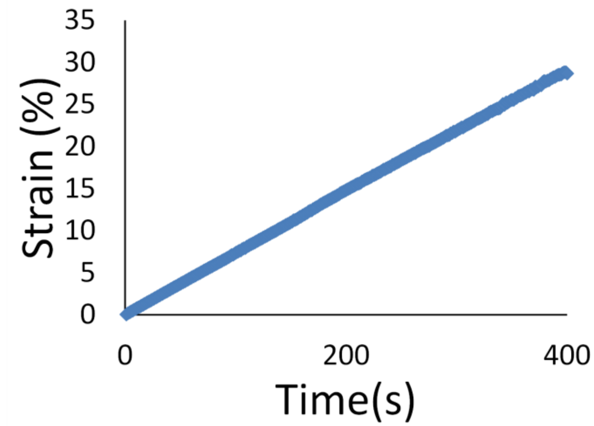
The LAS Test Method

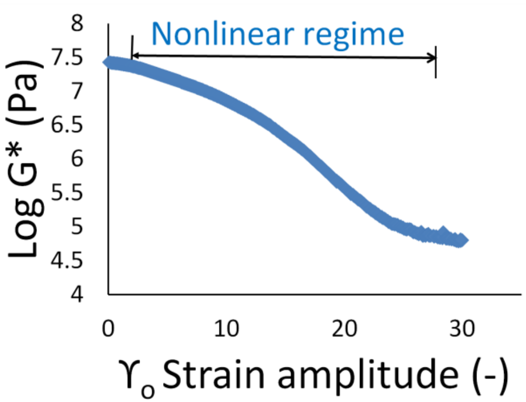
- The Frequency sweep is used to develop a relaxation parameter



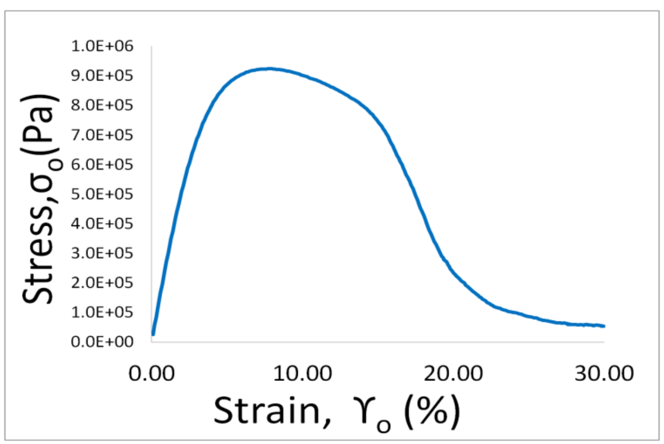
- Linear ramp (small discrete strain steps,) 0.1 to 30%, 10 Hz and 10 oscillations per step.



- LAS strain sweep is almost entirely in the nonlinear viscoelastic range



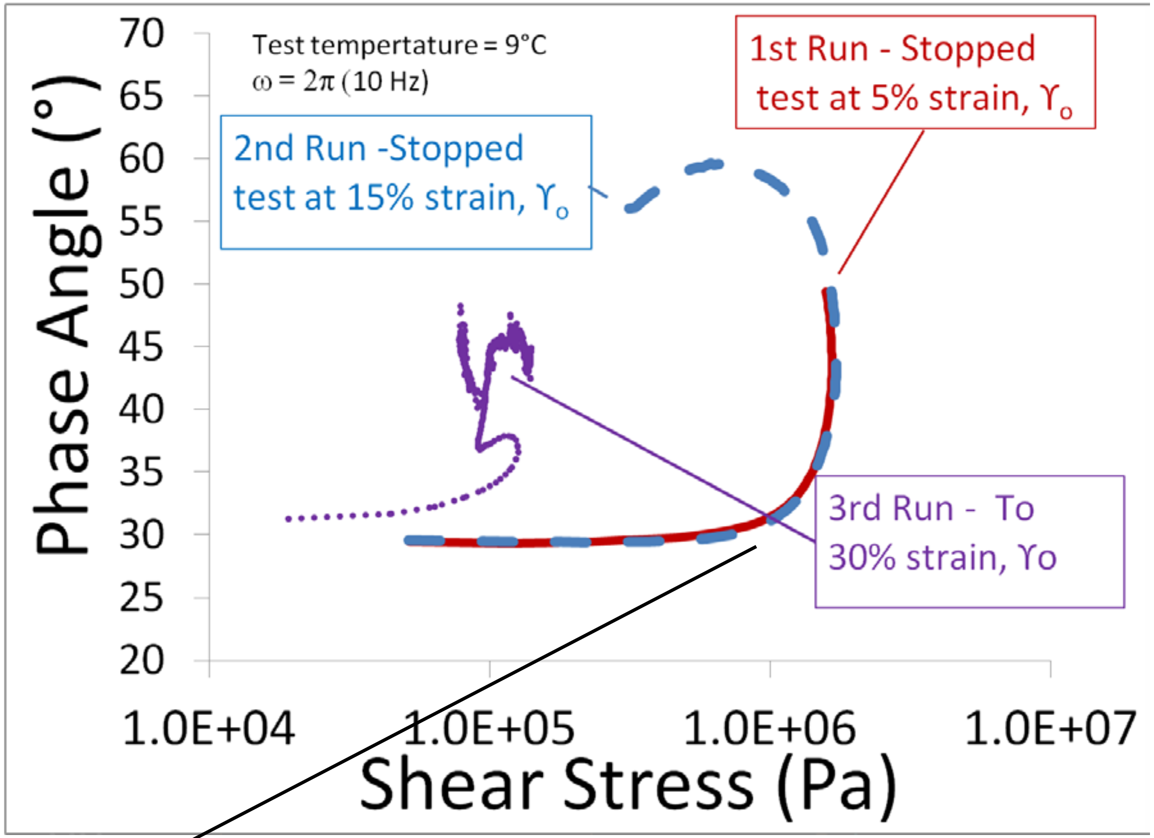
- Stress amplitude ,σ_o versus strain amplitude, Υ_o



TP 101-12-UL MARC website

We are seeing flow

- Analysis using first harmonic Fourier coefficients $G_1'(\omega)$, $G_1''(\omega)$



At ~ 5 % strain amplitude, Υ_o

At ~ 30 % strain amplitude, Υ_o

Yielding? Perhaps disruption of the molecular structure

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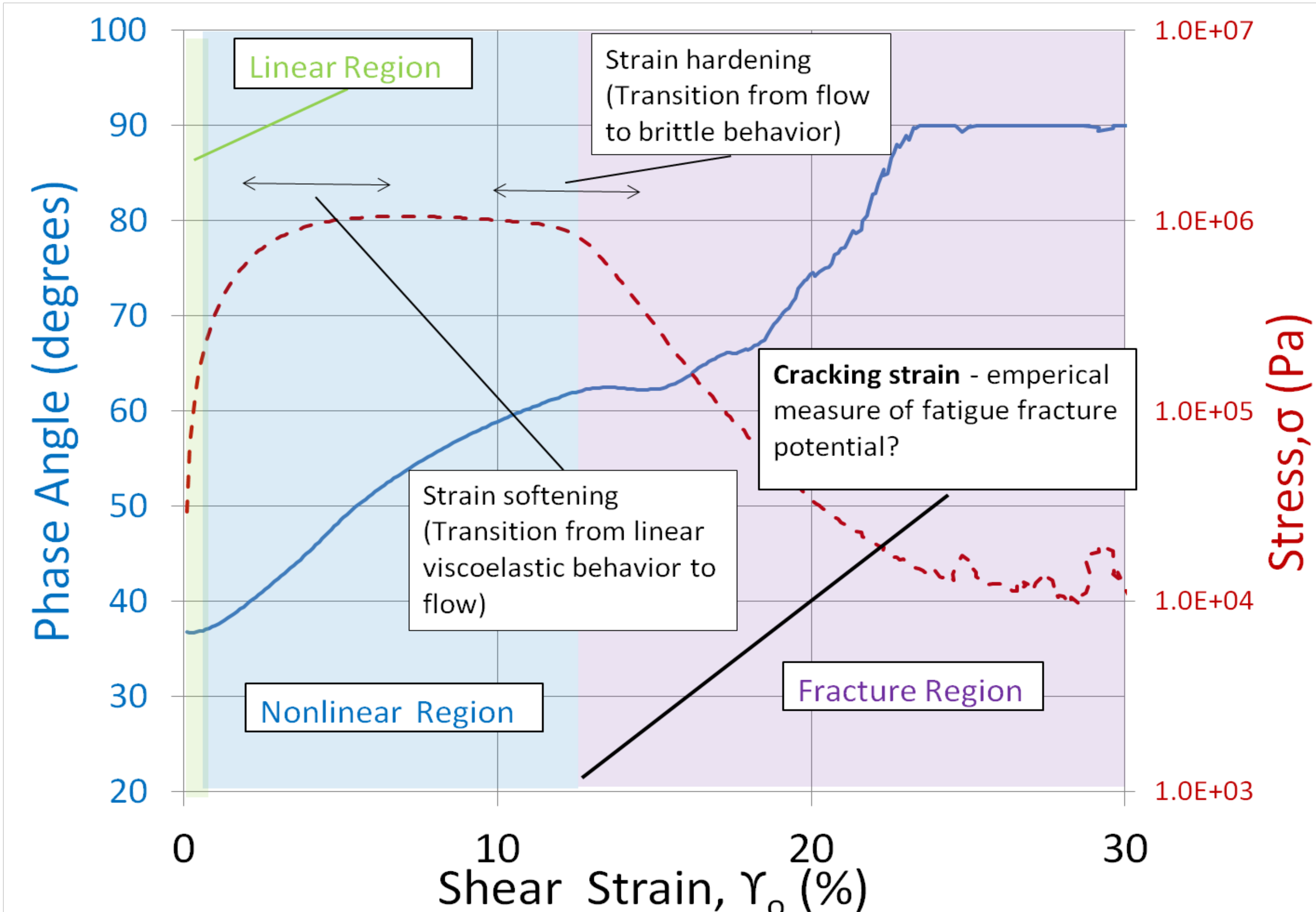
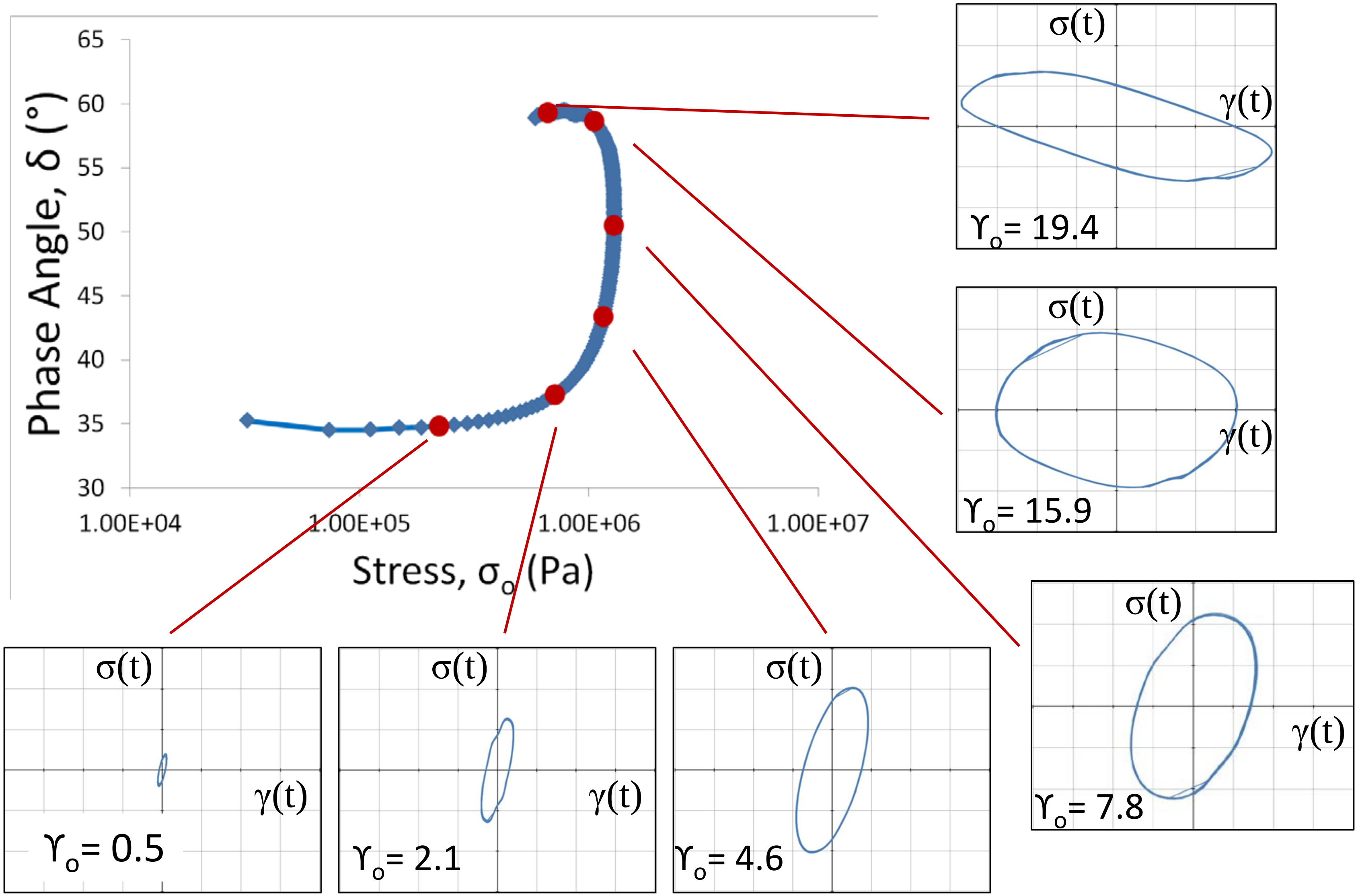
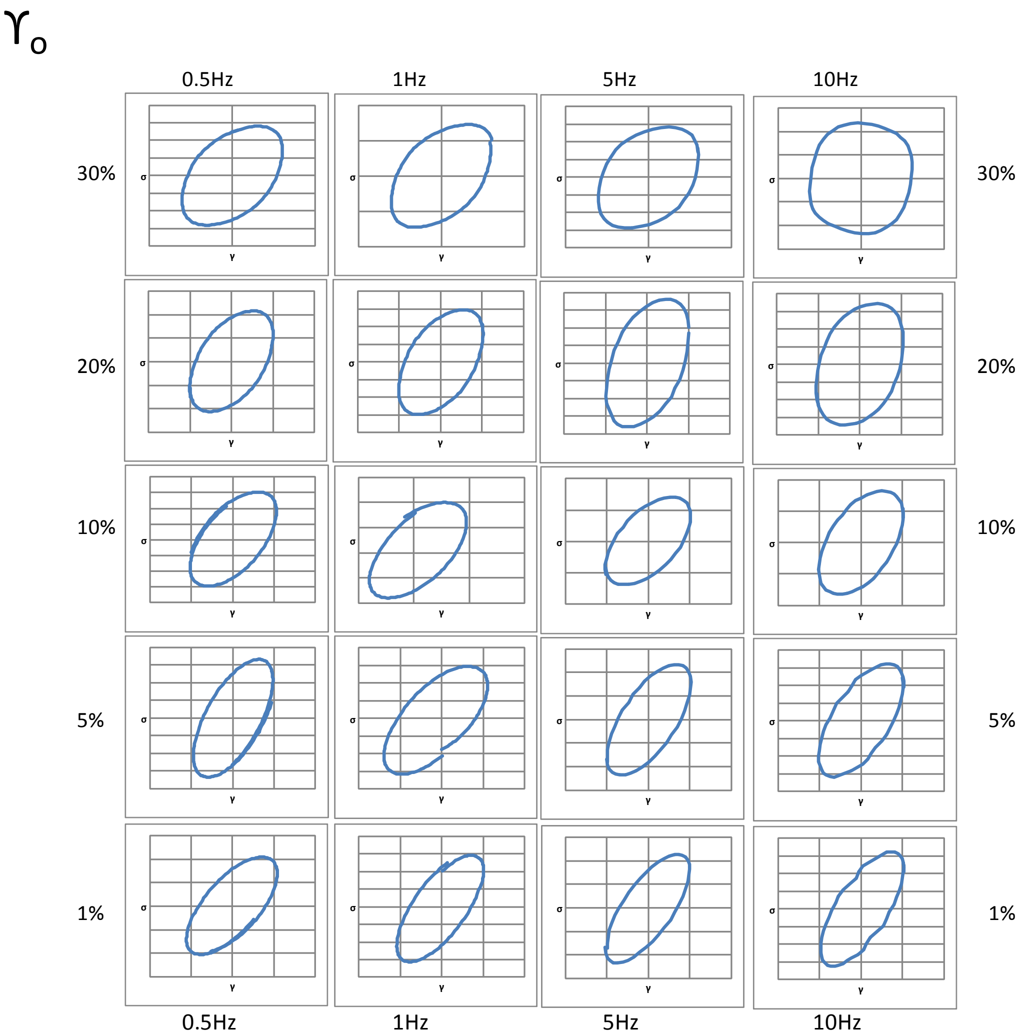
Cracking Strain



Application of LAOS



Pipkin Diagram



Frequency, $\omega/2\pi$

- PG 76 – 22, Test temp. = 28°C

•A Pipkin diagram characterizes the binder response as a function of both imposed frequency and strain amplitude

- It is a distinct rheological signature or "fingerprint" of the binder

- At all of the frequencies and strain amplitudes, except 30%, elasticity appears dominant. At 30% the binder transitions to a circular trajectory indicating the binder is behaving like a viscous dominated fluid, especially at high frequency

- Test temperature makes a big difference in all this

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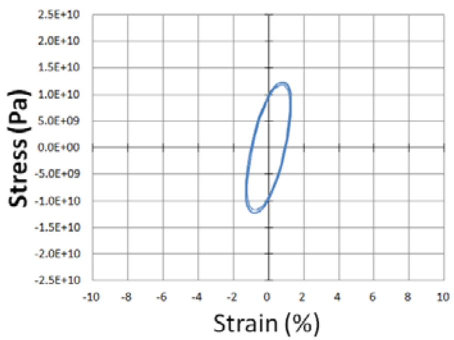
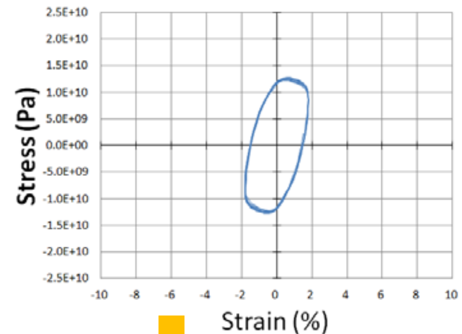
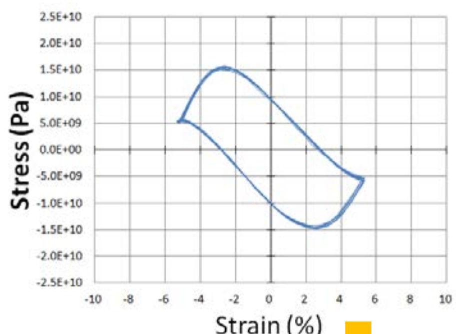
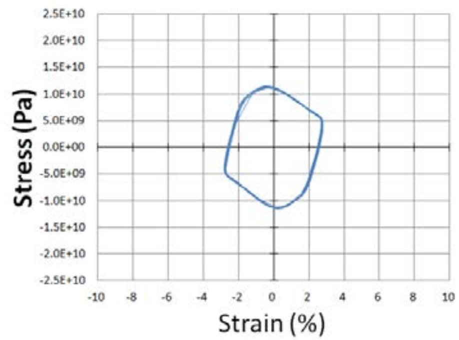
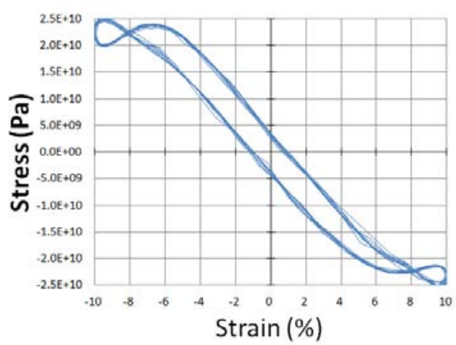
Inertia effects

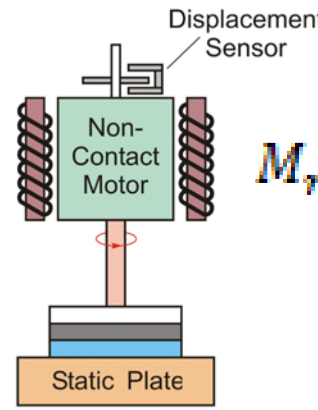












$$M_m = M_s + M_I$$

Stress Control Rheometer[1]
(single head)

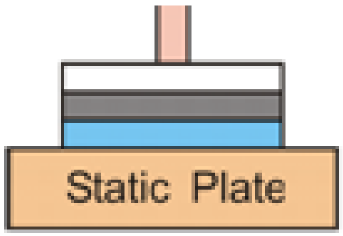
- For an SH rheometer, inertia effects are a function of the sample stiffness and freq.

- Inertia effects occur because the applied torque of the actuator has to overcome the viscous drag of the sample and instrument[1]
  - Shingle Material, very high viscosity, but after it cracks very low viscosity. After the sample cracks inertia could dominate and the raw phase angle could go to π

[1] Franck, Instrument Inertial Correction during Dynamic Mechanical Testing, TA Instruments

Parallel Plate Geometry

(Calculating the True Stress Response)



Parallel Plate Geometry

- Parallel plate geometry is unsuitable for nonlinear viscoelasticity measurements because **the strain field, and thus the nonlinear response, varies across the sample**[1] (this is only a problem in the nonlinear regime because the local stress depends linearly on strain).

- Fahimi[1] has recently proposed obtaining correct data from LAOS measurements which allows access to the true nonlinear response of a material based solely on the apparent response obtained using parallel plates geometry

[1]Fahimi et al Rheol Acta (2014)

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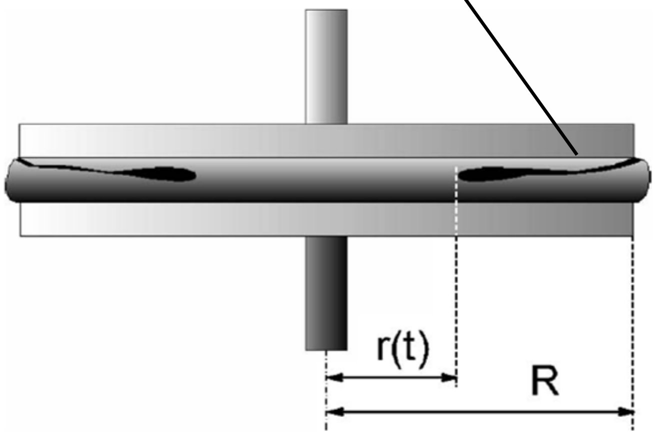
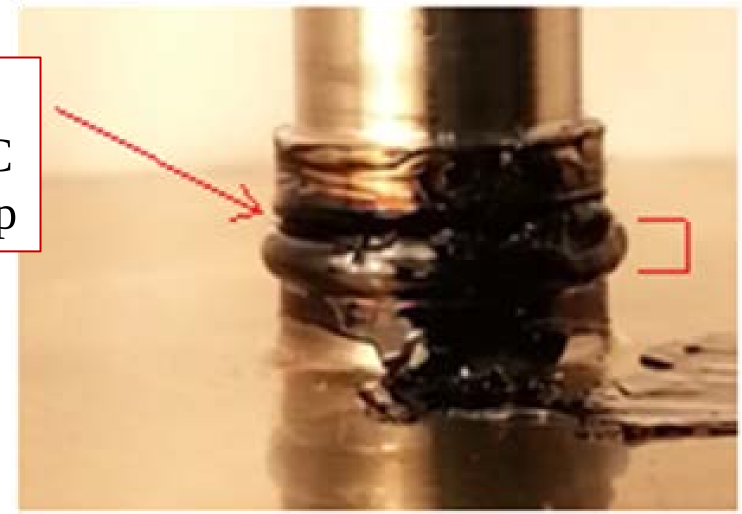
Edge Fracture

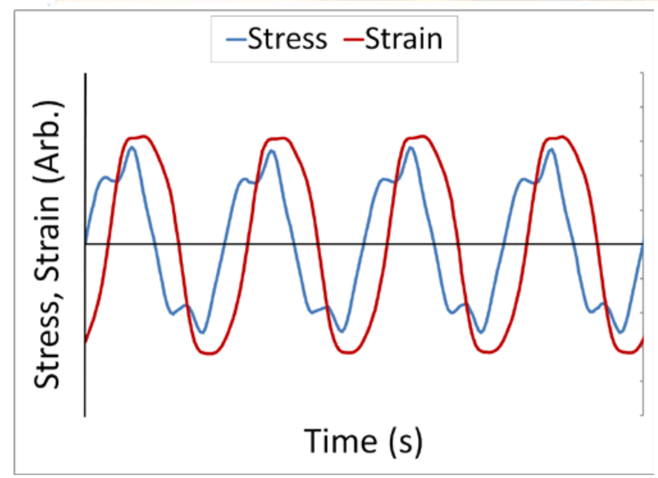
Edge Fracture



Schematic cross section of the edge fracture, parallel plate geometry (from Mattes et al[1])

Edge Fracture
Test Temp. = 9°C
LAS strain sweep





Stress and strain sine waves in the fracture zone

[1] Mattes et al, Rheol Acta (2008) 47:929–942

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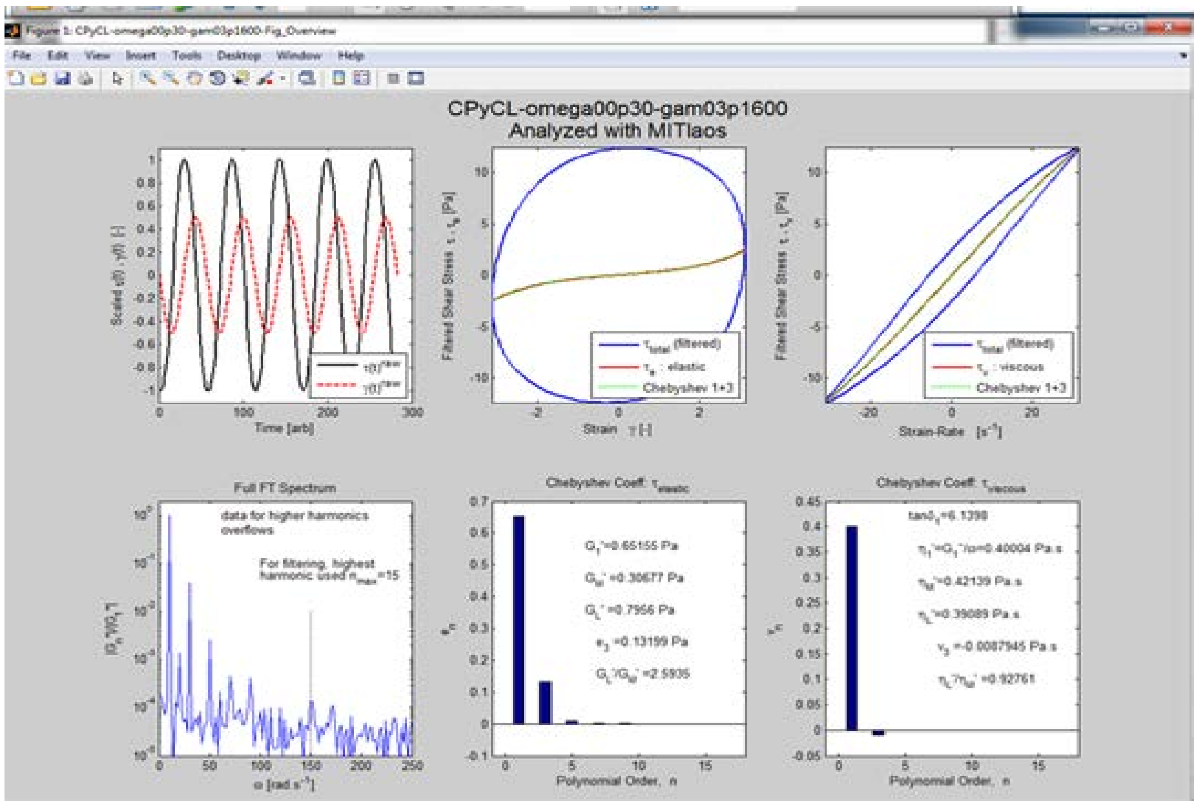
MITlaos software (Example of output)

- MITlaos is a data analysis program for analyzing rheological properties in large amplitude oscillatory shear (LAOS).
- As input, the program requires oscillatory waveforms of strain and stress from a strain controlled oscillatory shear test.



Version 2.2 Beta for MATLAB, Ewoldt et al,Hatsopoulos Microfluids Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology

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Summary

- LAOS presents a new framework for analyzing the linear and nonlinear material responses of complex fluids and soft solids.

- The common practice has been to apply the "viscoelastic moduli" corresponding to the first harmonic Fourier coefficients $G_1'(\omega)$, $G_1''(\omega)$. However, in many cases that can be misleading in describing the nonlinear phenomena.

- In the nonlinear regime, at intermediate temperature, asphalt binders appear to strain soften

- At very large strain amplitudes, binders appear to strain harden and fracture. We are uncertain of the type of fracture but the data so far suggest edge fracture

- Inertia effects can dominate when the binder fractures and there is a dramatic drop-off of stiffness

- LAOS is an amazingly interesting science with direct application to asphalt binders

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Thank You

Acknowledgements

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Questions?

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