CHARACTERIZATION OF A SHEAR THICKENING COLLOIDAL SUSPENSION USING HOPKINSON BAR METHODOLOGY

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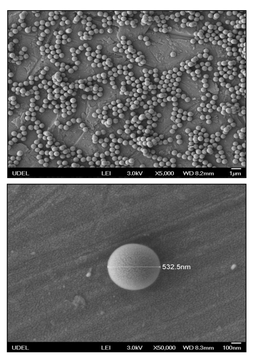
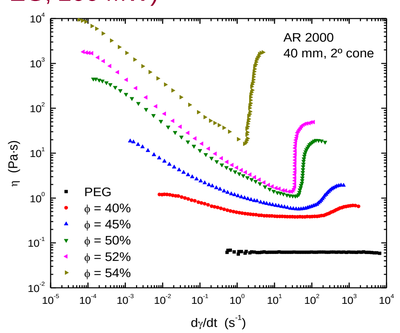
SHEAR THICKENING FLUID

- A discontinuous STF thickens rapidly above a critical shear rate.
  - Spherical silica particles (500-600 nm diam.)
  - Polyethylene glycol (PEG, 200 MW)
  - 52 vol% silica





- Low shear rate rheology:
  - STF shear-thins prior to transition

MOTIVATION

- Goal: Evaluate the mechanical response of the STF at high rates and stresses characteristic of an impact event.

Rheometer

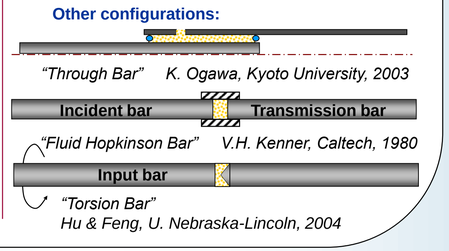
- Millisecond sensitivity (50 Hz)
- Max stress ~65 kPa
- Max shear rate for viscous fluids ~10^3 s^{-1}
- Slip can occur at higher rates
- Cannot measure viscous-solid transition continuously in a STF.

While capillary rheometers can be used to measure a material response at higher shear rates, shear thickening fluids often cause capillary rheometers to clog.

Hopkinson pressure bar

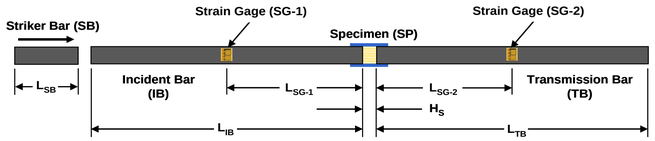
- Microsecond sensitivity (5 MHz)
- High stress, limited only by yield stress
  - σ_y = 250 MPa for aluminum
- High shear rates (>10^5 s^{-1})
- No slip
- Ability to measure viscous to solid transitions continuously

Other configurations:

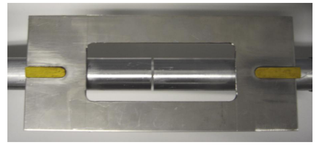


SPLIT HOPKINSON PRESSURE BAR

- The SHPB consists of a gas gun and 3 cylindrical bars:
  - striker (SB), incident (IB) and transmission bar (TB)



- The fluid is covered with a rubber balloon to prevent loss during testing.
  - Results in a high rate squeeze flow experiment
- A key and pin setup is used to control the gap size.
  - More repeatable results
  - i.e. in Newtonian fluids $\sigma = f(h^3)$



- Highly adaptable
  - Experimental parameters can be adjusted to achieve a thickening response within the material.

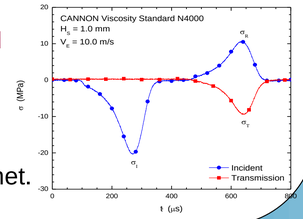
GOVERNING EQUATIONS

- The average force and displacement rate during testing are calculated by:

$$F = \frac{1}{2}\left[A_{IB}E_{IB}\left(\varepsilon_I + \varepsilon_R\right) + A_{TB}E_{TB}\varepsilon_T\right]$$

$$\dot{U} = \dot{U}_1 - \dot{U}_2 = C_{0,IB}\left(-\varepsilon_I + \varepsilon_R\right) + C_{0,TB}\varepsilon_T$$

- Conditions under which these equation may be applied:
  - Strong transmitted signal
  - Fluid must be in equilibrium
- The first is easily met.



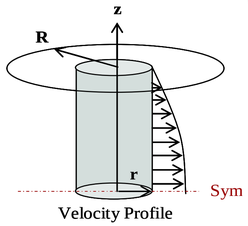
SQUEEZE FLOW THEORY

- A model assuming fully developed flow was used to predict experimental results.
  - Conservation of mass

$$\frac{1}{r}\frac{\partial(rV_r)}{\partial r} + \frac{1}{r}\frac{\partial V_\theta}{\partial_\theta} + \frac{\partial V_z}{\partial z} = 0$$

  - Navier-Stokes

$$\rho\left[\frac{\partial V_r}{\partial t} + V_r\frac{\partial V_r}{\partial r} + V_z\frac{\partial V_r}{\partial z}\right] = -\frac{\partial P}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rV_r)}{\partial r}\right) + \frac{\partial^2 V_r}{\partial z^2}\right]$$



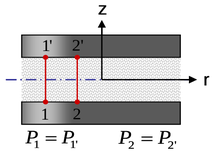
- Solving this system of equations yields:

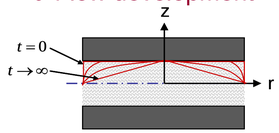
$$F = \underbrace{\frac{\pi\rho R^4}{8h}\left(\ddot{U}_1 - \ddot{U}_2\right)}_{\text{transient inertial}} + \underbrace{\frac{9\pi\rho R^4}{40h^2}\left(\dot{U}_1 - \dot{U}_2\right)^2}_{\text{bulk inertial}} + \underbrace{\frac{3\pi\mu R^4}{2h^3}\left(\dot{U}_1 - \dot{U}_2\right)}_{\text{viscous}}$$

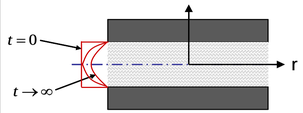
-no slip and zero body forces assumed

DYNAMIC TIMESCALES

- Dynamic processes to be considered:
  - Sound travel
  - Pressure wave travel
  - Flow development







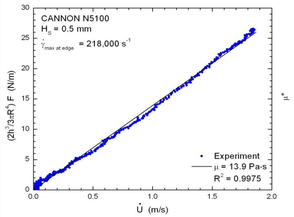
$$\tau_R = \frac{R}{c} \qquad \tau_H = \frac{H_S}{c}$$

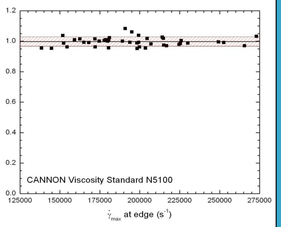
$$\tau_P \approx \frac{\nu R^2}{c^2 H_S^2} \qquad \tau_V \approx \frac{H_S^2}{\nu}$$

- This time is 13.6 μs (N5100) – small compared with the exp. time (200 μs).

SHPB VALIDATION

- With inertial forces subtracted out, we can determine the experimentally measured viscosity using the squeeze flow model.





- We compare this with the actual viscosity from temperature measurements.
  - Ideal match of 1.00 ± 0.03 (N5100).

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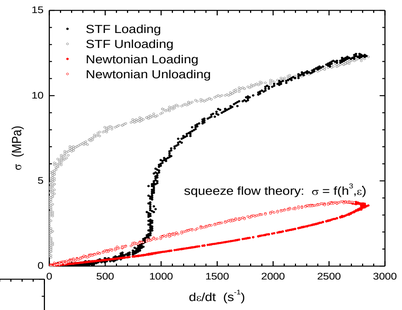
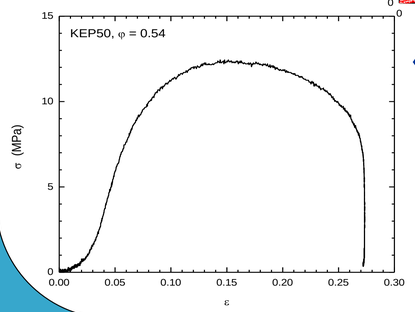
(Continued)

STF BEHAVIOR

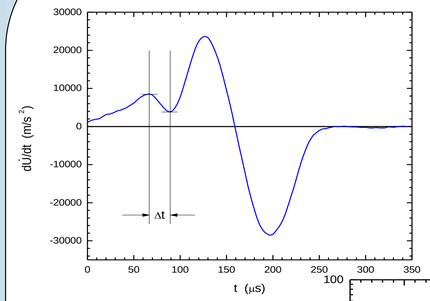
- Stress-strain response
  - STF exhibits nonlinear behavior, consistent with thickening.
  - Large hysteresis is seen.





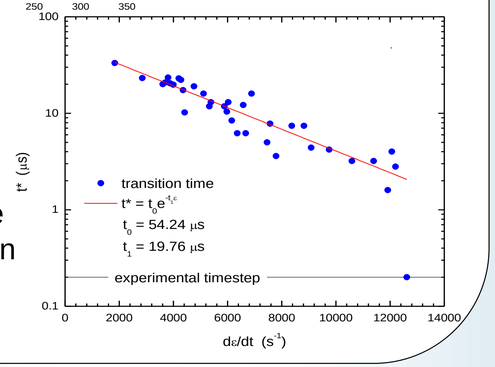
- Stress-strain rate graph (right)
  - Bars decelerate, indicating a change in material properties.
  - Newtonian behavior is plotted for comparison.

TRANSITION



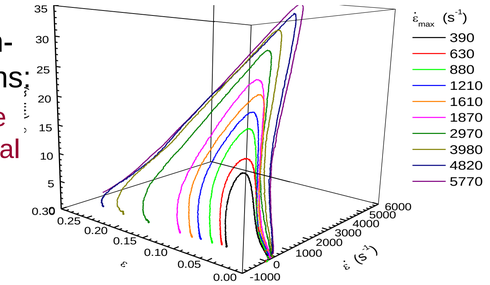
- Hydroclusters form and lock and jam resulting in an increased stiffness
- Definition: transition occurs when acceleration is < 0.

- Transition time decreases with loading rate.
- The experimental timestep limits the minimum transition time we can measure.

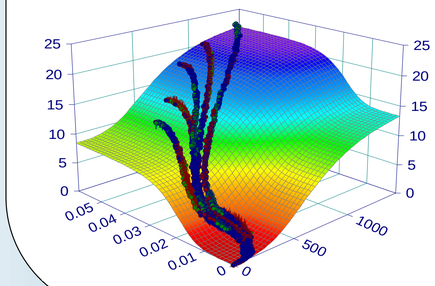


MODELING

- 3D stress-strain-strain rate graphs:
  - Helps to visualize the full mechanical response of the STF.



- Surface fitting

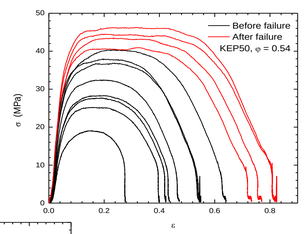


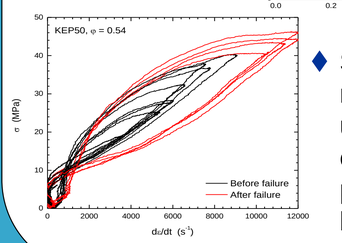
$$\sigma = a\left(\frac{(\dot{\varepsilon}\tau)^c}{1+(\dot{\varepsilon}\tau)^c}\right) + d\left(\frac{(\varepsilon/\varepsilon_0)^f}{1+(\varepsilon/\varepsilon_0)^f}\right)$$

  - Means of developing a phenomenological model describing the behavior of the STF under specific conditions.

FAILURE

- Deformation increases without σ.
- Repeatable failure:
  - σ > 40 MPa

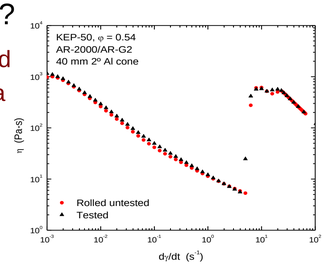




- Stress-strain rate curve unloading is evidence of particle clusters breaking down.

FAILURE MODE

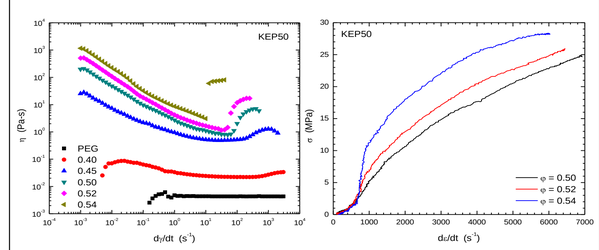
- Microstructural rearrangement or particle fracture?
  - Rheology before and after – stiffening at a slightly lower shear rate.
  - SEM – no broken particles found



- Particle size analyzer (light scattering)
  - Average particle size increase of 100 nm after testing – clear indicator of agglomeration.
- SEM: larger particle clusters in tested STF

FUTURE WORK

- A reduction in stiffness is evident for the lower concentration specimens.
  - 50% concentration still behaves drastically different than the 54%.



- Extend surface fitting approach to describe the concentration dependent behavior of the STF.

ACKNOWLEDGEMENTS

This research was supported by Army Research Office grant #W911NF-05-2-0006

Mentors
Eric Wetzel
Sergey Lopatnikov
Bazle Gama
Joseph Deitzel

Special thanks to
David Stepp
Caroline Laufer
Dennis Kalman

Advisor
Jack Gillespie

Committee
Norman Wagner
Tsu-Wei Chou
Chaoying Ni

Don Kessler III
Nadia Shobnam