IMPLEMENTING THE SPLIT-HOPKINSON PRESSURE BAR TECHNIQUE FOR SHEAR THICKENING FLUID EVALUATION

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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 at <20 s⁻¹

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 ~10³ 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 rates, shear thickening fluids often cause capillary rheometers to clog.

SQUEEZE FLOW THEORY

- A model assuming fully developed flow was used to predict experimental results.
- Conservation of mass
  \[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial V}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) = 0 \]
- Navier-Stokes
  \[ \frac{\partial V}{\partial t} + \nabla \cdot (V V) = \eta \nabla \cdot V \]
- Solving this system of equations yields:
  \[ F = \frac{\eta R}{2} \left( \left| V_i - V_j \right| - \left| V_i - V_j \right| \right) \]
  - no slip and zero body forces assumed

DYNAMIC TIMESCALES

- Dynamic processes to be considered:
  - Sound travel
  - Pressure wave travel
  - Flow development
  - \( \tau_R = \frac{R}{c} \)
  - \( \tau_H = \frac{H}{c} \)
  - \( \tau_P \approx \frac{v R^2}{c^2 H^2} \)
  - \( \tau_T \approx \frac{H^2}{v} \)

- 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).

GOVERNING EQUATIONS

- The average force and displacement rate during testing are calculated by:
  \[ F = \frac{1}{2} \left[ A_B E_B (\epsilon_i + \epsilon_R) + A_T E_T \right] \]
  \[ \dot{U} = U_i - U_j = C_{0,B} (\epsilon_i + \epsilon_R) + C_{0,T} \epsilon_T \]

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

SHEAR THICKENING FLUID EVALUATION

- 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
  - e.g. in Newtonian fluids \( \sigma = f(\dot{\gamma}) \)
  - Highly adaptable
  - Experimental parameters can be adjusted to achieve a thickening response within the material.

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A reduction in stiffness is evident for 0.4 50 \), extending surface fitting approach to Rheology before and Repeatable 4000 Hydroclusters form and lock and jam resulting in an increased stiffness. Definition: transition occurs when acceleration is < 0.

- Stress-strain rate graphs:
  - Helps to visualize the full mechanical response of the STF.
  - Surface fitting
  - Means of developing a phenomenological model describing the behavior of the STF under specific conditions.

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

**MODELING**

**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**

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

**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.

**FAILURES**

- Deformation increases without \( \sigma \).
- Repeatable failure:
  - \( \sigma > 40 \text{ MPa} \)

- 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

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