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.

GOVERNING EQUATIONS

- The average force and displacement rate during testing are calculated by:
  \[ F = \frac{1}{2} \left( A_t E_1 (\varepsilon_1 + \varepsilon_2) + A_r E_1 \varepsilon_3 \right) \]
  \[ \dot{U} = \dot{U}_i - \dot{U}_2 = C_{0,4} (-\varepsilon_1 + \varepsilon_A) + C_{0,2} \varepsilon_2 \]
- Conditions under which this 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
  \[ \frac{1}{\rho} \frac{\partial \rho V_r}{\partial t} + \frac{1}{\rho} \nabla \cdot (\rho V_r V_r) = \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V_r) = 0 \]
  - Navier-Stokes
  \[ \frac{\partial V_r}{\partial t} + (V_r V_r) \nabla = - \frac{1}{\rho} \nabla p + \nabla \times \tau \]
- Solving this system of equations yields:
  \[ F = \frac{\pi R^4}{k_0} \left( U_i - U_0 \right) + \frac{\pi R^4}{k_0} \left( U_i - U_0 \right) \]
  - no slip and zero body forces assumed

DYNAMIC TIMESCALES

- Dynamic processes to be considered:
  - Sound travel
  - Pressure wave travel
  - Flow development
  \[ \tau_2 = \frac{R}{c} \quad \tau_1 = \frac{H_c}{c} \quad \tau_3 \approx \frac{V^2}{c} \]
  - This time is 13.6 µs (N5100) – small compared with the exp. time (200 µs).

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 \( \sigma = f(h^2) \)
  - Highly adaptable
  - Experimental parameters can be adjusted to achieve a thickening response within the material.

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 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.

**FAILURES**
- Deformation increases without σ.
- Repeatable failure:
  - σ > 40 MPa
- Stress-strain rate curve unloading is evidence of particle clusters breaking down.

**FAILURES MODE**
- Microstructural rearrangement or particle fracture?
  - Rheology before and after – thickening 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.

**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.

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