Overview of Well Cement Behavior and Gas Migration During Early Hydration

PI: Dr. Eilis Rosenbaum

Project Participants

NATIONAL ENERGY TECHNOLOGY LABORATORY

Pitt

Julie Vandenbossche (U. of Pittsburgh)
Collaborator:
PhD Civil Engineering; Geotechnical and pavements engineering

Conducted prior research on SGS

Clarkson University

Goodarz Ahmadi
Collaborator:
PhD Mechanical Engineering; Mechanical and Aeronautical Engineering

NETL

Experimental/Lab
Modeling/Simulation

Eilis Rosenbaum
Principal Investigator (PI) / Research Lead:
PhD Computational Mechanics
M.S. Chemical Eng., B.S. Chem & Mechanical Engineering,

Experimental/Lab

Igor Haljasmaa
Experimentalist / Mechanical Engineer:
PhD Mechanical Engineering; Physical and mechanical properties of cement

James Fazio
Lab Manager / Technical Engineer

Richard Spaulding
Lead Experimentalist:
M.S. Geology; Physical and mechanical properties of cement

Barbara Kutchko
PhD Civil & Environmental Engineering; Cement Chemistry Expert

Modeling/Simulation

Mehrdad Massoudi
Fluid Dynamics Expert/Modeling Lead:
PhD Mechanical Engineering; Model development

Chengcheng Tao (ORISE)
Post Doc:
PhD Civil Engineering
Modeling and optimization in cement & concrete materials; Model development

Leebyn Chong (ORISE)
Post Doc:
PhD Chemical & Biochemical Engineering
Molecular Modeling of subsurface phenomenon

Kaushik Dayal (CMU)
Material Science / Modeling:
PhD Mechanical Engineering; Theoretical & computational multiscale methods

Task 2: Well Cement Behavior and Gas Migration During Early Hydration

PROBLEM

- Gas migration in wellbore cement after placement can lead to loss of well control and/or blow outs.
- Static Gel Strength (SGS) is current standard testing method for cement.
    - **Overestimated – costs money.**
    - **Underestimated – safety and environmental issues possible.**
- Previous research: NETL and U. of Pittsburgh → **Limitations of SGS**

BENEFIT

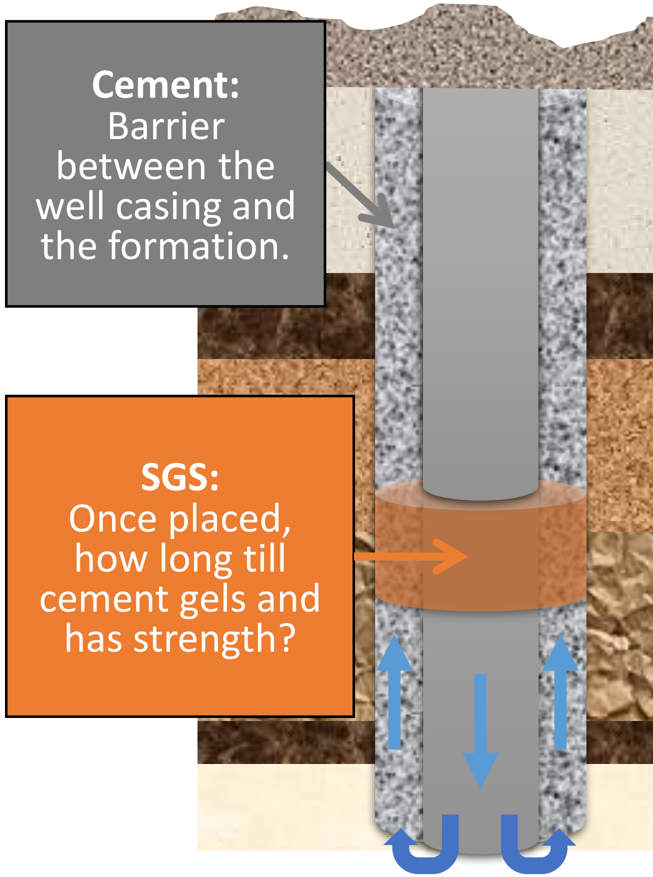
- Improved methods for predicting and preventing gas migration in cement.
- Current technology on market will have comparable measurements.
- Revised American Petroleum Institute recommended practices.
- *Lower costs for cementing and improve efficiency in completing wells.*

Highest priority task within American Petroleum Institute

APPROACH

- Align existing technology on the market that is used daily for all wells.
- Experiments in CT scanner and with wellbore simulation chamber under realistic onshore wellbore conditions to verify model and revise industry practices.
- Simulate cement interaction with formation gas to establish gas migration potential.

Will the Cement prevent fluid migration?

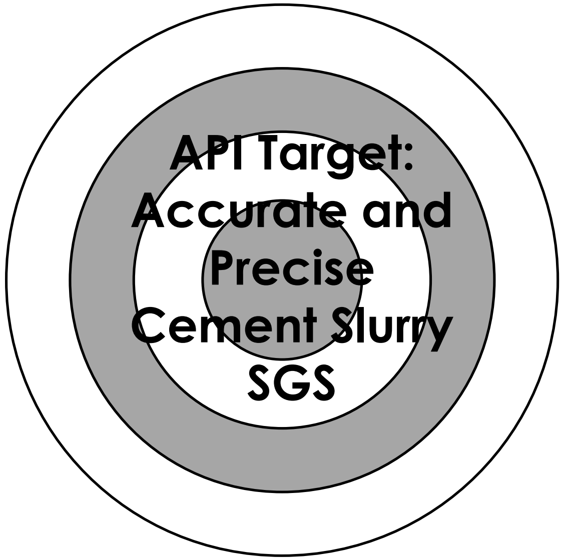


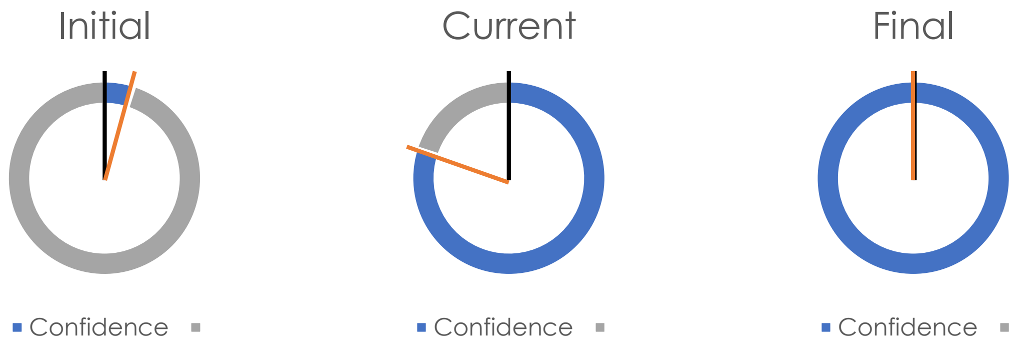
Barriers to Increasing Recovery

How far will the needle move?

- **Barrier to increasing recovery** → Gas migration in cement and uncertainty with standard measurements.
- **Project is addressing** → Improving accuracy and precision of industry's method to prevent gas migration.
- **Extent the needle has been moved**

  Confidence in SGS Measurement (estimate):



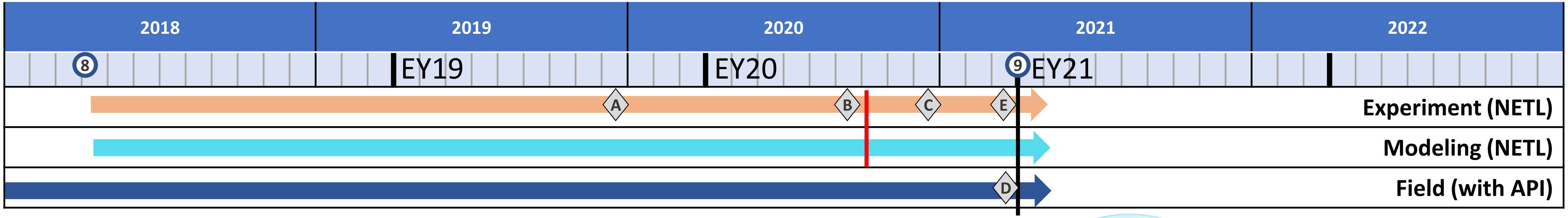


API Task Group:

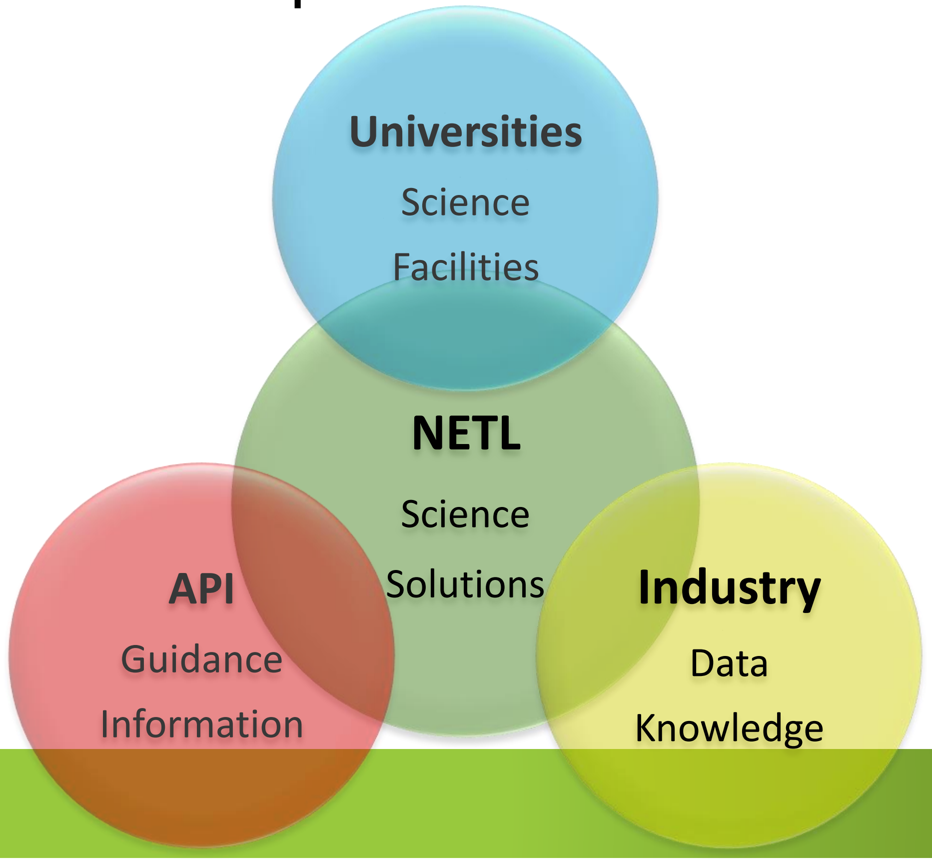
- Gas migration in cement is a known issue - around 60 years.
- SGS has been used for over 40 years to address issue of gas migration.
- 5 years of cement testing data.

Project Overview

PI: Dr. Eilis Rosenbaum Performance Dates: EY 2018 to EY 2020



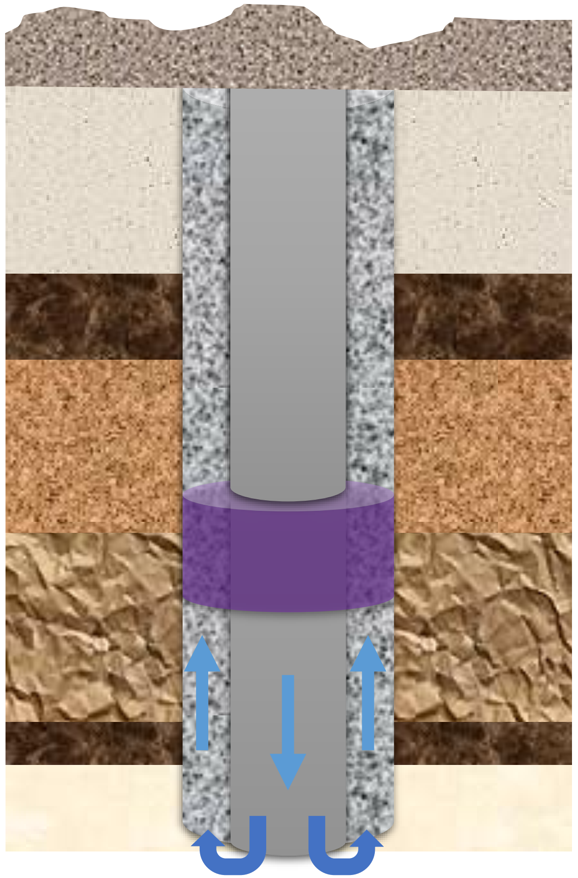
A. Tests in machine(s) at NETL with known materials.
B. Tests with materials with known properties to verify machine correlation.
C. The SGS properties of cement will be determined with correlated machines.
D. Tests with cement at participating laboratories will be completed.
E. Testing will be completed to determine parameters influencing the cement SGS.



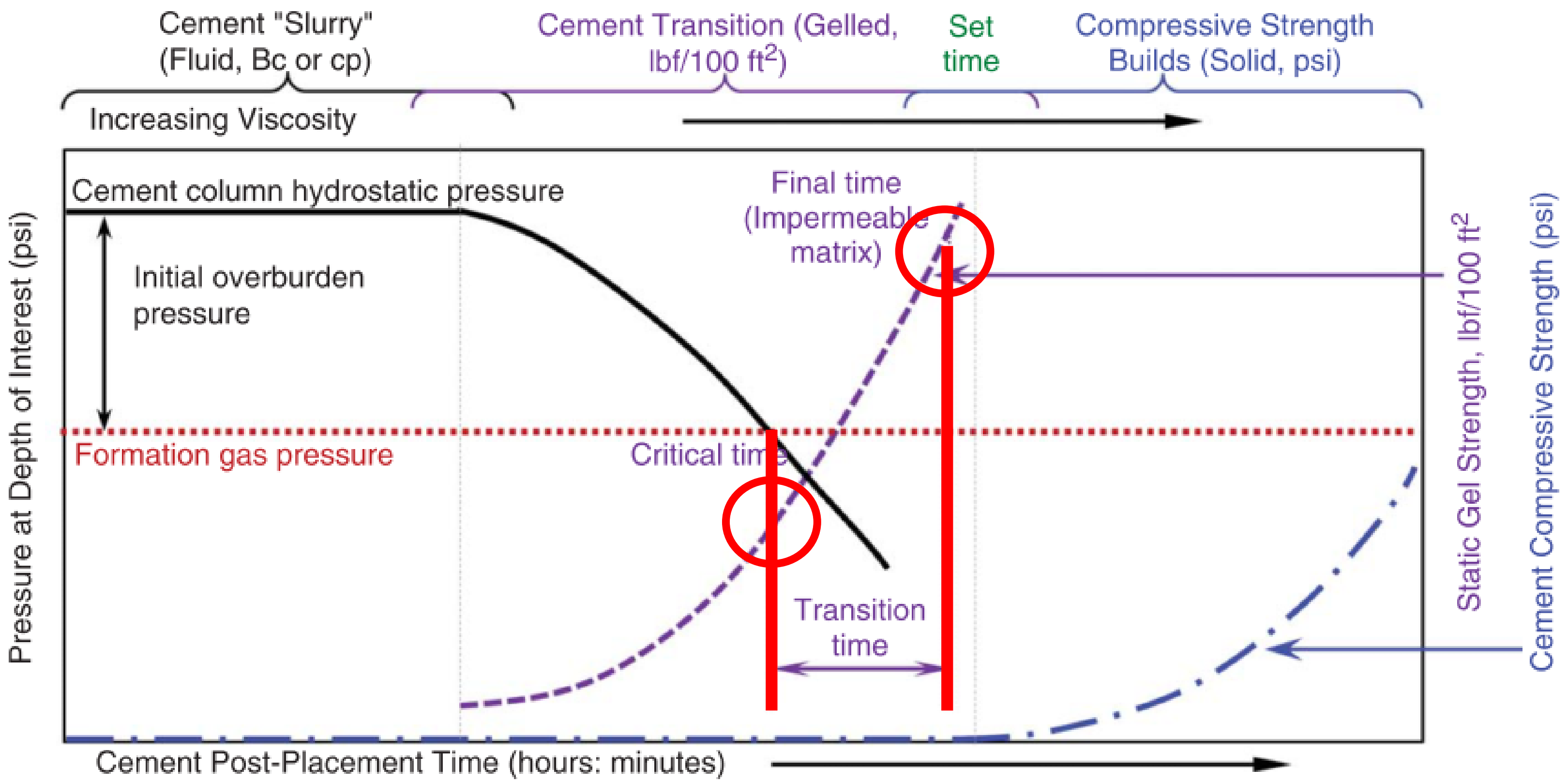
Gas Migration in Wellbore Cement and Cement Static Gel Strength

2 Static

1 Flow
Conditioning



Cement SGS:



100 $lb_f/100\ ft^2$ Critical (CSGS)

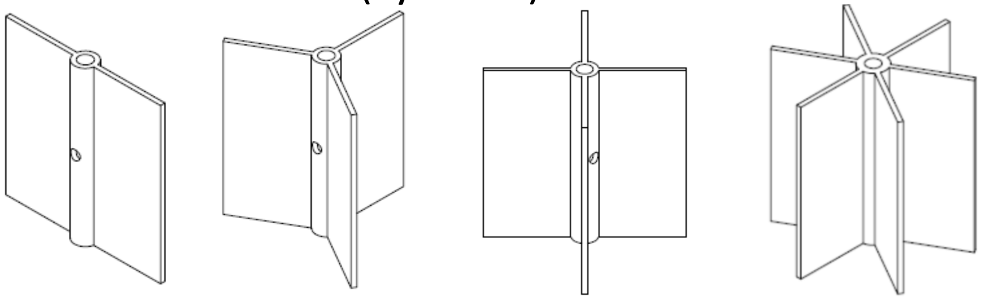
500 $lb_f/100\ ft^2$ Optimal (OSGS)

Cheung and Beirute, 1985

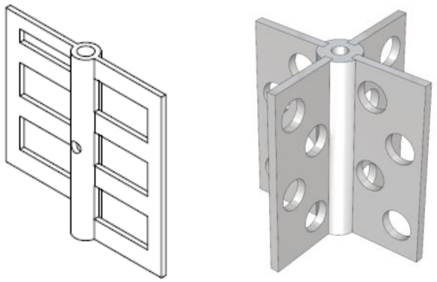
Static Gel Strength Measurements

Basic Design – Vane Method

Number of blades (cylinder):



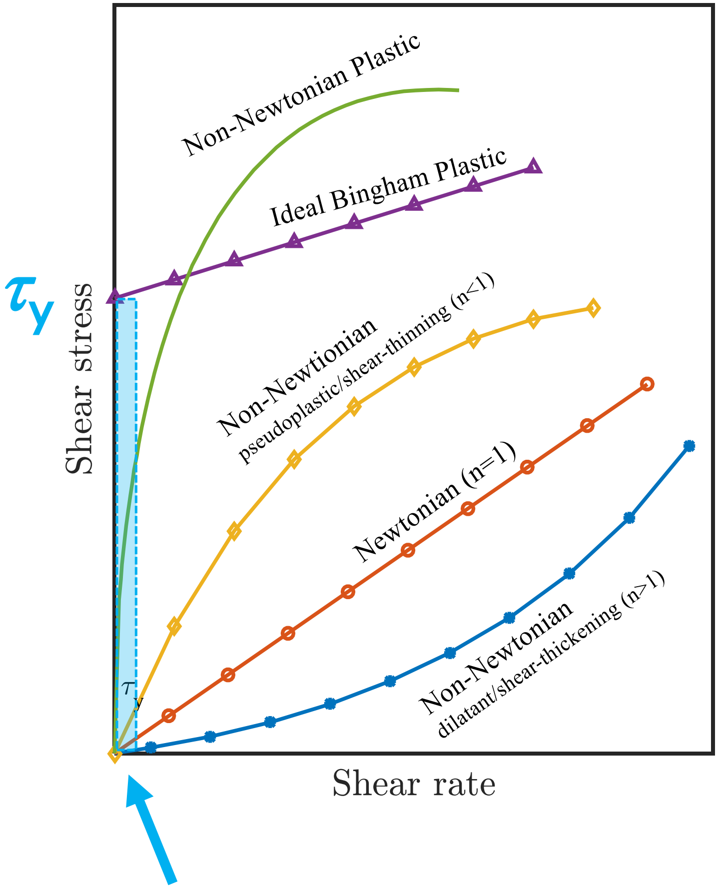
Non-solid blades – different geometries:



Relationship between torque and yield stress:

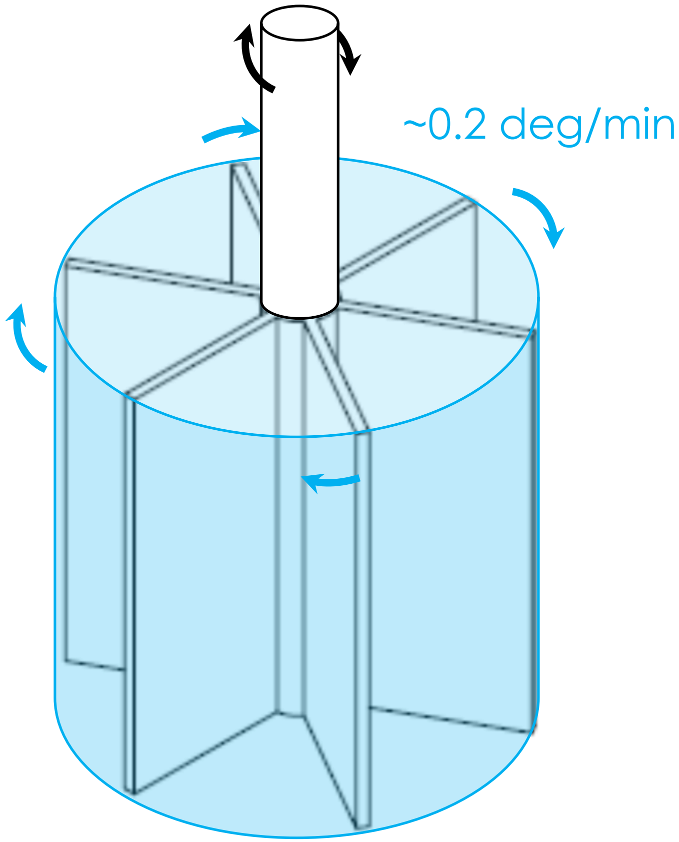
$$T_m = K\tau_y$$

$$K_{cylinder} = \left(\frac{\pi D^3}{2}\right)\left(\frac{H}{D} + \frac{1}{3}\right)$$



Measured at low shear rate

Vane Method



6 Blade Paddle

Tao, C.; Rosenbaum, E.; Kutchko, B.; Massoudi, M. The Importance of Vane Configuration on Yield Stress Measurements of Cement Slurry; DOE/NETL-2020/2116; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2020; p 24. DOI: 10.18141/1614691 http://netl.doe.gov/research/on-site-research/publications/featured-technical-reports.

Static Gel Strength Measurements

Testing of Materials with a Yield Stress and Constant SGS

- Vanzan/Xanthan Gum
- Aloe Vera Gel
- Laponite RD and RDS

Example: Laponite

Laponite RD +
Laponite RDS

DI Water

Detailed mixing instructions to reduce variables

Rheological Behavior of Non-Newtonian Fluids

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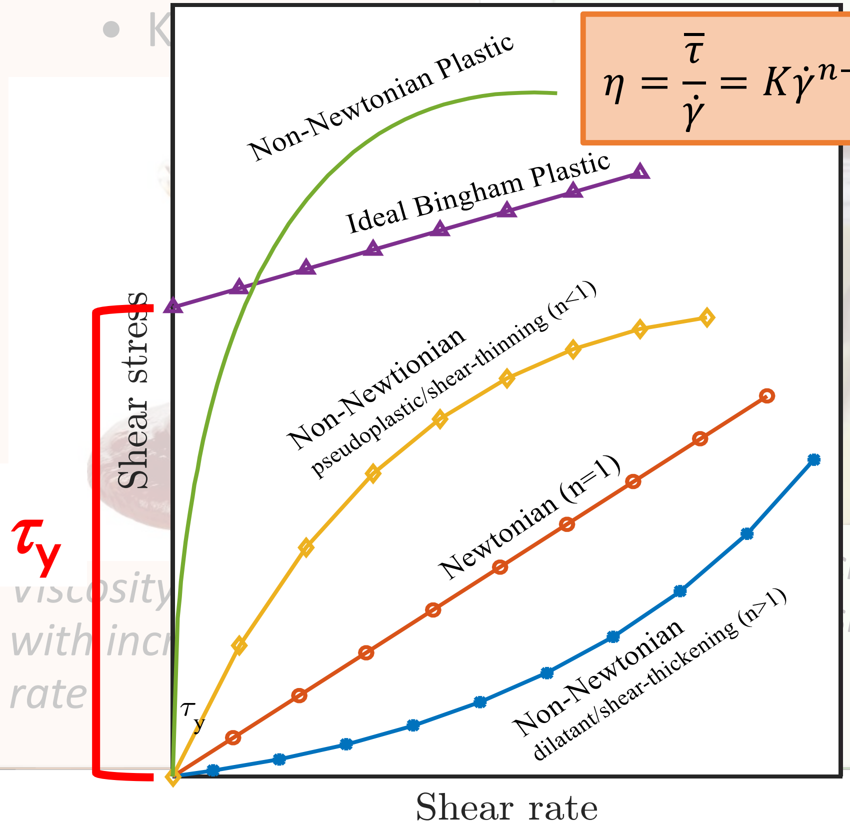
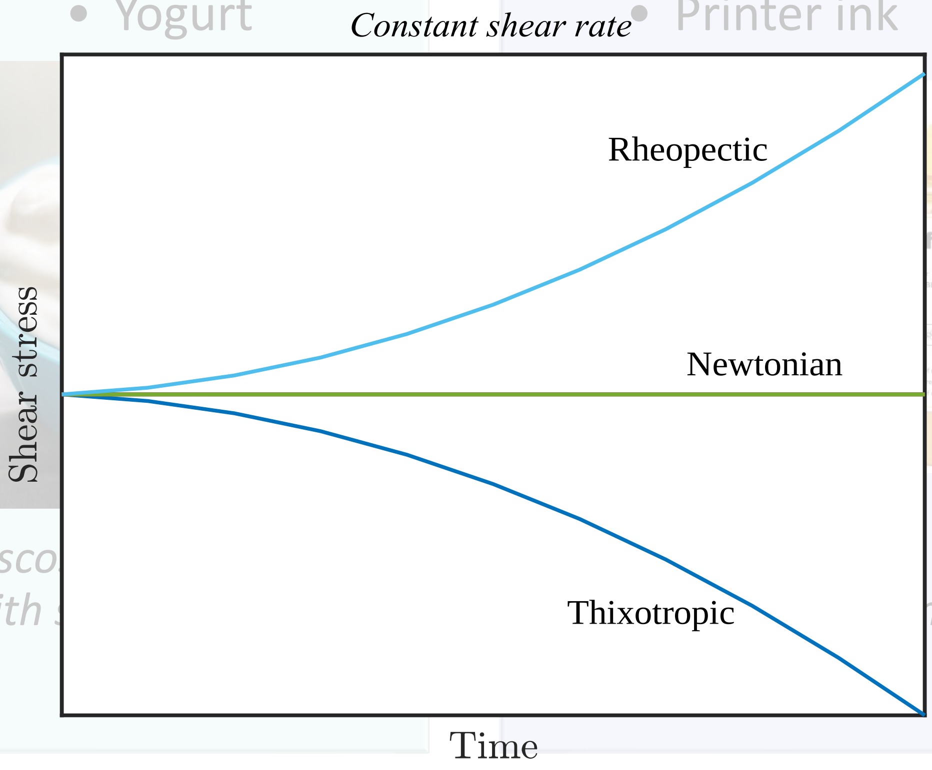
Shear Thinning (Pseudoplastic)	Shear Thickening (Dilatant)	Thixotropic	Rheopectic

- Yogurt
- Printer ink

$$\eta = \frac{\overline{\tau}}{\dot{\gamma}} = K\dot{\gamma}^{n-1}$$

1D





A Review of Rheological Modeling of Cement Slurry in Oil Well Applications. *Energies*, 13 (3), 570.

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NETL Cement Slurry Rheology Model

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Rheology of cement slurry:

- Viscosity depends on the **shear rate**, **particle concentration**,…
- Cement has a **yield stress**
- Cement shows **thixotropic** behavior

In house NETL constitutive model for cement slurry

3D

Total stress: $\boldsymbol{T} = \boldsymbol{T}_v + \boldsymbol{T}_y$

Viscous stress:

Shear rate

$$\boldsymbol{T}_v = -p\boldsymbol{I} + \mu_0\left(1-\frac{\phi}{\phi_m}\right)^{-\beta}(1+\lambda^n)\left[1+\alpha\mathrm{tr}\boldsymbol{A}_1{}^2\right]^m\boldsymbol{A}_1 + \alpha_1\boldsymbol{A}_2 + \alpha_2\boldsymbol{A}_1{}^2$$

Volume fraction

Thixotropic behavior

Yield stress:

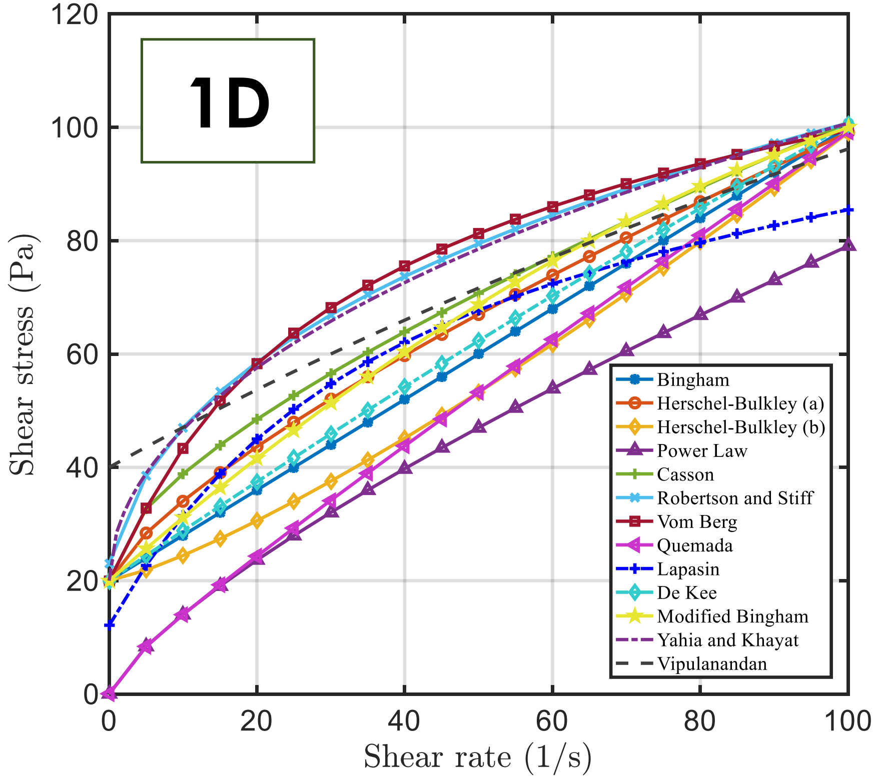
Volume fraction

Water to cement ratio

Shear rate

$$\boldsymbol{T}_y = \left[\frac{m_1\dfrac{\phi^2(\phi-\phi_{perc})}{\phi_m(\phi_m-\phi)}\times(-175w/c+137)}{\left|\Pi_{\boldsymbol{A}_1}\right|^{1/2}} + K\left|\Pi_{\boldsymbol{A}_1}\right|^{\frac{n-1}{2}}\right]\boldsymbol{A}_1 \quad \text{for} \quad \Pi_{\boldsymbol{A}_1}^{1/2} > \dot{\gamma}_c$$

Literature review of cement slurry constitutive models 304 References



Tao, C., Kutchko, B., Rosenbaum, E., and Massoudi, M., “A Review of Rheological Modeling of Cement Slurry in Oil Well Applications,” Energies, 13 (2020), 570, DOI:10.3390/en13030570 (https://www.mdpi.com/1996-1073/13/3/570/pdf).

NETL Cement Slurry Model

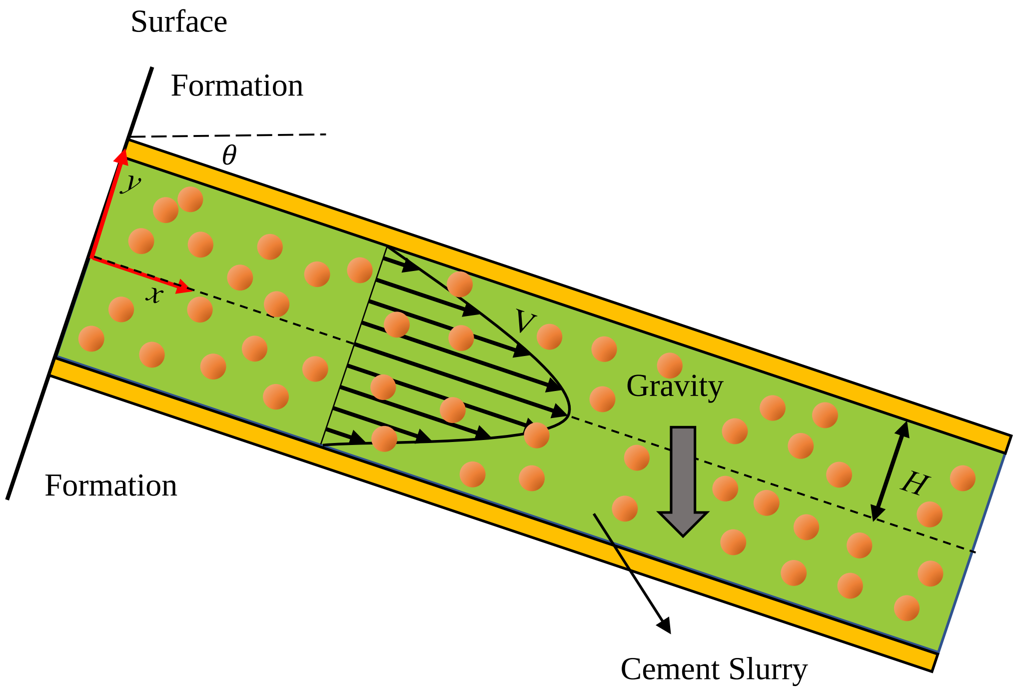
Steady Flow of a Cement Slurry

MODEL DESIGN

- Constitutive cement model – cement flow at onshore wellbore conditions
- Cement slurry modeled as non-Newtonian fluid
- Viscosity depends on the shear rate and particle concentration
- Study the impact of parameters on behavior of cement slurry

OUTCOMES

- Parametric study results indicate that the following significantly affect the **velocity** and **particle distribution**:
  - Angle of inclination θ
  - Maximum packing fraction of cement particles
  - Pressure and gravity terms

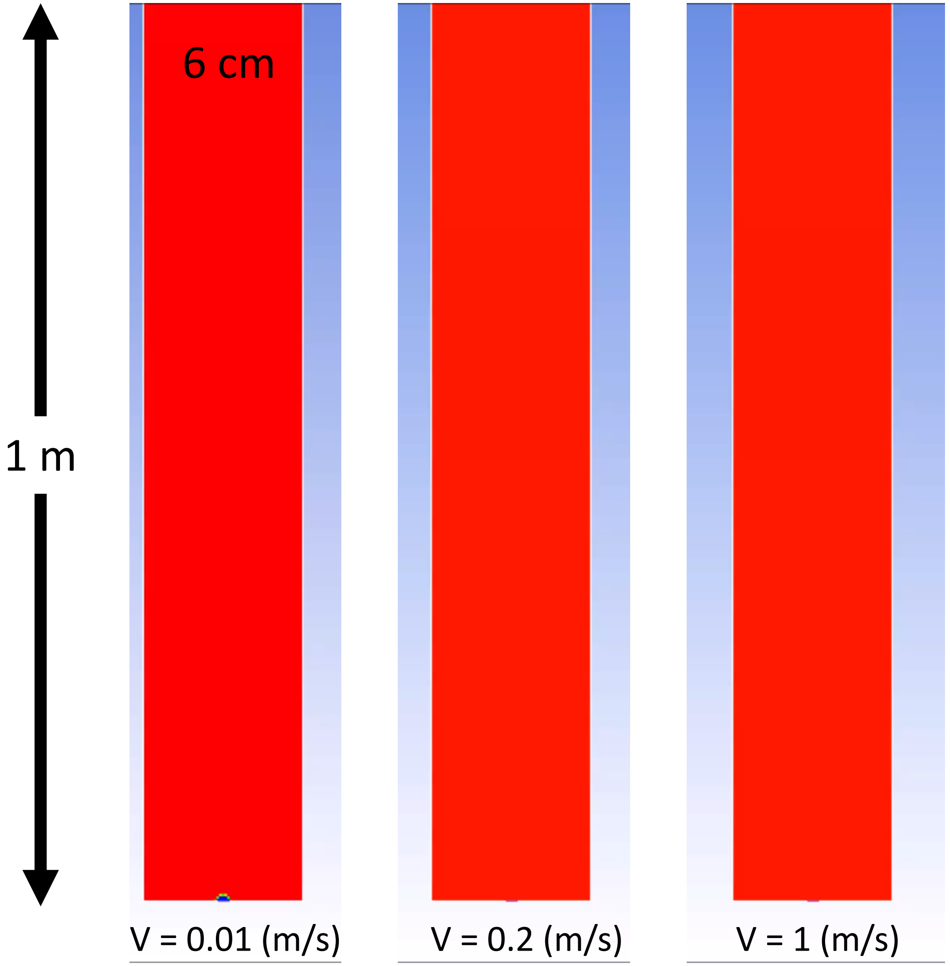


Schematic diagram of cement slurry flow in an inclined channel

“Steady Flow of a Cement Slurry”. *Energies, 12*, 13: 2604.

Simulations & Experiments

Simulations



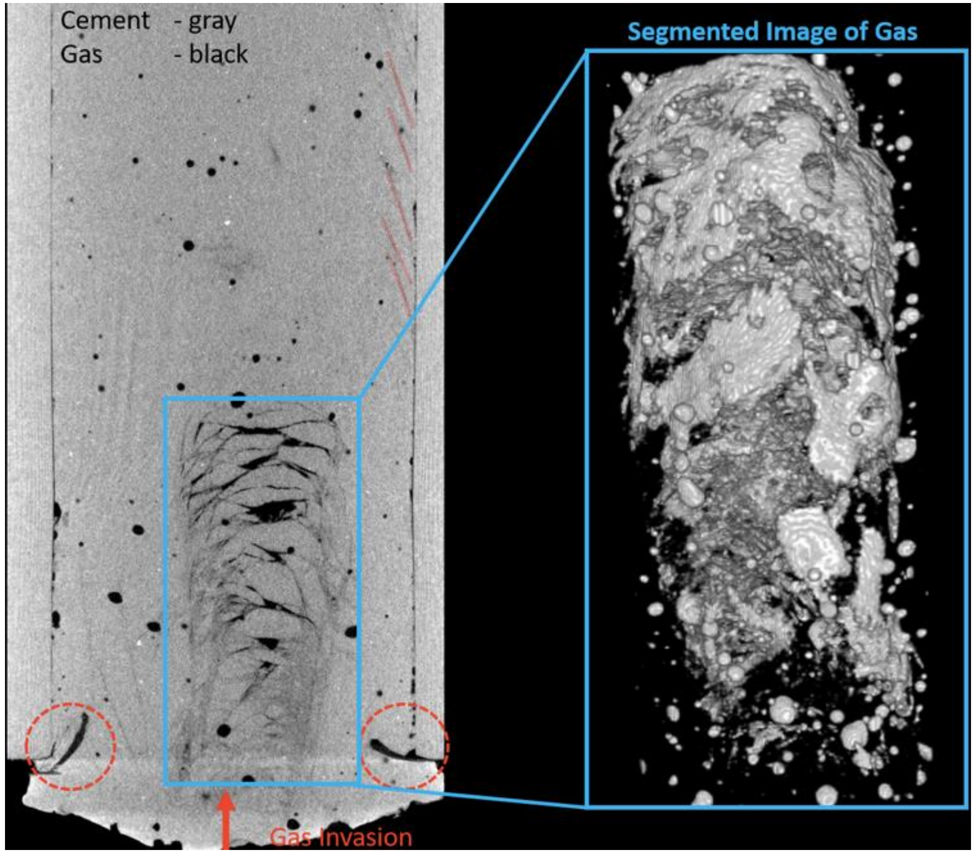
Example:
2D Channel Flow
Air in Water

Liquid Properties	
Viscosity	1 kg/ms
Density	998 kg/m^3
Surface Tension	0.07 N/m

Air inlet: 5 mm

Experiments

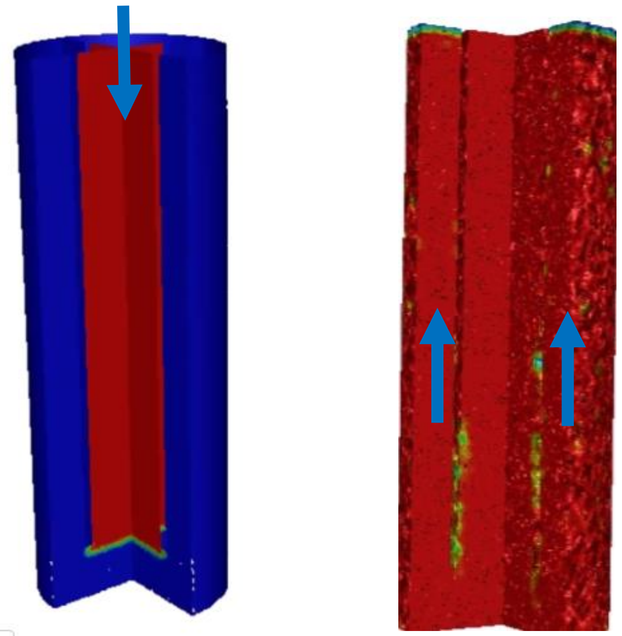
Example:
3D Pipe
Air injection into
Cement Slurry



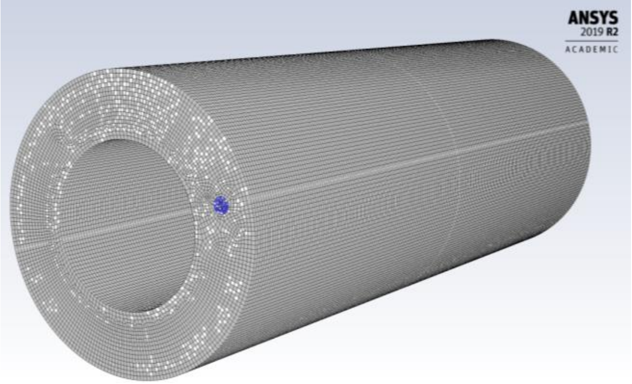
Mofakham, A., Ahmadi, G., Tao, C., Massoudi, M., Rosenbaum, E., Kutchko, B., Computational Modeling of Oil Well Cementing and Gas Migration Process, Proceeding of the ASME 2020 Fluids Engineering Division Summer Meeting, FEDSM2020, July 12-16.

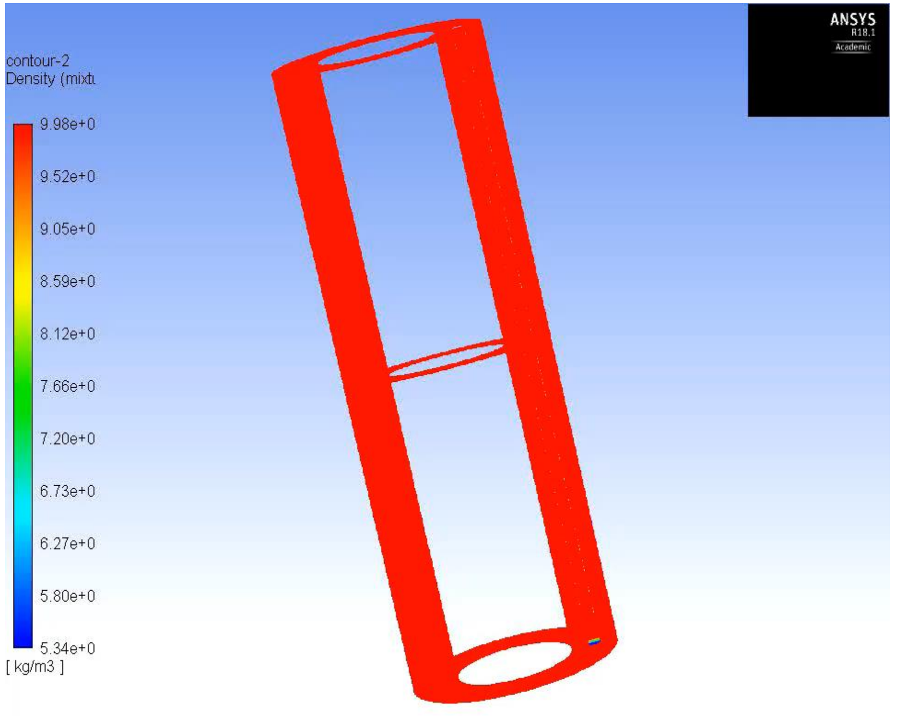
Multiphase Cement Slurry Flow

Simulation of Cement Slurry Placement



Gas Injection Into Cement in Annulus





Two-phase flow of 3D cylindrical geometry

SIMULATION DETAILS

- Applied ANSYS-Fluent volume of fluid (VOF) method for multiphase flow
- Simulated initial tests and geometries with Newtonian fluid
- Implemented NETL cement slurry model into ANSYS-Fluent with use of “user-defined functions”

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Summary

Progress and Conclusions

API TASK GROUP COLLABORATION

- NETL has NDAs with the 5 manufacturers of SGS machines.
- NETL is participating in co-op testing with the API Task Group.
- NETL has access to the data collected as part of this unprecedented collaboration.

EXPERIMENTAL WORK

- Extensively studied the machine designs.
- Provided a path forward to align industry testing and machines – API approved.
- Conducted testing to confirm calculations.
- Compared two separate machines and many paddles.

CEMENT SLURRY MODEL

- Studied the impact of parameters on behavior of cement slurry.
- Incorporating our models into computational fluid dynamics packages.

PRODUCTS

- Solution to API/industry priority.
- Improved technology currently on the market.
- Provided guidance on calibration process.
- Multiple presentations on the modeling results.
- Presentations at all API Conferences.
- Paper summarizing the modeling results to date; another one in draft.
- Report summarizing the study of the SGS device measurements.
- Analysis of API Co-op testing data.
- Report summarizing the influence of paddle design.
- Extensive review paper of cement slurry models.

TAKE AWAY

- Industry standard measurements can provide accurate and precise SGS information.

https://edx.netl.doe.gov/offshore/portfolio-items/well-cement-behavior-and-gas-migration/

Technology Transfer

PAPERS AND TECHNICAL REPORTS:

- Tao, C., Rosenbaum, E., Kutchko, B., and Massoudi, M. (2020). "Unsteady Flow of a Cement Slurry". Energies, in progress.
- Tao, C., Rosenbaum, E., Kutchko, B., and Massoudi, M. (2020). Gas Migration in Oilwell Cement, National Energy Technology Laboratory report, in progress.
- Tao, C., Kutchko, B., Rosenbaum, E., Wu, W., Massoudi, M., Steady Flow of a Cement Slurry, Special Edition of Energies, 2019, 2604. 10.3390/en12132604.
- Tao, C., Kutchko, B., Rosenbaum, E., and Massoudi, M., "A Review of Rheological Modeling of Cement Slurry in Oil Well Applications," Energies, 13 (2020), 570, DOI:10.3390/en13030570 (https://www.mdpi.com/1996-1073/13/3/570/pdf).
- Tao, C.; Rosenbaum, E.; Kutchko, B.; Massoudi, M. The Importance of Vane Configuration on Yield Stress Measurements of Cement Slurry; DOE/NETL-2020/2116; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2020; p 24. DOI: 10.18141/1614691 http://netl.doe.gov/research/on-site-research/publications/featured-technical-reports.

PRESENTATIONS AND CONFERENCES:

- *Numerical analysis for flow of a cement slurry*, Presented at Mid-Atlantic Numerical Analysis Day, November 9, 2018, Temple University, Philadelphia, PA.
- Tao, C., Rosenbaum, E., Kutchko, B., and Massoudi, M., "Effects of Shear-Rate Dependent Viscosity on the Flow of a Cement Slurry," poster presented at the Dynamics Days 2019, International Conference on Nonlinear Dynamics, Northwestern University, Evanston, IL, January 4-6, 2019.
- *Tao, C., Rosenbaum, E., Kutchko, B., and Massoudi, M., "Flow of cement slurry in a vertical pipe," accepted for presentation at the 2019 Joint Mathematics Meetings (JMM), American Mathematical Society (AMS), Mathematical Association of America (MAA), Baltimore, MD, January 16-19, 2019. http://jointmathematicsmeetings.org/meetings/national/jmm2019/2217_intro*
- Rosenbaum, E., Benge, G., Static Gel Strength Working Group Update to the API Subcommittee on Oil Well Cement (SC 10), API Winter Standards Meeting, January 21-24, 2019.*Steady and Transient Flow of a Cement Slurry*, presented at the Engineering Mechanics Institute (EMI2019) Conference, June 18-21, 2019.
- API 2019 Summer Standards Meeting, Hyatt Regency, New Orleans, LA, June 24-27, 2019.
- Tao, C., E. Rosenbaum, B. Kutchko, M. Massoudi, *Flow of a cement slurry modeled as a generalized second grade fluid,* presented at the *Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting*, August, 28, 2019.
- Rosenbaum, E., B. Kutchko, M. Massoudi, R. Spaulding, C. Tao, I. Haljasmaa, J. Fazio, K. Dayal, *Well Cement Behavior and Gas Migration During Early Hydration – Methods to Determine Slurry Gelation to Ensure Wellbore Integrity, presented at the Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, August, 28, 2019.*
- *Rosenbaum, E., Benge, G., Static Gel Strength Working Group Update to the API Subcommittee on Oil Well Cement (SC 10), API Winter Standards Meeting, January 20-24, 2020.*
- *Steady and Transient Flow of a Cement Slurry, presented at the Engineering Mechanics Institute (EMI2019) Conference, June 18-21, 2019.*
- Mofakham, A., Ahmadi, G., Tao, C., Massoudi, M., Rosenbaum, E., Kutchko, B., *Computational Modeling of Oil Well Cementing and Gas Migration Process,* Proceeding of the ASME 2020 Fluids Engineering Division Summer Meeting, FEDSM2020, July 12-16.

ADDITIONAL INFORMATION:

- https://edx.netl.doe.gov/offshore/portfolio-items/well-cement-behavior-and-gas-migration/