Modeling Smart Cement Time-Dependent Flow Properties Using Vipulanandan Rheological Model

A. Aldughather and C. Vipulanandan[1], Ph.D., P.E.
[1]Center for Innovative Grouting Material and Technology (CIGMAT)
Department of Civil and Environmental Engineering
University of Houston, Houston, Texas 77204-4003
E-mail: analdughather@uh.edu, cvipulanandan@uh.edu Phone: (713) 743-4278

Abstract: In this study, smart cement rheology was tested using oilfield viscometer. The rheological data was modeled using Vipulanandan model. Results showed that Vipulanandan model predicted the time dependent rheological behavior of smart cement as a function of polymer loading.

1. Introduction: Cement mixing and design is very critical for the cement performance. This is due to the time dependency of the cement properties which would make the repeatability of tests especially rheology results very difficult. Challenging High-pressure high-temperature (HPHT) conditions and especially unconventional wells, deviated and horizontal wells demand that cement mixing and design be optimized which is very crucial for ensuring the integrity of the cement for as long as the well remains in service. Operators usually perform rheological testing in order to insure that the slurries can be mixed and pumped with minimal pressure drop (Shahraiar and Nehdi, 2011). Hence, rheological properties should be predicted properly as overestimation or underestimation could be critical especially in severe conditions such as in HPHT operations. Pressure, however, has a minimal effect on the rheological properties of cement (Sutton et. al. 1990). Therefore, in this study, rheological properties of smart cement modified with latex polymer are investigated and modeled using Vipulanandan's Rheological model. Latex polymers are often used in cementing operations to reduce the matrix permeability of cement preventing by that gas migration while increasing the fluidity as well as improving the workability and durability of the cement. Hysteresis loops (flow curves) were generated for the cement samples as a function of polymer loading. The ramp-up and ramp-down curves are generated by applying angular velocities starting at 3 RPMs up to 300 rpm for the loading cycle and going back to the initial value of 3 rpm during unloading. These curves were analyzed separately to predict the time-dependent cement rheological properties using Vipulanandan rheological model.

2. Objective: The specific objectives of this study are the following:

a) Predict the Rheological Properties of smart cement using Vipulanandan model.
b) Characterize the shear thickening and shear thinning phenomenon in smart cement.
c) Verify the maximum shear stress (Shear stress capacity) from Vipulanandan model.

3. Background:

Table 1. Non-Newtonian rheological models constitutive equations

Rheological Model	$\tau = f(\dot{\gamma})$	$\lim_{\dot{\gamma}\to 0} \tau = \tau_0$	$\frac{d\tau}{d\dot{\gamma}} > 0$	$\frac{d^2\tau}{d\dot{\gamma}^2} < 0$	$\lim_{\dot{\gamma}\to\infty} \tau = \tau_{max}$
Bingham Plastic (1916)	$\tau = \tau_0 + \mu_p\dot{\gamma}$	τ_0	μ_p	0	∞
Power Law (1925)	$\tau = K\dot{\gamma}^n$	0	$Kn\dot{\gamma}^{n-1}$	$K(n-1)\dot{\gamma}^{n-2}$	∞
Herschel Bulkely (1926)	$\tau = \tau_0 + K\dot{\gamma}^n$	τ_0	$Kn\dot{\gamma}^{n-1}$	$K(n-1)\dot{\gamma}^{n-2}$	∞
Prandtl-Eyring (1936)	$\tau = A_t \sinh^{-1}(\frac{\dot{\gamma}}{B_p})$	0	$\frac{A_t}{B_p[\left(\frac{\dot{\gamma}}{B_p}\right)^2 + 1]^{0.5}}$	$-\frac{A_t\dot{\gamma}}{B_p{}^3[\left(\frac{\dot{\gamma}}{B_p}\right)^2 + 1]^{1.5}}$	∞
Casson (1956)	$\tau = [\tau_0{}^{0.5} + (\mu_p\dot{\gamma})^{0.5}]^2$	τ_0	$\frac{\mu_p\dot{\gamma}^{0.5} + \tau_0{}^{0.5}\mu_p{}^{0.5}}{\dot{\gamma}^{0.5}}$	$\frac{\mu_p}{2\dot{\gamma}} - \frac{\mu_p\dot{\gamma}^{0.5} + \tau_0{}^{0.5}\mu_p{}^{0.5}}{2\dot{\gamma}^{1.5}}$	∞-
Sisko (1958)	$\tau = a_s\dot{\gamma} + b_s\dot{\gamma}^{c_s}$	0	$a_s + b_s c_s\dot{\gamma}^{c_s-1}$	$b_s c_s{}^2\dot{\gamma}^{c_s-2}$	∞
Robertson-Stiff (1976)	$\tau = K(\gamma_0 + \dot{\gamma})^n$	$K(\dot{\gamma}_0)^n$	$Kn(\gamma_0 + \dot{\gamma})^{n-1}$	$K(n-1)(\gamma_0 + \dot{\gamma})^{n-2}$	∞
Vipulanandan (2014)	$\tau = \tau_0 + \frac{\dot{\gamma}}{A + D\dot{\gamma}}$	τ_0	$\frac{A}{(A + D\dot{\gamma})^2}$	$\frac{-2AD}{(A + D\dot{\gamma})^3}$	$\tau_0 + \frac{1}{D}$

There are many generic rheological models available in the literature to genrate time independent properties of cement which are listed in Table 1 above. These models were analyzed as shown with given conditions i.e. zero shear rate, infinite shear rate, and maximum shear rate. Also, the first and second derrivative of each model with respect to shear rate was listed. As shown, Vipulanandan model is the only model that provides a limit to the maximum shear achieved at infinite shear strain as opposed to the other models. It is also worthy to mention that Vipulanandan model gives values for shear thinning and shear thickening fluids which could be inferred from parameters A and D. With neat smart cement as shown in Table 2, the ramp-up curve shows shear thickening behavior whereas the ramp down curve shows shear thinning indicating that the cement is hydrating (Build up). Additionally, Vipulanandan model as opposed to the other models accounts for the time dependancy of cement phase shift. The results are shown in Table 1 and Table 2.

4. Materials and Methods:

Class H cement 0.38 water to cement ration (w/c) using (350 g) cement and (132 mL) of water and conductive fillers 0.1%. Latex polymer additive added as (1%, 2%, 5% BWOC) (Carboxylated styrene butadiene latex XSBR). The tests were done under ambient temperature and atmospheric conditions. The machine was calibrated with 100 cp viscosity calibration fluid. Testing was done in accordance with API RP10B-2 testing standards and procedures by mixing the polymer with water first then cement with carbon fibers dispersed inside was poured into the blender while spinning at 4000 RPMs within 15 s. Then the slurry was mixed for 35 s at 12000 RPMs.

5. Test Results:

Table 2. Ramp-up curve rheological properties generated using Vipulanandan model

BWOC %	τ_0 Pa	A $(Pa.s)^{-1}$	D Pa^{-1}	β_1 s	β_2 Pa.s	τ_{max} Pa	τ_0 / τ_{max}	R^2	RMSE Pa
0%	10.73	7.65	-0.0008	0.00010	0.13072	81.25	0.132	0.970	4.52
1%	10.89	9.34	-0.003	0.00032	0.10707	76.30	0.143	0.971	3.99
2%	10.48	10.74	-0.004	0.00037	0.09311	69.20	0.151	0.976	3.31
5%	10.93	17.81	-0.009	0.00051	0.05615	49.58	0.220	0.980	1.94

Table 3. Ramp-down curve rheological properties generated using Vipulanandan model

BWOC %	τ_0 Pa	A $(Pa.s)^{-1}$	D Pa^{-1}	β_1 s	β_2 Pa.s	τ_{max} Pa	τ_0 / τ_{max}	R^2	RMSE Pa
0%	6.01	2.59	0.007	0.00270	0.38610	148.87	0.0404	0.970	2.23
1%	7.37	3.13	0.007	0.00224	0.31949	150.23	0.0491	0.992	2.34
2%	8.09	3.89	0.008	0.00206	0.25707	133.09	0.0608	0.989	2.31
5%	9.07	6.27	0.018	0.00287	0.15949	64.63	0.1403	0.982	1.84

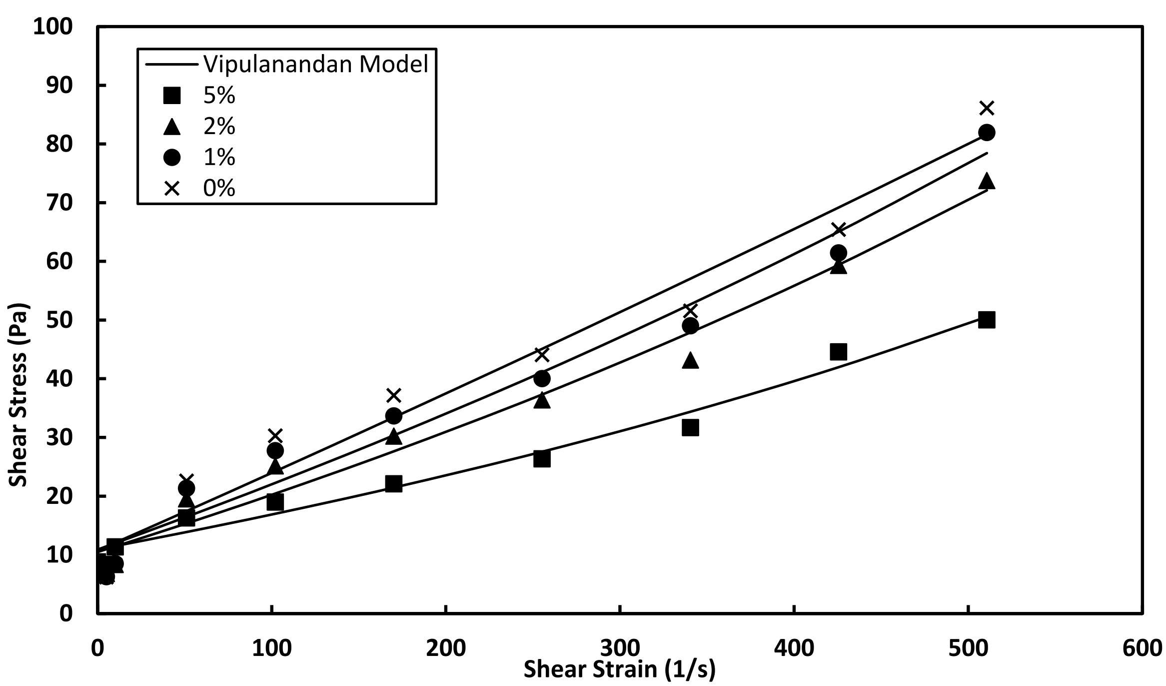

Figure 1. Ramp-up curves of polymer modified smart cement

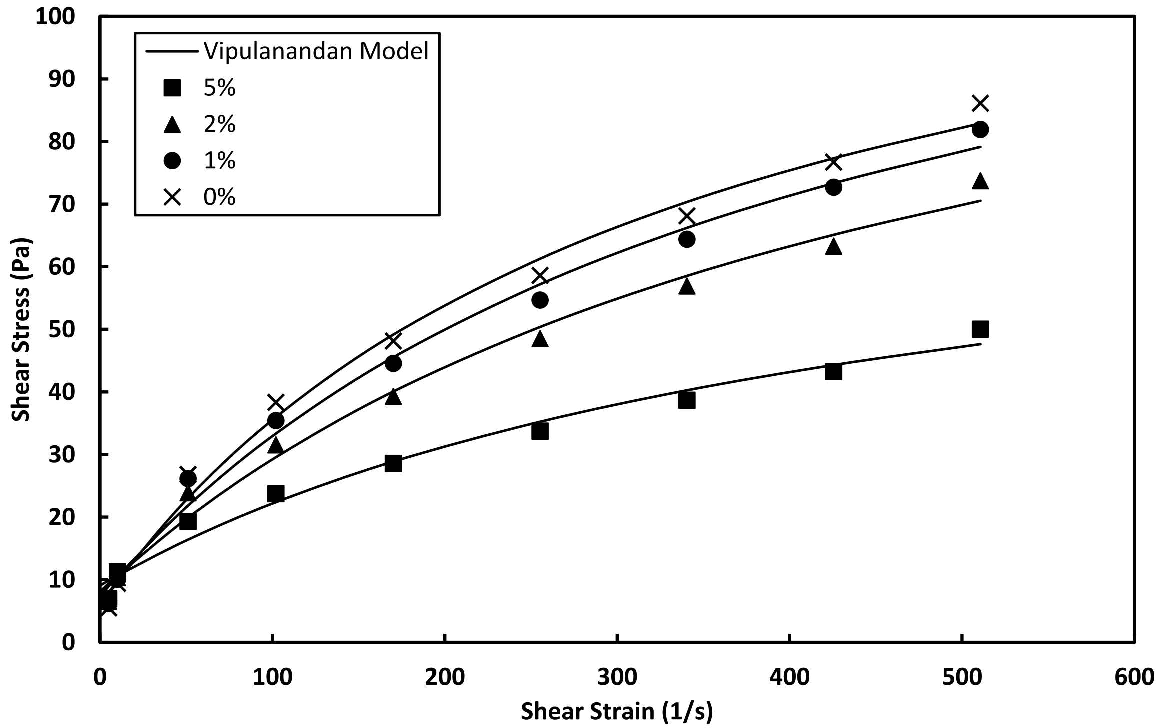

Figure 2. Ramp-down curves of polymer modified smart cement

6. Conclusion:

1. Vipulanandan model can predict both shear stress at zero shear rate and shear stress at infinite shear rate providing an upper limit for shear stress (shear stress capacity).
2. For both ramp-up and ramp-down curves, τ0 increase while τmax decreases with polymer loading.
3. For both ramp-up and ramp-down curves, the time constant β1 increases whereas the viscosity constant β2 decreases.

7. Acknowledgements:

The study was supported by the CIGMAT (Center for innovative grouting materials and Technology) and Texas Hurricane Center for Innovative Technology (THC-IT).

8. References:

1. Afolabi, Richard & Yusuf, Esther. (2020). "Modification of the Vipulanandan Rheological Model with Correlation for Temperature and Electrolyte Effect on Drilling Muds". Advanced Powder Technology. 31. 312-322. 10.1016/j.apt.2019.10.023.
2. API RP 10B-2, Petroleum and natural gas industries – Cements and materials for well cementing – Part 2: Testing of well cements.
3. Keke Sun, Shuping Wang, Lu Zeng, Xiaoqin Peng. "Effect of Styrene-butadiene Rubber Latex on Rheological Behavior and Pore Structure of Cement Paste". Composites Part B (2019)
4. Vipulanandan et. al. "Rheological Properties of Piezoresistive Smart Cement Slurry Modified with Iron-Oxide Nanoparticles for Oil well Applications" (2017) Journal of Testing and Evaluation.