Effects of Fly Ash on the Rheological Properties of Cement Slurry Using Vipulanandan Rheological Model

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Abstract

In this study cement (Portland Cement Type 1) grouts were prepared with water-to-cement ratios of 0.4 with fly ash (class C) content of 5% and 50%. The test results showed that the cement slurry tested were shear thinning fluids representing non-Newtonian fluids. The rheological constitutive relationships for the cement grouts were predicted using the new Vipulanandan rheological model (2014). Based on the root mean square error (RMSE) of the predictions of the experimental results, Vipulanandan rheological model predicted the measured shear stress at various shear strain rates for the grouts. The new Vipulanandan rheological model also has a limit on the shear stress tolerance for the cement slurry and changed with the addition of fly ash.

1. INTRODUCTION

Cement grouts are used in multiple applications including stabilizing the soils, repairing various damaged infrastructures, installing wells, leaking pipes and solidification of contaminated soils (Yeon et al. 1997;Stille et al. 2010; Taehee et al. 2013; Vipulanandan et al. 2014 and 2017; Vipulanandan 2021). In all these applications cement grouts have to be injected at varying pressures to flow through complex macro and microstructures and hence the cement grouts rheological properties become very important. One of the major variables for the cement grout is the water-to-cement ratio. Also for some applications cement grouts are modified by adding clay, which will also impact the rheological properties of the cement grouts. In the area of structural construction, cement grouts are used in the ducts of the post tensioned beams and the long-term performance of the beams are very much depended on the durability of the injected grouts to bond the concrete to the post-tensioned steel reinforcements and to transfer the loads. Cement grouts are used in cementing the oil, gas and water wells and the wells are expected to be productive for decades (Heinold et al. 2002; Vipulanandan et al. 2017 and 2018). Also cement slurries/grouts are used for repairing these wells and also in CO_2 sequestration wells.

Cement grouts and slurries are used in repairing beams, pipelines and underground storage facilities in-situ and the successful operations very much depends on the durability and long-term strength of the cement grouts (Vipulanandan 2021). Cement grouts are used in also stabilizing the soils to strength them for multiple applications. Hence there is an increasing interest in understanding and quantifying not only the variation of strength with curing time but also the long-term stress-strain behavior of the cement grouts. For grouting applications modifiers such as various types of clays (metakaolin, bentonite) ashes, silica fume and cement kiln dust have been used. Modifiers with reactive minerals with the cement grout changes the hardening process and the flow properties of cementitious grouts (Vipulanandan et al. 2014; Celik et al. 2015; Mohammed 2017). The fly ash has been used as cement replacement material up to 50% leading to microstructure modification, protecting against aggressive action of organic acids and diffusion of harmful ions which can lead to degradation of the cement matrix (Vipulanandan et al. 2017 and

2018). Also to reduce the impact on the environment, fly ash has been used to partially replace the cementitious materials (Vipulanandan 2021).

In order describe the behavior of various types of fluids such as grouts and drilling fluids, Power law and Herschel-Bulkley have been used for decades and the flow properties have been estimated based on these models (Celik et al. 2015; Afolabi et al. 2017 and 2019; Tchameniet al. 2019). The Herschel-Bulkley model that was developed in 1926 has been used to predict the shear-thinning and shear-thickenning behaviors of various types slurries. The new Vipulanandan rheological model that was developed in year 2014 for all types of fluids (shear thining, shear thickening and Newtonian) has been used to characterize shear thinning behavior of drilling muds and oil well cement slurries (Afolabi et al. 2017 and 2019 and 2017; Tchameniet al. 2019; Mohammed, 2017; Vipulanandan et al. 2014 and 2017). In addition, the new Vipulanandan rheological relationship for shear thinning fluids limits the magnitude of the shear stress tolerance of drilling mud but all the other relationships predicted infinite shear stress tolerance for the drilling mud (Vipulanandan et al. 2014; Mohammed 2017; Afolabi et al. 2019 and Tchameniet al. 2019) have clearly stated that of the several rheological models that were investigated to predict the rheological properties of nano-modified bentonite drilling muds, the new Vipulanandan rheological model better predicted the test results.

Model Verification

Studies have been performed around the world to verify the application of the Vipulanandan Rheological Model compared to other rheological models for various types of drilling fluids, smart spacer fluids, smart cement and smart foam cement with and without nanoparticles. All the studies have used statistical parameters such as root mean square error (RMSE) and coefficient of determination (R^2) to compare the various model predictions of the experimental results. Afolabi et al. (2017) investigated the addition of nano silica to bentonite drilling mud and used several models to compare the predictions and concluded that the Vipulanandan Rheological Model had the best prediction of the experimental results. In this study the maximum shear stress tolerance parameter was also used to compare the effect of adding nano silica. Montes (2019) used the model to investigate the effect of nanofluids in the viscosity reduction of extra-heavy oils. Tchameni et al. (2019) used the Vipulanandan Rheological Model to evaluate the thermal effect on the rheological properties of waste vegetable oil biodiesel modified bentonite drilling muds**.** Afolabi et al. (2019) used it to predict the rhological properties on nano particle modified drilling muds. Mohammed (2017) used the Vipulanandan Rheological Model to characterize the rheological properties of cement slurry modified with nano clay. Vipulanandan et al. (2016a,b and 2018a,i) used the model to characterize the behavior of smart foam cement, grouts and smart spacer fluids and compared it the to the Herschel-Bulkley model.

2. OBJECIVES

The focus was to test and quantify the addition of fly ash on the rheological properties of the cement slurry. The specific focus of the study are as follows:

i. Test the rheological properties of cement slurry modified with fly ash with water-to-cement (w/c) of 0.4.

ii. Model the rheological behavior of cement grouts with and without fly ash.

MODEL

Constitutive Models for Fluids

The cement slurry showed that the rate of increase in the shear stress (τ) decreased with the increase in shear strain rate ($\dot{\gamma}$) (tangent viscosity), representing a shear thinning fluid. It is important to satisfy the observed test results with the constitutive model. Some of the observed conditions for cement slurries are as follows (Vipulanandan et al. 2014, 2015b):

Yield shear stress $\tau = \tau_o$ when the shear stain rate is zero.

The tangential viscosity is $\frac{d\tau}{d\dot{\gamma}} > 0$ (1)

Also the rate of change of tangential viscosity is $\frac{d^2\tau}{d\dot{\gamma}^2} < 0$ (2)

At the strain rate of infinity (very large shear stain rate) the ultimate shear stress $\tau = \tau_{max}$ (3)

Vipulanandan rheological model (2014)

The performance of Vipulanandan Rheological Model predictions have been verified researchers around the world (Afolabi et al. 2017 and 2019; Mohammed, 2017; Tchameniet al. 2019). The constitutive model is represented as follows (Vipulanandan et al. 2014, 2017):

$$\tau - \tau_{o2} = \frac{\dot{\gamma}}{A + B * \dot{\gamma}} \quad (7)$$

Where the model parameters are τ_{o2}: yield stress (Pa); A $(Pa.\ s)^{-1}$ and B $(Pa)^{-1}$. So the tangential viscosity and rate of change of tangential viscosity for shear thinning fluids will be represented as follows (Vipulanandan et al. 2014, 2015b):

$$\frac{d\tau}{d\dot{\gamma}} = \frac{(A + B\dot{\gamma}) - \dot{\gamma} * B}{(C + B\dot{\gamma})^2} = \frac{A}{(A + B\dot{\gamma})^2} > 0 \Rightarrow A > 0$$

$$\frac{d^2\tau}{d\dot{\gamma}^2} = \frac{-2AB}{(A + B\dot{\gamma})^3} < 0 \Rightarrow B > 0$$

Also when the shear stain rate reaches infinite the ultimate shear strength

$$\tau_{max} = \frac{1}{B} + \tau_{o2} \quad (8)$$

Hence, the Eqn. (7) has a limit to the fluid shear stress tolerance representing the ultimate shear strength of the fluid.

3. MATERIALSAND METHODS

Cement slurry/grout
Portland cement (Type 1) (ASTM C 150 -16) was used in preparing the cement slurry.
Fly ash
Commercially available fly ash was used in this study. Different percentages of the fly ash up to 50% (by the weight of dry cement) was added to the cement.
Rheological test
The cement slurry with and without fly ash were tested using a rheometer with varying speed. The speed accuracy of this device was 0.001 rpm. A standard solution with a viscosity of 100 cP was used to calibrate the instrument. All the rheological tests were performed after 10 minutes of mixing of the cement slurry. For all the tests, at least three samples were tested for each condition.

4. RESULTS AND DISCUSSION

Rheological properties
The test results are shown in Figures 1 and 2. Vipulanandan Rheological Model was used to predict the results and are summarized in Table 1. Yield stress is an important parater to determine the initial pumping pressure for the cement slurry.
Yield Shear Stress (τ_{o2})
Based on the rheological model prediction of the test results, Vipulanandan Rheological Model predicted the yield stresses for the cement slurry mixes as summarized in Table 1. Adding the fly ash reduced the yield stress 21.5 Pa of the cement slurry. Adding 5% of fly ash reduced the yield stress to 12.5 Pa, 41% reduction. Also adding 50% of fly ash (class C) reduced the yield stress to 19.7 Pa.
Maximum Shear Strength ($\tau_{max.}$)
Based on the Vipulanandan rheological model there is a limit to the maximum shear stress ($\tau_{max.}$) for the cement slurry at the relatively high rate of shear strains. The τ_{max} for the cement slurries was 142 Pa as summarized in Table 1. Adding 5% fly ash reduced the τ_{max} to 102.9 Pa, a 27.5% reduction. With the addition of 50% fly ash the τ_{max} was 145.7 Pa, 2.6% higher than the cement slurry without any fly ash.

Table 1. Rheological Model Parameters for the Smart Cement Slurries Modified with Fly ash

Amount of Additives	Vipulanandan Rheological Model					
	τ_y (Pa)	A (Pa.s^{-1})	B (Pa)$^{-1}$	$\tau_{max.}$ (Pa)	RMSE (Pa)	R^2
Cement Only						
0	21.5	2.65	0.0083	142	2.1	0.98
Cement and Fly Ash						
5%	12.5	3.16	0.011	102.9	2.6	0.99
50%	19.7	4.74	0.0079	145.7	2.8	0.99

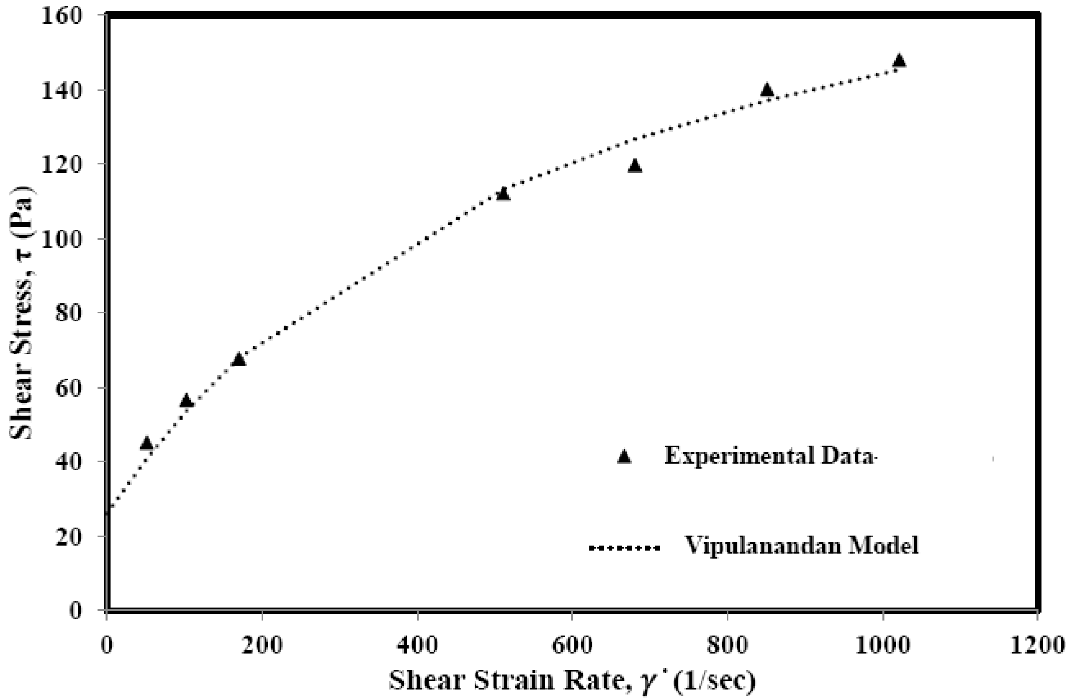

Figure 1. Shear Stress-Shear Strain Rate Relationship for Cement Slurry and Predicted Using the Vipulanandan Rheological Model

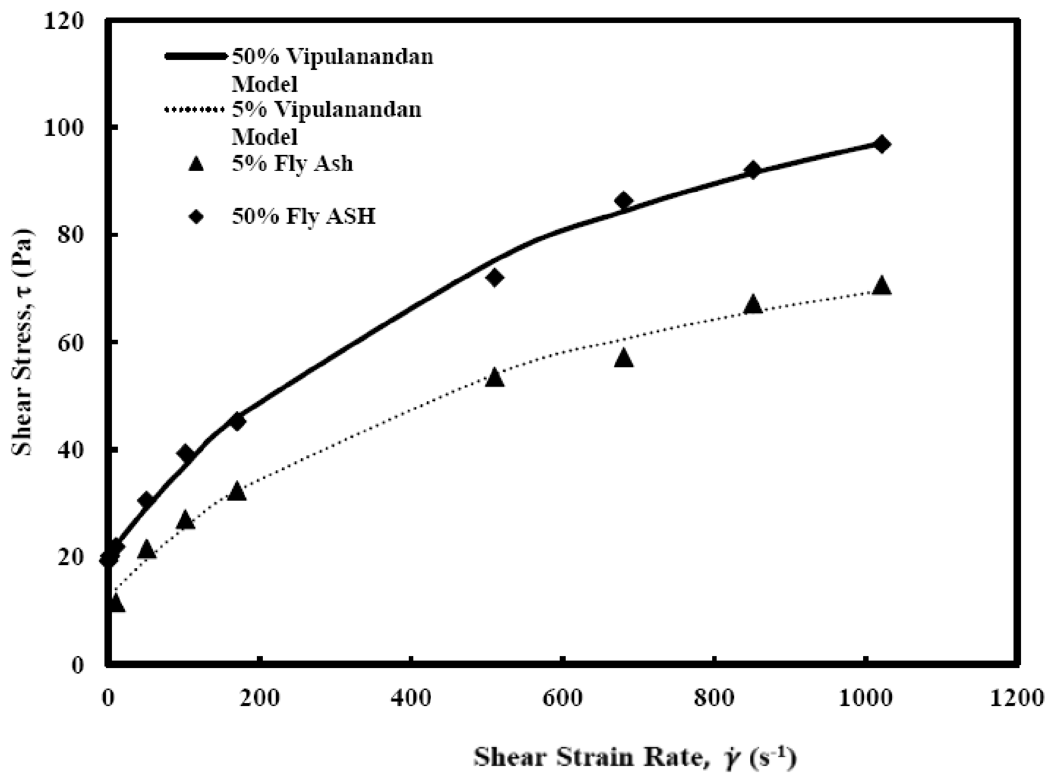

Figure 2. Shear Stress-Shear Strain Rate Relationship for Cement Slurry With Fly Ash and Predicted Using the Vipulanandan Rheological Model

5. CONCLUSIONS

Based on the experimental and analytical modeling of the rheological properties of cement slurry modified with up to 50% fly ash (class C) following conclusions are advanced:

1) The rheological tests showed that the cement slurry with and without up to 50% fly ash additive had a shear thinning behavior.
2) Vipulanandan rheological model was used to predict shear stress- shear strain rate relationship and the rheological model predicted the test results very well.
3) The yield stress reduced with the addition of fly ash. The maximum shear stress limit reduced with 5% fly ash but increased with 50% fly ash. These two properties were quantified with the Vipulanandan rheological model.

6. ACKNOWLEDGEMENT

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