Comparison of Rheological Modeling for Jet Grout Cement Mixture

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Abstract: In this study, two rheological models were used to predict the rheological behavior of jet cement grout with different additives. Based on the root mean square error and correlation coefficient value, it is evident that applicability of different models depends on the additives which change the rheology of the jet grout cement.

1. Introduction: Jet grouting technology is used in the improvement of the weak soils mostly available at the construction sites of. In this technique, a slurry grout is injected into the subsoil at high pressure and velocity. The injected grout slurry and soil together produce an improved soil mass with the favorable characteristics in strength, deformability and permeability. (Hamza, 2015)

Sufficient fluidity and stability of grout mixture with adequate mechanical properties are the main requirements for the ground treatment due to jet grouting .The deformation characteristics of cement-based grout mixtures on the flow capability are generally explored by the flow curve (i.e., the shear stress versus shear rate curve) experimentally obtained from the flow test. They can be constructed by a mathematical formula in various approximations developed from the flow curve of fresh grout mixture. The rheological models are able to predict the deformation of cement paste with reasonable accuracy when they have a successful model capability to describe the viscous behavior. (Hamza, 2015)

Performances of the two rheological models (Herschel-Bulkley model and Vipulanandan model) for prediction of flow behavior of cement grout mixtures was analyzed in this study. For this purpose, a thorough comparison of the rheological models has been performed using the flow curves of the shear stress-shear rate data collected from a previous study.

2. Objective: To verify two rheological models to predict the experimental data for cement grouts with additives (lime and bottom ash).

3. Methods:

Modeling of non-Newtonian flow behavior

Non-Newtonian fluids do not show a linear relationship between shear stress and shear rate. This is due to the complex structure and deformation effects exhibited by the materials involved in such fluids. The non-Newtonian fluids are however diverse and can be characterized as e.g. pseudo plastic, viscoplastic, dilatant and thixotropic fluids (Annika Björn et al,2012).There are many models which have been used to predict the behavior of these different type of fluids. In this study, the following models have been chosen to model the behavior jet grout cement.

Herschel Buckley rheological model (Herschel and Bulkley, 1926)

The Herschel Bulkley model relates shear stress to shear rate using three parameters

$$\tau = \tau_o + k\gamma^n \quad (1)$$

Where, γ is shear rate (s^{-1}), τ is shear stress (Pa), n is the flow behavior index, K is the consistency index, and τ_o is yield stress.

It is applied on fluids with a nonlinear behavior and yield stress. It is considered as a precise model since its equation has three adjustable parameters.(Rao, 2007)

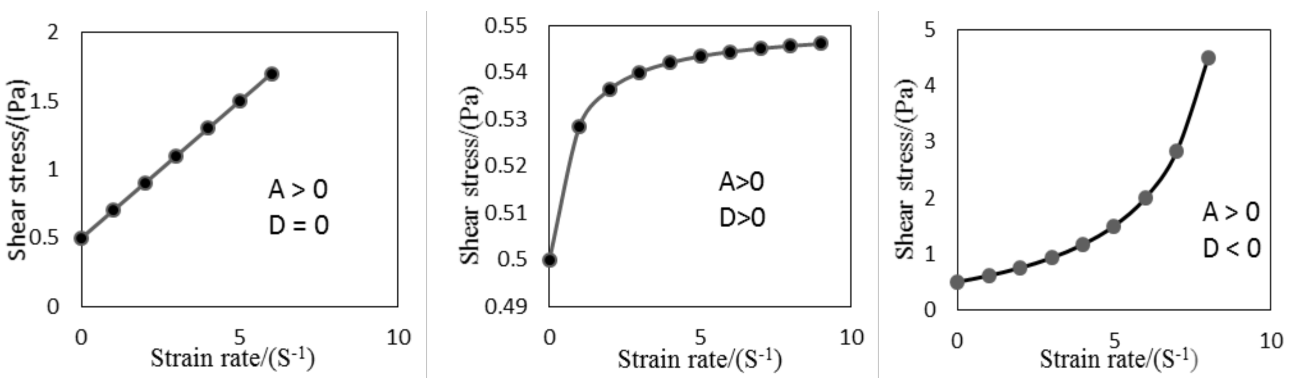
Herschel–Bulkley model does not satisfy the upper limit condition for the shear stress limit

Vipulanandan rheological model (2104)

This model was developed to predict the behavior of various types of fluids. The drilling muds showed non-linear shear thinning behavior with a yield stress. Based on the test results, following conditions have to be satisfied for the model to represent the observed behavior. (Vipulanandan and Mohammed, 2014)

$$\tau = \tau_o + \gamma/(A + D\gamma) \quad (2)$$

Where $\boldsymbol{\tau_o}$ is the yield stress, A and D are the model parameters.



(A) (B) (C)

Figure 1 Prediction of (A) Newtonian behavior (B) Shear thickening behavior (C) Shear thinning behavior by Vipulanandan rheological model

Experimental data was obtained from previous study. This study investigated the viscous properties of cement based grout mixtures with different stabilizers comparatively, for jet grouting, in the point of rheological characteristics. The stabilizer inclusions were clay, lime and bottom ash in various proportions at the dosage rates from 0% to 100%, by dry weight of binder. An extensive experimental study was carried out by conducting the rheometer tests with ten replicates for each stabilizer rate. Using statistical analysis of quality control charts, satisfactory tests within the ten replicates were determined and employed throughout their investigations in the study. (Hamza, 2015)

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Through the experimental points, a line can be fitted using the least squares root method considering above mentioned two equations. For the stabilizer proportions presented in the experimental program, the shear stress-shear rate curves were drawn, and then compared with the rheological models .Root mean square error (RMSE), and correlation coefficient (R) were used to evaluate the accuracy and reliability of fitting between the experimental shear stress-shear rate data and the rheological models.

4. Results and Discussion

Table 1: Comparison of rheological model for bottom ash addition (70% BA)

	Vipulanandan model						Hershel-Buckley model				
	τ_o	A	D	τ_{max}	R^2	RMSE	τ_o	K	n	R^2	RMSE
cement	0.2646	7.5198	0.4564	1.926	0.9919	0.0460	0.1752	0.2675	0.5081	0.9944	0.0382
CL10	0.1098	6.3969	0.3059	3.379	0.9889	0.0730	0.0000	0.3091	0.5545	0.9969	0.0388
CL20	0.0796	4.1596	1.1456	0.953	0.9909	0.0261	0.0000	0.3012	0.3253	0.9641	0.0518
CL30	0.1237	12.3149	0.9122	1.220	0.9769	0.0417	0.0196	0.2048	0.4235	0.9920	0.0246
CL40	0.0650	15.2908	0.9574	1.109	0.9725	0.0411	0.0000	0.1491	0.4744	0.9895	0.0253
CL50	0.0866	16.2011	0.9338	1.158	0.9685	0.0443	0.0192	0.1529	0.4643	0.9917	0.0228
CL60	0.1817	26.1699	0.7049	1.600	0.9602	0.0466	0.1097	0.1148	0.5291	0.9792	0.0337
CL70	0.2570	9.3603	1.0555	1.204	0.9409	0.0665	0.1589	0.2404	0.3686	0.9889	0.0289
CL80	0.1866	7.4878	1.0106	1.176	0.9277	0.0793	0.0000	0.3410	0.3180	0.9740	0.0475
CL90	0.0000	70.5812	0.0000	∞	0.9251	0.0505	0.0000	0.0012	1.7256	0.9958	0.0119
CL100	0.0000	69.6785	0.0000	∞	0.9191	0.0536	0.0000	0.0010	1.7813	0.9953	0.0130
BA10	0.1098	6.3969	0.3059	3.379	0.9889	0.0730	0.0000	0.3091	0.5545	0.9969	0.0388
BA20	0.2079	6.8203	0.2366	4.434	0.9819	0.0707	0.1418	0.2355	0.6816	0.9905	0.0512
BA30	0.0475	22.4338	0.3812	2.671	0.9941	0.0253	0.0069	0.0873	0.6917	0.9971	0.0178
BA40	0.0000	12.1520	0.3912	2.556	0.9940	0.0349	0.0000	0.1137	0.7059	0.9912	0.0422
BA50	0.0445	5.3223	0.2115	4.773	0.9914	0.0872	0.0000	0.2972	0.6395	0.9905	0.0912
BA60	0.9140	1.8399	0.0754	14.184	0.9869	0.2963	0.2232	1.2719	0.5405	0.9921	0.2310
BA70	0.1497	0.5771	0.1082	9.388	0.9946	0.2070	0.0000	2.1013	0.4045	0.9504	0.6277
BA80	1.5530	0.3484	0.0901	12.656	0.9533	0.7655	0.0000	4.2308	0.3091	0.9643	0.6692
BA90	2.0197	0.2399	0.0614	18.306	0.9930	0.4265	0.0000	6.0726	0.3065	0.9676	0.9194
BA100	2.5993	0.1584	0.0533	21.348	0.9692	1.0954	0.9612	7.3248	0.2945	0.9886	0.6670
L10	0.0000	487.4464	0.0000	∞	0.7353	0.0151	0.0000	0.0000	4.2487	0.9973	0.0015
L20	0.0000	134.6337	0.0000	∞	0.7605	0.0506	0.0000	0.0000	2.6141	0.9763	0.0159
L30	0.0000	51.5935	0.0000	∞	0.7397	0.1430	0.0000	0.0000	3.2033	0.9851	0.0342
L40	0.1012	0.6072	0.1996	5.112	0.9760	0.2519	0.0000	1.5232	0.3507	0.9340	0.4177
L50	0.0866	16.2011	0.9338	1.158	0.9685	0.0443	0.0192	0.1529	0.4643	0.9917	0.0228
L60	0.2121	0.4756	0.1267	8.106	0.9753	0.4041	0.0000	2.2352	0.3620	0.9146	0.7520
L70	0.3507	0.3052	0.0712	14.390	0.9791	0.6203	0.0000	3.6666	0.3789	0.9275	1.1544
L80	0.6387	0.2835	0.0581	17.859	0.9720	0.8531	0.0000	4.5532	0.3706	0.9152	1.4855
L90	1.4115	0.3693	0.0438	24.222	0.9894	0.6499	0.0000	4.7470	0.4173	0.9657	1.1705
L100	0.9217	0.3098	0.0248	41.318	0.9513	2.2846	0.0000	5.0785	0.5191	0.9111	3.0868

From the correlation coefficient and RMSE, it is clear that Hershey Bulkley (HB) model predicts the behavior of clay added grout (CL) better than Vipulanandan model. R^2 value of HB model varies from

0.96 -0.99 while in Vipulanandan model it varies from 0.91-0.99. The reason for that can be the dilatant behavior for the clay additions after a certain dosage of clay. In addition to that Vipulanandan model predicts the value of yield stress in most of the cases. But HB model did not predict it most of the time. It is a deviation from the actual behavior of the fluid.

Both the HB and Vipulanandan models predict the behavior of bottom ash added grout (BA) cement. The value of R^2 both models vary from 0.96-0.99.Bottom ash added cement show of pseudo plastic or yield-pseudo plastic behaviors. In this case also HB model fails to predict the yield stress in most cases.

For lime added grout cement (L), HB model predicts the behavior better than Vipulanandan model for the addition of up to 30% lime. Beyond that addition Vipulanandan model predicts the behavior better than HB model. Dilatic behavior of lime added grout cement up to 30% of lime addition can be the reason for it. After 30% of addition it shows pseudo plastic or yield-pseudo plastic behavior. In this case also HB model fails to predict the yield stress in almost all the cases.

5. Conclusion:

Based on correlation coefficient and RMSE values HB model predicts the shear stress – shear strain rate behavior of clay added cement grout better than Vipulanandan model. Both models predict the shear stress – shear strain rate behavior of BA added cement grout. Vipulanandan rheological model predicts the shear stress – shear strain rate behavior of lime added cement grout better than HB model.In addition to that Vipulanandan model predicts the yield stress value which HB model often failed to do.

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