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Rheological Study of Formate (Nacl) and Ethylene Glycol Based Drilling Fluid Using MATLAB

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Abstract: Non-Newtonian models are used in describing the rheology of drilling fluids. Models, such as Power Law, Bingham Plastic, and the Hershel-Buckley model are used to predict drilling fluid behaviour. Selection of the best rheological model that accurately represents the shear stress-shear rate data is optimal in determining fluid use and predicting realistic rheological behaviour. This research is aimed at studying the best rheology model to fit collected data from sodium chloride (NaCl) and ethylene glycol (EG) based drilling fluid. The assessment utilized a total of ten sets of experimental viscometry data from laboratory-formulated drilling fluid samples A to J with the varying volume of formate sodium chloride (NaCl) and ethylene glycol (EG). Using Equations relating shear rates to shear stress, MATLAB non-linear regression approach was used to determine the best of the three rheological models to fit the experimental. The Root square (R^2), Adjusted Root square (Adj R^2), and Root Mean Square Error (RMSE) were used in determining the goodness of fit and degree of deviation of the experimental data. data. High concentrations of both NaCl and ethylene glycols in the formulation provide a better shear rate shear stress fit. Although the ethylene glycol presence may have account for the improved fit, as Sample E, F and G despite containing high volume of the formate NaCl, the data where not effectively fitted by the models. From the results, the power law model was the least suitable with an R^2 value of 0.881-0.956, Adj R^2 83-96%, and a poor RSME in the range 2-9. The Herschel-Bulkley model showed an improved fit for the fluids with an R^2 0.897-0.973, Adj R^2 87- 98%, and a better RSME <3. this model also shows a good shear thinning behaviour from its three parameter consistency (n) index values. The Bingham plastic model best fits the rheology of the drilling fluid data R^2 0.93-0.99, Adj R2 93-98%, and RSME of <2.

Keywords: Drilling fluids, rheology model, formate sodium chloride, ethylene glycol

1. Introduction

Drilling operations require the use of viscous fluids, otherwise known as drilling fluids. These fluids serve various purposes, including lubricating the bit and drill string, drill pipe cooling, movement of drill cuts to the surface, pressure control within the formation, and permeable formation sealing among others [1]. The drilling process is widely acknowledged as a complex and costly procedure. To significantly raise drilling process efficiency, it is important to study the rheological performance of drilling fluid. It plays a key role in successful drilling operations, downhole safety, and improving drilling speed [2].

Water based drilling fluid (Water bentonite suspensions) is one of two main classes of drilling fluids used in drilling. They have a variety of applications in drilling, particularly in offshore drilling sites, because of their robust colloidal characteristics and ability to raise liquid viscosity [3]. When not sheared, these fluids have the unique tendency to gel, but when sheared, they behave as non-Newtonian fluids. Depending on the use case, the bentonite

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concentrations contained in water bentonite suspensions may vary [4]. In recent times due to increased low temperature drilling expenditures in a deep well, various formate (Na, K, and Cs salts) and antifreeze agents (glycols) have been used to regulate the filtration and rheological qualities of drilling fluid in deep wells [5]. For the best operation and maintenance of the wellbore hydraulics, it is necessary to measure the rheological characteristics of the drilling fluids. Most drilling practices monitor the shear stress of the drilling fluid by applying varying shear rates. According to American Petroleum Institute (API) standards, these measurements are carried out by laboratory mud test protocols utilizing tools like the viscometer or rheometer that can measure the correlation between the fluid's shear stress and shear rate [6].

1.1 Bingham Plastic Model

This mathematical model is frequently employed in the drilling fluid sector to illustrate the flow properties of various mud forms. It has the following mathematical representation:

$$\tau = \mu p\ (\gamma\ ) + \tau 0 \qquad (1)$$

where γ is the shear rate, τ is the shear stress, μp is the dynamic viscosity and $\tau 0$ is the yield point. A yield point (0) and dynamic viscosity p that is independent of the shear rate are characteristics of fluids that exhibit Bingham plastic behavior [7].

1.2 Power Law Model

The Power law model expresses the relationship between shear stress (τ) and shear rate (γ) of a fluid that exhibits non-Newtonian behavior [8]. It can be quantified through viscosity and shear strain rate. The mathematical formula is presented as follows:

$$\tau = k\gamma^n \qquad (2)$$

where k is the consistency coefficient and n is the flow behavior index.

1.3 Herschel–Bulkley Model

This model is a variant of the Power law model and a hybrid of the Bingham plastic and Power law models. Shear thinning and non-Newtonian fluid yield behavior can be quantified using this model. Through measuring the shear rate, the shear stress is expressed as follows:

$$\tau = \tau o + K\gamma^{\,n} \qquad (3)$$

Bentonite content, the presence of additives, temperature, and pH of the suspension are all important factors that determines the fluid rheology of aqueous bentonite suspensions. [9]. The rheological behavior of water based bentonite suspensions has been the subject of extensive research in recent years, and the subject has become well established. Despite all this previous knowledge, there is still a limited understanding of the rheological behaviour of water bentonite suspension when formate salt is added to the composition [5,10].

The aim of the present paper is thus to establish the rheological behaviour of formate NaCl and ethylene glycol water-based drilling fluid. This was done by investigating the best rheology model to fit experimental viscometry data of formulated formate NaCl and ethylene glycol water-based drilling fluid. The scope is limited to the use of three rheological models namely, Power law, Bingham plastic, and the Hershel-Buckley models as these are the most widely used in describing drilling fluids and bentonites solutions in general [9,10]. Furthermore, MATLAB was used to establish a nonlinear regression fit of the models to the shear rate shear stress data from a Fann viscometer. The Root square (R^2), Adjusted Root square (Adj R^2), and Root Mean Square Error (RMSE) were used to judge and determine the goodness of fit and degree of deviation of the experimental data from the models.

2. Materials and Methods

2.1 Fluid Preparation

Formate salt /polymer type drilling fluids have been widely used in deep well and offshore regions all over the world, for their good shale inhibition and rheological properties [10]. NaCl salt and ethylene glycol (EG) were used as the viscosity control and antifreeze agent in this study. The drilling fluid sample was prepared by adding NaCl, ethylene glycol, PAC (polyanionic cellulose), gum Arabic, Barite, and coconut oil to a bentonite water suspension. The composition and function of the formate NaCl and ethylene glycol (EG) based drilling fluid are listed in Table 1 below.

Table 1 - Composition of the formate NaCl and Ethylene glycol based drilling fluid

S/No:	Function	Component	Amount (wt%)	% Purity	Supplier
1.	Viscosifier and filtration control	Bentonite	14		
2.	Viscosity and inhibitory control	NaCl	48	98	Vinipul Inorganics Pvt. Ltd
3.	Inhibitory control	Ethylene glycol		97	GZ Industrial Supplies, Nigeria
4.	Suspension liquid	Distilled Water	28	99	Ahmadu Bello University, Nigeria
5.	Weighing agent	Barite	4		
6.	Lubricating agent	Coconut oil	3	87	Orobo farm Kano Nigeria
7.	Emulsifier	gum Arabic	1		
8.	Viscosifier	PAC (polyanionic cellulose)	2		Schlumberger, Nigeria.

To investigate the viscosity and inhibitory properties of the NaCl and ethylene glycol components. A blending amounting to 48% of the NaCl and Ethylene glycol composition was done to obtain ten varying volume samples (A to J) as shown in Table 2.

Table 2 - Formulation of the viscosity and inhibitory components

NaCl and EG formulation	Ethelyn glycol (EG) (ml)	NaCl (ml)
Sample A	121	89
Sample B	116	94
Sample C	110	100
Sample D	108	102
Sample E	105	105
Sample F	100	110
Sample G	94	116
Sample H	89	121
Sample I	0	210
Sample J	210	0

2.2 Sample Measurement and Data Collection

A concentric-cylinder rotational viscometer Fann-35SA was used to measure the drilling fluid rheology according to the API recommended test. This involves running the viscometer at various dial speeds of 600, 300 200 100, 6, and 3 rpm. The dial readings at all rotational speeds were recorded. The fluid testing was done at ambient 25°C temperature for all the formulations. Each test was repeated at least three times for consistency and accuracy. The dial readings in degrees were converted using the equations below to convert the dial readings in degrees to shear stress (τ) in Ibf/100ft^2 and shear rate (γ) in second^{-1} respectively.

$$\tau = 1.067\theta \tag{4}$$

$$\gamma = 1.703S \tag{5}$$

where τ is in Ibf/100ft^2; θ is rotational viscometer dial readings in degrees; γ is shear rate in sec^{-1} and S is speed of rotation of outer cylinder of the viscometer in rpm.

2.3 Fitting Mathematical Methods

There are various rheological models that are used to describe the rheological properties of drilling fluid and non-Newtonian fluids in general [11,12]. In this study, only two and three parameters of rheological models in equations 1, 2 and 3 were used. Using MATLAB, a nonlinear regression algorithm was used to fit the shear stress and shear rate data from the preceding sample measurement. In order to solve for the parameters of the three models and their statistical fit, a numerical algorithm code was implemented through MATLAB nonlinear regression solver using the equations and details in Table 3. For each set of experimental data, a plot (rheogram) was produced, and a set of statistical measurements of Root square (R^2), Adjusted Root square (Adj R^2), and Root Mean Square Error (RMSE).

This plot and the statistical measurement were used as a base to choose the model that best fit the drilling fluid. The correlation coefficient R^2 is used for linear regressions, to validate the value and to examine the fit to non-linear models [5,12,13] suggested that by considering R^2, Adj R^2, and RMSE is more effective to quantify the goodness of fit to non-linear functions. By presenting the results in a table and displaying the rheograms, which represent the experimental data τ_0 plotted against the shear rates, the results are analyzed on a value basis. The three experimental model equations, the Constraints, and the initial guess used in this work are shown in Table 3.

Table 3 - List of rheological models, parameters constraints, and initial evaluation. Adapted from [14]

Model Name	Model Equation	Parameter Constraints	Initial Guess	Parameters Definition
Bingham Plastic	$\tau = \tau_0 + \mu_p(\gamma)$	$\mu_p > 0$, $\tau_0 \geq 0$	$\mu_p = 0.02$, $\tau_0 = 1$	τ_0: Yield stress μ_p: Plastic viscosity
Power Law	$\tau = K\gamma^{n}$	$K > 0$, $0 < n < 1$	K=2, n = 0.4	n: Flow behaviour index K: Consistency coefficien
Herschel-Bulkley	$\tau = \tau_0 + K\gamma^{n}$	$\tau_0 \geq 0$, $K > 0$, $0 < n < 1$	$\tau_0 = 1$, K = 2, n = 0.4	τ_0: Yield stress n: Flow behaviour index K: Consistency coefficient

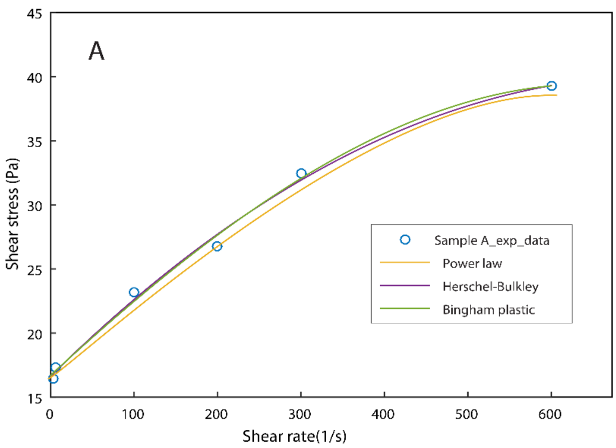
3. Results

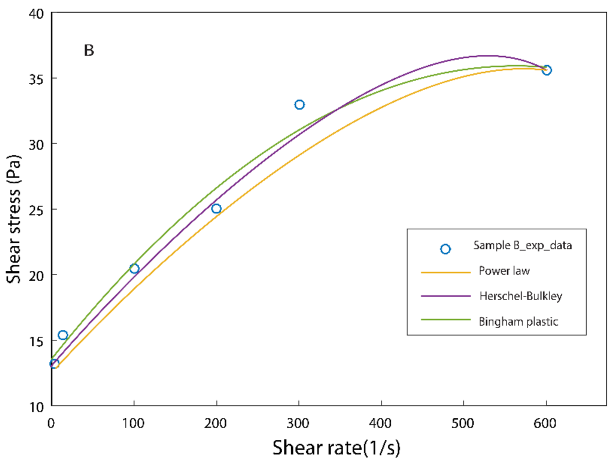
For each rotational speed, the shear stress is calculated using the equations (4 and 5) and Table 4 was generated. The data from the table were plotted to obtain the rheograms shown in Figure 1 for each fluid sample.

Table 4 - Experimental rheological data

Dial speed (rpm)	Temp (°C)	Sample Shear stress (τ_0 Pa)									
		A	B	C	D	E	F	G	H	I	J
600	25	39.25	35.56	27.40	20.75	18.17	12.83	30.45	33.33	48.42	65.57
300	25	32.44	33.00	25.38	19.25	16.67	9.75	24.97	27.75	41.76	53.00
200	25	26.73	24.56	23.67	15.17	9.92	7.33	23.52	25.17	37.83	46.33
100	25	23.17	20.45	19.00	12.33	6.50	5.58	20.58	22.00	33.25	37.25
6	25	17.32	15.34	13.52	8.17	3.25	3.67	14.67	17.33	20.87	23.58
3	25	16.40	13.20	11.20	7.70	2.80	3.25	8.75	11.70	18.76	18.46

Following the methodology described above, the experimental data from Table 3 was fitted to the three mathematical models. The rheograms for each of the samples (A to J) are depicted in figures 1.





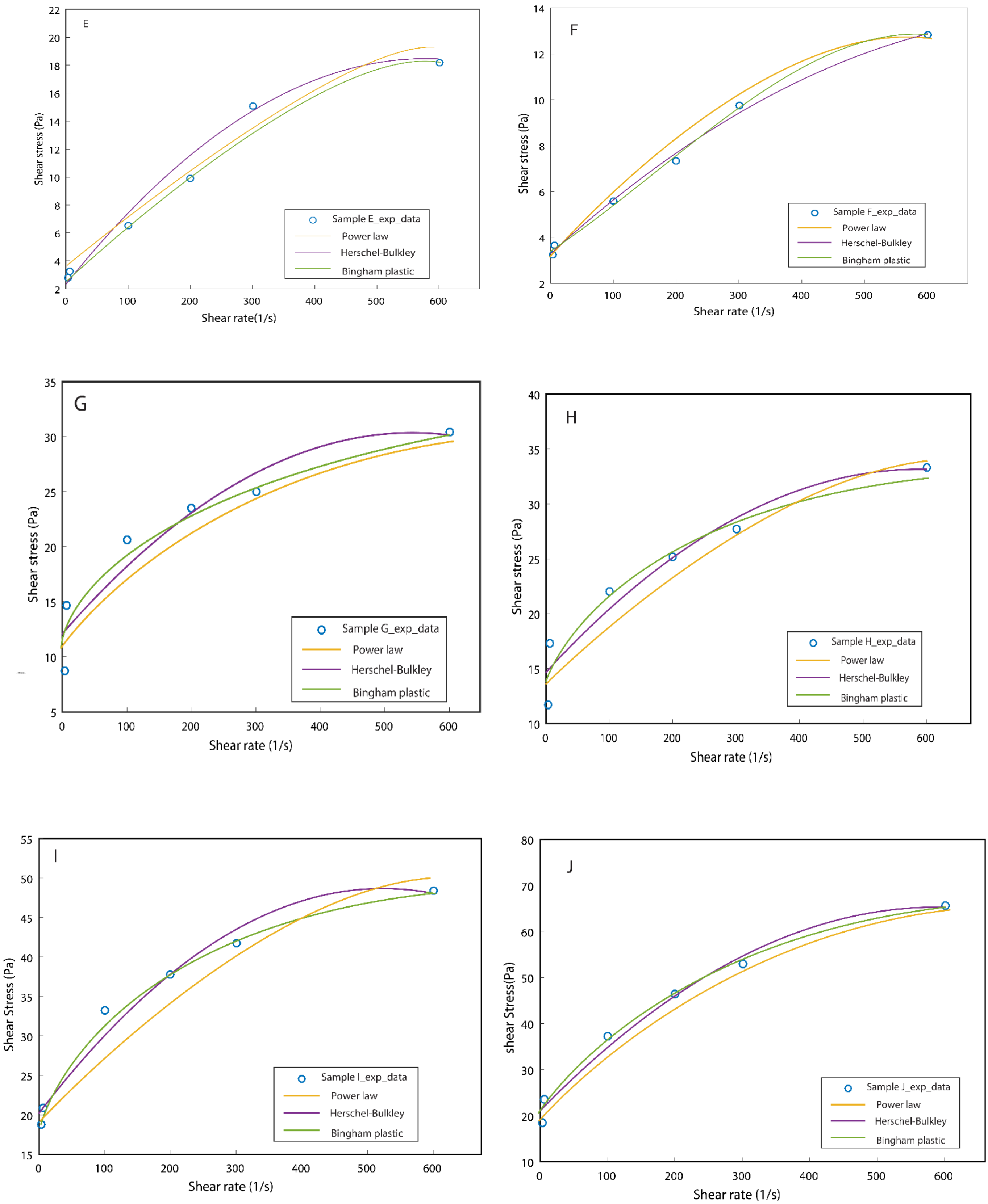


Fig. 1 - Rheograms of Sample C to J data fitted to Power law, Herschel-Bulkley, and Bingham plastic model

The rheological parameters and statistical measurements for the models were computed for the ten Samples and the results are listed in Tables 5 and 6.

Table 5 - Rheological parameters form rheological fitted data

Sample	Bingham plastic Model		Power Law Models		Herschel-Bulkley Model		
	μ_p (Pa.s)	τ_0 (Pa)	K (Pa.s^n)	n	τ_0 (Pa)	K (Pa.s^n)	n
A	0.07257	4.68	10.381	0.733	2.15	7.309	0.426
B	0.04654	5.55	9.646	0.596	5.615	6.946	0.744
C	0.04094	3.91	9.067	0.644	1.818	3.639	0.629
D	0.03975	3.79	4.993	0.785	3.788	2.354	0.562
E	0.03175	2.79	5.635	0.569	2.818	5.154	0.509
F	0.03854	3.67	3.432	0.523	2.693	7.741	0.491
G	0.02834	3.97	6.258	0.761	3.968	5.473	0.425
H	0.02326	3.22	6.306	0.543	3.215	3.235	0.690
I	0.09387	3.53	6.143	0.461	1.404	6.034	0.465
J	0.1101	8.81	7.986	0.782	0.97	8.177	0.568

Table 6 - Statistical measurement from rheological data fitted to models

Sample	Bingham plastic Model			Power Law Models			Herschel-Bulkley Model		
	R^2	Adj R^2 (%)	RSME	R^2	Adj R^2 (%)	RSME	R^2	Adj R^2 (%)	RSME
A	0.949	0.936	0. 141	0.912	0.896	7.88	0.955	0.873	0.734
B	0.969	0.980	0.425	0.911	0.886	6.06	0.946	0.948	1.172
C	0.948	0.985	0.724	0.885	0.850	5.364	0.918	0.897	2.212
D	0.963	0.974	0.344	0.927	0.908	4.714	0.963	0.929	3.862
E	0.967	0.988	1.528	0.936	0.919	3.524	0.967	0.945	3.919
F	0.956	0.945	2.567	0.982	0.978	3.353	0.931	0.985	2.748
G	0.938	0.944	2.117	0.863	0.828	4.672	0.914	0.924	3.769
H	0.956	0.946	0.599	0.881	0.851	3.542	0.897	0.887	1.467
I	0.992	0.989	0.211	0.986	0.921	4.863	0.942	0.983	0.836
J	0.990	0.988	0.276	0.964	0.955	9.031	0.973	0.941	0.253

4. Discussions

4.1 Effects of Formate Salt and Ethylene Glycol on Drilling Fluid

Experiments conducted on mixtures was done at 25°C. The plots of the shear stress shear rate relationship are shown in Figure 1. It can be inferred from the plots that the volume mixture has an effect on the experimental data and their fit to the model tested. For sample with high concentrations, an increase of the fit in data point to the model was observed. This is evident in sample A, B, I and J with high volume of the mixtures as compared to those containing small volume of the based fluid. This was similar to observation made by [11,13] that may be explained by a disintegration of structures and macromolecules of the formate salt as recorded in their work. Drilling fluids, A, B and J show a nearly Newtonian behavior, that is probably related to the high salt concentration and ethylene glycol in the solution. High salt concentration implies huge amounts of active ions, which do not only destroy water structure, but also break water or polymer bonding [9,13] as observed in potassium and caesium formate. Another situation observed from Table 6 with the statistical measure. Despite fluids E, F and G, containing high concentration of NaCl formate salt, the curves of these models only slightly fit the data especially the power law curve. This may imply that despite high volume of the NaCl salt, ethylene glycol presence plays a significant role to improve the Newtonian behaviour and better fit of the experimental data to the models. High concentrations of glycols have been found by [9,14] to increase the drilling fluid property, and improve rheological parameter control of mud properties, and suspension of weighting agents, especially at high concentration as in Sample J. In summary, the fluids have significant increase in impact on the shear rate for the drilling formulation.

4.2 Power Law Model

From the plots in Figure 1, the power law model looks the least consistent and close to the experimental data. Both the consistency coefficients K and flow performance index n from Table 5 are also generally low for most of the samples considering this model. In this study, the consistency coefficient K, and the flow behaviour index n of formate NaCl and Ethylene glycol drilling fluids were affected significantly by the volume of each fluid in the sample. For samples with a high volume of Ethylene glycol, as in samples A, B, and J, the consistency coefficient, K increased with increasing volume, while the flow behavior index n increased slightly. Similar observation using KCl formate polymer fluid was made by [12]. Additionally, the performance index n of these samples as they approach 1 is slightly better than those with more formate NaCl which is far from 1, indicating a gradual approach to shear thinning which is a desired property as observed by [14]. The adjusted R^2 for the power law model range from a low of 0.828% to a high of 0.955%. This is relatively poor when compared to the remaining two models tested. The R^2 for this model is also relatively low, all within the range of 0.881 and 0.965. Considering the root mean square errors, which are relatively high, with the highest having a value of 9.031. Therefore, all the statistical measures indicating the fitness of the model poorly describe the drilling fluids samples. Previous works by [11,13] also observed similar results from using this model to describe KCl formate polymer drilling fluid.

4.3 Herschel-Buckley

The Hershel-Bulkley model provided a good and better description of the flow curves in Figure 1. This describes the rheograms better than the Power law model. In the Herschel-Bulkley model, the parameters n and K are similar to those of the power law model [11]. Like that model, the consistency coefficient K and the flow behavior index n of the drilling fluids were affected significantly by the volume of formate NaCl and Ethylene glycol present in the drilling fluid samples. For a volume distribution of NaCl and Ethylene glycol, the consistency coefficient K increased most with an increasing Ethylene glycol amount as seen in samples A and J with the highest value of 7.309 and 8.177. While flow behavior index n for this model decreased slightly and is better than those of the power law. The sample I and J shows the highest flow behavior index n with value 0.465 and 0.568. This is similar to the power law observation and previous work done by [11,13]. The R^2 for this model is also relatively better than those of the power law, all within the range of 0.897 and 0.973. The adjusted R^2 for the power law model range from a low of 0.873% to a high of 0.983%. This is relatively better and fits the experimental data better than the power law when compared. Considering the root mean square errors, which are relatively low, with the highest having a value of 3.919. Therefore, the plots in figure 1 and the results from Table 6 obtained showed a good fit with the experimental data series. The Herschel-Bulkley model outperforms the power law models in many aspects as it more accurately reflects the behavior of the drilling fluid over the entire sample set. From the Herschel–Bulkey correlation on Table 5. the high consistency index (K) value implies superior hole cleaning efficiency; therefore, a higher K value is appropriate for drilling operations. A reduction in the value n also indicates that the drilling fluid has a more excellent shear-thinning characteristic, which is favorable for optimal hole cleaning as observed [17].

4.4 Bingham Plastic Model

Among the three models, The Bingham plastic model best fits the experimental plot. Examining Figure 1, it is much visible from the shapes of the rheograms remaining essentially unchanged and lined the experimental plot most perfectly using this model. This indicates a good fit of the model to the plotted data. Samples A, B, I, and J containing high volumes of formate NaCl, and ethylene glycol showed the best fit to the model from Tables 5 and 6. This agrees with the rheological parameters from the two earlier models indicating clearly that the amount of formate substance and ethylene glycol had a combined effect on the rheology of drilling fluids. [17] also observe a similar effect of volume on drilling fluid rheological parameters using KCl formate/polymer fluid. The shear stress of this model is also very close to the Herschel-Bulkley model, as these two models gave the best fit for the experimental data. [1,5] observed similar behavior and trend in shear stress for two models closely describing a set of data. From the statistical measure in Table 6, the R^2 of the Bingham plastic model provided the highest and best fit with a low value of 0.938 and a high value of 0.999. The Adj R^2 was also high in the range of 0.936% to 0.988%. Additionally, the measures of the average difference between values predicted by this model and the actual values as indicated by RSME values (0.141 to 2.567) are the least for any of the models tested.

5. Conclusion

Power law, Herschel-Bulkley, and Bingham plastic models have been used to fit the experimental data and to establish the rheological behaviour of formate NaCl and ethylene glycol water-based drilling fluid. The amount of formate NaCl salt and Ethylene glycol have combined effect on the rheological drilling fluid parameters. From various samples of drilling fluid tested, the Bingham plastic model gave the best fit for the drilling fluid. Although the Herschel-Bulkley model did not give a fit as good as the Bingham plastic, its equation is a three-parameter model that also provides a better understanding of the flow behaviour parameter like the consistency coefficient (K) and performance index (n). This can be used to describe the shear-thinning behaviour of the drilling fluid formulations. Therefore, constitutes a complementary advantage when both models are employed to give a better fluid description. Finally, the rheological properties of the fluid can be improved with an increase in the concentration of the formate NaCl and ethylene glycol used in the drilling fluid. This is evident from the good rheological parameter of the samples containing high volumes of these fluids.

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