RHEOLOGICAL STUDY OF PERFORMANCE ENHANCEMENT OF UBAKALA CLAY FOR USE AS DRILLING MUD

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ABSTRACT
This work studied the performance enhancement of Ubakala clay for use as drilling mud. A sample of Ubakala clay was used for this research. The clay sample was collected, processed and beneficiated with varying concentrations of soda ash (0-6wt %). Experiments were conducted to determine the viscosities of the control and clay-soda ash mixture at different curing time intervals (0-8hours), temperatures (30^OC-90^OC) and speed of agitation (200rpm-600rpm). Response surface methodology, with the aid of MATLAB statistical toolbox was used to perform a statistical study and optimization of the data obtained from the study. The MATLAB curve-fitting toolbox was also used to determine the rheological model that best fit the beneficiated clay and its control. The result revealed that soda ash concentrations, temperature, curing time and their interactions terms are significant variables in the statistical model with temperature being the most significant term, while time is the least significant term. The rheological study of the process showed that the Bingham plastic model appropriately described the performance of the clay samples as it gave the best fit for most of the samples (71.67%) studied, based on the value of the adjusted R^2. The graphical representation of the control showed a decreasing rate in viscosity within the required range of speed of agitation unlike those of the clay soda ash mixture. Further work on Bingham model shows that an optimum predictive value of yield stress occurs for a curing time of 8hours, temperature of 90^0C and soda ash concentration of 5.183wt% are the operating parameters for enhancing the performance of Ubakala clay sample for use as a drilling mud.

Keywords: Clay, Drilling Mud, Rheological Study, Model, Viscosity.

1.0 INTRODUCTION
Drilling the wellbore is the first and most expensive step in the oil and gas industry. Expenditure for drilling represents 25% of the total oil field exploitation cost and is concentrated mostly in exploration cost and development of well drilling (Adam *et al*, 1986). Drilling fluid which represent about one-fifth of the total cost of petroleum well drilling, must generally comply with three important requirements – they should be easy to use, not too expensive and environmentally friendly. Drilling mud is important to petroleum and gas production due to its use in cleaning the rock fragment from beneath the bit to the surface, sufficient hydrostatic pressure exertion against sub-surface formations, cool and lubricate the rotating drill string and bit. When oil and gas operations began in Nigeria in the early fifties, local clay was used in the preparation of drilling fluids and cement slurries. The introduction of imported commercial bentonite in the year 1960 drastically reduced the use of Nigerian local clay in the petroleum and gas industries (Omole *et al*, 1989). This also led to a significant reduction in research into local bentonite clay that could have been used in oil and gas operations like drilling, cementing, simulation and others.

Prior to the government's initiative to develop local content, the cost of importation of bentonite for drilling activities in Nigeria runs into millions of dollars annually which has been detrimental to the economy of the country considering that one-fifth of the cost of drilling a well which ranges between 1 million to 100 million dollars accounts for drilling fluids. Therefore, it is imperative to locally outsource these clay materials in order to conserve foreign exchange, create employment and to enhance Nigerian content development in the drilling component of oil and gas industry

Nigeria is blessed with abundant reserve of oil, gas and clay (Emofurieta, 2010), but yet spends millions of dollars yearly importing drilling mud despite the proven reserve of clay deposits, if these local deposits are beneficiated and efficiently enhanced, they would be readily used as drilling mud (Agle *et al*, *2013*). Several researchers have studied some local clay samples (Omole *et al*., 1989; Falode *et al*., 2008; Okogbue and Ene, 2008; Apugo-Nwosu *et al*., 2011; Nweke et al., 2015), but studies on Ubakala clay, which is one of the abundant local clays, is not rife in literature, and especially, the authors did not find any works that considered the effect of temperature, thus the need for this study.

2.0 EXPERIMENTAL METHODOLOGY

The study area chosen for this work was Ubakala town. The town is located in Umuahia South Local Government Area of Abia State, south-eastern Nigeria and lies on longitude 7^{o}24'E and latitude 5^{o}10'N on the geological map of Nigeria.

Materials: Ubakala clay; Sodium carbonate; Distilled water.

Equipment: Ostwald viscometer (Model NDJ95N); Thermometer; Pipette; Weighing balance; Measuring cylinders; Stopwatch; Mechanical agitator; 200 mesh Tyler Sieve (approx. 75 µm size); Hammer mill; Mortar and pestle/grinder; Plastic buckets

The apparatus consists of an Ostwald viscometer which is a U-shaped glass tube with two arms and is made of clear borosilicate and constructed in accordance with the dimension as shown below. In one arm, N, an upper bulb C is connected with a fine capillary, R. The lower end of the capillary is connected with a U-tube, P, provided with bulb A in the second arm, L. This bulb is necessary to maintain the hydrostatic pressure during flow of liquid. Through the capillary tube, the liquid flows with measurable speed. There are two marks E and F above and below the upper bulb C.

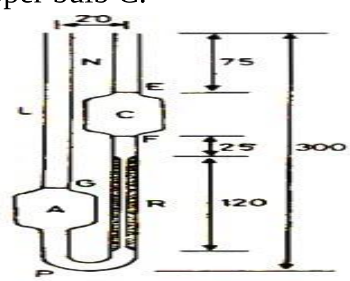

Figure 1: Ostwald Viscometer (with dimensions in mm)

2.1 Processing the clay samples

The collected clay sample is sun-dried to remove moisture and then pounded with the aid of a mortar and pestle to reduce the particle size and increase the surface area. The pounded clay sample is then put in a furnace for further drying to remove the possible moisture content in sample. After drying, the sample is taken to mill for further grinding to get the desired particle size. A hammer mill is mounted vertically and is designed to have two funnels. The upper funnel serves as the clay sample inlet while the bottom one serves as the clay sample outlet. The mill has a hammer at the centre which is driven by an electric motor part of the mill. The function of the hammer is to continuously reduce the particles of the clay to obtain the desired size. Below the hammer is a sieve with mesh of size 75 µm. The mesh is changeable and the mesh size used determines the size of the clay particle to be obtained. After passing through the mill, the clay gotten is packaged for the experiment.

Sample preparation

Four different samples were prepared and labeled as follows:

- Sample A: 50g of clay/700ml of distilled water.
- Sample B: 50g of clay/700ml of distilled water + 2 wt. % $Na_2CO_{3(s)}$
- Sample C: 50g of clay/700ml of distilled water + 4 wt. % $Na_2CO_{3(s)}$
- Sample D: 50g of clay/700ml of distilled water + 6 wt. % $Na_2CO_{3(s)}$

Procedure:

The viscometer was washed with distilled water and completely dried. Sample A was heated on heating stirrer setting the temperature at 30^0C and rotor at 100 rpm.

Sample A is then introduced through tube L to slightly above the mark G, using a long pipette to minimize wetting the tube above the mark. The tube is clamped vertically and allowed to stand to maintain equilibrium. The volume of the liquid sample is adjusted so that the meniscus settles at the mark G. It is then sucked through arm N about 5 mm above the mark E. After releasing pressure or suction, the time taken for the bottom of the meniscus to fall from the top edge of mark E to the top edge of mark F was taken at curing time intervals of 0, 2, 4, 6, and 8 hours and at temperature of 30^0C, 60^0C and 90^0C. Then, the viscosity was read using Ostwald viscometer. This was repeated for speed of agitation of 200 rpm, 300 rpm, 400 rpm, 500 rpm and 600 rpm. The above procedure was repeated for Samples B, C and D.

3.0 METHODOLOGY

The data of viscosity obtained from the experiment will be plotted against shear rate and its fit to: Bingham Plastic model, Power Law model, Herschel-Bulkley model and Casson model determined and compared based on the adjusted R-squared value. The model that gave the best fit to most or all of the plots will be considered the model that best explains the rheology of the process. The rheological models used are represented as follows:

The Bingham Plastic Model is given mathematically as:

$$\boldsymbol{\tau = PV * \gamma + YP} \qquad \textbf{(1)}$$

Where τ is Shear stress (Viscosity for this case), PV is plastic viscosity, YP is yield point and γ is Shear rate.

The power Law model, which best describes a fluid in which the shear stress (which is directly proportional to viscosity) increases as a function of the shear rate to the power of some index. This model is demonstrated mathematically by equation

$$\tau = K(\gamma)^n \quad (2)$$

Where τ is Shear stress (Viscosity for this case), k is Consistency index, γ is Shear rate and n is Power Law index or flow behavior index.

Herschel-Bulkley Model, the relationship exists

$$\tau = \tau_0 + K(\gamma)^n \quad (3)$$

Where K is consistency index, n is flow behavior and the index 0 is the fluid´s yield point at zero shear rate. In theory, this value is similar to the Bingham Plastic yield point, though the calculated value is different. With n = 1, the Bingham Plastic Model is formed and with n = 0, the Power Law Model is derived.

The Casson Model is a two-parameter model that is widely used in some industries but rarely applied to drilling fluids. The point at which the Casson curve intercepts the shear stress (Viscosity) axis varies with the ratio of the yield point to the plastic viscosity (Skalle, 2012).

$$\tau = [\tau_0^{1/2} + \mu_\infty \gamma^{1/2}]^2 \quad (4)$$

4.0 RESULTS AND DISCUSSION

The experimental data of viscosity against shear rate was fit to the rheological models above and the adjusted-R^2 values displayed below.

Table 1: Adjusted R^2 for all Models (0% Na_2CO_3 at 30°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.8893	0.9624	0.9367	0.9754	0.9275
Power law	0.7241	0.9355	0.9918	0.9543	0.9548
Herschel-Bulkley	0.6330	0.9175	0.9897	0.9385	0.9387
Casson	0.8624	0.9737	0.9856	0.9877	0.9647

Table 2: Adjusted R^2 for all Models (2% Na_2CO_3 at 30°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9609	0.9786	0.9377	0.9708	0.9423
Power law	0.9617	0.8337	0.8923	0.8583	0.7999
Herschel-Bulkley	0.9388	0.7838	0.8595	0.8109	0.7384
Casson	-0.2281	0.9407	0.9502	0.7247	0.9132

Table 3: Adjusted R^2 for all Models (4% Na_2CO_3 at 30°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.7503	0.7107	0.9428	0.9447	0.9260
Power law	0.9076	0.4628	0.8183	0.7916	0.7756

Herschel-Bulkley	0.3067	0.7884	0.7638	0.7289	0.7076
Casson	-1.825	0.6732	0.9228	0.9117	0.8975

Table 4: Adjusted R^2 for all Models (6% Na_2CO_3 at 30°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9071	0.9487	0.9745	0.9293	0.9217
Power law	0.8938	0.7850	0.8238	0.7601	0.7456
Herschel-Bulkley	0.5394	0.7172	0.7707	0.6873	0.6691
Casson	-3.972	0.8722	0.9354	0.8924	0.8827

Table 5: Adjusted R^2 for all Models (0% Na_2CO_3 at 60°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	-7.470	0.8255	0.7861	0.7929	0.8436
Power law	0.8089	0.5726	0.5288	0.5444	0.6401
Herschel-Bulkley	0.5394	0.7172	0.7707	0.6873	0.6691
Casson	-91.73	0.7706	0.7359	0.7455	0.8079

Table 6: Adjusted R^2 for all Models (2% Na_2CO_3 at 60°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9387	0.7764	0.8450	0.8346	0.8545
Power law	0.9519	0.5219	0.5956	0.6377	0.6563
Herschel-Bulkley	0.5394	0.7172	0.7707	0.6873	0.6691
Casson	0.4989	0.7274	0.7879	0.8069	0.8179

Table 7: Adjusted R^2 for all Models (4% Na_2CO_3 at 60°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.8932	0.8593	0.8485	0.8691	0.8848
Power law	0.9244	0.6681	0.6036	0.6549	0.7084
Herschel-Bulkley	0.8861	0.5696	0.4947	0.5575	0.6275
Casson	0.8305	0.8246	0.7930	0.8201	0.8524

Table 8: Adjusted R^2 for all Models (6% Na_2CO_3 at 60°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9219	0.8979	0.6824	0.7744	0.8914

Power law	0.9217	0.7762	0.4174	0.5709	0.8493
Herschel-Bulkley	0.8915	0.7112	0.2395	0.4469	0.8087
Casson	0.4751	0.8831	0.6456	0.7482	0.9155

Table 9: Adjusted R^2 for all Models (0% Na_2CO_3 at 90°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.8941	0.8374	0.9222	0.9683	0.9117
Power law	0.8723	0.6308	0.8651	0.8726	0.9157
Herschel-Bulkley	0.5993	0.5214	0.8293	0.8398	0.8903
Casson	-0.3952	0.7982	0.9271	0.9501	0.9418

Table 10: Adjusted R^2 for all Models (2% Na_2CO_3 at 90°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9567	0.7950	0.8493	0.9477	0.9486
Power law	0.9802	0.5837	0.6449	0.7874	0.8352
Herschel-Bulkley	0.9040	0.4591	0.5409	0.7258	0.7902
Casson	-0.7361	0.7615	0.8063	0.9066	0.9262

Table 11: Adjusted R^2 for all Models (4% Na_2CO_3 at 90°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9926	0.8234	0.9051	0.9078	0.8029
Power law	0.9368	0.6023	0.9507	0.7003	0.6075
Herschel-Bulkley	0.9059	0.4823	0.9361	0.6134	0.4885
Casson	0.9873	0.7792	0.9591	0.8390	0.7727

Table 12: Adjusted R^2 for all Models (6% Na_2CO_3 at 90°C)

Model/Curing time	0 hour	2 hour	4 hour	6 hour	8 hour
Bingham	0.9890	0.8903	0.9432	0.7856	0.8014
Power law	0.9135	0.7023	0.7907	0.5717	0.6180
Herschel-Bulkley	0.7885	0.6138	0.7387	0.4413	0.5015
Casson	-1.058	0.8475	0.9093	0.7503	0.7766

From table 1, the mean adjusted R^2 of Casson model is 0.95482 against 0.93826, 0.9121 and 0.88348 for Bingham model, Power law model and Herschel-Bulkley model respectively. This showed Casson model describes the behavior of viscosity of clay sample for 0% weight of soda ash, at different time intervals and temperature of 30℃.

From table 2, the mean adjusted R^2 of Bingham plastic model is 0.95806 against 0.86918, 0.82628 and 0.66014 for Power Law model, Herschel-Bulkley model and Casson model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 2% weight of soda ash, at different time intervals and temperature of 30℃. From table 3, the mean adjusted R^2 of Bingham plastic model is 0.8549 against 0.75118, 0.65906 and 0.31604 for Power Law model, Herschel-Bulkley model and Casson model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 4% weight of soda ash, at different time intervals and temperature of 30℃.

From table 4, the mean adjusted R^2 of Bingham plastic model is 0.93626 against 0.80166, 0.67674 and -0.07786 for Power Law model, Herschel-Bulkley model and Casson model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 6% weight of soda ash, at different time intervals and temperature of 30℃. From table 5, the mean adjusted R^2 of Herschel-Bulkley model is 0.67674 against 0.61896, -0.84438 and -17.73402 for Power Law model, Bingham plastic model and Casson model respectively. This showed Herschel-Bulkley model describes the behavior of viscosity of clay sample for 0% weight of soda ash, at different time intervals and temperature of 60℃.

From table 6, the adjusted R^2 of Bingham plastic model is 0.84984 against 0.7278, 0.67674 and 0.67268 for Casson model, Herschel-Bulkley model and Power Law model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 2% weight of soda ash, at different time intervals and temperature of 60℃. From table 7, the mean adjusted R^2 of Bingham plastic model is 0.87098 against 0.82412, 0.71188 and 0.62708 for Casson model, Power Law model and Herschel-Bulkley model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 4% weight of soda ash, at different time intervals and temperature of 60℃.
From table 8, the mean adjusted R^2 of Bingham plastic model is 0.8336 against 0.7335, 0.7071 and 0.61956 for Casson model, Power Law model and Herschel-Bulkley model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 6% weight of soda ash, at different time intervals and temperature of 60℃. From table 9, the mean adjusted R^2 of Bingham plastic model is 0.90674 against 0.8313, 0.73602 and 0.6444 for Power Law model, Herschel-Bulkley model and Casson model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 0% weight of soda ash, at different time intervals and temperature of 90℃.

From table 10, the mean adjusted R^2 of Bingham plastic model is 0.89946 against 0.76628, 0.6840 and 0.5329 for Power Law model, Herschel-Bulkley model and Casson model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 2% weight of soda ash, at different time intervals and temperature of 90℃. From table 11, the mean adjusted R^2 of Bingham plastic model is 0.88636 against 0.86746, 0.75952 and 0.68524 for Casson model, Power Law model and Herschel-Bulkley model respectively.

This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 4% weight of soda ash, at different time intervals and temperature of 90℃.

From table 12, the mean adjusted R^2 of Bingham plastic model is 0.8819 against 0.71924, 0.616676 and 0.4451 for Power Law model, Herschel-Bulkley model and Casson model respectively. This showed Bingham Plastic model describes the behavior of viscosity of clay sample for 6% weight of soda ash, at different time intervals and temperature of 90℃.

Out of the sixty plots for the four models used, the Bingham Plastic model fits best to the forty-three of the plots, which makes it the fit for 71.67% of the data, followed by Casson model which gave best fit to 13.33% of the data, thus making Bingham Plastic model the model of choice.

CONCLUSION

Nigerian (Ubakala) clay samples do not possess the desired property on their own for use as drilling mud because their viscosity and other properties do not meet the American Petroleum Institute (API) specifications, but on beneficiation with various concentrations of soda ash, ion exchange occurred and the calcium ion in the clay samples was replaced with sodium ion and this greatly improved the viscosity of the clay.

The rheological study of the process showed that the Bingham Plastic model appropriately describes the performance of the clay samples as it gave bets fit to more than 70% of the experimental data from the study.

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