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Statistical Modelling and Optimization of the 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 clay sample was collected from Ubakala in Abia State of Nigeria, 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^{O}C-90^{O}C) and speed of agitation (100rpm-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 results 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 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. The optimum predicted value of yield stress occurs for a curing time of 8hours, temperature of 90^{0}C and soda ash concentration of 5.183wt% and this is recommended as 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, optimization.

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I 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 [1]. 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 [2]. 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 [3], 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 [4]. Several researchers have studied some local clay samples [2], [5], [6], [7], [8], [9], [10], 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.

II 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 $7^{0}24'$E and latitude $5^{0}10'$N on the geological map of Nigeria.

Materials: Ubakala clay; Sodium Ash; 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.

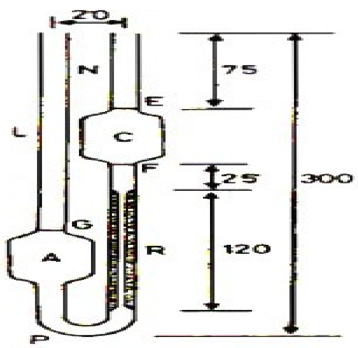

Figure 1: Ostwald Viscometer (Dimensions in mm)

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.

Mathematical 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^2-squared value. The model that gave the best fit to most or all of the plots will be used to evaluate the parameters for statistical study and optimization [11].

The statistical study will be done based on a full factorial experimental design using the statistical toolbox of MATLAB software for statistical modeling, response surface study and optimization. The study will be done for each data using curing time (x_1), temperature (x_2) and soda ash concentration (x_3) as factors, with model parameter (yield stress or viscosity) (y) as response while a-k are constant terms. The value of selected model parameter will be fit to four response surface models:

Linear: $$\boldsymbol{y = a + bx_1 + cx_2 + dx_3} \quad (1)$$
Interaction: $$\boldsymbol{y = a + bx_1 + cx_2 + dx_3 + ex_1x_2 + fx_1x_3 + gx_2x_3} \quad (2)$$
Pure-quadratic: $$\boldsymbol{y = a + bx_1 + cx_2 + dx_3 + ex_1^2 + fx_2^2 + gx_3^2} \quad (3)$$
Quadratic: $$\boldsymbol{y = a + bx_1 + cx_2 + dx_3 + ex_1x_2 + fx_1x_3 + gx_2x_3 + ix_1^2 + jx_2^2 + kx_3^2} \quad (4)$$

The model that best fits, based on the adjusted R-squared, will be considered the statistical model that best describes the parameter and will be used for optimization to determine optimum conditions for the parameter.

The value of the R-squared will be used as a measure of model accuracy and values greater than or equal to 0.90 will be considered acceptable. The p-value of the F-statistics will be used as a measure of model adequacy and a value less than or equal to 0.05 will be acceptable using 95% confidence interval. The significance of the main effects will be determined using Analysis of variance (ANOVA) which will be judged in a similar way to the F-statistics, using the p-value, while the statistical significance of each element in the model will be determined using the t-statistics value or its associated p-value.
The interaction between the factors will be determined using the surface plots, especially its contour lines, and the optimization toolbox of MATLAB used for the optimization of selected model parameter based on the model [12]-[16].

III RESULTS AND DISCUSSION

TABLE 1: DATA FOR STATISTICAL MODELING/OPTIMIZATION

Time	Temp.	Soda ash conc.	
X_1	X_2	X_3	τ_γ
0	30	0	6.921
2	30	0	6.922
4	30	0	6.924
6	30	0	6.935
8	30	0	6.938
0	30	2	6.931
2	30	2	6.931
4	30	2	6.932
6	30	2	6.640
8	30	2	6.940
0	30	4	6.932
2	30	4	6.932
4	30	4	6.936
6	30	4	6.938
8	30	4	6.940
0	30	6	6.933
2	30	6	6.936
4	30	6	6.938
6	30	6	6.939
8	30	6	6.939
0	60	0	7.042
2	60	0	7.050
4	60	0	7.052
6	60	0	7.060
8	60	0	7.065
0	60	2	7.060
2	60	2	7.087
4	60	2	7.081
6	60	2	7.096
8	60	2	7.123
0	60	4	7.060
2	60	4	7.088
4	60	4	7.082
6	60	4	7.097
8	60	4	7.124
0	60	6	7.061
4	60	6	7.090
6	60	6	7.096
8	60	6	7.094
0	90	0	7.128
2	90	0	7.120
4	90	0	7.168
6	90	0	7.208
8	90	0	7.234
0	90	2	7.251
2	90	2	7.121
4	90	2	7.169
6	90	2	7.216
8	90	2	7.237
0	90	4	7.255
2	90	4	7.141
4	90	4	7.173
6	90	4	7.229
8	90	4	7.239
0	90	6	7.142
2	90	6	7.175
4	90	6	7.227
6	90	6	7.240
8	90	6	7.258

RESULT OF RESPONSE SURFACE MODELANALYSIS

The result of the MATLAB programming of the response surface modelling is presented below.

It can be observed from table 2 using the t-stat value (which should have a magnitude of ≥2 for significant variables) and its p-value (which should be ≤ 0.05 at 95% confidence interval for significant variables), that the most significant terms appear to be temperature (X_3) and soda ash concentration (X_2). The model is adequate for study Based on the p-value of the F-stat (which is ≤ 0.05) and the three terms time (X_1), soda ash concentration (X_2) and temperature (X_3) are all significant based on the analysis of variance (table 3).
The adjusted R^2 values reveal that the statistical model explains about 99% of the observed variability in the experimental data. The model is 99% accurate.

TABLE 2: RESPONSE SURFACE MODEL STATISTICS

Variables	Coefficients	F -stat

Constants	6.7727	Sse=0.0064742
X_1	-0.0036	Dfe=50
X_2	0.0053	Dfr=9
X_3	0.0073	Ssr=0.77556
X_1X_2	$2.3917*10^{-4}$	F=665.51
X_1X_3	$1.3333*10^{-5}$	P val=0
X_2X_3	$1.4167*10^{-5}$	
X_1^2	$-3.6905*10^{-4}$	
X_2^2	$-1.4861*10^{-5}$	
X_3^2	$-8.3750*10^{-4}$	

Variables	t-stat	P values
Constants	486.9739	$1.4028*10^{-93}$
X_1	-1.6214	0.1112
X_2	12.0931	$1.8439*10^{-16}$
X_3	2.4845	0.0164
X_1X_2	11.2795	$2.3991*10^{-15}$
X_1X_3	0.0574	0.9545
X_2X_3	0.5282	0.5997
X_1^2	-1.6815	0.0989
X_2^2	-4.2920	$8.1171*10^{-5}$
X_3^2	-2.2804	0.0269

Result of the Analysis using Surface Plots.

Using the programming for the mesh grid, the surface plots are presented below.

From table 3 it can be deduced that soda ash concentration (X_3) is the least significant variable while temperature (X_2) and time (X_1) are the most significant variables. It can be observed from figure 2, the surface plot of temperature and time, that temperature shows a progressive colour variation and is more significant than time and the two factors seem linearly related to the yield stress.
It can be observed from figure 3, the surface plot of time and soda ash concentration, that time shows more significant than soda ash concentration. In addition, time seems to be linearly related to yield stress while soda ash concentration seems quadratically related.

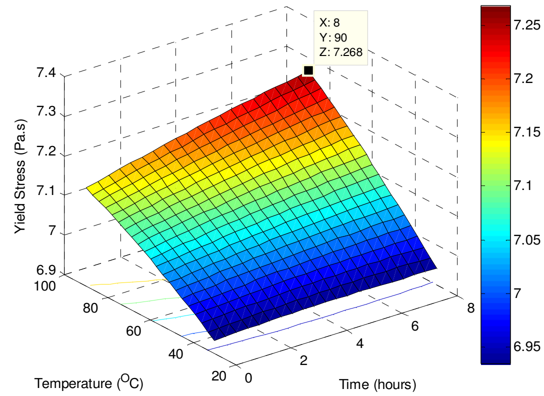

Figure 2: Surface Plot Interactions between Temperature (°C) and Time (hr)

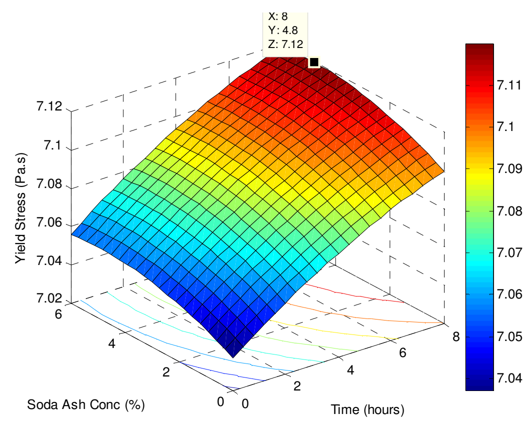

Figure 3: Surface Plot Interactions between Soda Ash Conc. (wt %) and Time (hr)

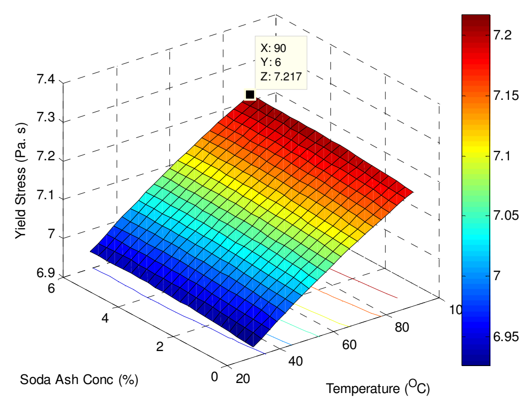

Figure 4: Surface Plot between Soda Ash Conc. (wt %) and Temperature (°C)

TABLE 3: ANALYSIS OF VARIANCE TABLE

source	Sum sq.	d. f.	Mean sq.	F	Prob>F
X_1	0.02056	4	0.00714	15.66	0
X_2	0.7268	2	0.3634	796.91	0
X_3	0.00387	3	0.00129	2.83	0.0476
Error	0.0228	50	0.00046		
Total	0.78203	59			

It can be observed from figure 4, the surface plot of temperature and soda ash concentration, that the temperature seems to be more significant than soda ash concentration. Also the interaction level is low.

Therefore, time, temperature and soda ash concentration are significant as variables with only interaction between time and temperature being significant.

Optimization shows that an optimum predictive value of yield stress occurs for a curing time of 8 hours, temperature of 90℃ and soda ash concentration of 5.1831. The predicted optimum (7.2716) only deviates from the experimental value by 0.2%.

The optimization also indicated that the optimum values of curing time and temperature are local optimum which can be improved by using higher curing time and temperature values. The optimum value of soda ash concentration is global optimum that cannot be improved upon by shifting lower or upper bounds.

IV CONCLUSION

The surface plots showed that curing time and temperature are significant variables, but temperature is more significant than time and both are linearly related to yield stress. The surface plot of time and soda ash concentration showed that time is more significant than soda ash concentration. In addition, time seems to be linearly related to yield stress while soda ash concentration seems quadratically related. The surface plot of temperature and soda ash concentration showed that temperature seems to be more significant than soda ash concentration and the interaction level is low. Therefore, the order of decreasing significance is: temperature, curing time, and soda ash concentration. All variables are however significant in the analysis of viscosity of clay.

Optimization shows that an optimum predictive value of yield stress occurs for a curing time of 8 hours, temperature of 90℃ and soda ash concentration of 5.1831. The predicted optimum (7.2716) only deviates from the experimental value by 0.2%.

The optimization also indicated that the optimum values of curing time and temperature are local optimum which can be improved by using higher curing time and temperature values. The optimum value of soda ash concentration is global optimum that cannot be improved upon by shifting lower or upper bounds.

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