MODELING RHEOLOGICAL BEHAVIOUR OF UBAKALA BENTONITE AS BINGHAM PLASTIC AND POWER LAW FLUIDS

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ABSTRACT

The Bingham Plastic model and the Power Law model have been used to determine whether they describe appropriately the rheology of Ubakala clay suspensions, after proving of course that the clay is actually bentonitic via X-Ray Diffraction and X-ray Fluorescence analysis. The mud samples were formulated by beneficiating Ubakala mud at 24.5g /350ml of water with various concentrations of Carboxyl Methyl Cellulose (CMC) and Sodium Carbonate (Na_2CO_3) to improve properties. Rheological properties of the samples were determined using a rheometer (OFITE model 900 viscometer). Plots of shear stresses against shear rates were obtained. Microsoft Excel software (Microsoft Office, 2007) was use to determine the rheological parameters for both the Bingham Plastic model and the Power Law model. The results showed that both models describe well the experimental data with good statistical indicators. The coefficient of determination, R^2, for the Bingham Plastic model had an average value of 0.9772 and that for the Power Law model had an average value of 0.908. Summarily, the results showed that the Bingham Plastic model fitted the experimental data better than the Power Law model did.

Keywords: *Bingham Plastic model, Power Law model, X-Ray Diffraction, X-ray Fluorescence, Rheological Properties, Co-efficient of determination*

1. INTRODUCTION

The term bentonite is used for clay consisting essentially of smectite regardless of origin and whose physical properties are dictated by this mineral (Chritidis, *et al.*, 1995). Bentonites are included in the class of the minerals with larger industrial interests (Amorim *et. al*, 2004). The several industrial applications of these clays are due to their physical and chemical properties (such as high surface area, and cation exchange capacity). Bentonites have significant number applications, like in preparation of green sand moulds for metal casting, as a thixotropic fluid in wall and road construction, in grouting and tunneling, as a sealant in land-fill, as a binder for iron-pellet preparation, as adsorbing material in hygiene sand for cat litter and as an additive in drilling fluids for oil-well, geothermal and water-well drilling to control viscosity and filtration properties (Kelessidis and Maglione, 2006).

Depending on the dominant exchangeable cations present the clay may be referred to as either calcium betonite or sodium bentonite, the two varieties exhibiting marked different properties and thus uses. The term non-swelling bentonite and swelling bentonite are synonymous with calcium and sodium bentonite respectively. When mixed with water, swelling bentonites exhibit a greater degree of dispersion and better plastic and rheological properties than non-swelling bentonites (Inglethorpe *et al.*, 1993).

Water bentonite suspensions have strong colloidal properties and increase liquid viscosity, behave as non-Newtonian fluids when sheared while under certain circumstances have the unique ability to gel when sheared. The concentration of bentonite in water suspension varies depending on the application, hence may range between 3 to 7% in drilling fluids to control rheological and filtration properties.

After hydration of bentonite particles, rheology of bentonite suspensions depends amongst other things on bentonite concentration, the presence of ions, particularly electrolytes, temperature and pH of suspensions (Kelessidis and Maglione, 2006).

Rheological models are useful tools to describe mathematically the relationship between shear stress and shear rate of a given fluid. Various rheological models have been proposed which describe the rheological behavior of bentonite suspensions. The models of Bingham Plastic and of Power Law are the most popular because the flow equations are easy to use and describe the rheological data with sufficient accuracy (Kelessidis and Maglione, 2006). The aim of this paper is to model Ubakala clay suspension as Bingham Plastic and Power Law fluids.

Location and Geological Setting of Study Area

Clays of various kinds and grades abound throughout Nigeria's sedimentary basins and on the basement (Falode, *et al.*, 2007). Recent investigations by the Nigerian mining corporation established the existence of bentonitic clay reserves of over 700 million tonnes in the country, with the largest single deposit at Afuze in Edo State holding 70–80 million tonnes (R.M.R.D.C., 2005). In

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Abia State, 5.8 million tonnes of bentonite has been proven while 7.5 million tonnes are inferred.

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 (Encarta, 2009).

2. MATERIAL AND METHODS

2.1 Sampling and Collection

Field sampling exercise of the clay sample was done during the dry season (in the month of January, to be precise, 2008). Fresh samples were collected from four pits dug to depths of 1.5m at a choice deposit of the clay sample, at about 5m apart. Clay sample obtained included Ubakala clay from Ubakala, Umuahia-South Local Government Area of Abia State.

Preparation of Clay Sample

The clay sample was soaked in water for 72 hours (Baba, 1999, Unpublished results). It was stirred every 24 hours to release organic materials. After 72 hours, the clay was sieved using a 200 mesh Tyler sieve and allowed to settle down. Water was then decanted from it. The concentrated clay was then transferred to a jeans bag for dewatering.

After a while, the clay sample was spread on a pan and sun-dried for a period of 5 days. The dried clay was grinded to a fine size (about 75μm) with mortar and pestle while continuously sieving with a 75μm Tyler sieve until a homogeneous sample was gotten.

2.2 Mineralogical Characterization

X-Ray Diffraction

The clay minerals were mineralogically characterized to identify their mineralogical compositions and hence their characteristics. This was done using a diffractometer (MD-100.000 UM, version 2.00) to carry out X-ray diffraction with Cu-Kα radiation (λ = 0, 15406 nm). The diffractogram was scanned in the range 2° to 10° at a scan rate of 1° 2θ min^{-1}. The diffractogram of the clay sample is as presented in Figure 1.

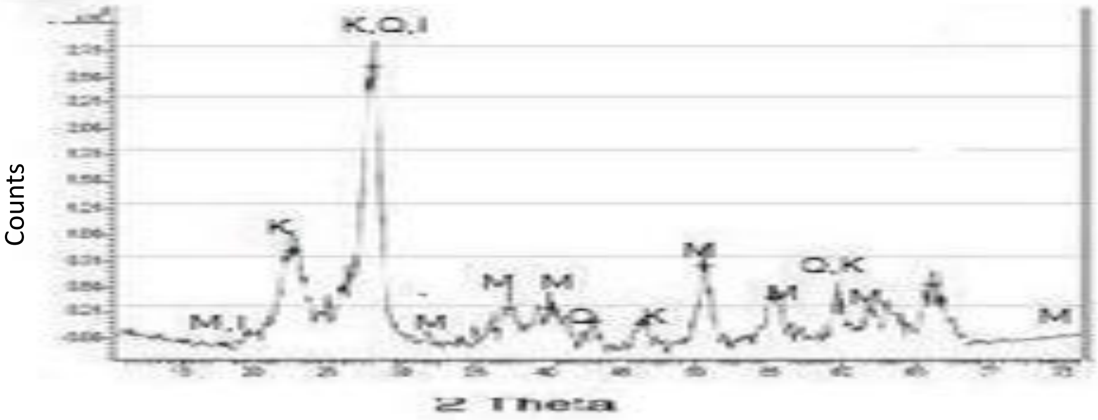

Figure 1: X-ray Diffractogram of Ubakala Clay

K= Kaolinite; Q=Quartz; I= Illite; M= Montmorillonite

X-Ray Fluoresence

The crystalline component of the clay sample was determined using Energy Dispersive X-Ray Fluorescence Spectrometer (ED-XRF), MiniPAL4 model. 20g of the sample was finely ground to pass through a 200-250 mesh size. The clay sample was dried in an oven at 105^{o}C for at least an hour and cooled. Thereafter, the sample was intimately mixed with a binder in the ratio of 5.0g sample(s) to 1.0g cellulomase flakes binder and pelletized at a pressure of 137.9MPa to 206.8MPa in a pelletizing machine. At this stage, the pelletized sample(s) were stored in a desiccator.

The ED-XRF machine was switched on and allowed to warm up for 2 hours. Finally, appropriate programs for the various elements of interest were employed to analyze the sample material for their presence or absence. The result was reported in percentage (%) for minor and major concentrations of elements.

2.3 Mud Preparation

In this study, the Hamilton beach multi-mixer (Model 9B with 9B29X impeller) was used to prepare the mud samples.

The mud samples were prepared by weighing out 24.5 grams of the clay samples using a triple beam balance (Ohaus Model 1650-00). These measurements of each of the clay samples were poured into separate mixer cups containing 350ml of fresh water each. The clay samples and water were vigorously agitated with the multi-mixer to produce a homogeneous mixture.

The mud samples were aged for 24 hours to allow for adequate hydration after which the rheological properties, were tested. At this stage, the rheological properties and density were found to be low, hence the need to treat the mud to meet the required API standards.

To improve the viscosity of the mud sample, Carboxymethyl Cellulose (CMC) was added to the mud samples formulated in increasing proportions of 0.2g, 0.8g, 1.0g, 1.5g and 2.0g. Finally, 1g of Sodium Carbonate was added to a mud sample containing 2g of CMC. The mixture of clay, water and viscosifiers were vigorously mixed and the homogeneous mixture with increased viscosity was allowed to age for 24 hours.

Rheological Properties Determination:

To determine the rheological properties of the formulated mud a rotational Couette-type rheometer (OFITE Model 900 viscometer) with an inner cylinder diameter of 1.7245cm and an outer rotating cylinder diameter of 1.8415cm, giving a diameter ratio δ = 1.0678, was used. The equipment was put on and allowed to stabilize. The thermal cup was filled to 2/3 full of the mud sample. The thermal cup was placed on the viscometer stand and adjusted with the stand until the rotor sleeve was immersed in the formulated mud at the scribe-line. The viscometer stand was held in position by tightening the lock screw on the left leg of the instrument. The button 'mud test' was pressed on the equipment and the dial readings at 600rpm, 300rpm, 200rpm, 100rpm, 60rpm and 3rpm were taken.

Rheological Model Determination

Having gotten the dial readings, the shear stresses and shear rates of each of the formulated mud sample at each rotor speed was calculated and the shear stresses plotted against their corresponding shear rates. The data of the flow curves were fitted with both Power Law and Bingham plastic models using Microsoft Excel package (Microsoft office, 2007).

The Bingham plastic model is given by,

$$\tau = YP + PV\gamma,\ \tau > YP \qquad (1)$$

While the power law model by,

$$\tau = K\gamma^{n} \qquad (2)$$

Where,

τ - Shear Stress
γ - Shear Rate
YP -Yield Point
PV - Plastic Viscosity
K - Power law fluid consistency index (M/LT^{2-n})
n - Flow behavior index (-)

The shear stresses were calculated using the following equation given by (Enilari, 2005);

$$\tau = 0.01066\times\theta i \times N_i \times 47.88\ (Pa) \qquad (3)$$

(The factor, 47.88 converts lb_f/ft^2 to Pa)

The shear rates were calculated using the equation given by (Kelessidis and Maglione, 2006);

$$\gamma = \left(\frac{dV}{dr}\right) = \frac{2\delta^2}{\delta^2-1}\Omega \quad (s^{-1}) \qquad (4)$$

The rotational speed, Ω is related to the rotor speed, N_i and is given by (Kelessidis and Maglione, 2006);

$$\Omega = \frac{2\pi\theta_i}{60} \qquad (5)$$

Where,

θ	Revolution per minute
N	Rotation per minute of outer cylinder
Ω	Rotational speed of outer cylinder($radsT^{-1}$)
δ	Radius of Couette viscometer (-)

3. RESULTS AND DISCUSSION

3.1 Mineralogical and Chemical Analysis

X-ray diffraction analysis as shown in Figure 1 was carried out in order to identify the mineralogical structure of the clay samples studied. The clay sample composed mainly of smectite, kaolinite, albite and quartz. There is almost complete absence of basal reflections in the 2-20° 2Θ (CuKα) range hence it is suspected that there is interstratifications between kaolinite and montmorillonite (Cradwick *et al*., 1972). The mineralogical composition of Ubakala clay is summarized in Table 1.

Table 1: Summary of Crystalline Minerals in Clay Sample

Clay/Mineral	Ubakala
Montmorillonite	25.6
Kaolinite	11.01
Quartz	35.2
Calcite	Tr
Biotite	Tr
Feldspar(Albite)	28.66
Total	**100.00**

The chemical analyses of the samples are as shown in Table 2. Chemical analyses results showed that Al_2O_3/ SiO_2 ratio in the Ubakala clay was about 1/4.35. The presence of alkalis and magnesia in the samples suggests significant presence of montmorillonite. Magnesia is normally used to enhance gel strength of mud samples. Ubakala clay showed low value of Fe_2O_3, this indicates low laterite concentrations. The clay showed low sodium ion concentration, which indicates less attraction between clay and water. The sodium ion concentration can be boosted by beneficiating the mud with Sodium Carbonate in order to improve its swelling properties.

Potassium may act as an exchangeable cation, located between unit layer and act as an interlayer cation. Ubakala bentonitic clay would require some beneficiation to improve the swelling properties.

3.2 Dial Readings of Mud Samples at Various Concentrations of Additives

The results of the dial readings of the formulated drilling mud at various rotor speeds from Ubakala clay beneficiated with various concentrations of Carboxymethyl Cellulose (CMC) using the Couette type rheometer (OFITE 900 model) are shown in Table 3.

Table 3 showed that the dial reading increased with increase in concentration of Carboxymethyl Cellulose (CMC) and further increased when 1 gramme of Sodium Carbonate (Na_2CO_3) was added. N_{600} is the dial reading at 600RPM, N_{300} is the dial reading at 300RPM, etc.

3.3 Fitting Experimental Data with Bingham Plastic and Power Law Models

The shear stresses were calculated from equation (3) and the shear rates from equation (4). Plots were made between the shear stresses and their corresponding shear rates and the rheograms fitted with the Bingham Plastic and Power Law models, using Microsoft Excel software (Microsoft Office, 2007).

Table 2: Chemical Composition of the Clay Samples

Chemical Oxide	Chemical Composition of Ubakala clay, %
MgO	0.156
Na_2O	0.056
Al_2O_3	16
SiO_2	69.6
SO_3	0.45
K_2O	0.599
CaO	0.22
TiO_2	2.64
V_2O_5	0.11
Cr_2O_3	0.039
Fe_2O_3	2.99
NiO	0.0096
CuO	0.057
ZnO	0.007
Rb_2O	0.0098
SrO	0.034
Y_2O_3	0.028
ZrO_2	0.219
RuO_2	0.384
Re_2O_7	0.01
OsO_4	0.02
L.O.I.	6.6
Total	**100.00**

Table 3: Dial Readings at Various Rotor Speeds of Drilling Mud formed from Ubakala Clay with CMC as Additives

Sample	Wt. of CMC (g)	N_{600}	N_{300}	N_{200}	N_{100}	N_{60}	N_{30}	N_6	N_3
Ubakala mud	0.2	3.3	1.5	1.5	0.9	0.8	0.5	0.5	0.5
	0.8	4.6	2.7	1.0	1.0	0.3	0.1	0.1	0.0
	1.0	9.1	3.8	2.8	2.1	1.3	0.7	0.4	0.2
	1.5	13.5	6.9	4.2	1.5	0.4	0.1	0.0	0.0
	2.0	22.5	13.4	11.3	5.3	2.9	1.3	0.3	0.2
Ubakala mud+ 1g Na_2CO_3	2.0	52.4	33.7	27.7	18.8	15.0	11.3	8.9	8.9

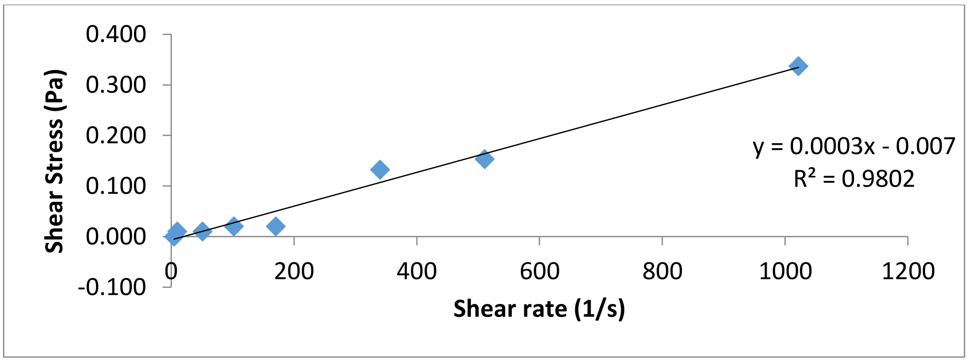

Figure 1: Rheogram of Ubakala mud beneficiated with 0.2g Carboxymethyl Cellulose (CMC) fitted with Bingham Plastic model

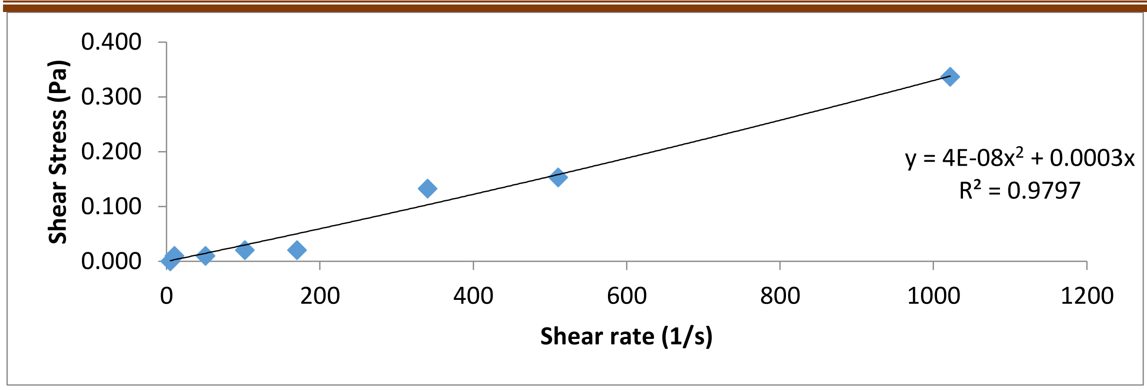

Figure 2: Rheogram of Ubakala mud beneficiated with 0.2g Carboxymethyl Cellulose (CMC) fitted with Power Law model

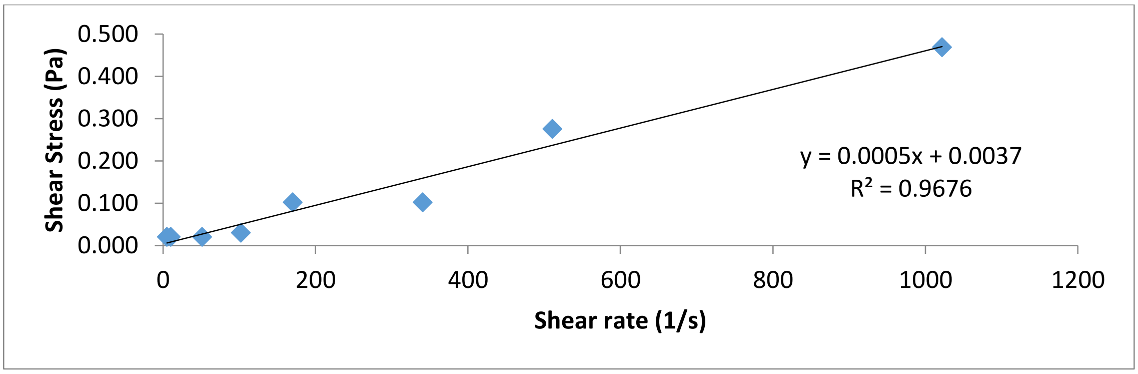

Figure 3: Rheogram of Ubakala mud beneficiated with 0.8g Carboxymethyl Cellulose (CMC) fitted with Bingham Plastic model

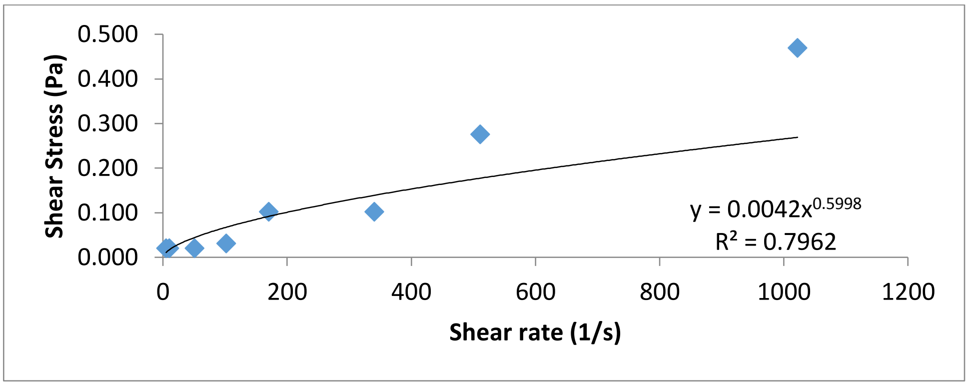

Figure 4: Rheogram of Ubakala mud beneficiated with 0.8g Carboxymethyl Cellulose (CMC) fitted with Power Law model

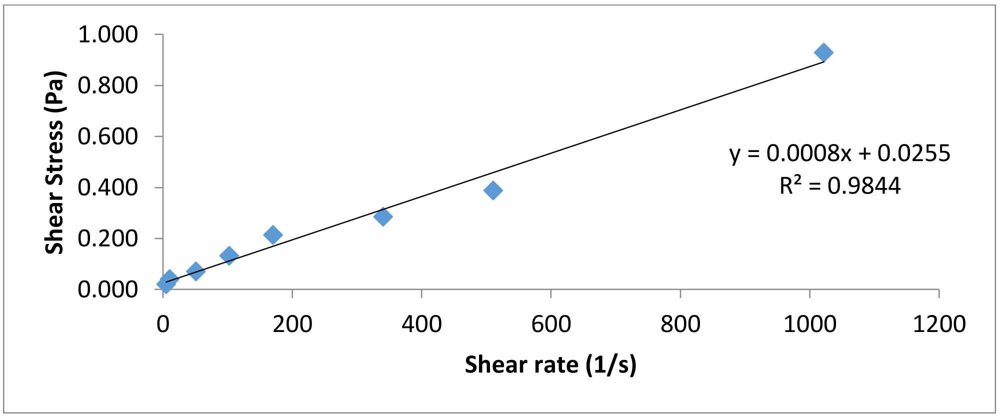

Figure 5: Rheogram of Ubakala mud beneficiated with 1.0g Carboxymethyl Cellulose (CMC) fitted with Bingham Plastic model

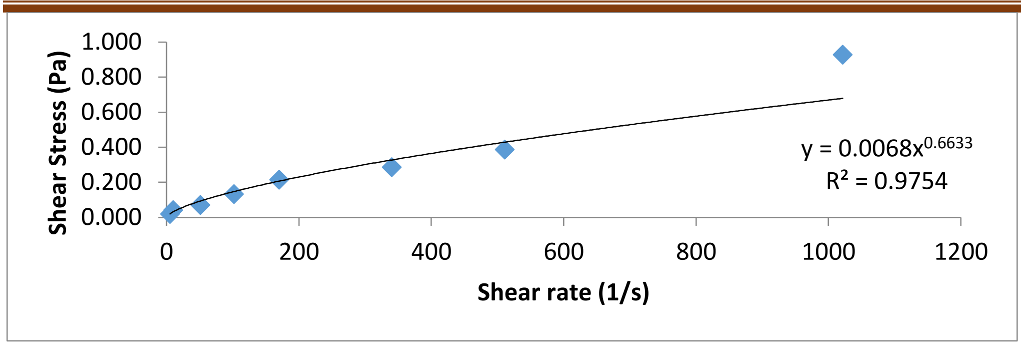

Figure 6: Rheogram of Ubakala mud beneficiated with 1.0g Carboxymethyl Cellulose (CMC) fitted with Power Law model

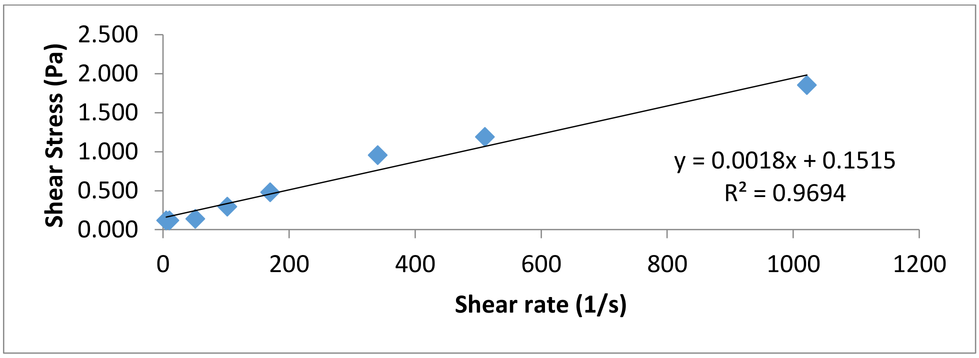

Figure 7: Rheogram of Ubakala mud beneficiated with 2.0g Carboxymethyl Cellulose (CMC) fitted with Bingham Plastic model

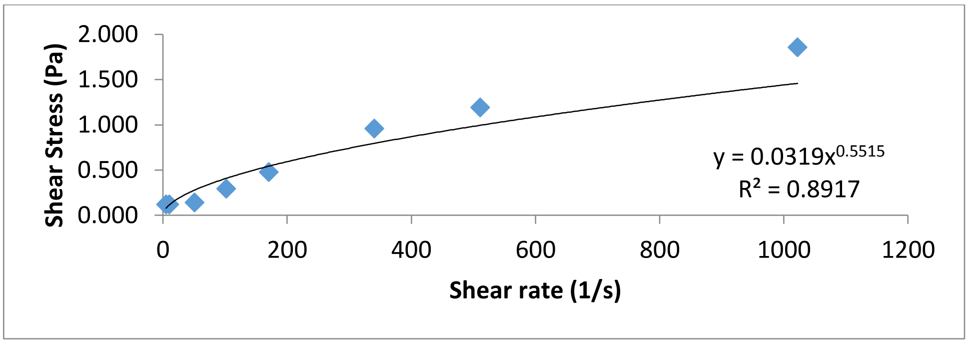

Figure 8: Rheogram of Ubakala mud beneficiated with 2.0g Carboxymethyl Cellulose (CMC) fitted with Power Law model

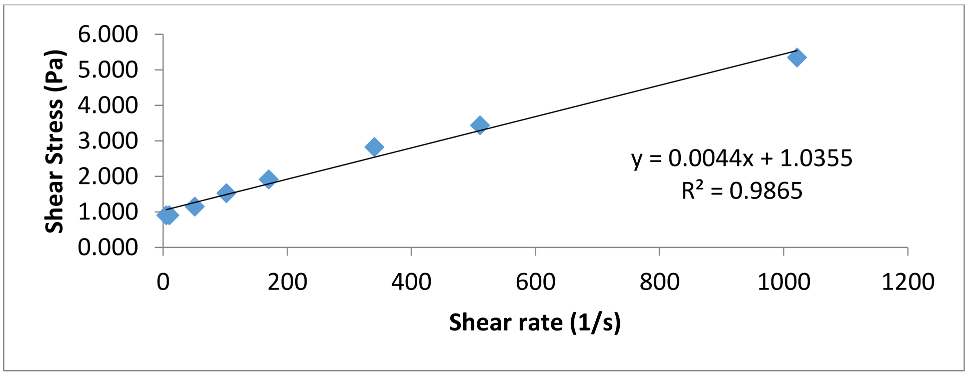

Figure 9: Rheogram of Ubakala mud beneficiated with 2.0g Carboxymethyl Cellulose (CMC) and 1.0g Sodium Carbonate (Na_2CO_3) fitted with Bingham Plastic model

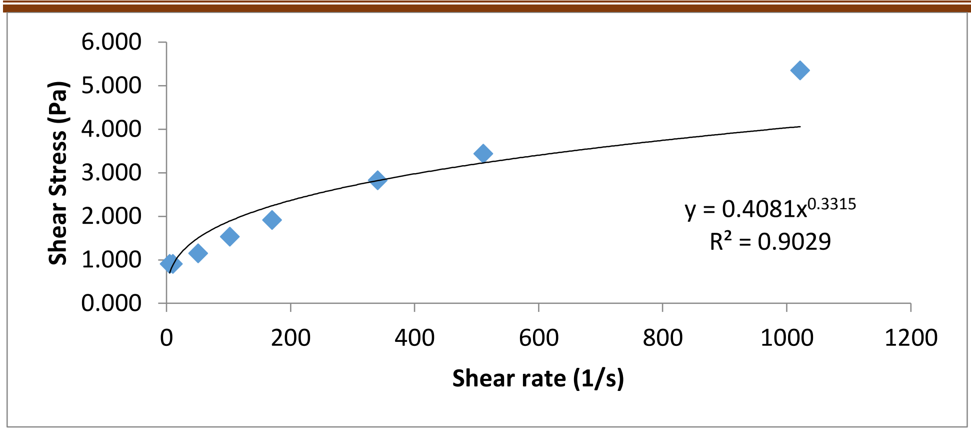

Figure 10: Rheogram of Ubakala mud beneficiated with 2.0g Carboxymethyl Cellulose (CMC) and 1.0g Sodium Carbonate (Na_2CO_3) fitted with Power Law model

Table 4: Bingham Plastic Parameters of Ubakala-based mud samples

Mud Composition	Coefficient of Determination (R^2)	Bingham Plastic parameters	
		PV(Pa.s)	YP(Pa)
Ubakala +0.2g CMC	0.980	0.0	-0.007
Ubakala +0.8g CMC	0.967	0.0	0.003
Ubakala +1.0g CMC	0.984	0.0	0.025
Ubakala +2.0g CMC	0.969	0.001	0.151
Ubakala +2.0g CMC+1gNa_2CO_3	0.986	0.004	1.035

Table 5: Power Law Parameters of Ubakala-based mud samples

Mud Composition	Coefficient of Determination (R^2)	Power Law parameters	
		K ($Pa.s^n$)	n
Ubakala +0.2g CMC	0.979	0.0	1.0
Ubakala +0.8g CMC	0.796	0.004	0.599
Ubakala +1.0g CMC	0.975	0.006	0.663
Ubakala +2.0g CMC	0.891	0.031	0.551
Ubakala +2.0g CMC+1gNa_2CO_3	0.902	0.408	0.331

Figures 1-10 shows the rheograms obtained with the Couette type rheometer (OFITE 900 model) for the formulated mud samples. The curves are typical of yield-pseudoplastic materials (Kelessidis and Maglione, 2006). For most of the rheograms, the high shear rates region displays a fairly linear behavior, but strong non-linearity is observed for shear rates less than approximately 300 s^{-1}. All the experimental data fitted well with both Bingham Plastic and Power law models and the values of their rheological parameters are given in Tables 4 and 5, respectively. The coefficient of determination, R^2, which indicates closeness of fit to experimental data, was also displayed.

For the Bingham Plastic parameters, the plastic viscosity(PV), which is a measure of the internal resistance to fluid flow attributable to the amount, type and size of solids present in a given fluid (Garvey, 1988), increased with increase in concentration of Carboxymethyl Cellulose(CMC) and further increased when 1 gram of Sodium Carbonate (Na_2CO_3) was added. The same goes for the yield point (YP), which is the resistance to initial flow and represents the stress required to start fluid movement (Garvey, 1988). The coefficient of determination, R^2, ranged between 0.967 and 0.986, with an average value of 0.9772.

For the Power Law parameters, the "n" parameter which is called the flow-behavior index signifies the type of viscosifier used to increase fluid viscosity. This value ranges between 0.331 and 1.0. Some viscosfiers provide the lowest "n" value, however, for proper hole cleaning and penetration "n" should be between 0.3 and 0.6(Okorie, 2006). The "K" value, which is called the consistency index, indicates the type of viscosifier and solid content of the mud. It increased with increase in concentration of the Carboxymethyl Cellulose (CMC) and further increased when 1 gram of Sodium Carbonate (Na_2CO_3) was added. The coefficient of determination, R^2, ranged between 0.796 and 0.979, with an average value of 0.908.

4.CONCLUSIONS AND RECOMMENDATIONS

The Ubakala clay is proven to be bentonitic given the amount of montmorillonite present in the clay (25.6%). Its rheological properties can be improved by beneficiation with Carboxymethyl Cellulose (CMC), and further improved by adding sodium Carbonate (Na_2CO_3). The dial readings were sufficiently high when 2 grams of Carboxymethyl Cellulose (CMC) and 1 gram of Sodium Carbonate (Na_2CO_3) was added to Ubakala mud at 24.5g /350ml of water.

The results showed that both models describe well the experimental data with good statistical indicators. The coefficient of determination, R^2, for the Bingham Plastic model had an average value of 0.9772 and that for the Power Law model had an average value of 0.908, this indicates that the Bingham Plastic model fitted the experimental data better than the Power Law model did.

Experimental data could be fitted with models such as Herschel-Bulkley model and Casson model to account for non-linear behavior and yield stresses at the same time.

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