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ENHANCEMENT OF GAMBE CLAY USING UN-FERMENTABLE POLYMERS FOR DRILLING MUD FORMULATION

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ABSTRACT

There is availability and large deposits of bentonite (700 million tons in North Eastern part) in Nigeria but the clays had not been abundantly harnessed and enhanced with polymer for drilling fluid formulation because they are mostly composed of calcium montmorillonite. This work was aimed at enhancing Gambe clay using un-fermentable polymers (three carboxy methyl cellulose (CMC) with different average molecular weight). The clay was obtained from Gambe town in Adamawa State, Nigeria, beneficiated for quartz removal, as well as enhancement with Na_2CO_3 (6 wt.%). The mineral and oxides composition of the clay was determined using X-ray diffraction and X-ray fluorescence analyses respectively, and finally used to formulate the drilling fluid. The effect of the polymer on the rheological and physico-chemical properties of the formulated drilling fluid was investigated employing FANN 35SA viscometer. It was found that the carboxy methyl cellulose enhanced the plastic viscosity from 1.5 cP to 34 cP and the apparent viscosity from 2.25 cP to 44 cP. The higher the average molecular weight of the sodium carboxy methyl cellulose the higher the apparent and plastic viscosities of the formulated fluid. Similarly, the resultant viscosities compared well with that of commercial standard of 15 cP and 14 cP of apparent and plastic viscosities respectively. The sets of data generated from this work is going to be very useful for water and oil/gas drilling operations.

Keywords: *Drilling mud, Gambe clay, carboxy methyl cellulose, rheological properties, average molecular weight.*

1. INTRODUCTION

In the drilling of oil and gas wells by the rotary method, a drilling fluid is used which generally consists of an aqueous clay suspension often containing additives to increase the hydrostatic head. The drilling fluid serves to transport cuttings to the surface, to cool the bit and to keep the oil, gas and water confined to their respective formations during the drilling process [1]. For these functions, it is necessary that the drilling fluid must have sufficient carrying capacity to bring cuttings to the surface, fluid enough to release cutting and entrained gas at the surface and above all, be of pump-able viscosity of which polymers can be very useful.

Polymers are very large molecules made by covalently binding many smaller ones called monomers. They are classified widely based on applications and are essential to modern society. A wide variety of polymer serve a number of useful purposes in drilling fluids, the most important of which are to increase viscosity and control filtration rates [2].

Clays are comprised of certain groups of hydrous aluminium, magnesium, and iron silicates that may contain sodium, calcium, potassium, and other ions. These silicates are called the clay minerals, and the major clay mineral groups are kaolins, smectites, illites, chlorites, and palygorskite and sepiolite [3]. The active ingredient in bentonite is a smectite, montmorillonite, an expandable 2:1 aluminosilicate mineral, having a three-layer plate-shaped crystalline structure. The colloidal system of bentonite has highly non-Newtonian rheological properties and the suspending and shear-thinning characteristics desired in a drilling fluid [2]. Hence, rheology is an extremely important property of drilling fluid. A rheological model describes the flow behaviour of a fluid by developing a mathematical relationship between shear stress and shear rate [5]. According to [6] and [7], numerous flow models which can be encountered in the rheology literature include Bingham Plastic, Power-law, Herschel-Bulkley, Mizhari and Berk, etc.

Importation of bentonites is expensive and most importantly discourages the efforts to look inwards for the availability and potentials of local clay deposits [8]. The raw materials for the development of drilling mud are abundant and estimated to be about 700 million tonnes located in the north-eastern Nigeria [9].

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2. MATERIALS AND METHODS

2.1 Gambe Clay Collection and Preparation

Sample of the raw bentonite clay were collected from Gambe, Mayo Belwa LGA, Adamawa state. They were first sun dried for six hours, crushed and pulverized with the aid of a jaw crusher and a ball mill machine, and then sieved to American Petroleum Institute (API) specification (63 μm).

2.2 Determination of the Mineral Composition of the Gambe Clay

Empyrean diffractometer with a copper anode material manufactured by Panalytical was used. The powdered sample was prepared using the sample preparation block and compressed in the flat sample holder to create a flat smooth surface that was later mounted on the sample stage in the XRD cabinet. The sample was analyzed using the reflection-transmission spinner stage using the Theta-Theta settings. Two-Theta starting position was 0.00483 and ends at 50.96483 with a two-theta step of 0.026 at 3.57 seconds per step. Tube current was 40 mA and a voltage of 45 kV was used.

The d-spacing of each peak was then obtained by solution of the Bragg equation for the appropriate value of λ. Once all d-spacing have been determined, automated search/match routines compare the d-spacing of the unknown to those of known materials. The difractograms were processed and displayed automatically using software.

2.3 Determination of the Oxide Composition of the Gambe Clay Sample

Mimipal 4 energy dispersive X-ray fluorescence spectrometer was used for the analysis. It consisted of 12 compartments for samples to be analysed simultaneously. The clay was dried in an oven at 105 °C for an hour and allowed to cool. Twelve grams of the Gambe clay was thoroughly mixed with 3 g of binder (stearic acid) in agate mortar. The mixtures were then formed into a pressed powder pellet using a hydraulic pressure press, a weight of 20 tons was used. The pressed powder pellets were then analysed for oxide composition using X-ray fluorescence (XRF) spectrometer, a computer system and software for the analysis.

2.4 Chemical Beneficiation of the Gambe Clay

One hundred grams of the clay was dispersed in 150 mL of 6 g/L Na_2CO_3 solution and then 50 mL of distilled water was added and stirred for 5 minutes. It was allowed for 24 h for proper ion exchange. This was to obtain base clay which has far better swelling capacity than the predominantly abundant calcium clay. The paste was then oven dried at 70 °C for 24 h. The clay was then grinded for particle size reduction and sieved to 63 μm.

2.5 Determination of the Average Molecular Weight of the Polymer Using Viscometer

Brookfield DV-I prime viscometer was used and spindle s61 was selected for the test. The viscosity of the solvent was first determined at 100 rpm and then the viscosity of the polymer-solvent system at different concentrations was determined at 100 rpm. From the concentration and viscosity, the specific viscosity, reduced viscosity and inherent viscosity were calculated using Equations 1, 2 and 3 respectively.

$$Specific\ viscosity, \eta_{sp} = \frac{\eta - \eta_0}{\eta_0} \quad (1)$$

$$Reduced\ viscosity, \eta_{red} = \frac{\eta_{sp}}{c} \quad (2)$$

$$Inherent\ viscosity, \eta_{Inh} = \frac{\ln \eta_{red}}{c} \quad (3)$$

where η is the viscosity of the solution and η_0 is the viscosity of the pure solvent.

A graph was drawn by plotting reduced viscosity and inherent viscosity against concentration. The intrinsic viscosity was obtained by extrapolating the two graphs to zero concentration and the average was calculated. From the value of the intrinsic viscosity, the viscosity average molecular weight of the polymer was calculated using the Equation 4.

$$[\eta] = kM_v^a \quad (4)$$

Where $[\eta]$ is the intrinsic viscosity, M is molecular weight, k and a are Mark-Houwink constants for a particular polymer solvent system.

2.6 Drilling Fluid Formulation

Drilling fluid was formulated by mixing of 22.5 g of the clay to 350 ml of water with a high speed mixer at 18 000 rpm for 60 s to obtain a homogenous mixture. The carboxy methyl cellulose of 0.5 g was also added to the mixture and then mixed at 18 000 rpm for 40 s. The mud formed was allowed to hydrate for 24 h. Similar procedure was done for other formulation of weight of polymer ranging from 1.0 g to 3.5 g as shown in Table 1.

2.7 Determination of Rheological Properties of the Drilling Fluid

FANN 35SA viscometer was used to determine the rheological properties. The design includes R1 Rotor Sleeve, B1 Bob, F1 Torsion Spring, and a stainless steel sample cup for testing according to API recommended practice for field testing water based drilling fluids. The mud sample was mixed at 18 000 rpm with a mixer until a homogeneous mixture was obtained, while avoiding formation of foam. The sample was then poured into heat cup (sample holder) and mounted to position.

Table 1: Concentration of polymer for drilling fluid formulation

Mass of polymer (g)	0.5	1.0	1.5	2.0	2.5	3.0	3.5
Concentration of the polymer (wt %)	0.13	0.27	0.40	0.53	0.67	0.80	0.93

The base was lifted until the level of fluid met the scribed line on the rotor sleeve and the lock screw was tightened. The Model 35SA viscometers operate at six speeds, which are 3, 6, 100, 200, 300 and 600 rpm. To select the 3 rpm, the speed switch (located on the right side of the base) was set low speed position. Then the motor was turned on and moved the gear shift knob (located on the top of the instrument) to the centre. The 3 rpm reading was recorded when the indicator dial value was steady. Similar procedure was done for 6, 100, 200, 300 and 600 rpm. The apparent viscosity, plastic viscosity (PV) and yield point (YP) were determine using Equations 5, 6 and 7.

$$AV = \frac{Dial\ reading\ at\ 600\ rpm}{2}(cP) \quad (5)$$

$$PV = \{Dial\ reading\ at\ 600\ rpm - dial\ reading\ at\ 300\ rpm\}(cP) \quad (6)$$

$$YP = \{Dial\ reading\ at\ 300\ rpm - PV\}\left(\frac{lb}{100\ ft^2}\right) \quad (7)$$

2.8 Determination of Gel Strength of the Drilling Fluid

The FANN 35SA viscometer was used to determine the gel strength of the mud at 10s and 10min. The formulated mud was poured into heat cup and mounted to position. The base was lifted until the level of fluid met the scribed line on the rotor sleeve and the lock screw was tightened. The sample was stirred at 600 rpm for 15 s and the gear assembly was lifted to the neutral (centre) position. The motor was shut off and waited for 10 s. The switch to the low-speed position was flipped and maximum deflection was recorded in lb/100 ft^2 as 10-s gel. The same procedure used to determine the gel strength at 10 s was repeated for 10 min to obtain the 10-min gel.

2.9 Fitting of Rheological Models for the Gambe Drilling Mud

In this study, the measured shear stress and shear rate were fitted to four rheological models using commercial mathematical software, MATLAB® version 8.4. The models were fitted to the experimental data using lsqcurvefit solver, which is available in MATLAB®. The lsqcurvefit solves nonlinear curve-fitting problems in least-squares sense. In addition, commercial statistical parameter including R-square (R^2) was also calculated using the software. The four rheological models used were Bingham plastic model, Power Law model, Herschel-Bulkley model, and Mizhari and Berk model. The experimental shear stress and shear rate were evaluated using Equations 7 and 8 on the dial readings obtained in the experiment.

$$\tau = 0.5107 \times \theta_i \quad (7)$$

$$\gamma = 1.703 \times rpm \quad (8)$$

where τ = shear stress (Pa), γ = shear rate (s^{-1}), θ_i = dial reading and rpm = rotational dial speed. The rheological models were solved using lsqcurvefit solver and, Levenberg-Marquardt algorithm was selected.

3. RESULTS

Figure 1 showed the XRD result of raw Gambe clay compared with montmorillonite (Ca) of Joint Committee on Powder Diffraction Standards (JCPDS) published by International Centre for Diffraction Data.

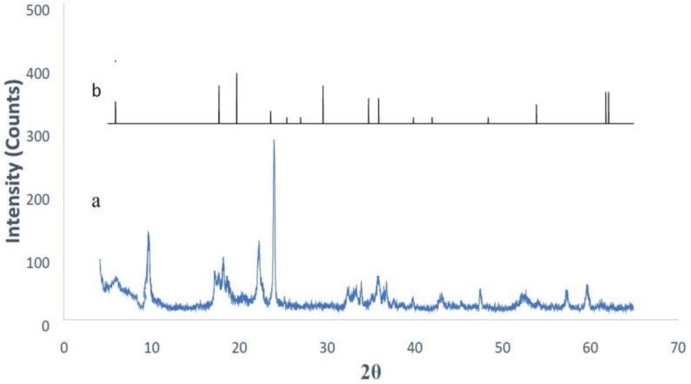

Figure 1: XRD patterns for (a) raw Gambe clay (b) Montmorillonite (Ca) (JCPDS)

The summary of the mineral oxides is hereby presented in Table 2.

Table 2: Summary of the oxide composition of the clay samples

Oxide composition	Raw Gambe clay (%)	Beneficiated Gambe clay (%)
Al_2O_3	15.13	20.30
SiO_2	40.57	45.10
TiO_2	2.68	1.64
Fe_2O_3	11.87	9.76
CaO	20.00	15.56
Na_2O	0.21	1.56
K_2O	0.51	0.61
MnO	0.15	0.07
MgO	0.98	2.51

The average molecular weights of the polymers as a function of both dynamic and the intrinsic velocities are generated and the results displayed in Table 3. Figures 2 to 11 display the profiles of the flow behaviour, the rheological properties and gel strength of Gambe clay and various polymers treated samples compared with the API standards.

Table 3: Average molecular weight and intrinsic viscosity of the carboxy methyl cellulose

Polymer	Dynamic viscosity, *cP* (3g/L at 100rpm)	Intrinsic viscosity, *dL/g*	Average molecular weight, *g/mol*	Range of Average molecular weight, *g/mol*
CMC-a	5.4	1.976	88,924	40,000-1,000,0000 [16]
CMC-b	6.0	2.769	140,327	
CMC-c	10.3	5.074	318,131	

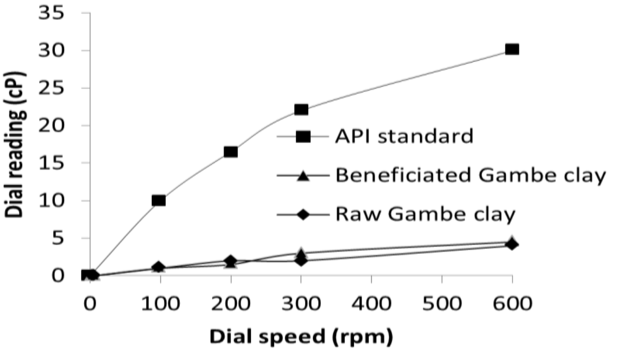

Figure 2: Behaviour of Gambe clay

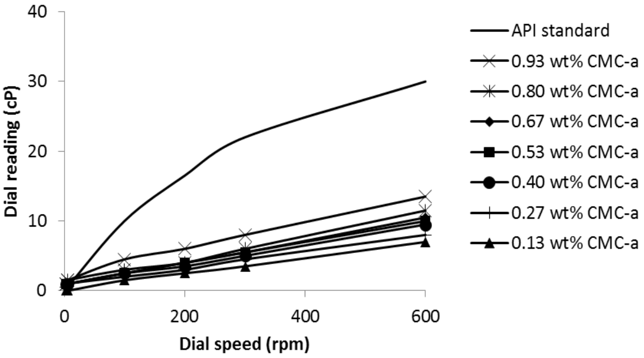

Figure 3: Behaviour of Gambe clay treated with CMC-a.

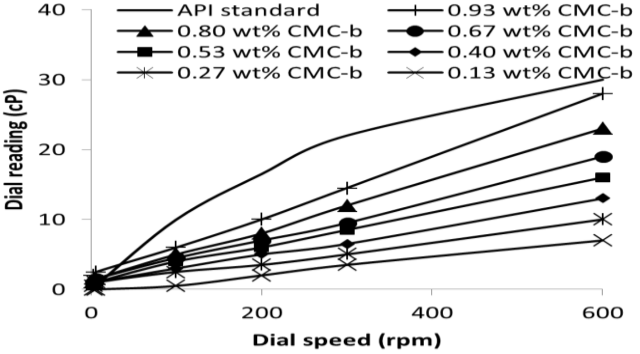

Figure 4: Behaviour of Gambe clay treated with CMC-b.

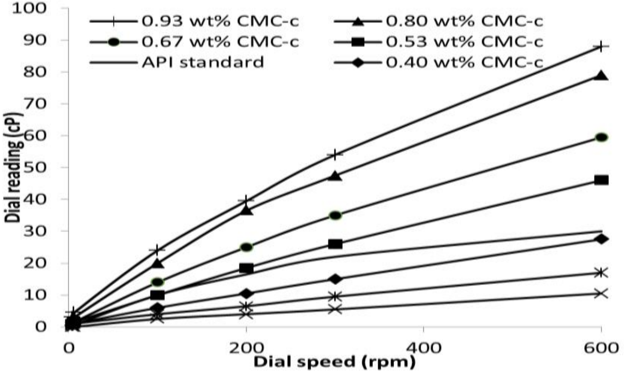

Figure 5: Behaviour of Gambe clay treated with CMC-c.

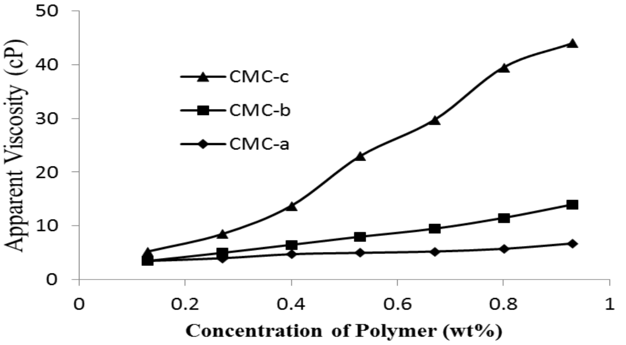

Figure 6: Variation of apparent viscosity of the mud with the polymers.

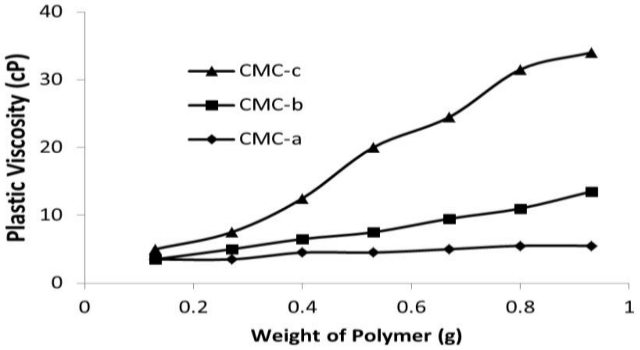

Figure 7: Variation of plastic viscosity of the mud with the polymers

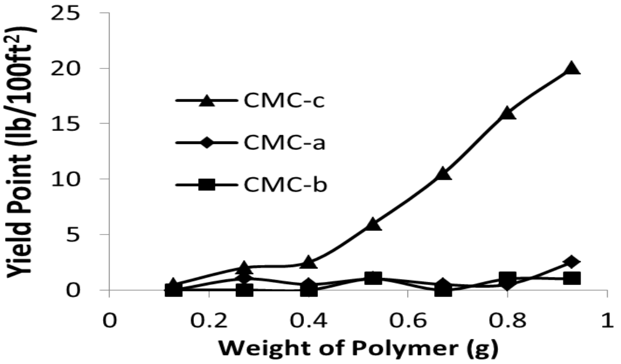

Figure 8: Variation of yield point of the mud with the polymers.

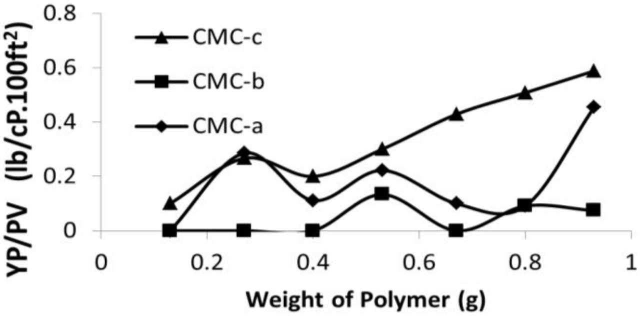

Figure 9: Variation of ratio of yield point to plastic viscosity of the mud with the polymers.

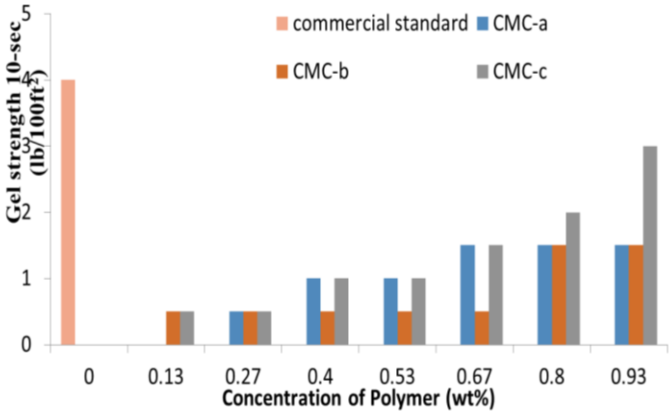

Figure 10: Variation of Gel strength (10-sec) of the mud with the polymers.

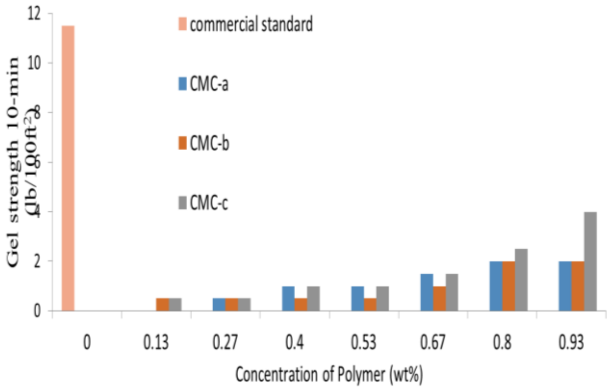

Figure 11: Variation of Gel strength (10-min) of the mud with the polymers.

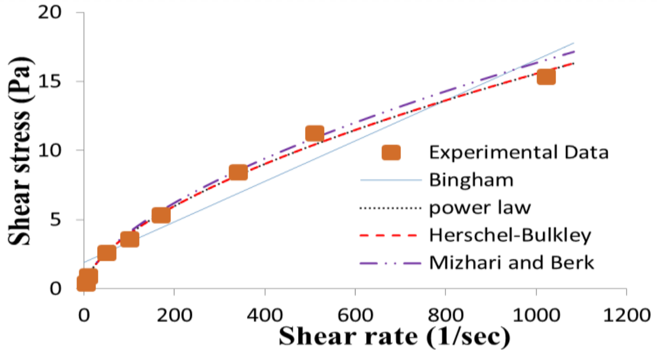

Figure 12: Rheogram of beneficiated Wyoming clay mud showing the experimental and models fitting [20]

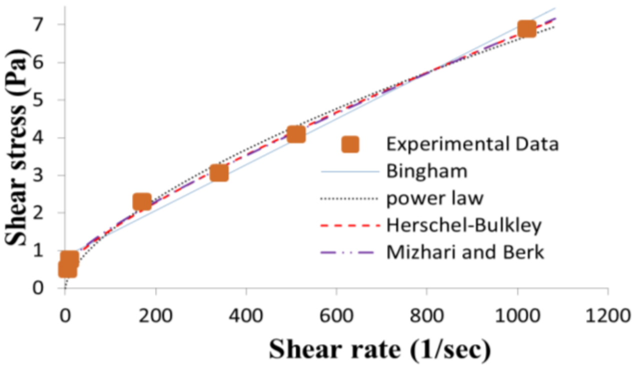

Figure 13: Rheogram of Gambe clay mud treated with 0.93 wt% of CMC-a showing the experimental and models fitting

Table 4: Rheological parameters of Gambe clay mud treated with carboxy methyl cellulose

Polymer (%)	Bingham Plastic Model Eq.			Power Law Model Eq.			Herschel–Bulkley Model Eq.				Mizhari-Berk Model Eq.			
	τ_{o1} (Pa)	μ_p (Pa.s)	R^2	k_1 (Pa.s^n)	n_1	R^2	τ_{o2} (Pa)	k_2 (Pa.s^n)	n_2	R^2	K_{OM} (Pa)	K_M (Pa.s^n)	n_M	R^2
Commercial standard (Wyoming clay mud)														
0.00	1.92	0.015	0.93	0.249	0.59	0.99	0.00	0.259	0.59		0.00	0.509	0.30	0.99
Gambe clay mud treated with CMC-a														
0.13	0.04	0.003	0.99	0.006	0.93	0.99	0.00	0.006	0.93	0.99	0.02	0.071	0.47	0.99
0.27	0.36	0.004	0.99	0.017	0.79	0.97	0.35	0.004	0.99	0.99	0.55	0.016	0.65	0.99
0.40	0.46	0.004	0.99	0.018	0.80	0.96	0.51	0.003	1.06	0.99	0.68	0.009	0.73	1.00
0.53	0.46	0.005	1.00	0.020	0.80	0.97	0.47	0.004	1.00	1.00	0.64	0.016	0.67	1.00
0.67	0.45	0.005	1.00	0.017	0.83	0.97	0.49	0.003	1.05	1.00	0.66	0.013	0.70	1.00
0.80	0.54	0.005	0.99	0.019	0.83	0.96	0.64	0.002	1.11	0.99	0.77	0.008	0.77	0.99
0.93	0.85	0.006	0.98	0.081	0.64	0.98	0.54	0.027	0.79	0.98	0.65	0.059	0.51	0.99
Gambe clay mud treated with CMC-b														
0.13	0.00	0.003	0.98	0.001	1.15	0.99	0.00	0.001	1.15	0.99	0.00	0.036	0.57	0.99
0.27	0.34	0.005	0.99	0.012	0.87	0.98	0.39	0.003	1.06	0.99	0.59	0.013	0.70	0.99
0.40	0.38	0.006	0.99	0.017	0.86	0.98	0.36	0.007	0.99	0.99	0.54	0.028	0.62	0.99
0.53	0.45	0.008	0.99	0.025	0.84	0.99	0.33	0.013	0.92	0.99	0.50	0.050	0.56	0.99
0.67	0.59	0.009	0.99	0.023	0.87	0.98	0.63	0.007	1.02	0.99	0.73	0.002	0.66	0.99
0.80	0.55	0.011	1.00	0.023	0.90	0.99	0.58	0.010	1.01	1.00	0.68	0.036	0.63	1.00
0.93	0.92	0.013	1.00	0.030	0.89	0.98	1.08	0.008	1.07	1.00	0.97	0.022	0.70	1.00

Polymer (%)	Bingham Plastic Model Eq.			Power Law Model Eq.			Herschel–Bulkley Model Eq.				Mizhari-Berk Model Eq.			
	τ_{o1} (Pa)	μ_p (Pa.s)	R^2	k_1 (Pa.s^n)	n_1	R^2	τ_{o2} (Pa)	k_2 (Pa.s^n)	n_2	R^2	K_{OM} (Pa)	K_M (Pa.s^n)	n_M	R^2
Gambe clay mud treated with CMC-c														
0.13	0.12	0.005	0.99	0.013	0.87	0.99	0.00	0.013	0.87	1.00	0.00	0.114	0.43	0.99
0.27	0.47	0.008	0.99	0.028	0.83	0.99	0.28	0.017	0.89	1.00	0.42	0.070	0.52	1.00
0.40	0.53	0.013	0.99	0.036	0.86	1.00	0.21	0.029	0.89	1.00	0.30	0.119	0.49	1.00
0.53	1.00	0.023	0.99	0.074	0.83	1.00	0.25	0.064	0.85	1.00	0.24	0.210	0.45	1.00
0.67	1.46	0.029	0.98	0.127	0.79	1.00	0.00	0.127	0.79	1.00	0.00	0.356	0.40	1.00
0.80	2.72	0.039	0.98	0.251	0.73	1.00	0.13	0.241	0.74	1.00	0.04	0.485	0.37	1.00
0.93	3.52	0.043	0.98	0.317	0.72	1.00	0.71	0.259	0.74	1.00	0.46	0.403	0.40	1.00

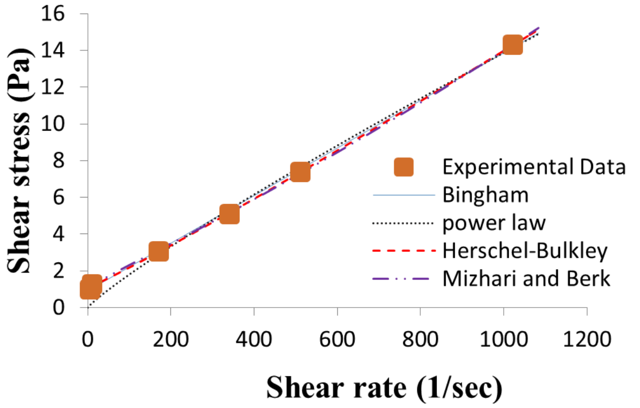

Figure 14: Rheogram of Gambe clay mud treated with 0.93 wt% of CMC-b showing the experimental and models fitting

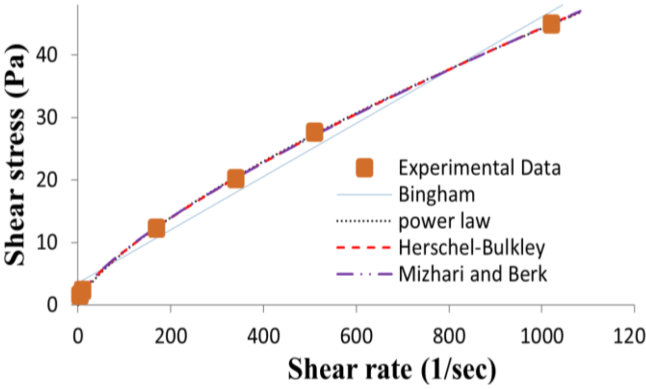

Figure 14: Rheogram of Gambe clay mud treated with 0.93 wt% of CMC-c showing the experimental and models fitting

4. DISCUSSION

4.1 Mineral and Elemental Composition of the Gambe Clay

From Figure 1, it is shown that Gambe clay has characteristics peaks of Ca-montmorillonite at Bragg angle of 5.8 ° and 17.6°. The chemical composition of the clay as shown in Table 2 indicated that the ratio of alumina to silica of raw and beneficiated Gambe clay were 0.37 and 0.45 respectively which are slightly higher than the standard API requirement of 0.33 [10]. The analysis further showed that on beneficiation of the clay, the Na_2O increased from 0.21 % to 1.56 % and according to [10], this could be as a result of the addition of Na_2CO_3.

4.2 Average Molecular Weight of the Polymers

From Table 3, it could be seen that as the intrinsic viscosity of carboxy methyl cellulose increases, the average molecule weight increases. Similarly, as the average molecular weight of the carboxy methyl cellulose increases, the dynamic viscosity also increases. The solutions of low-molecular-weight CMC have low absolute viscosity and generally are less pseudo plastic than are solutions of higher molecular weight products and this is well in agreement with [12].

4.3 Flow Properties of the Formulated Mud

The viscometer dial reading at 600 rpm of the beneficiated Gambe bentonite clay was 4.5 cP which was lower than commercial standard of 30 cP as indicated in Figure 2. This is in agreement with [13] who found that although sodium treatment improves the rheological properties of the bentonite from north-eastern Nigeria, it was still far below the required specification for drilling fluid application.

Figure 3 showed the beneficiated drilling fluid treated with 0.93 wt% CMC-a raised the 600 rpm from 4.5 cP to 13.5 cP which is about 200 % higher. As shown in the figure, the CMC-a treated mud did not still meet commercial standard because of its low average molecular weight (90,000 g/mol).

Figure 4 showed the beneficiated drilling fluid treated with 0.93 wt% CMC-b raised the 600 rpm from 4.5 cP to 28 cP which is about 520 % higher, this was also higher than its equivalent value using CMC-a. As shown in the figure that CMC-b treated clay also did not meet commercial standard because of its low average molecular weight.

Figure 5 showed the beneficiated drilling fluid treated with 0.93 wt% CMC-c raised the 600 rpm from 4.5 cP to 28 cP which is about 1850 % higher, this was also higher than its equivalent value using both CMC-a and CMC-b.

The formulated mud with CMC-c was found to have viscometer dial reading at 600 rpm lower than that of the mud formulated using poly-anionic cellulose (PAC) by 14.8 % prepared in the work of [14]. From that figure, by interpolation it can be reasonably interpreted that 0.53 wt% CMC-c treated would yield properties close to the commercial standard.

4.4. Rheological Properties of the Treated Gambe Clay Mud

Figure 6 showed the variation of apparent viscosity of the mud with the polymers. It was found that the carboxy methyl cellulose enhanced the apparent viscosity from 2.25 cP to 44 cP which was higher than commercial standard of 15 cP. It was also found that increase in the average molecular weight of the sodium carboxy methyl cellulose resulted to increase in the apparent viscosity of the mud. Figure 7 shows variation of plastic viscosity of the mud with the polymers. It was found that the carboxy methyl cellulose enhanced the plastic viscosity from 1.5 cP to 34 cP which was higher than commercial standard of 8 cP. The formulated mud with CMC-c was found to have higher plastic viscosity than the formulated mud with PAC as reported by [14]. It was found that an increase in the average molecular weight of the sodium carboxy methyl cellulose resulted to increase in the plastic viscosity of the mud.

Figure 8 shows variation of yield point of the mud with the polymers. It was found that the carboxy methyl cellulose enhanced the yield point from 1.5 lb/100ft^2 to 20 lb/100ft^2 which was higher than commercial standard of 14 lb/100ft^2. The formulated mud with CMC-c was found to have lower yield point than the formulated mud with PAC as reported by [14]. This could be due to PAC having a higher degree of substitution than CMC [2]. It was found that the increase in the average molecular weight of the sodium carboxy methyl cellulose did not result to increase in the yield of the mud.

The ratio of the yield point to the plastic viscosity (known as the YP/PV ratio) is a measure of thinning, the higher the ratio the greater the shear thinning [15]. Figure 9 showed that the YP/PV ratio decreased from 1 cP.lb/100ft^2 to 0.59 cP.lb/100ft^2 which was lower than commercial standard of 3 cP.lb/100ft^2. It was found that the increase in the average molecular weight of the sodium carboxy methyl cellulose did not result to increase in the YP/PV ratio of the mud.

4.5 Gel Strength of the Treated Gambe Clay Mud

As shown in Figures 10 and 11, It was found that the carboxy methyl cellulose enhanced the gel strength at 10 seconds and 10 minutes from 0 lb/100ft^2 to 3 lb/100ft^2 and 0 lb/100ft^2 to 4 lb/100ft^2 respectively. It was found that the increase in the average molecular weight of the sodium carboxy methyl cellulose did not result to increase in the gel strength of the mud. CMC-a and CMC-b had almost the same gel strength while a slight increase gel strength was observed for CMC-c. CMC treated mud did not meet commercial standard. The formulated mud with CMC-c was found to have lower gel strength at both 10 seconds and 10 minutes than the formulated mud with guar gum as reported by [14].

4.6 Fitting of Rheological Models for Gambe Clay Drilling Mud

In relation to the work reported in [15], it was found that the flow index of power law, n, can be used to characterize the shear thinning properties of the mud. The lower the value of *n*, the higher the shear thinning.

In Table 4 it was found that the formulated fluids treated with CMC-a did not satisfy the shear thinning conditions stated in [7] because flow index behaviour, *n* was greater than 1.0 and 0.5 for Herschel-Bulkley model and Mizhari -Berk model respectively which implies that rheology of these fluids is Newtonian. It was also found that plastic viscosity increased initially from 0.002 Pa.s to 0.006 Pa.s which was lower than commercial standard of 0.015 Pa.s and yield value increased initially from 0.05 Pa to 0.85 Pa which was lower than commercial standard of 1.92 Pa. The flow behaviour index, n, was found to have decreased initially from 0.84 to 0.64 in the power law model which did not meet commercial standard of 0.59. The best model that fitted that the rheological data of these formulated mud was Mizhari-Berk model because they had the highest value of R^2.

It was also found that these formulated muds treated with CMC-b did not satisfy the shear thinning conditions stated in [7]. It was also found that plastic viscosity increased initially from 0.002 Pa.s to 0.013 Pa.s which was lower than commercial standard of 0.015 Pa.s and yield value increased initially from 0.05 Pa to 0.91 Pa which was lower than commercial standard of 1.92 Pa. The flow behaviour index, n, was found to have decreased initially from 1.15 to 0.89 in the power law model which did not met commercial standard of 0.59. The best model that fitted that the rheological data of these formulated mud was Mizhari-Berk model.

It was found that these formulated muds treated with CMC-c satisfied the shear thinning conditions stated in [7]. It was also found that the plastic viscosity increased initially from 0.002 Pa.s to 0.043 Pa.s which was higher than commercial standard of 0.015 Pa.s and yield value increased initially from 0.05 Pa to 3.52 Pa which was higher than commercial standard of 1.92 Pa. The flow behaviour index, n, was found to have decreased initially from 0.84 to 0.72 in the power law model which did not met commercial standard of 0.593. The best model that fitted that the formulated mud (at concentration of 0.53

wt% and 0.93 wt% CMC-c) was Herschel-Bulkley model while the best model that fitted that formulated mud (at concentration of 0.67 wt% and 80 wt%) CMC-c was Power law model with agrees with [17] who reported that Power law model provides the best fit for water-based mud. They also met commercial standard.

5. CONCLUSIONS

The conclusions compiled from this research study are as follows: Viscometer dial reading at 600 rpm of the beneficiated Gambe bentonite clay was 4.5 cP which was lower than commercial standard of 30 cP. One of the three polymers (i.e. CMC-c) used enhanced the properties of the mud having higher rheological properties than the standard mud (Wyoming clay). The carboxy methyl cellulose enhanced the plastic viscosity from 1.5 cP to 34 cP and the apparent viscosity form 2.25 cP to 44 cP. Increase in average molecular weight of sodium carboxy methyl cellulose resulted to increase in the apparent and plastic viscosities. Herschel-Bulkley model ($R^2 = 0.99$) gave a good fit for CMC-c treated mud while Mizhari-Berk model ($R^2 = 0.99$) gave a good fit for CMC-a and CMC-b treated mud.

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