Petroleum and Coal

Article Open Access

Rheological Evaluation of Composite Natural Polymers as Rheology Control Additive in Water-Based Drilling Fluid

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Received September 20, 2019; Accepted January 24, 2020

Abstract

The high cost of synthetic additives stemming from importation necessitates the use of materials which are cheaper and biodegradable for water-based drilling fluid (DF) employed in oil and gas exploration. Obtaining drilling fluid with comparable rheology to that of the American Petroleum Standard depends on the in-depth understanding of the formulation of DF using locally sourced materials. Therefore, this study investigated effects of cassava starch (CS), breadfruit starch (BFS), bush mango seed (BMS) and corn fibre (CF) as an additive on rheological properties of water based drilling fluid formulated using treated Nigerian clay. The additives were characterized using SEM and EDX for morphology and elemental composition respectively. Experiments were conducted to study the effects of each additive on the plastic viscosity, apparent viscosity, yield stress, consistency and flow index of the developed drilling fluid. The effect of each additive on the rheology was investigated using OFAT, by varying the concentration between 1 g and 8 g and fixing others at 4.5 g. Further experiments were conducted using to study the interactive effect and the optimum concentration of the polymers. SEM results reveal oval, ellipsoidal and cylindrical polymer granules. Element present in the CS and BFS includes C, O, Al, Si and Na. K is also detected in CS and BMS. Flow and consistency index plots reveal the drilling fluid rheological properties could be optimized at concentrations between 4 g and 7 g. Optimum viscosity of 28 cp at 600 rpm was achieved using 7 g of CS, BFS and BMS 2 g corn fibre. Sensitivity analysis revealed that all additives contributed significantly to the rheological properties and the developed drilling fluid is suitable for the efficient drilling process.

Keywords*: Nigerian clay; Natural polymer; Water-based drilling fluid; Rheology; Additives.*

1. Introduction

Clay suspensions, especially bentonite, have been used extensively in the water-based drilling fluid. Several clay deposits have been identified in Nigeria; however, studies have shown that most of these clay minerals are low grade montmorillonite which requires pre-treatment before they can be used effectively for drilling fluid development [1-2]. The pretreatment is aimed at improving the suitability of clay for drilling fluid via cation exchange.

Drilling fluids are extremely important in the drilling process because of the various functions they perform. These functions include carrying cuttings from the hole to the surface, cleaning and cooling the drill bit, reducing friction between the drill pipe and wellbore, the formation of low permeable filter cake, prevention of fluid inflow from the wellbore [3-4]. Various synthetic polymers such as carboxyl methylcellulose (CMC), Cabopol 980, Polyanioinic cellulose (PAC), Hydroxyl ethyl cellulose (HEC), polyacrylate and polyacrylamide and tetrapolymers have been used to improve the rheological properties of drilling fluids due to the inability of clay-water suspension to perform tasks required of a functional drilling fluid during oil and gas exploration [5-9]. Synthesis and importation of these synthetic polymers are time consuming and very expensive [10].

Attempt to develop drilling fluids that are less expensive, and non-damaging to both the formation and environment prompted the use of natural polymers for drilling fluid development. Natural polymers are ready for use after slight processing and are basically classified into two categories; biopolymers and starches [2]. The use of natural biopolymer such as xanthan gum and scleroglucan gum as viscosifier in water based drilling fluid has been investigated [8, 11-12]. Starch is a carbohydrate mixture consisting of two polymers, amylase and amylopectin [13]. It is the most abundant renewable energy source in plants and is found in leaves, stem, seeds, fruits and roots [14-17]. Several previous research efforts have confirmed that starch can function both as fluid loss reducer and rheology control agent in water-based drilling fluids [2, 18-19]. Starches made from corn [12, 20-22], cassava and its derivatives [19, 21, 23-25], potatoes [23, 26] have been used to improve the rheological properties of water-based drilling fluid.

The quest for local content in all aspect of technology especially in the oil and gas sector by the Nigerian government has necessitated further need to carry out more research on the development of water-based drilling fluid using locally sourced clay and additives. The act was signed into law in 2010 with the purpose of encouraging the use of local content to address technical challenges facing all industrial sectors in the country [27]. This study presents a novel drilling fluid using pre-treated Nigeria clay and a combination of cassava starch (CS), breadfruit starch (BFS), bush mango seed (BFS) and corn fibre as rheology control additives. The effect of each additive on plastic viscosity, apparent viscosity, yield point, flow index and consistency index were studied.

2. Materials and method

2.1. Materials procurement and processing

Breadfruits, cassava roots and bush mango seeds were obtained from local markets in Ifetedo, Osun state. Both the breadfruits and cassava roots were thoroughly washed in clean water, peeled, ground and wet sieved. The slurry was allowed to sediment for 12 hours, and the supernatant was decanted. The resultant starch was pre-gelatinized following the method of Ohwoavworhua and Osiniwo [28]. Pre-gelatinized starch was grinded using an electric grinder (Marlex Appliances PVT Limited). Particle size was further reduced using ball milling machine for 20 hours. Clay sample was obtained at a clay deposit in Ubakala (7º36´N/5º86´E), Abia State, Nigeria and treated with 3.3 M $NaHCO_3$.

2.2. Clay treatment and characterisation

Raw clay was pre- treated with 3.3 mol/dm^3 $NaHCO_3$ for possible ion exchange. Morphology and elemental compositions of pre-treated and additives were determined using a Scanning Electron Microscope (Zeiss Zigma Apparatus) coupled with Oxford EDX. All samples were sprinkled on the stub of double sided adhesive tape and sputter-coated with Gold/palladium, except clay which was carbon coated for charge dissipation during SEM imaging.

2.3. Drilling fluid formulation and characterization

The experiment was initially designed using OFAT (one factor at a time) to study the individual effect of the additives on the rheological properties of the developed drilling fluid. The quantities of all additives were fixed except one; experiment conditions are shown in Tables 5-8. Another experiment was designed (Table 10), to study the interactive effect and optimization of the novel drilling fluid. Laboratory barrel of fluid was prepared by dispersing the clay and additives in 350 ml of water [29]. The developed fluids were aged for 24 hours for proper hydration and the viscosity was determined using a rheometer (Antar Paar Rheolab QC). Viscosities were determined at a constant shear rate of 5.11 s^{-1} (3 rpm), 511s^{-1} (300 rpm) and 1022 s^{-1} (600 rpm). Flow properties such as plastic viscosity (PV), apparent viscosity, yield point, flow and consistency index were evaluated from the viscometer dial readings using Equations 1-5. For each experimental run, the quantities of clay, barite and distilled water were fixed at 24.5 g, 6 g and 350 mL, respectively.

$$AV = 600\, rpm\ dial\ reading/2 \quad in\ cP \tag{1}$$
$$PV = 600\, rpm\ dial\ reading - 300\, rpm\ dial\ reading \ \ in\ cP \tag{2}$$
$$YP = 300\, rpm\ dial\ reading - PV \quad in\ lb/100ft^2 \tag{3}$$
$$Flow\ index\ (n) = 3.32 \log R1/R2 \tag{4}$$
$$Consistency\ index\ (k) = 5.11\ {R^2}/{R^1} \ \ in\ dynes - \frac{secs}{cm^2} \tag{5}$$

3. Results and discussion

3.1. Morphology and elemental composition of clay

Morphology and elemental composition of the pre-treated clay sample are shown in Figure 1 and Table 1, respectively. The SEM micrograph shows irregular platelets with a sub-rounded porous surface that looks less compact (spaces indicated by the circle in Figure 1). This structure may be attributed to the presence of quartz and kaolinite and possible expansion of the interlayer space as a result of the pretreatment. A most abundant element found in the clay sample is oxygen (54%). Other elements include Si, Al, Na, Fe, K, and Ti (9.05, 7.13, 1.53, 1.47, 0.35, 0. 22) % respectively (Table 1). The elemental analysis indicates the presence of Na-montmorillonite, quartz and little amounts of hematite and rutile as impurities. Nwosu *et al.* [30] reported the mineral composition of Ubakala raw clay to consist of montmorillonite, kaolinite, quartz, biotite, calcite and feldspar.

Table 1. Elemental composition of the treated Ubakala clay sample

Element	C	O	Na	Al	Si	K	Ti	Fe	Total
Weight %	17.73	49.01	1.99	10.89	14.37	0.77	0.60	4.65	100
Atomic %	26.09	54.16	1.53	7.13	9.05	0.35	0.22	1.47	100

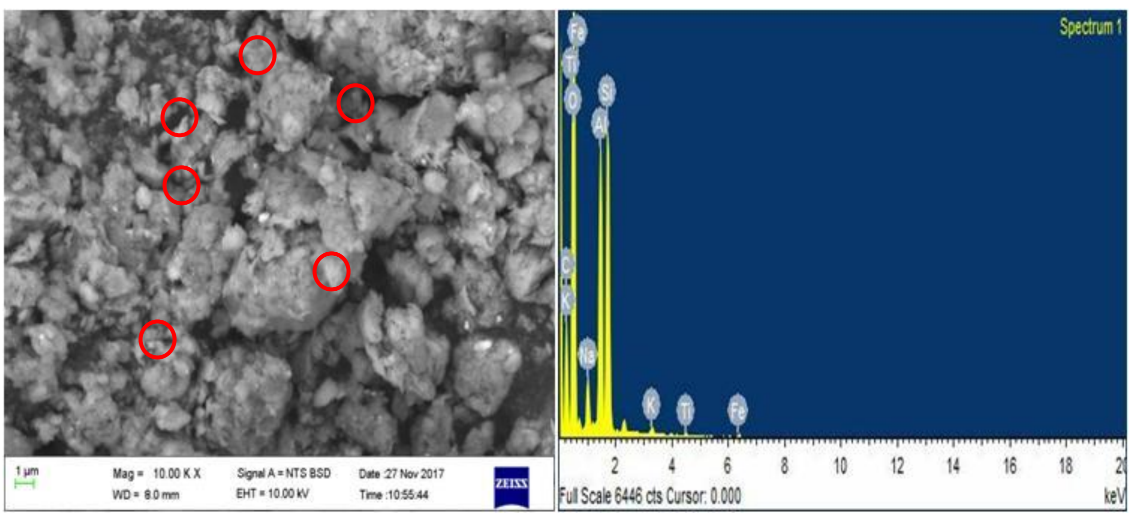

Figure 1. Scanning electron microscope image and EDX plot of the treated clay sample

3.2. Morphology and elemental composition of additives

Figures 2- 5 and Tables 2 - 5 show the surface morphology and elemental compositions of barite, cassava starch, breadfruits starch and bush mango seed, respectively. Expectedly, the locally sourced barite contains a substantial amount of barium, sulphur and oxygen as shown in the EDX spectrum and Table 2. Barite ($BaSO_4$) is the most common mineral of barium which is used as a weighing agent in drilling fluid due to its relatively high density and chemical inertness [31-32]. Barite increases the hydrostatic pressure of the drilling mud allowing it to compensate for high-pressure zones experienced during drilling. The softness of the mineral also prevents it from damaging drilling tools during drilling and enables it to serve as a lubricant [33]. The presence of Fe, Al and Si and O (Table 2) indicates the presence of accessory minerals such as quarts, muscovite and iron minerals in the barite sample. SEM image shows fragments of barite particles with a square, angular and sub-angular shape that support its utilization as a weighting agent in drilling fluid formulation [34-35].

Table 2. Elemental composition of barite sample

Elements	C	O	Al	Si	S	Fe	Ba	Total
Weight %	5.53	28.78	1.31	4.10	8.30	9.31	42.67	100
Atomic %	14.42	56.39	1.52	4.58	8.12	5.23	9.74	100

Table 3. Elemental composition of cassava starch

Elements	C	O	Na	Al	Si	K	Pd	Au	Total
Weight %	24.39	53.42	1.93	3.02	4.86	2.29	5.87	4.23	100
Atomic %	34.57	56.85	1.43	1.91	2.94	1.00	0.94	0.37	100

Table 4. Elemental composition of breadfruit starch

Elements	C	O	Na	Si	Pd	Au	Total
Weight %	65.05	27.24	0.41	0.30	3.30	3.49	100
Atomic %	75.13	23.80	0.25	0.15	0.43	0.25	100

Table 5. Elemental composition of bush mango seed

Elements	C	O	Al	Si	K	Pd	Au	Total
Weight %	72.65	15.57	1.07	1.65	1.34	3.94	4.19	100
Atomic %	84.03	13.52	0.55	0.62	0.48	0.51	0.30	100

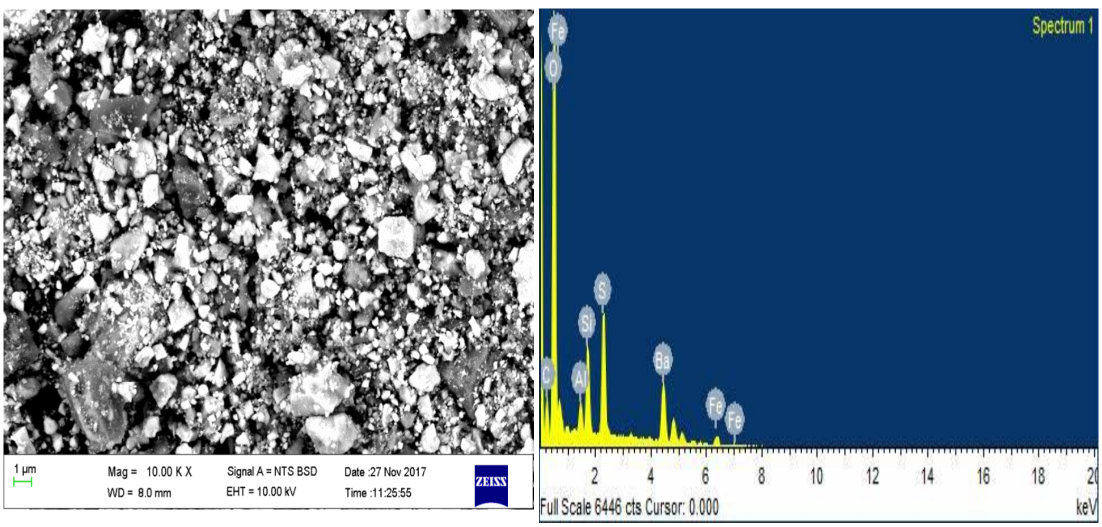

Figure 2. SEM and EDX image of barite

The SEM image in Figures 3 (cassava starch) shows scattered irregular, oval and ellipsoidal morphology of the particles while that of Breadfruit starch granules (Figure 4) is more cylindrical and oval. Several fixtures and cracks were observed in the breadfruit starch. Fissures and cracks in the BFS image can be attributed to the drastic extraction and processing of the starch [36]. Bush mango seed granules (Figure 5) were bigger than that of CS and BFS, and it exhibited a truncated oval morphology. Yamani *et al.* [37] reported similar morphology for local starches obtained from tubers of Oca (*Oxalis tuberosa* Molina), olluco (*Ullucus tuberosus* Caldas) and mashua (*Tropaeolum tuberosum*). The results obtained by the authors for Oca was similar to that of breadfruit starch while olluco starch is similar to cassava starch morphology. Mashua morphology was oval and truncated but smaller than that of Oca and Olluco.

Surface morphology and surface charge of polymer play an important role in the clay-polymer interaction mechanism. It is generally believed that clay particles should disperse as single platelets throughout the polymer matrix [38]. The adsorption of the positively charged polymer by clay largely occurs through electrostatic interaction between the cationic group of the poly-mer and the negatively charged site at the clay mineral surface [39]. This interaction is possible if both the polymer and clay layer have polar groups that have favourable interactions [40].

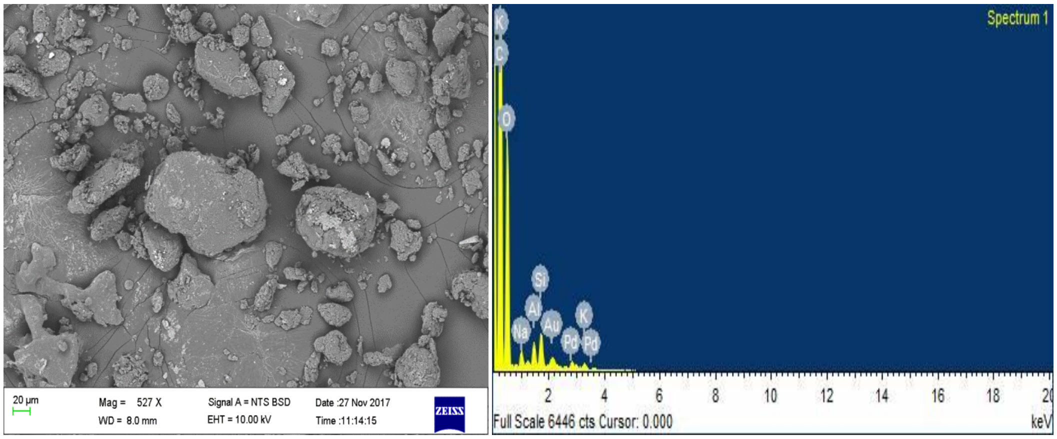

Figure 3. SEM and EDX image of Cassava starch

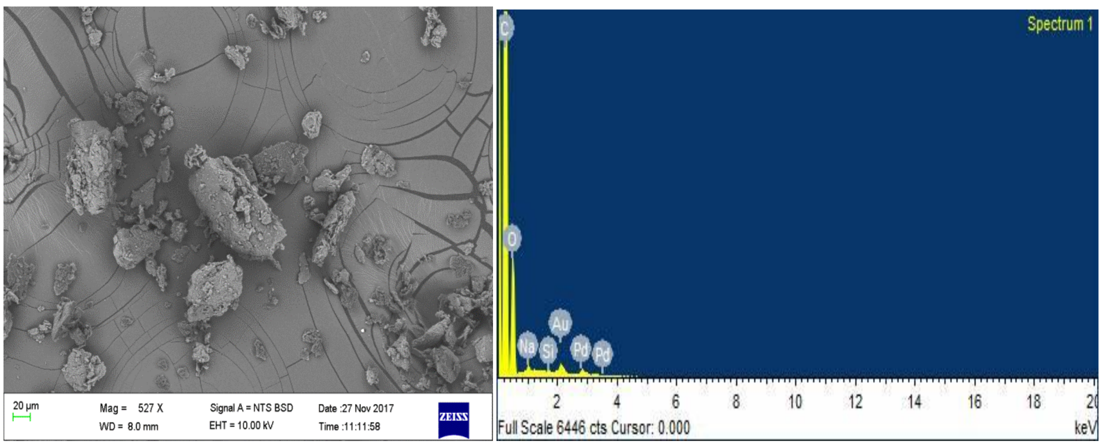

Figure 4. SEM and EDX image of breadfruit starch

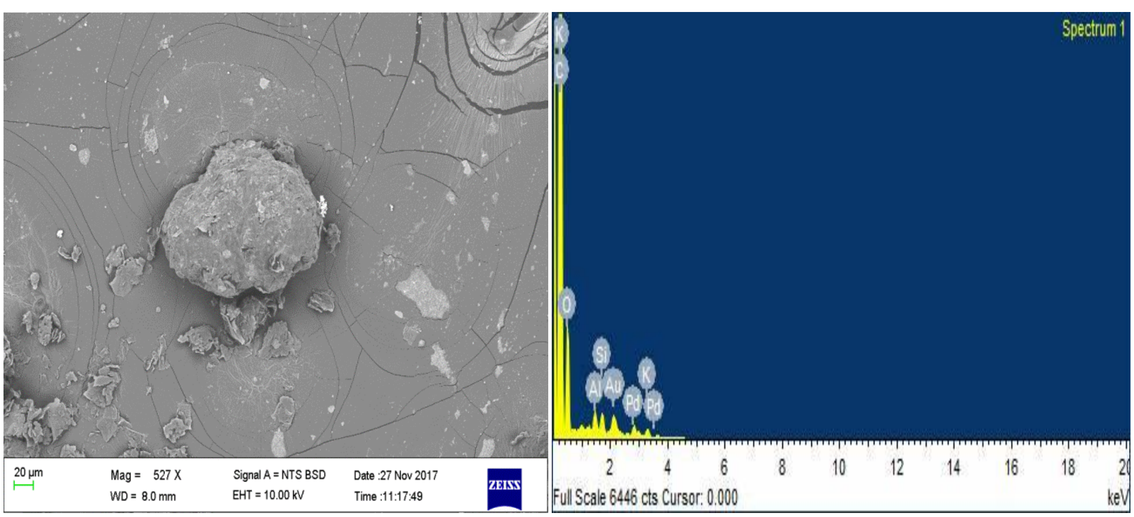

Figure 5. SEM and EDX images of bush mango seed

Modified layered silicates are composed of silicate layers that can intercalate organic polymer chains if appropriate ionic or hydrogen bonding groups are present on the polymer. Thus, the compatibility of the mineral with the organic phase, in terms of wetting and dispersion, may be substantially increased by the prior adsorption of a monolayer of a suitable substance [41]. Prior treatment of the clay sample with $NaHCO_3$ is expected to create a more negative charge on the clay platelets through cation exchange, which will subsequently enhance the compatibility, intercalation and adsorption of the polymer matrix on the clay.

Cassava and Breadfruit starch contain cations such as Al, Si and Na as shown in different proportions Tables 3 and 4 while bush mango seed (Table 5) contains Al, Si and K. The presence of Na^+ confirms that the pre-gelatinized starch will be highly soluble in water (hydrophilic) and hence expected to adsorb more on the clay. Sheu and Perricone [42] reported that almost all water soluble polymers contain polar or ionic groups which can interact with water molecules. The degree of hydration will affect the tendency of the polymer molecules to become disaggregated. It is therefore conceivable that the use of these 3 polymers (CS, BFS and BMS) is capable of resulting in an enhanced water-based drilling fluid whose rheology will be stable under strict borehole conditions.

3.3. Drilling fluid rheology

Table 6 through Table 9 show the rheological properties of the developed drilling fluid. The tests were performed by varying the concentration of one additive between 1 and 8 g while the quantities of others are fixed at 4.5 g except for corn fibre which is fixed at 1.13 and varied between 0.15 and 2.25 g.

Table 6. Drilling fluid developed at varying concentration of Cassava starch (CS)

	Sample	1	2	3	4	5	6	7	8
Additives	BMS (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	BF (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	CF (g)	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
	CS (g)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Properties	μ (300)	9.45	10.12	10.62	12.00	12.60	12.60	12.80	13.70
	μ (600)	13.17	14.30	14.82	15.42	17.47	19.40	20.23	22.30
	PV (cP)	3.72	4.18	4.20	3.42	4.87	6.80	7.43	8.60
	AV (cP)	6.59	7.15	7.41	7.71	8.74	9.70	10.12	11.15
	YP (lb/100ft²)	5.73	5.94	6.42	8.58	7.73	5.80	5.37	5.10
	N	0.48	0.50	0.48	0.36	0.47	0.62	0.66	0.70
	K	0.48	0.45	0.53	1.26	0.67	0.26	0.21	0.17

Table 7. Drilling fluid developed at varying concentration of bush mango seed (BMS)

	Sample	1	2	3	4	5	6	7	8
Additives	BMS (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	BF (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	CF (g)	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
	CS (g)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Properties	μ (300)	10.28	10.53	12.73	12.82	13.24	13.32	13.68	14.26
	μ (600)	13.01	13.37	16.42	17.36	18.63	19.95	21.01	22.22
	PV (cP)	2.73	2.84	3.69	4.54	5.39	6.63	7.33	7.96
	AV (cP)	6.51	6.69	8.21	8.68	9.32	9.98	10.51	11.11
	YP (lb/100ft²)	7.55	7.69	9.04	8.28	7.85	6.69	6.35	6.30
	N	0.34	0.34	0.37	0.44	0.49	0.58	0.62	0.64
	K	1.24	1.23	1.29	0.84	0.61	0.35	0.29	0.26

Viscosities at 600 rpm is plotted against the varying quantities of additive as shown in Figure 4. The results obtained show the drilling fluids exhibited shear thickening properties (viscosity increases with increasing shear rate) at room temperature. Olatunde *et al.* [1] reported a similar trend in their findings using Nigerian clays. As shown in Figure 6, a significant increase in viscosity was not observed until the quantities of additives were increased above 4 g up to 7 g. This implied that quantities of additives below 4 g for the 3 additives (cassava starch, bush mango seed and breadfruit starch) would rather yield lesser value of viscosities than the ones obtained in the experiments. However, the obtained values are still slightly below the API recommendations (Table 5). Therefore, values between 4 and 7g could be used for possible optimization to meet the API recommended standard.

Table 8. Drilling fluid developed at varying concentration of breadfruit starch (BFS)

	Sample	1	2	3	4	5	6	7	8
Additives	BMS (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	BF (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	CF (g)	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
	CS (g)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Properties	μ (300)	10.40	10.50	11.23	11.32	11.68	12.01	12.85	16.94
	μ (600)	14.36	15.29	16.86	17.66	18.74	19.67	21.50	22.87
	PV (cP)	3.96	4.79	5.63	6.34	7.06	7.66	8.65	5.93
	AV (cP)	7.18	7.65	8.43	8.83	9.37	9.84	10.75	11.44
	YP (lb/100ft²)	6.44	5.71	5.60	4.98	4.62	4.35	4.20	11.01
	N	0.47	0.54	0.59	0.64	0.68	0.71	0.74	0.43
	K	0.57	0.36	0.29	0.21	0.17	0.14	0.13	1.14

Table 9. Drilling fluid developed at varying concentration of corn fibre (CF)

	Sample	1	2	3	4	5	6	7	8
Additives	BMS (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	BF (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	CF (g)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
	CS (g)	0.15	0.45	0.75	1.05	1.35	1.65	1.95	2.25
Properties	μ (300)	10.40	10.50	10.73	11.18	11.53	11.59	11.85	12.22
	μ (600)	14.82	14.93	15.26	16.06	16.74	16.86	17.15	17.46
	PV (cP)	4.42	4.43	4.53	4.88	5.21	5.27	5.30	5.24
	AV (cP)	7.41	7.47	7.63	8.03	8.37	8.43	8.58	8.73
	YP (lb/100ft²)	5.98	6.07	6.20	6.30	6.32	6.32	6.55	6.98
	N	0.51	0.51	0.51	0.52	0.54	0.54	0.53	0.51
	K	0.43	0.44	0.45	0.43	0.40	0.40	0.43	0.49

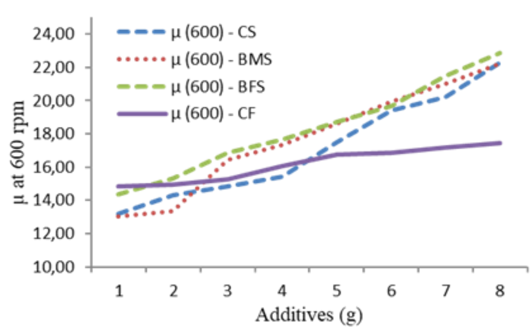

Figure 6. Effect of additives on viscosity of drilling fluid at 600 rpm
CS= Cassava starch, BMS = Bush mango seed, BFS = Breadfruit starch and CF = corn fibre

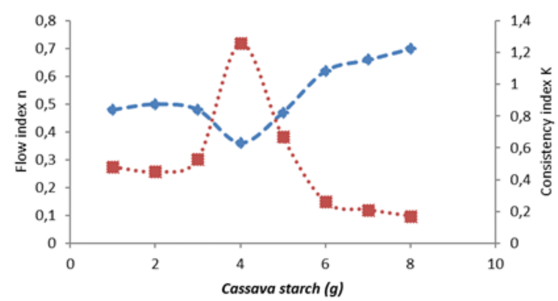

Figure 7. Flow index and consistency of drilling fluid at varying quantities of cassava starch

Flow index and consistency index of the developed drilling fluid are illustrated in Figures 7-10. Flow index and consistency are rheological parameters used to describe the behaviour of drilling fluids. Consistency index (K) describes the thickness of drilling fluid at a low shear rate, while flow index indicates the degree of non-Newtonian behaviour over a range of shear stress [43]. Increase in cassava starch up to 3 g did not have any effect on the flow index as shown in Fig. 7. A decrease in flow index (n) was observed when the quantity of CS was increased to 4g. Further increase in CS increases the value of flow index. However, after 7 g, the increase was very slight. Similarly, an increase in CS up to 3 g did not have much effect on the consistency (k) of the fluid. Contrary to the flow index, increase in CS to 4 g sharply increases the consistency of the developed drilling fluid while the further increase of CS decreases the consistency. This indicated that quantities of CS between 4 and 7 g contributed sensitively to the flow ability and consistency of the formulated fluid. Khamechi *et al.* [43] stated that hole cleaning and suspension efficiency of drilling fluid could be improved by increasing k value. The lower the flow index (n), the more shear thinning the fluid will be.

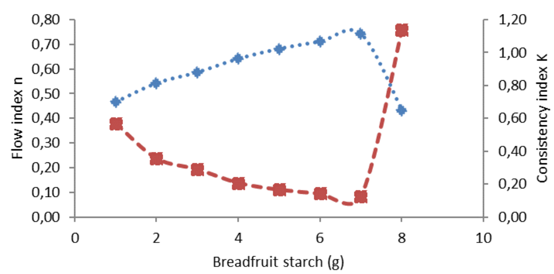

Figure 8. Flow index and consistency of drilling fluid at varying quantities of breadfruit starch

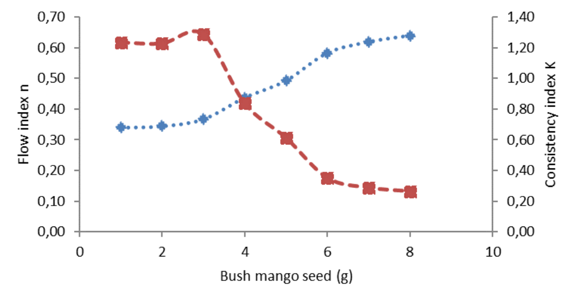

Figure 9. Flow index and consistency of drilling fluid at varying quantities of Bush mango seed

As observed in Fig. 8, the flow index increases with the increasing quantity of breadfruit starch (BFS) up 7 g and decreases afterward. A reverse trend was observed for the consistency in the same condition. A similar trend was reported by Meng *et al.* [44], where the flow index was used to describe the shear dilution of carbon ash in bentonite dispersion. The flow index decreased as the concentration of carbon ash increased. The authors stated that this is an indication that the shear dilution performance was improved and the capacity of bentonite dispersion for carrying the cuttings was enhanced.

Figure 9 shows that flow index increases while consistency decreases as the quantity of BMS increases. This implies that when other additives are fixed, an increase in BMS will shear thick the resulting fluid. The decrease in consistency of the developed drilling fluid reflected an increase in viscosity as more BMS is added. The implication is that too much of BMS in the fluid may result in excessive viscosity and will subsequently affect the pumpability of the fluid.

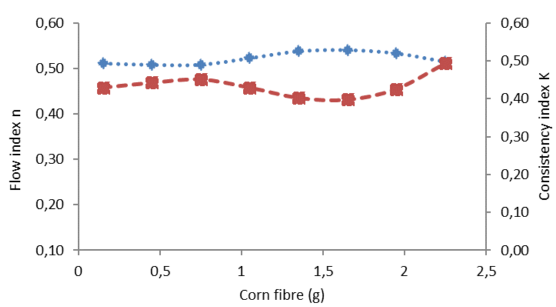

Figure 10. Flow index and consistency of drilling fluid at varying quantities corn fibre

Effect of corn fibre (Figure 10) was very slight on both the flow index and consistency of the developed drilling fluid. Flow index remains constant at 0.51 as CF is increasing from 0.15 to 0.75 g, further increase of CF to 1.35 g slightly increases the value of n to 0.54. A slight decrease in n value was observed when CF was increased to 2.25 g. Consistency index followed a similar but opposite trend.

3.4. Interactive effect of additives on rheology

Table 10 shows the rheological properties of drilling fluid (DF) developed at concentrations between 4 and 7 g for CS, BMS and BFS; and 0.25 and 2 g for CF. The formulation at experimental run 3 gave the highest dial reading, 28.46 cp with corresponding values of 10.23 cP, 14.23 cp and 8.00 lb/100ft^2 for plastic viscosity (PV), apparent viscosity (AV) and yield stress (YP) respectively. The viscosity of 28.46 cP at 600 rpm is close to the API recommendation which is 30 cp minimum while that of PV compared favourably with the API recommendation of 8-10 cP [45]. Low PV indicates the drilling fluid is capable of drilling rapidly due to low viscosity of the fluid existing at the bit [47]. However, YP of 8.00 lb/100ft^2 is still below the API recommendation (3*PV). YP is the resistance of the initial flow of fluid or the stress required in order to move the fluid. It is used to evaluate the ability to drill fluid to lift the cuttings at dynamic conditions (when drilling fluid is being circulated). DF with high YP are expected to carry cuttings better than DF of the same density but low YP [46]. Ryen [46] reported that high temperature tends to increase the viscosity and YP of water-based drilling fluid. This value of YP is expected to increase if the developed DF is subjected to higher temperatures typical of oil wells.

Table 10 Experimental design and rheological properties to determine optimal formulation

Run	Coded Factors				Responses				
	BMS (g)	BFS (g)	CS (g)	CF (g)	μ_{300} (cP)	μ_{600} (cP)	PV (cP)	AV (cP)	YP (lb/100ft^2)
1	1	1	-1	-1	13.85	22.86	9.01	11.43	4.84
2	-1	-1	-1	-1	10.22	15.61	5.39	7.81	4.83
3	1	1	1	1	18.23	28.46	10.23	14.23	8.00
4	-1	-1	1	1	14.01	22.01	8.00	11.01	6.01
5	-1	1	-1	1	13.34	21.62	8.28	10.81	5.06
6	-1	1	1	-1	13.84	22.56	8.72	11.28	5.12
7	1	-1	1	-1	13.23	19.42	6.19	9.71	7.04
8	1	-1	-1	1	14.50	21.98	7.48	10.99	7.02

Table 11. Statistical summary from analysis of variance

Parameters	$\mu_{600\,rpm}$ (cP)		PV (cP)		AV (cP)		YP (lb/100ft^2)	
	F-value	P>F	F-value	P>F	F-value	P>F	F-value	P>F
Model	13.84	0.0282	6.65	0.0758	13.77	0.0284	6.97	0.0713
A = BMS	9.65	0.0530	1.39	0.3232[a]	9.58	0.0535	12.71	0.0377
B = BFS	21.98	0.0183	18.47	0.0232	21.85	0.0185	1.30	0.3370[a]
C = CS	8.72	0.0599	1.95	0.2574[a]	8.69	0.0601	7.18	0.0750
D = CF	15.01	0.0304	4.80	0.1162[a]	14.96	0.0306	6.67	0.0815
R^2	0.9486		0.8987		0.9483		0.9028	
Adjusted R^2	0.8801		0.7635		0.8795		0.7733	

[a] = *insignificant model terms*

3.4.1. Statistical analysis

Relative impacts of the additives on rheological properties were statistically analyzed using the analysis of variance (ANOVA). Experimental results in Table 10 were historically analyzed using Design Expert (version 11). Summary of the statistics from ANOVA at 95% confidence level (α = 0.05) and correlation coefficients obtained for dial readings at 600 rpm ($\mu_{600\,rpm}$), PV, AV and YP models are shown in Table 11. The significance of the regression model and its terms were based on the principle of Fisher's statistical test (F-value) which is the ratio of the mean square of regression to the mean error. P-values lesser than 0.0500 indicates the significant model and p-values greater than 0.1000 indicates model term is not significant. Correlation coefficients (R^2) for the $\mu_{600\,rpm}$, PV, AV and YP (0.9486, 0.8987, 0.9483, 0.9028 respectively) were reasonable for the fitted linear models.

$$\mu_{600\,rpm} = 30.33 + 1.37A + 2.06B + 1.30C + 2.92D \quad (6)$$

$$PV = 10.84 + 0.32A + 1.15B + 0.37C + 1.00D \quad (7)$$

$$AV = 15.6 + 0.68A + 1.03B + 0.65C + 1.46D \quad (8)$$

$$YP = 8.65 + 0.74A + 0.23B + 0.55C + 0.91D \quad (9)$$

Regression models in term of coded factors are presented in Equation (6) through Equation (9). These equations are useful for identifying the relative impact of the factors (additives) by comparing the factor coefficients. The higher the F-value, the more significant the model. The models for $\mu_{600\,rpm}$ and AV were exceptionally significant ($p < 0.05$), 0.0282 and 0.0284 respectively at 95 % confidence level. The independent variables BFS and CF are the most significant model terms for $\mu_{600\,rpm}$ and AV, respectively.

3.4.2. Sensitivity analysis

Interactive effect of additives on viscosity at 600 rpm on 3-dimensional plots and tornado plots showing the sensitivity of the additives to rheological properties are illustrated in Figures 11 and 12.

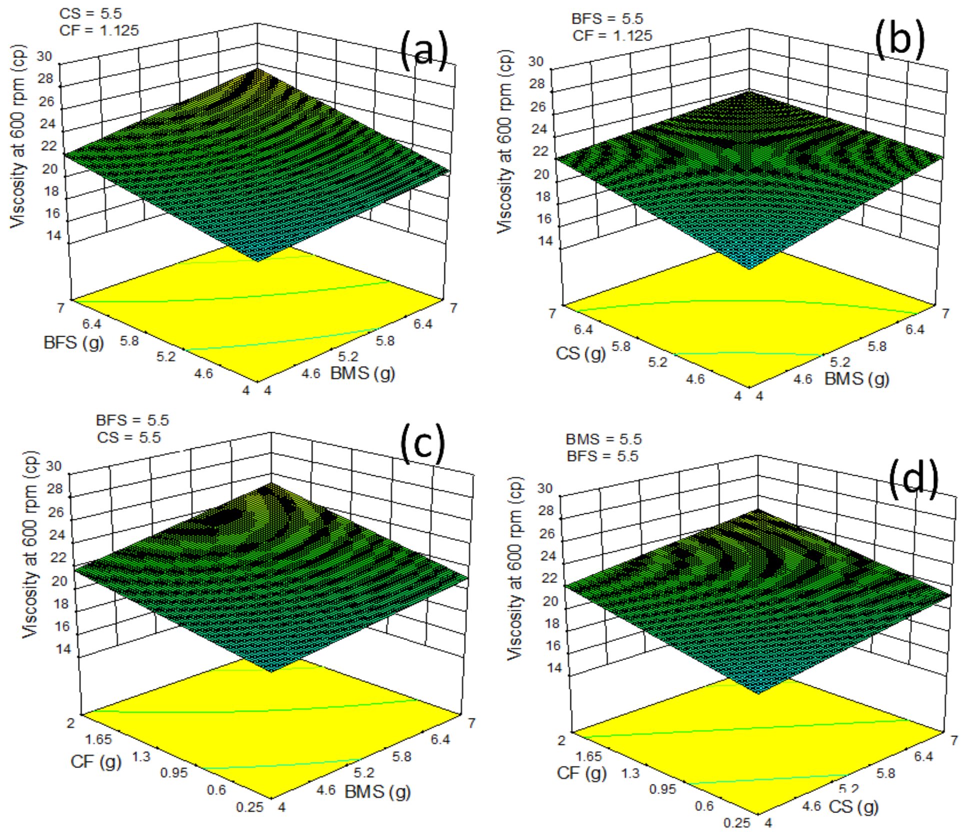

Fig 11. Response surfaces showing the interactive effect of the additives on viscosity: (a) Effect of BMS and BFS on viscosity (b) Effect of BMS and CF on viscosity (c) Effect of CF and BMS on viscosity (d) Effect of CF and CS on viscosity

As shown on the 3-D plots, viscosity increases as the quantities all additives increases. The tornado plots compared the relative importance of additives on the rheological properties of the developed drilling fluid based on the estimated coefficient for each additive from the ANOVA for two factor interaction (2F1). Individually, all the additives have a positive effect on the viscosity of DF at 600 rpm and PV with BFS having the most significant contribution. Similarly, the trend in contribution was observed for YP except for BFS. This suggests that increasing the concentration of BFS excessively will have a detrimental effect on the drilling fluid YP which may subsequently affect its ability to lift drilling cuttings. The combined effect of BMS and CF on the YP is observed to be very significant while relative significance on PV is small. This further suggests that the formulated fluid is applicable when drilling a large diameter hole where high YP is required to efficiently clean the hole. This also implies that the developed fluid will be able to drill more rapidly as excessive PV reduces the rate of penetration and causes stuck pipe during drilling [47]. Interactive effect of the addition of BMS and CS is observed to have a positive effect on YP but a negative effect on PV. This explains a possible shear thinning effect of the drilling fluid with high yield point and low plastic viscosity as a result of the addition of these two additives (BMS and CS). It has been reported that DF shear thinning properties contribute to effective cutting transportation [48-49].

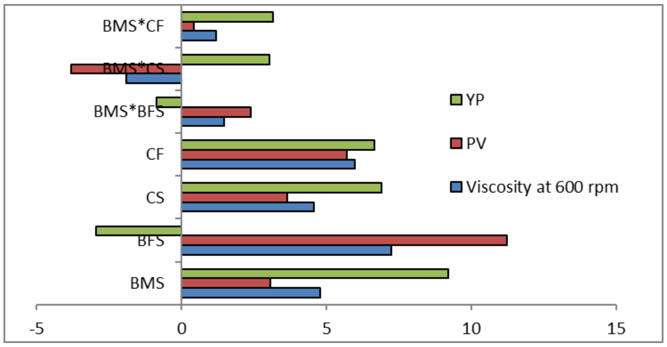

Fig 12. Tornado plots showing the relative contribution and importance of additives on rheological properties

BMS and BFS interaction has a positive effect on PV, but a negative effect on YP. This dynamic contribution of these additives can be attributed to the rate at which the polymers adsorb on the clay surface as they exhibited different properties. Generally, all the additives in the drilling fluid have remarkable control over the rheological properties. Analysis of the relative contribution of each additive on the rheological properties suggests that the additives have Potentials to complement each other if - the DF is subjected to various harsh conditions typical of the oil well.

4. Conclusions

Water-based drilling fluid was developed using treated Ubakala clay, non-synthetic biopolymers and additives. Experimental results indicate that the natural polymer used significantly improve the rheological properties of the developed drilling fluid. The developed drilling fluid exhibited dilatants (shear thickening) behaviour at room temperature. Viscosities increases with increasing quantities of additive and all formulations showed shear thickening behaviour (Pseudoplastic) at room temperature. The optimum results obtained at 7 g compared favourably with the API recommendation; hence the formulated fluid can be used in the drilling process.

Acknowledgement

The authors wish to acknowledge the financial support of The Petroleum Trust Development Fund, Nigeria through the 2017 Local Scholarship Scheme for PhD.

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