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Optimization of Water-Based Drilling Fluid Produced Using Modified Nigerian Bentonite and Natural Biopolymers: Reduced Experiment and Response Surface Methodology

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ABSTRACT

Research has shown that many Bentonite products in Nigeria are unsuitable for oil well drilling in their natural states. Their modification and blend with some additives could increase the yield and boost their suitability. Many indigenous polymers have become very popular due to environmental friendliness and their ability to modify the rheology of clay suspension. However, the common natural polymers are characterized by excessive fluid loss and low gel strength in typical reservoir conditions. The aim of this study is, therefore, to examine the influence of selected polymers on the physicochemical and rheological properties of Nigerian clay-water suspension. Mud samples were prepared with polymers according to mud formulations currently used in the wells drilling with properties varied and optimized in a Reduced Central Composite Design (RCCD). The physico-chemical (pH, mud weight), rheological (plastic viscosity, yield point), and fluid loss were measured out on the studied muds. The results show that the rheological characteristics of studied muds (PV (19.4 ± 1.50 cp) and Yp (21.5 ± 0.79 lbf/100ft^2), the Fluid loss (10.12 ± 0.45 ml/30 minutes/100 psi), and 10 min and sec Gel value (4.6 ± 0.05 and 5.1 ± 0.01 lb/100ft^2) were clearly improved. However, the recorded mud weight values (8.6 – 8.9 lb) satisfied the minimum 8.6 lb/gal ceiling value, resulting from the local barite that this study evaluated. The barite is characterized with low specific gravity, and we recommend its modification prior to use to avoid high sand content.

1. Introduction

Imported bentonite may not be, in its natural state, a high-yield clay mineral. Mostly, it is a blend of clay with some specific additives in order to increase the yield and control filtration properties. Various polymers have different rheological and stabilization effects on bentonite slurries. Because water-based mud (WBM) is the most common drilling fluid for both offshore and onshore areas,

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water-soluble polymers (WSPs) are preferred in drilling fluids. Synthetic polymers react with calcium and exhibit severe viscosity and gelation [1]. Synthetic polymers are expensive and generally salt- and pH-sensitive, compared to natural polymers.

Natural polymers rely on chain extension and physical entanglement of solvated chains for viscosity enhancement. They are non-charged and less sensitive to salts in contrast to the synthetic ones [2]. Examples of natural polymers include starch, carboxymethyl cellulose (CMC), and Hydroxyethyl cellulose (HEC). Some hemicelluloses, such as mannans (guar gum, locust bean gum, and konjac glucomannan), have been utilized for a long time due to their nontoxicity, solubility in water, and ability to form gels [3]. Examples of gums include exudate (arabic, karaya), microbial fermentation (pullulan, xanthan gum, dextran, and gellan gum), and seed gums (guar gum) [4].

Different natural polymers such as starch, soy protein isolate, guar gum, xanthan gum, and cellulose derivative have been applied to improve the rheological and filtration performances of WBMs [5-9]. Starch properties in drilling mud depend on the source, granule size distribution and morphology, amylose/amylopectin ratio, and other factors such as composition, pH, and nature of chemical modifications [10]. The stability and texture of starch-based products depend on the gelatinization and reorganization behaviors [11]. Locally sourced cassava starch at a 4 % concentration was enough to improve rheology of water-based mud significantly [12].

Scleroglucan, also known as schizophyllan, was reported to have exhibited high viscosity at a low concentration [13]. Compared with other biopolymers, Scleroglucan was reported to be more stable thermally, more tolerant of divalent and trivalent cations, such as Ca^{2+}, Mg^{2+}, and Fe^{3+}, and characterized by excellent carrying capacity. However, it is highly sensitive to chemically reactive additives and geological formations at high temperatures [13].

Many indigenous polymers have become very popular for their use in drilling fluid due to their ability to modify rheological properties of clay suspension and their environmental friendliness [14]. The common experienced challenges are excessive fluid loss, low-gel strength, and the need to formulate a fluid with desirable rheological properties to withstand increasing temperature and pressure conditions [15]. An example includes Welan gum (WLG). WLG is widely used as a thickener in the food industry. Its molecule consists of repeating tetrasaccharide units with single branches of Lmannose or L-rhamnose. According to Chen (2007) [16], WLG exhibits good viscosity at elevated temperatures and in the presence of sodium chloride. However, the use of WLG gum in drilling mud formulations was accompnied by excessive fluid loss in the drilling mud [17].

Considering the economic, sustainable, and environmental effects, the evaluation of natural polymers has gained considerable attention. Some efforts using wholly or partially substituted local materials have been reported in the design of muds for drilling [15, 18, 19]. In this study, two lesser known natural polymers and two natural fibers were examined experimentally on the basis of rheology, filtration control, and thermal stability.

2. Objectives

The major objective was to investigate the performance of some selected locally sourced

biopolymers on the basis of rheology, filtration control, and thermal stability of water-based drilling fluid. The specific objectives are as follows:

(i). Characterization of clay and additives using XRD, XRF, and FTIR.

(ii). Performance evaluation of clay and selected additives using a reduced central composite design at elevated temperatures.

(iii). Numerical optimization of rheological and filtration properties of the drilling fluid at elevated temperatures.

3. Material and method

The polymers, food gum, and Ofo (Cissus populnea and Detarium micocarpum, respectively) were locally sourced from markets in Lagos, South-west Nigeria. Analytical grade $NaHCO_3$, NaCl, and $CaCl_2$ were purchased from local suppliers. The fibers (Rosaline and Cocoanut) were sourced locally. The bentonite clay was obtained from Ohia in Abia state (007º 25” N/007º 47” E), Nigeria through Nigeria Geological Survey.

3.1. Clay characterization

The wet sieved raw bentonite clay was characterized by X-ray diffraction (XRD). Figure 1 shows the X-ray diffraction pattern which revealed that Ohia clay in its natural state is predominantly composed of kaolinite, illite, and quartz. The description of the beneficiation is available elsewhere [20]. The chemical composition of the beneficiated clay with sodium bicarbonate ($NaHCO_3$) was determined using X-ray fluorescence spectroscopy (XRF). The physicochemical properties of the raw and the modified samples are shown in Table 1. The major oxides are oxides of silica and alumina. The silica content (68.9 %) is comparable to that of Wyoming bentonite (68.0 %) [21]. However, Fe_2O_3 and TiO_2 (8.5 and 7.67 %) contents were higher than the reported Wyoming bentonite (3.94 and 0.16 %, respectively).

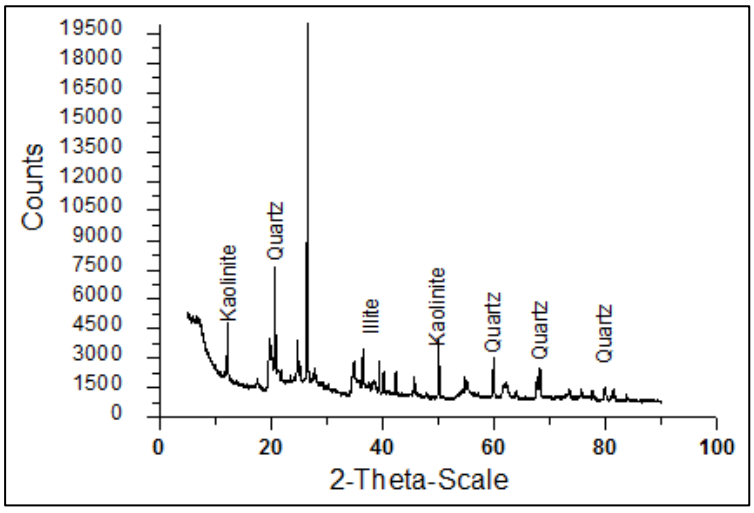

Figure 1. Diffraction of X-rays: microscopic structure of the raw clay.

3.2. Characterization of additives

3.2.1. *Cissus populnea*

C. populnea plant, also called food gum plant, can be found in the western part of Africa. The Cissus gum extracted from the plant was reported to be used as a soup thickener for treatment of venereal diseases, indigestion [22, 23], and drug binder [24]. As shown in

Table 2, food gum plant contains more than 60 % cellulose and about 15 % Hemicelluloses by weight. Table 3 shows the peak assignments of the absorption bands for Fourier Transform Infra-Red (FTIR) spectroscopy of raw C. populnea fiber. The FTIR shows all the functional groups. A broad, strong band from the cellulose, hemicellulose, and lignin dominates the peaks.

Table 1
XRF result for the analysis of chemical composition of the raw and modified samples of Nigeria Bentonite.

		Ohia clay	
Oxides	**Element**	**Raw**	**Treated**
SiO_2	Si	68.9	67.5
Al_2O_3	Al	11	10
Fe_2O_3	Fe	8.5	8.48
MnO	Mn	ND	ND
MgO	Mg	ND	ND
CaO	Ca	ND	ND
Na_2O	Na	0.08	3.12
K_2O	K	1.4	ND
TiO_2	Ti	7.67	7.87
P_2O_5	P	ND	ND
LOI	LOI	2.15	3

Table 2
Proximate composition of *C. populnea* fibers.

Composition	Percentage (w/w %)
Moisture	3.94 ± 0.23
Dry matter	96.06 ± 0.2
Ash	1.59 ± 0.14
Wax	2.94 ± 0.31
Water soluble	2.33 ± 0.27
Pectins	1.14 ± 0.03
Lignins	11.52 ± 0.27
Hemicelluloses	14.74 ± 0.42
Celluloses	61.80 ± 0.45

Table 3
FTIR data of unmodified white *C. populnea* fibers.

Wave number (cm^{-1})	Functional group
3425.7 - 3253.8	ν (-OH) broad, strong band from the cellulose, hemicellulose, and lignin of *C. populnea* fiber
~2905.5	ν (C-H) in aromatic rings and alkanes
~2347.9	ν (C=C) aromatic skeletal ring vibration due to lignin
~1645.4	-OH from water content of the fiber
~1432.7	δ (C-H) from pectins, lignins, and hemicellulose
~1255.4	δ (C-OH) out-of-plane
~1121.3	ν (C-OH) secondary alcohol
~842.4	phenyl ring substitution band from lignin

3.2.2. *Detarium micocarpum*

D. micocarpum is a biopolymer confined to West and Central Africa. It is typically a species of dry savanna [25]. It is popular among the Ibo tribe of South-eastern Nigeria. *D. microcarpum* bears different local names among socio-cultural groups of different countries. For examples, socio-cultural groups, like Yoruba, Igbo, Kanuri, and Hausa, in Nigeria named the plant as Ogbogbo, Ofo, Gatapo, and Taure, while Fulbe, Sonrai, and Soninke in Mali called it Doli, Tambacounba, and Fantu, respectively [26]. It is the most investigated species of the genus because of its importance in African traditional medicine. The legume is very rich in polysaccharide gum.

Table 4 shows the proximate composition of *D. micocarpum* fruit. The seed polysaccharide was described as a stabilizer and a gelling agent in some processed fruit products [27].

All other additives (roseline and cocoanut fibers) were purified, dried at ambient temperature, ground, and then passed through a six-micron mesh sieve. The powder was kept at room temperature until required.

Table 4
Proximate composition of *D.micocarpum* [28].

Composition	Mesocarp (%)	Seed (%)
Moisture	15.0 ± 0.01	5.0 ± 0.01
Crude fat	10.5 ± 0.01	15.5 ± 0.02
Crude Ash	3.3 ± 0.01	3.5 ± 0.02
Crude fiber	10.2 ± 0.02	11.2 ± 0.01
Crude protein	6.0 ± 0.03	13.5 ± 0.02
Total Carbonhydrate	54.0 ± 0.01	50.5 ± 0.03

* Results are mean ± SD of duplicate determinations.

3.3. Preparation of the mud

A base mud of fixed volume was prepared by mixing 24 g of beneficiated Ohia clay into 350 ml of fresh water. The laboratory equipment used for measurements of viscosity and filtrate loss are all industry-standard devices. Fluid viscosity was measured by an OFITE 8-speed viscometer with rotational speeds ranging from 600 to 3 rpm and that could be related directly to plastic viscosity (PV), yield point (YP), and apparent viscosity (AV) using appropriate mathematical expressions [29]. Fluid filtrate was measured with filter press (OFITE Model 14030). Table 5 consists of all the proposed additives listed in ascending order of importance according to the major objective of this study.

Table 5
Additives in the increasing order of importance.

S/N	Additives	Total mixture basis (%)	Weight composition (grams)
1	A:Ufor	30.19	5.25
2	B:F.Gum	22.64	2.000
3	C:R.Fibre	22.64	0.63
4	D:C.Fibre	13.21	0.63
5	E: Barite	11.32	12.50
Total		100	21.01

3.4. Transformation of additives

For practical consideration, the additives were expressed in percentages as shown in Equation 1. This was done to reduce experimental runs and minimize the cost. For example, a full central composite design (CCD) for 4 and 5 factors would require 30 and 47 experimental runs, respectively. Where delivery time and material costs are limited, 17 runs can make a difference. This is one important contribution of our methodology.

$$\beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 = 100 \quad (1)$$

The expression of Equation 1 implies that the variables are dependent linearly. Therefore, the quantity of any additive will be uniquely determined from the amounts of others. To implement this hypothesis in a multiple factor analysis, a central composite design was selected because of its uniqueness for response surface (RSM) construction.

Here, the additives' center point X_i (0) was obtained from the normal weight composition of the formulation using Equations 2-5. The choice of increment (α) for each variable around the center point (X_i (±1), X_i (±2), and ± star points) was dictated by cost, experience, and availability of the additives. Table 6 shows the corresponding additives' fractions ± 1 and ± 2 away from center point $X_i(0)$ for specified incremental value, α.

$$x_1 = \frac{A}{B + C + D + E} \quad (2)$$

$$x_2 = \frac{B}{C + D + E} \quad (3)$$

$$x_3 = \frac{C}{D + E} \quad (4)$$

$$x_4 = \frac{D}{E} \quad (5)$$

Table 6
Additives' coded levels for different increments values.

	Coded level (Xi)					
	± α	**-2**	**-1**	**0**	**1**	**2**
x_1	0.05	0.233	0.283	0.333	0.383	0.433
x_2	0.05	0.045	0.095	0.145	0.195	0.245
x_3	0.01	0.028	0.038	0.048	0.058	0.068
x_4	0.01	0.030	0.040	0.050	0.060	0.070

3.5. Conversion to working quantity

The coded ratio (X_i) for each treatment was translated into working quantities of additives by randomly selecting four numeric factors (X_1, X_2, X_3, and X_4). Each factor varied over 5 levels according to Central Composite Design (CCD). Table 7 shows the design matrix for fully randomized coded realizations and responses obtained at 89.6 and 212 ^{o}F. Table 8 shows a summary of all experiments performed at low and high temperatures. It is clear that all mud properties exhibit degradation with a temperature.

The actual working values were obtained by estimating the actual factor ratio, ω_i, using Equation 6 from the coded random factor of a particular experimental run. This was then followed by systematic algebraic solutions of Equations 7-11 for β_1, β_2, β_3, β_4, and β_5 for the same run.

$$X_i = \frac{\omega_i - X_i(0)}{\alpha_i} \quad (6)$$

$$\beta_1 = \frac{\omega_1}{1 + \omega_1} \quad (7)$$

$$\beta_2 = \frac{\omega_2(1-\beta_1)}{1+\omega_2} \quad (8)$$

$$\beta_3 = \frac{\omega_3(1-\beta_1-\beta_2)}{1+\omega_3} \quad (9)$$

$$\beta_4 = \frac{\omega_4(1-\beta_1-\beta_2-\beta_3)}{1+\omega_4} \quad (10)$$

$$\beta_5 = \frac{\beta_4}{\omega_4} \quad (11)$$

For practical purpose, only the experiments performed at elevated temperature (212 ^{o}F) was analyzed to study the thermal stability of the proposed formulation.

Table 7
Design matrix for coded variables and responses at different temperatures.

	Treatment (Coded)				Temperature of 89.6 ^{o}F					Temperature of 212 ^{o}F				
Exp. No	X1 (g)	X2 (g)	X3 (g)	X4 (g)	Fluid loss ml/30 mins	PV cp	Yp lb/100 ft^2	Gel 10 Sec lb/100 ft^2	Gel 10 Mins lb/100 ft^2	Fluid loss ml/30 mins	PV cp	Yp lb/100 ft^2	Gel 10 Sec lb/100 ft^2	Gel 10 Mins lb/100 ft^2
1	-1	-1	-1	-1	8	20	25	3	3	9	9	10	3	3
2	1	-1	-1	-1	7	36	40	4	5	8.2	19	15	4	5
3	-1	1	-1	-1	8	21	33	4	5	9	7	18	3	4
4	1	1	-1	-1	5.8	25	44	4	5	6.4	16	4	3	4
5	-1	-1	1	-1	6.9	20	25	4	4	7.4	10	10	3	3
6	1	-1	1	-1	5.5	31	60	5	7	6.2	11	25	4	4
7	-1	1	1	-1	8	23	34	5	7	8.8	14	7	3	4
8	1	1	1	-1	7	34	54	5	6	8	11	26	4	4
9	-1	-1	-1	1	7.6	22	37	5	7	7.2	16	5	3	4
10	1	-1	-1	1	6.5	32	56	5	7	6.8	11	26	4	4
11	-1	1	-1	1	8	23	36	5	5	9	19	2	3	3
12	1	1	-1	1	6	31	63	5	6	6.4	12	24	3	4
13	-1	-1	1	1	7	24	40	5	5	7.4	7	19	3	3
14	1	-1	1	1	7	29	57	5	7	7.8	8	29	3	3
15	-1	1	1	1	7.5	24	36	5	5	8	17	5	3	4
16	1	1	1	1	7.5	28	56	5	7	8.2	19	11	4	5
17	-2	0	0	0	8.2	18	24	4	5	9.2	4	14	3	3
18	0	-2	0	0	6.4	25	45	5	5	9	15	7	3	4
19	0	0	-2	0	9.5	27	50	5	6	9.6	5	23	3	4
20	0	0	0	-2	10	22	38	5	6	9.4	14	2	3	3
21	2	0	0	0	8	32	78	5	7	9	22	21	4	5
22	0	2	0	0	10	28	47	5	6	11.2	16	8	3	4
23	0	0	2	0	14	26	48	5	7	14.4	21	8	4	4
24	0	0	0	2	7.8	25	55	5	6	8.8	20	7	4	5
25	0	0	0	0	8	23	49	5	7	9.2	19	4	3	4
26	0	0	0	0	8.2	22	51	4	7	9.2	19	4	3	4
27	0	0	0	0	8.1	21	50	5	6	9.2	19	4	3	4
28	0	0	0	0	8.05	20	48	4	7	9.2	19	4	3	4
29	0	0	0	0	8.3	22	49	5	7	9.2	19	4	3	4

** Average mud weight = 8.72 lb/gal*
*** The sand content range = 6 – 8 %*
**** pH range = 9 - 12*

3.6. Data analysis

The ultimate goal in this section is to build a representative model relating to some selected independent variables based on their significance over the dependent variable. This was done at a 95 % confidence interval (α = 0.05) using F and "prob>F" statistics. Only experimental data obtained at 212 ^{o}F were analyzed to mimic fluid under the reservoir conditions. The selection of the model and terms was estimated using Analysis of Variance (ANOVA). The following models were tested: linear, quadratic, and factorial.

The two hypotheses used for the test include:

(i). The null hypothesis: all treatments are of

equal effects.

$$H0: \beta_1=\beta_2=\ldots\beta_k=0$$

(ii). The alternative hypothesis: some treatment is of unequal effects.

$$H1: \beta_j \neq 0 \text{ for at least one j}$$

To reject null hypothesis H_0, at least one of the model/variables explains significantly the variability observed on the response. Table 9 shows the final result of ANOVA. The adjusted correlation coefficient provided in the last column of Table 9 is an indication of the goodness of fit of the selected models. The closer to unity, the better the model.

3.7. Response surface models

Equations 12-17 show all of the developed models. The significance of model terms was captured in the value of their F, which suggested true reflections of experimental data and not noise. In addition, the values of "prob>F" values in Table 9 are less than 0.05 in most cases, which suggested that the analysis is reliable with a 95 % confidence probability.

Table 8
Summary of experimental runs.

		Rheological and filtration properties					
Temperature	**Statistics**	**PV (cp)**	**Yp (lb/ft^2)**	**10 Secs**	**10 mins**	**Fl (ml)**	**CT (mm)**
	Min	18	24	3	3	5.5	0.1
	Max	36	78	5	7	14	0.3
89.6 ^{o}F	Mean	25.310	45.793	4.690	5.966	7.857	0.166
	SD	4.684	12.187	0.541	1.085	1.600	0.052
	Min	5	2	3	3	6.2	0.1
	Max	22	24	4	5	11.2	0.2
212 ^{o}F	Mean	14.556	9.833	3.259	3.889	8.585	0.131
	SD	4.807	6.806	0.447	0.577	1.038	0.031

Table 9
Analysis of variance for mud properties at different temperatures.

		Model	**Sum of square error**	**DF**	**Mean square error**	**F- value**	**prob>F**	**Adj. R-square**
	PV	Quadratic	542.98	11	49.36	45.89	0.0001*	0.7855
	Yp	Linear	3798.63	4	949.66	65.04	0.0001*	0.9954
89.9 ^{o}F	Fluid loss	Linear	8.64	4	1.48	4.23	0.0537**	0.678
	10 mins Gel	Quadratic	27.18	10	2.72	7.98	0.0001*	0.823
	10 Sec Gel	Quadratic	1.8	14	0.13	8046.37	0.0001*	0.8269
	PV	Quadratic	471.82	8	58.98	8.24	0.0001*	0.9804
	Yp	Quadratic	1060.44	14	75.75	139.4	0.0001*	0.922
212 ^{o}F	Fluid loss	Linear	10.77	4	2.69	3.49	0.0246*	0.722
	10 mins Gel	Linear	5.05	4	1.26	7.66	0.0005*	0.9133
	10 Sec Gel	Quadratic	4.29	9	0.48	9.02	0.0001*	1

* Significant at p <0.05
** Significant at other CI (0.0537)

$$\text{PV (cp)} = -198.51438 + 27.43777 * X_1 - 14.35804 * X_2 + 437.87718 * X_3 + 51.17091 * X_4 - 250.63727 * X_3^2 - 24.57098 * X_1X_3 - 17.60336 * X_1X_4 + 25.18461 * X_2X_4 \quad (12)$$

$$\text{Yp}\left(\frac{\text{lb}}{\text{ft}^3}\right) = 511.95888 - 125.15450 * X_1 - 0.21552 * X_2 - 231.56113 * X_3 - 356.90277 * X_4 + 10.79714 * X_1^2 + 0.52512 * X_2^2 + 193.53359 * X_3^2 + 17.25572 * X_4^2 + 3.02818 * X_1X_2 - 31.68744 * X_1X_3 + 47.86853 * X_1X_4 - 6.03814 * X_2X_3 - 22.00652 * X_2X_4 + 219.05497 * X_3X_4 \quad (13)$$

$$\text{API FL}\left(\text{ml}/30\,\frac{\text{mins}}{100}\,\text{psi}\right) = 11.06561 - 0.21187 * X_1 + 0.76549 * X_2 - 3.28562 * X_3 - 1.23814 * X_4 \quad (14)$$

$$\text{10 Sec Gel}\left(\text{lb}/\text{ft}^3\right) = 31.46397 - 7.98599 * X_1 + 0.46274 * X_2 - 14.39837 * X_3 - 19.96375 * X_4 + 0.52506 * X_1^2 + 7.82547 * X_4^2 - 0.079274 * X_1X_2 + 3.12364 * X_1X_3 + 2.18326 * X_1X_4 \quad (15)$$

$$\text{10 Mins Gel}\left(\text{lb}/\text{ft}^2\right) = -2.42875 + 0.79495 * X_1 + 0.19563 * X_2 - 0.16720 * X_3 + 0.58095 * X_4 \quad (16)$$

$$\text{Cake thickness (inch)} = -1.44032 + 0.52212 * X_1 + 0.19563 * X_2 - 0.16720 * X_3 + 0.58095 * X_4 - 0.041697 * X_1^2 - 0.26493 * X_3^2 - 0.40678 * X_4^2 - 0.024154 * X_1X_4 - 0.076092 * X_2X_4 + 0.64971 * X_3X_4 \quad (17)$$

3.8. Interaction effects of factors

The magnitude of factor coefficients in any of the model equations developed is an indication of its degree of sensitivity. The sign (positive or negative) they carry, however, shows whether the response changes based on the increase or decrease of the degree of sensitivity, accordingly. Factors X_1 and X_3 are undoubtedly good sources of viscosity, while factors X_2 and X_4 show better fluid loss additives and the real source of Gel strength. The presence of factors interaction was evident from the ANOVA. Figure 2 shows 3-Dimensional and contour plots of the effects of interaction of different factors on plastic viscosity, yield point, and fluid loss. As shown in Figure 2, the mud plastic viscosity increases as X_1 and X_3 increase up to a point (optimum point); a further increase in X_3 results in a decrease in plastic viscosity. Factor X_2 has a positive effect on yield point. Increasing X_1 in the mud with an increase in X_2 decreases the yield point up to the optimum point. An increase in both factors leads to the corresponding yield point increase. Both factors X_3 and X_4 are good stabilizers of fluid loss; however, the amount of fluid loss is dictated by the quantity of X_1 and X_2.

4. Multi-objective optimization study

The models (PV, Yp, FL, and Gel) indicate the direction in which variables change in order to, for example, maximize the Gel strength and minimize the API filtrate. The multiple regression equations were solved numerically for the maximum Gel strength

and minimum API filtrate loss, while other variables were left in their ranges. The solved objective function was desirability (D) as in Equation (18). The overall desirability (D) is the geometric (multiplicative) mean of all individual desirabilities (di) that range from 0 (least) to 1 (most).

$$D = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \qquad (18)$$

where n is the number of responses. The input variables (X_1, X_2, X_3, and X_4) were adjusted numerically within range goals that keep the solution within the experimental boundaries. The PV and Yp were also set to be in range, yet their lowest limits were set to values of 8 and 5, respectively, according to the API standard [30].

Figure 3 shows optimum variable quantities X_1 (6.35 g), X_2 (3.10 g), X_3 (0.61 g), and X_4 (0.60 g) for the proposed drilling mud. The corresponding responses at the optimum points are shown in Figure 4. These values were validated experimentally and are within an acceptable range as stipulated by API. The normal experimental values in optimum conditions include PV (19.4 ± 1.50 cp), Yp (21.5 ± 0.79 lbf/100ft^2), FL (10.12 ± 0.45 ml/30 minutes/100 psi), and 10 min and sec Gel value (4.6 ± 0.05 and 5.1 ± 0.01 lb/100ft^2).

The mean experimental and simulated values with their standard deviations were in good agreement with the standard [31].

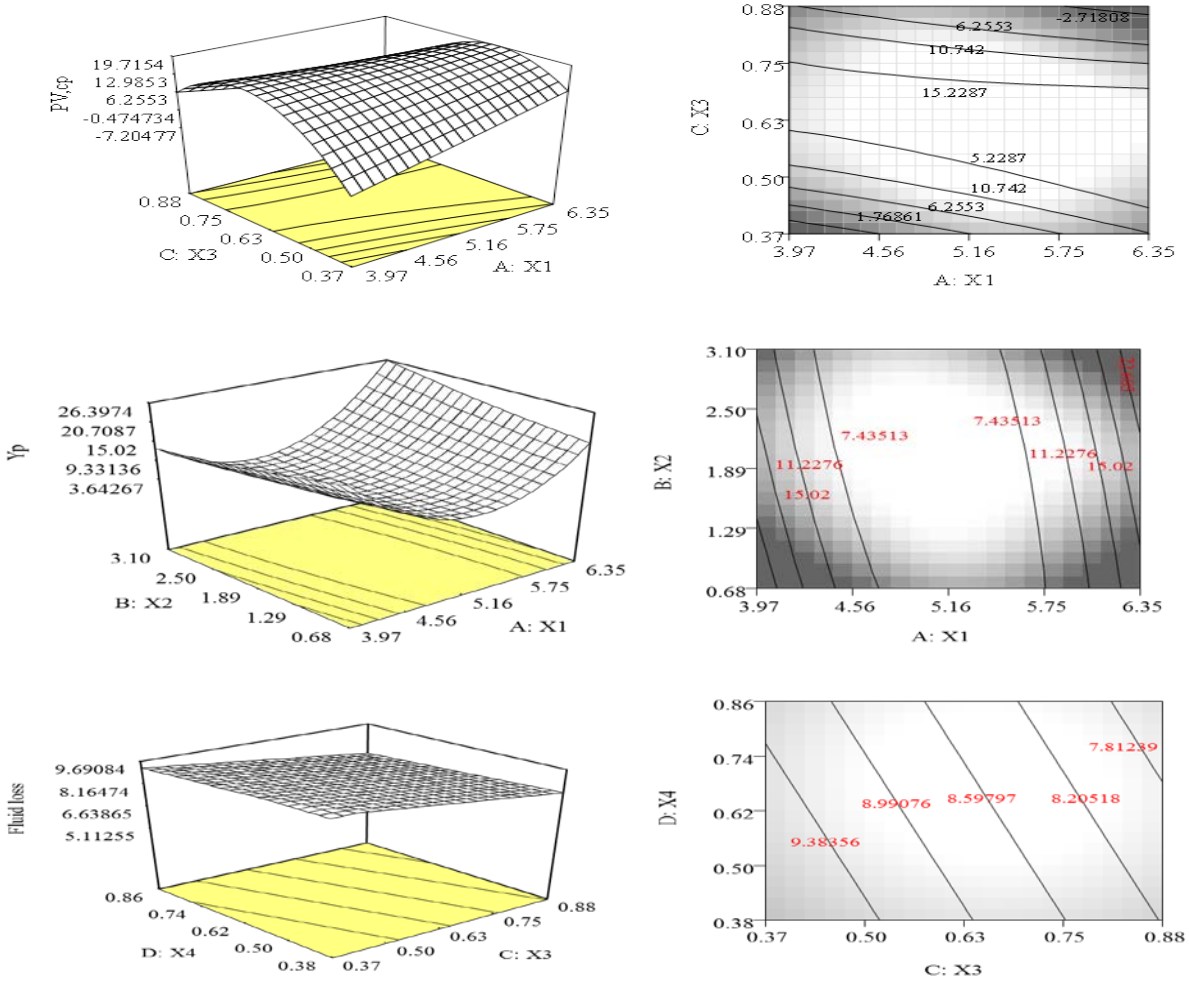

Figure 2. 3-Dimensional and contour plots showing the effects of interaction of different factors on plastic viscosity, yield point, and fluid loss.

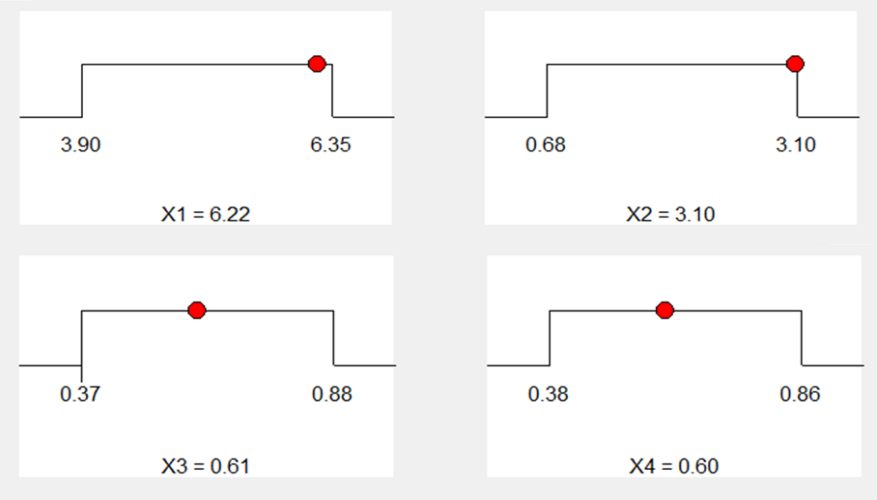

Figure 3. Ramps of the optimum variable quantities in the proposed drilling mud.

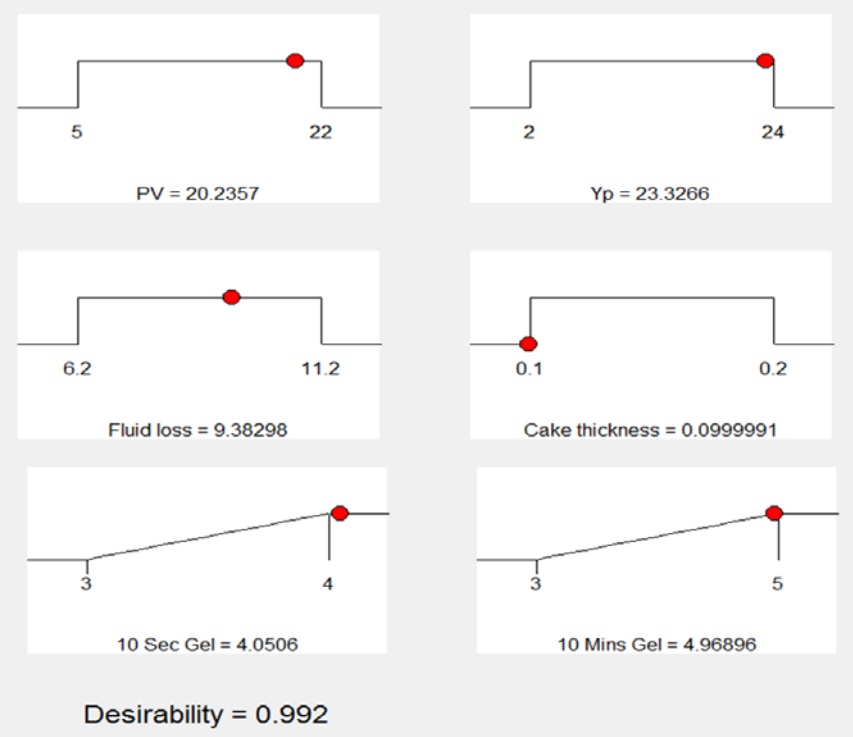

Figure 4. The corresponding responses in the optimum conditions (based on the desirability value of 0.992, there is a 0.008 percent probability that this could occur due to noise).

5. The present and the existing studies

The uniqueness of this present study is, in one way, related to the economic considerations as reflected in the design of the work. The other reason for the uniqueness of this study is the discovery of two other biomaterials (*C. popunea* and Rosaline fiber) that were evaluated at a temperature of 212 ^{o}F. Previous studies have reported poor viscosity at a temperature above 120 ^{o}F for for mud prepared using gum arabic with excessively high API fluid loss [15]. They reported FL values to be higher than 17 ml/30 min/100 psi at 120 ^{o}F, which was observed to be higher at higher tempearatures due to its fizzing tendency. The viscosity and FL of 19.5 cp and

10.12 ml/30 minutes/100 psi obtained in this present study show that the optimum formulation obtained with the new set of biomaterials selected can replace the existing formulation. The water loss analysis of another biomaterial, cellolose generated from groundnut husk, was studied at 176 ^{o}F [32]. The result shows that the drilling fluid formulated from groundnut husk cellulose has a high fluid loss of 7.6 mls with a maximum percentage deviation of 13.2 % in 30 minutes. However, about 50 % reduction of rheological properties was reported to be relative to the API standard value. Igwilo et al. [18] selected D. marcocarpon, B. eurycoma mixd with XCD polymer. Salawudeen et al. [19], on the other hand, selected a cocoanut fiber as a filtrate loss reducer with B. eurycoma to boost the viscosity. In contrast, the present study selected D. marcocarpon, the *C. popunea* (Food gum), Rosaline and Cocoanut fibers for developing drilling mud. Both rheological, physical, and filtration properties were evaluated using a new experimental methodology, which is not only cost effective, but also accurate and flexible. Technically, with the exception of Salawudeen et al. [19], the rheological results were consistent with the findings of this present study, though no filtration loss result was found in the report of Igwilo et al. [18] that clearly discouraged the use of biomaterials in formulating drilling muds from economic considerations, which was not considered by the present study. This assertion would be further investigated with the current crop of biomaterials selected for this study.

6. Summary and conclusions

This paper evaluated and optimized local biopolymers using a reduced central composite experiment for the development of a new generation of water-based drilling fluid. On the basis of our analysis, the following conclusions are drawn.

1. The reduced central composite design of the experiment demonstrated in this paper is flexible in that it allows for the integration of engineering judgment and economic decisions. Besides, it utilized fewer experiments without compromising the details.
2. Based on the evaluated experimental results and API standards, the performance of various biopolymers in the water-based mud complied with the API specifications. The (API) filtration loss of a bentonite/distilled water slurry, containing 24 g of bentonite in 350 mL of distilled water and aged for 24 h, shall not exceed 15 mL. Again, in optimal conditions, 10.12 mL of fluid loss shows that the proposed mud complies with the standard [30, 31].
3. The physico-chemical and rheological properties of the base mud slurry significantly improved in the presence of Ufor, Food gum, roseline fiber, cocoanut fiber, and local barite. The two factors, Ufor and food gum, are good sources of viscosity, while Rosaline and Cocoanut fibers are good fluid loss reducers.
4. The average mud weight values recorded (8.6 – 8.9 lb) resulted from local barite that this study evaluated. Although these values satisfied the minimum 8.6 lb/gal ceiling value, its low specific gravity is clearly highlighted, and this study recommends applying modifications prior to use so as to avoid high sand content.
5. At the test temperature (212 ^{o}F), all additives were found to be thermally stable and, then, applicable as a rheology stabilizer and filtrate reducers under reservoir

conditions.

6. The accuracy of all measurements was made relative to the actual experimental result and comparison with the recommended API standard [33]. The repetitiveness of the experiment for field use was captured using the standard deviation after 3-time repetition. The recorded standard deviations include ±1.50 cp for viscosity, ± 0.79 lbf/100ft^2 for Yp, ± 0.45 ml/30 minutes/100 psi for fluid loss, and ± 0.05 and ± 0.01 lb/100ft^2 for 10 min and sec Gel, respectively.

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