Application of *Irvingia gabonensis*, *Manihot esculenta* and *Artocarpus altilis* as rheological modifier in water-based drilling fluid

A.O. Arinkoola [a,c], M.O. Jimoh [a,*], T.O. Salawudeen [a] , M.O. Daramola [b]

[a]Chemical Engineering Department, Ladoke Akintola University of Technology, Ogbomoso, Nigeria
[b]Department of Chemical Engineering, Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Hatfield, Pretoria, South Africa
[c]Department of PetroleumEngineering, African University of Science and Technology (AUST), Abuja, Nigeria

*Corresponding author. Email: jimonseur2013@gmail.com

Abstract

The influence of natural polymers (cassava starch, breadfruit starch, bush mango seed and corn fibre) on the rheological properties of Uturu bentonite clay was investigated in this study towards developing a water-based drilling fluid. Before the fluid development, the additives were ball-milled to nano-sized particles for effective dispersion in the fluid. Individual effects of each additive on rheological properties (plastic viscosity (PV), apparent viscosity (AV), yield point (YP), consistency index (k) and flow index (n) of the formulated drilling fluid (DF) were initially evaluated using One-factor-at-time (OFAT) method to understand the heavy hitters. To gain insight to the interactive effects of these factors, a statistically designed experiment Central Composite Design (CCD) was used. Results from the experiments via CCD were analyzed and regression models were developed for each rheological property. The optimum rheological properties of the DF were 28.24 cp; 7.78 cp; 14.21 cp and 12.86 lb/100ft^2, for µ600, PV, AV and YP, respectively. These properties indicate that the developed DF could be suitable for drilling in a typical oil well.

Keywords: Uturu bentonite; Natural polymers; Rheology; Drilling fluid

1. Introduction

The development of water-based drilling fluid from locally available clays and additives emerged as one of the solutions to high cost associated with oil and gas drilling. However, most of the drilling fluid (DF) developed from this effort suffered from excessive fluid losses, low Gel strength and thermal instability. Therefore, the suitability of chemically treated and ball-milled local clays and additives for enhanced drilling fluid production was investigated in this present study. Water-based drilling fluids are basically clay-water suspensions to which chemical additives are added for improved rheological and filtration properties. They are formulated to perform specific tasks such as carrying drill cuttings from the wellbore to the surface, prevention of drill pipe against corrosion, cooling and cleaning of the drill bit, maintaining wellbore stability, formation of thin, low permeable filter cake, prevention of fluid inflow from the wellbore [1], [2], [3].

To enhance the performance of DF for drilling operations, polymers, which could either be natural or synthetic, are added to water-based drilling fluid as viscosity enhancer and filtration control agent [4], [5]. Natural polymers are cheaper and biodegradable in comparison to the synthetic polymers and they are non-charged and less sensitive to salty environment [6].

Based on these reasons, recent advances have been made on formulation of water-based drilling fluid using natural polymers such as starches (obtained from cassava, corn and potatoes) [7], [8], [9]; biopolymers such as welan gum, achi, xanthan gum, gum Arabic, food gum [6], [10], [11], [12], [13]. Reports from these researchers have shown that these materials are suitable as rheology control additives. However, excess fluid loss, low gel strength and low resistance to thermal degradation at high temperature conditions typical of wellbore were reported for some of the formulations. Therefore, in-depth study is still required on the use of natural polymers for possible adoption in oil field by oil and gas exploration companies.

Example of a natural polymer is breadfruit (*Artocarpus altilis)*, an underutilized tropical fruit that grows freely in some parts of Nigeria. Breadfruit is one of the highest yielding plants with a single tree producing more than 200 fruits per annum [14]. It is rich in complex carbohydrates and fibre with low fat content [15]. Despite its confirmed high nutritional and medicinal values, cultivation of breadfruit plant suffers serious neglect, thereby reducing all possible socio-economic impact. Although the use of various natural polymers as drilling fluid additive has been reported, but as far as could be ascertained the use of breadfruit as additive in drilling fluid has not been reported. Therefore, exploring the beneficiation of breadfruit, especially in development of drilling fluid, could offer a platform of utilizing this valuable plant to harness its full socio-economic potentials.

Against this background, investigation on the use of breadfruit as an additive for Uturu DF was performed against other natural polymers such as cassava starch, bush mango seed and corn fibre on the rheological properties of water-based drilling fluid.

2. Materials and method

2.1. Materials

Clay sample was obtained from Uturu (5°78'N/7°43'E) in Abia state, Nigeria. Cassava roots, bush mango seeds and corn fibre were obtained from a local market in Ede, Osun state while breadfruits were plucked from an abandoned breadfruit tree at Ifetedo in Osun state.

2.2. Processing of clay and additives

The obtained Uturu bentonite was wet-sieved to remove all possible impurities and sun-dried to reduce the moisture content to <10%. Pre-gelatinized starch was obtained from breadfruits and cassava starch following the modified method of [16]. Resulting starch was initially ground using an electric grinder (Marlex appliance) and later ball-milled for 20 hr for further size reduction. Size reduction was carried out using High Energy Ball Milling (HEBM) technique available at the ceramic laboratory, Federal University of Technology, Akure. The choice of HEBM technique was based on its cheap cost, simplicity, environment friendliness, applicable to any class of material and can be scaled up to large quantities. The clay was fed into the mill, and operated at a speed of 5550 rpm with a transmission ratio of 1.8. The mill was loaded with a ball to powder ratio of 10:1. Milling was done for 20 h and samples were checked at one hour interval to observe progress of size reduction. The resulting micro-nano particles were analyzed for particle size using Malvern Master Sizer (MS 2000).

2.3. Preparation and characterization of drilling fluid

Drilling fluids were developed using the processed additives and clay samples. Rheological properties of the developed DF, such as viscosities and yield point, were measured at room temperature using a Antar Paar rheometer (Rheolab QC). In order to investigate the individual effect of each additive on the rheological properties, experiments were performed by varying the concentration of one of additives between 1 g and 8 g while the quantities of others were fixed at 4.5 g, except for Corn Fibre which was fixed at 1.13 g and varied between 0.15 and 2.25 g. Further experiments were conducted using Central Composite Design (CCD) and the results were statistically analyzed (Analyses of variance, ANOVA) using the Design expert software (Design Expert v11.0, State Ease) to investigate the interactive effect of the additives on the rheological properties of the developed fluid. Fractional factorial design was used for the design, with 4 and 7 as the low and high values. Rheological parameters (n, k, PV, AV and YP) were estimated according to the API recommendations [19]:

$$AV = 600rpm\ \ dial\ \ reading/2\ \ in\ \ cp \tag{1}$$

$$PV = 600\ \ rpm\ \ dial\ \ reading - 300\ \ rpm\ \ dial\ \ reading\ \ \ in\ \ cp \tag{2}$$

$$YP = 300\ \ rpm\ \ dial\ \ reading - PV\ \ in\ \ lb/100\ \ ft^2 \tag{3}$$

$$Flow\ \ index\ \ (n) = 3.32 \log R1/R2 \tag{4}$$

$$Consistency\ \ index\ \ (\mathrm{k})\ = 5.11 \frac{R_2}{R_1} indynes - \frac{secs}{cm^2} \tag{5}$$

where AV, is the Apparent viscosity; PV is the plastic viscosity; YP is the yield point; n, the flow index; k, the consistency index; R_1, the dial reading at 600 rpm; and $R_{2,}$ the dial reading at 300 rpm.

3. Results and discussion

3.1. Particle size analysis

Particle size of additives is very essential in the development of a drilling fluid as it greatly influences hydration and viscosity of particles in liquid medium. Smaller particles disperse more quickly and give higher suspension viscosities than larger particles [16]. Particle size distribution of the Uturu clay sample was reported in [17]. The clay sample has particle size with diameter <0.1 µm (100 nm). Particle size distribution of cassava starch (CS), breadfruit starch (BFS), bush mango seed (BMS), corn fibre (CF) and barite are shown in Fig. 1, Fig. 2, Fig. 3, Fig. 4, Fig. 5. The particle size which has been transformed to a log scale shows an average particle diameter size of 104.962 µm, 108.930 µm, 63.434 µm, 96.698 µm and 0.790 µm for CS, BFS, CF and Barite, respectively. Summary of the particle size distribution of the additives is provided in Table 1.

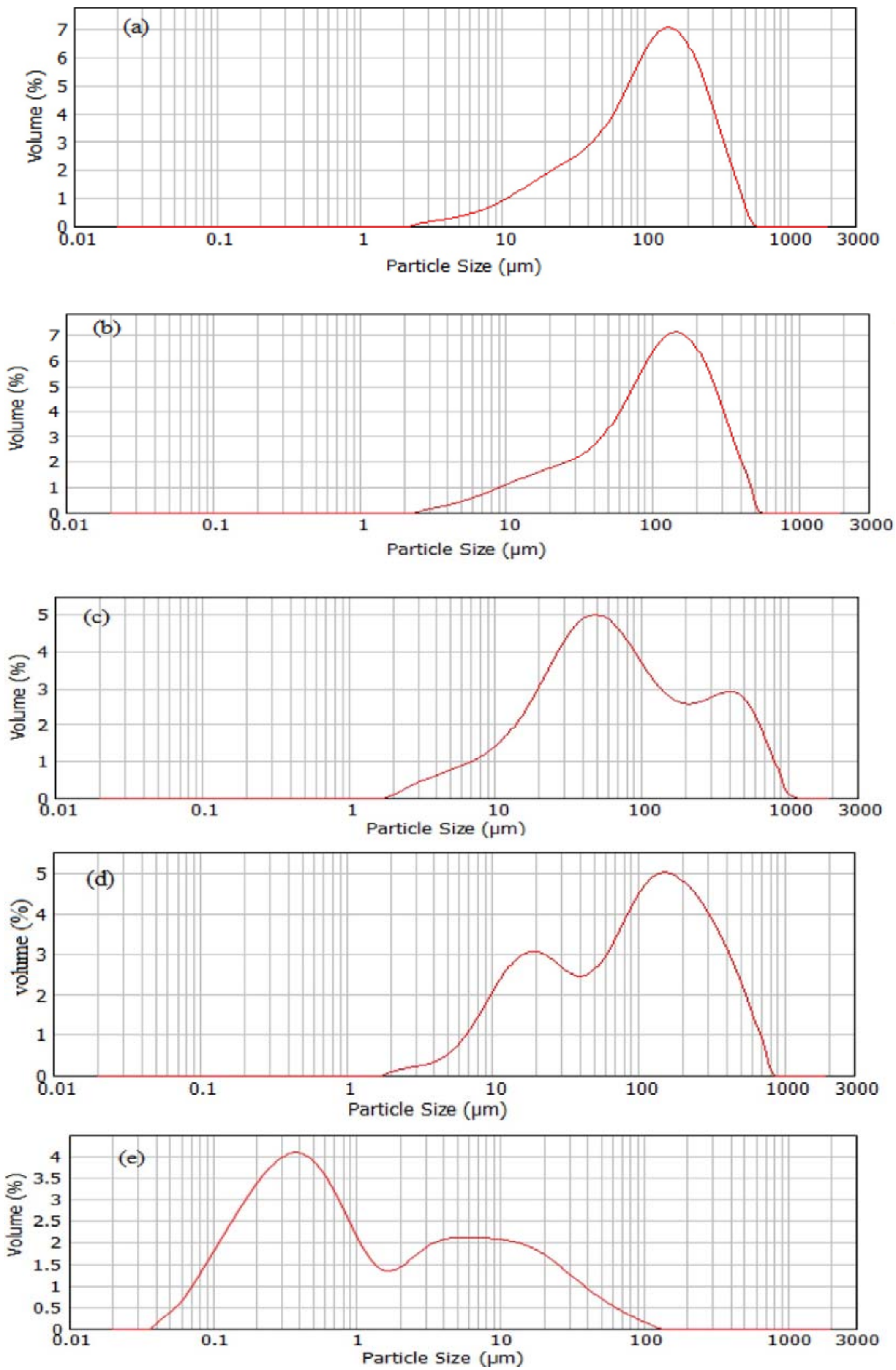

Fig. 1. Particle size distribution of (a) pre-gelatinized cassava starch (b) pre-gelatinized bread fruit starch (c) Bush mango seed (d) corn fibre (e) barite.

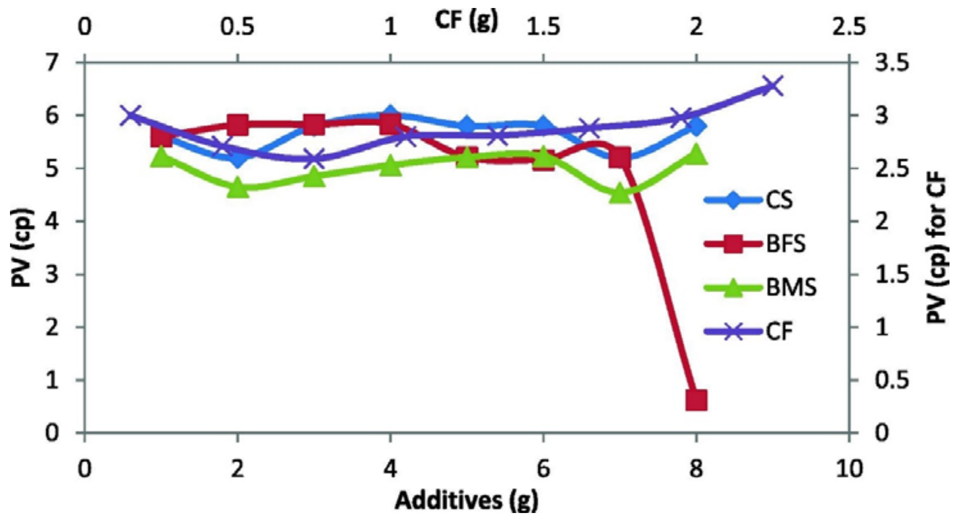

Fig. 2. Effect of additive on Plastic viscosity.

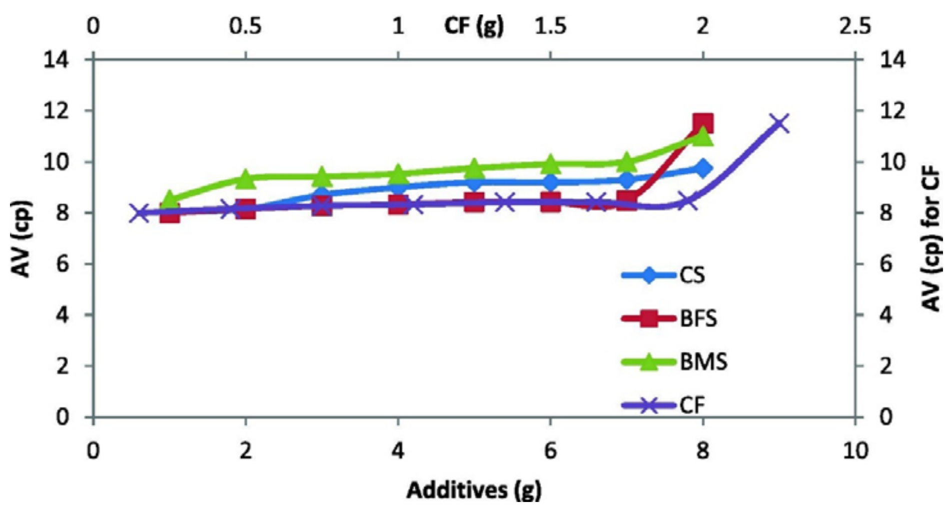

Fig. 3. Effect of Additive on apparent viscosity.

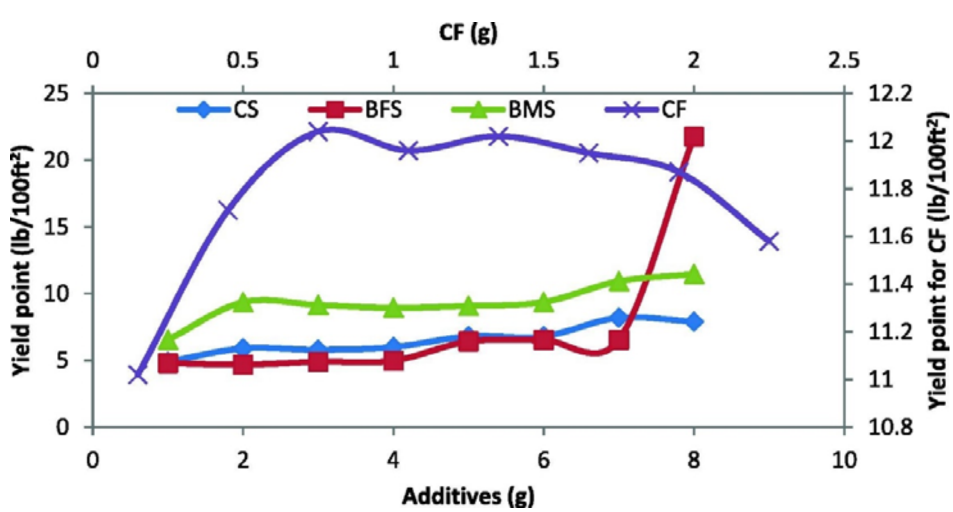

Fig. 4. Effect of additive on yield point.

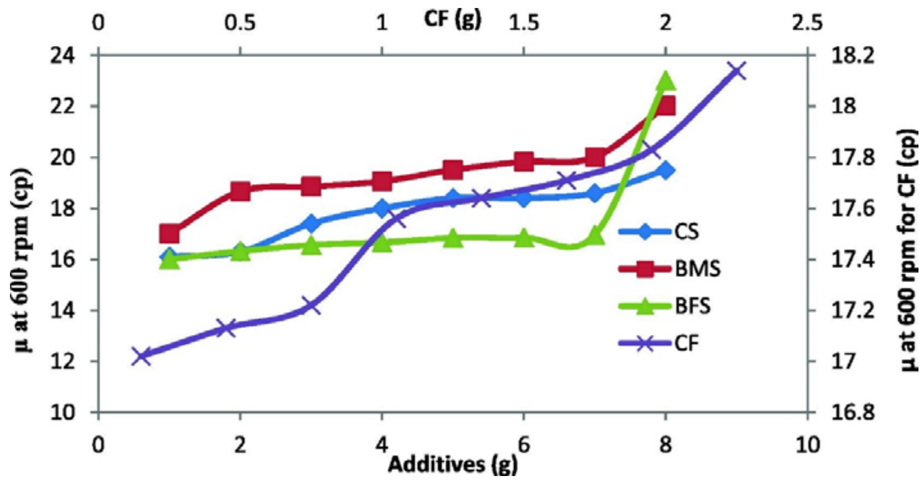

Fig. 5. Effect of additive on viscosity at 600 rpm.

Table 1. Particle size distribution of additives.

Sample	d (0.1)/µm	d(0.5)/µm	d(0.9)/µm
CS	12.287	104.962	271.2.1
BFS	18.252	108.93	280.805
BMS	12.847	63.434	429.464
CF	12.287	96.698	369.941
Barite	0.143	0.782	19.062

CS = Cassava starch, BFS = Breadfruit starch, BMS = Bush mango seed, CF = corn fibre.

Similar results were reported by [18] for partially pregelatinized cassava starch prepared by ball milling. The authors reported that ball milling significantly destroy the starch granules contributing to improved cold water solubility and flowability of the starch granules. The higher the solubility of starch granule in cold water, the better its absorption on clay particle surface hence, improved filtration and rheological properties of the drilling fluid.

3.2. Rheological properties of drilling fluid developed using Uturu clay

The effects of CS, BFS, BMS and CF on PV, AV, YP and dial readings for Uturu mud are illustrated in Fig. 2, Fig. 3, Fig. 4, Fig. 5. There are changes in PV of the mud as amount of CS, BFS, BMS was varied between 1 and 7 g and CF varied between 0.25 and 2.25 g. Inclusion of CS and BMS beyond 7 g and CF beyond 2.0 g did not significantly increase the PV. Thus, the PV recorded ranged between 5.12 and 5.84 cp. The maximum value of 5.84 cp is below the API recommended value of ≥8. Thus, further optimization of the formulation is still required.

Apparent viscosity is a measure of the dynamic viscosity. It indicates the expected viscosity at higher shear rate. As shown in Fig. 3, the AV averaged at 9 cp was recorded when CS, BFS, and

BMS were added between 1 and 7 g and about 1.8 g CF was used. Beyond these limits, additional increase of CS, BFS, BMS and CF resulted to dramatic increase in AV. Too much viscosity increase is not desirable. Fig. 4 illustrates the effect of additives on yield point (YP) of Uturu mud. The YP is the initial stress required in order to move the fluid. It is a property that quantifies resistance to initial flow by the fluid. If the applied stress exceeds the yield stress, DF displays viscous flow characteristics otherwise, it experiences strain recovery [23]. The results obtained showed YP increased from 4.9 to 5.9 lb/100ft^2 as CS increased from 1 to 2 g. There was no significant increment in YP until CS was added between 4 and 7 g. A negative effect on YP was observed when CS was added beyond 8 g. YP decreased from 8.2 lb/100ft^2 to 7.9 lb/100ft^2 when CS was increased from 7 g to 8 g.

Similar trend was observed for the effects of BMS on yield point as depicted in Fig. 4. The YP obtained when 4–7 g BMS was used ranged between 8.5 and 11.0 lb/100ft^2. This was higher than the one obtained when CS was added between the same range 4.9–8.2 lb/100ft^2. The results obtained for CS was similar to [24]; while that for BFS, BMS and CS were higher than the one reported by the same authors. The disparity in the results may be attributed to the type of clay and additives. It was observed from Fig. 4 that addition of BFS from 1 to 4 g did not significantly increase the YP (4.6–4.98 lb/100ft^2). Further increase of BFS to 7 g in the mud however increased the YP to 6.54 from 4.98 lb/100ft^2. However, when 8 g was used, a dramatic increase of YP to 21 lb/100ft^2 was recorded. YP initially increases with CF and gradually decreases as CF was increased above 1 g.

The viscosity recorded at 600 rpm (μ_{600rpm}) increased with increasing amount of CS, BMS and CF. As shown in Fig. 5. μ remained fairly constant between 16.0 and 16.9 cp when BFS was incrementally added from 1 to 7 g. Further increase of BFS to 8 g resulted to higher viscosity of 23.0 cp. However, it is noteworthy to state that the PV 0.62 cp recorded when 8 g of BFS was used was due to insignificant difference between the dial reading of 600 and 300 rpm.

Based on the above observations, it can be deduced that significant effect of each additive was noticeable when added between 4 and 7 g in the mud. Furthermore, increasing the amount of BFS to 8 g may not be desirable due to the excessive increase in YP and drastic reduction of PV. Conclusions on optimum amount of additives required for the formulation of an API standard DF cannot be reached, hence need to study the interaction effects of the additives on rheological properties and perform optimization to ensure all results are comparable to API recommendations.

3.3. Flow hydraulic rheology

Fig. 6, Fig. 7, Fig. 8, Fig. 9 shows the effects of CS, BFS, BMS and CF on the hydraulic properties, flow (n) and consistency (K) indexes. The two parameters describe the behaviour of drilling fluids in dynamic condition. While K describes the viscosity of drilling fluid at low shear rate, n indicates the degree of non-Newtonian behaviour experienced over a range of shear stress [22]. It was observed that value of n decreases as CS increased up to 7 g. Further increase to 8 g, increased the value of n. An opposite trend was observed for the consistency index (Fig. 6). The mud consistency K value increases with CS in the mud. Ref. [18] stated that drilling fluid exhibits strong dilution performance at lower values (<0.5) of n. Based on this, it may not be desirable to increase the amount of CS beyond 7 g in the mud.

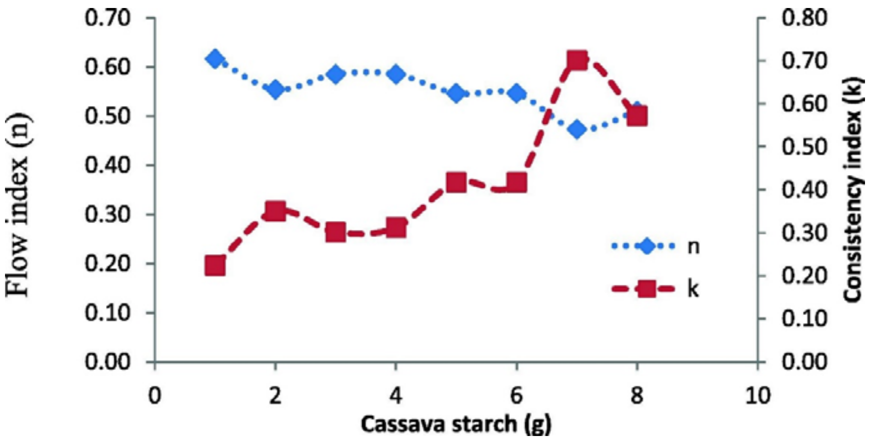

Fig. 6. Effect of varying cassava starch on flow and consistency index.

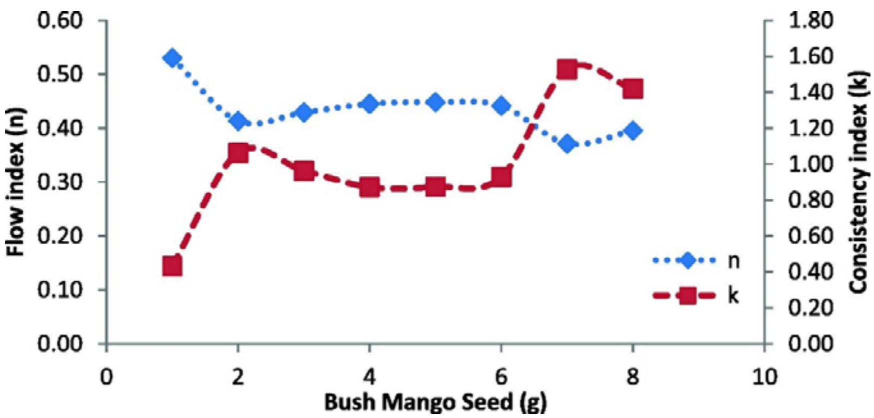

Fig. 7. Effect of varying concentration of Bush mango seed on flow and consistency index.

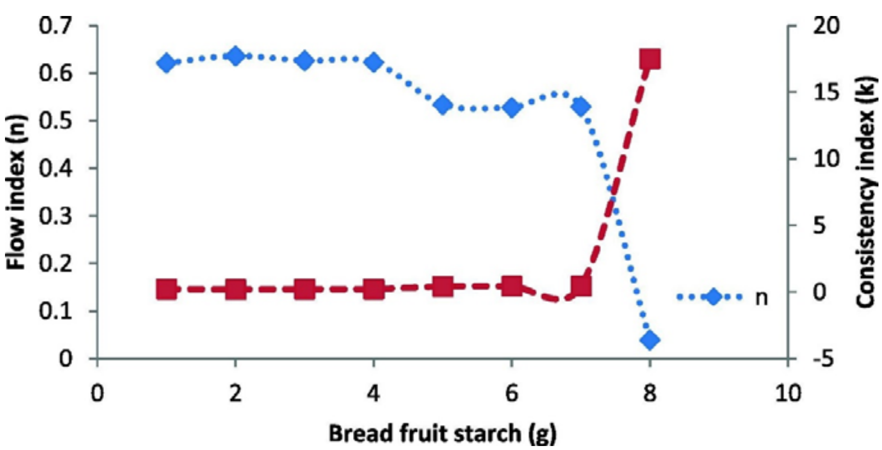

Fig. 8. Effect of varying concentration of bread fruit starch on floe and consistency index.

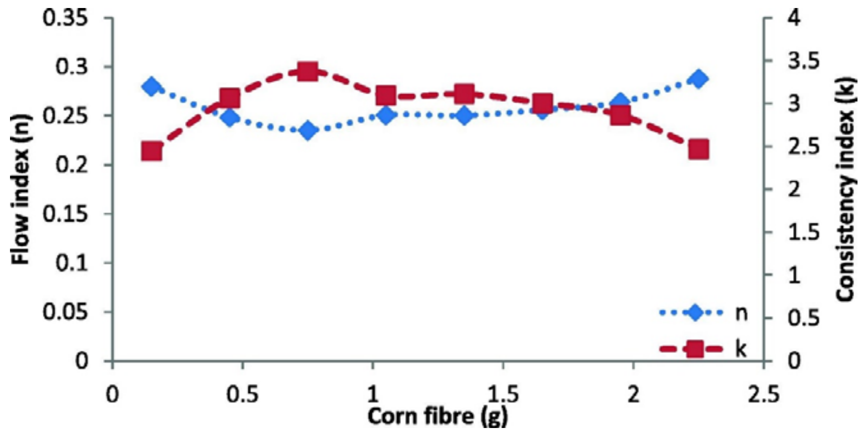

Fig. 9. Effect of corn fibre on flow and consistency index.

Flow and consistency index for varying quantity of BFS is depicted in Fig. 7. It was observed that value of n decreases gradually with increasing amount of BFS. The reduction from 0.53 to 0.04 became extremely obvious at 8 g of BFS. The reverse trend was however observed for the consistency index. K value of 17.52 obtained when 8 g of BFS was added, this is considered to be extremely high. The quantity of additives corresponding to the intersection of n and K curves may be considered the near starting point for mud optimization.

In case of BMS, the flow index was observed to decrease with increasing quantity of BMS. At 6 g of BMS, flow index increased and later decreased when it was increased to 7 g. Consistency index followed a similar but opposite trend. Flow index decreases with increasing amount of CF up to 1.35 g, after which it increases slowly and remained constant before further increase (Fig. 9) The results observed in this study agree with literature [20], [21].

Based on the above observations, it can further be affirmed that the mud needed to be optimized. Additives values between 4 and 7 g for CS, BFS and BMS and 0.25–2 g for CF were considered for optimization study.

3.4. Optimization of rheological properties

Rheological properties of drilling fluid developed using additive ranges between 4 and 7 g is shown in Table 2. As shown in the Table 2, various formulations yielded different rheological properties. Apparently, the highest value of rheological properties were recorded at experimental run 3, 28.42 cp, 7.78 cp and 12.86 lb/100ft^{2}for dial reading at 600 rpm, plastic viscosity, apparent viscosity and yield point respectively. Rheograms of experimental run 1, 3 and 7 are presented in Fig. 10, according to the rheogram, all the developed drilling fluids exhibited non-Newtonian flow. Formulation with properties close to API (experimental run 3) was best described by Herschel Bulkley model with correlation coefficient (R^2) of 0.9939.The shear stress for this formulation (run 3) was higher compared to the other two runs (1 and 7) indicating its ability to transport cuttings better than other formulation.

Table 2. Experimental Design and Rheological Properties to Determine Optimal Formulation for Uturu clay.

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	16.2	21.72	5.52	10.86	10.68
2	−1	−1	−1	−1	13.36	18.16	4.8	9.08	8.56
3	1	1	1	1	20.64	28.42	7.78	14.21	12.86
4	−1	−1	1	1	14.01	19.02	5.01	9.51	9
5	−1	1	−1	1	12.53	17.26	4.73	8.63	7.8
6	−1	1	1	−1	12.33	20.87	8.54	10.435	3.79
7	1	−1	1	−1	16.23	23.42	7.19	11.71	9.04
8	1	−1	−1	1	14.28	20	5.72	10	8.56

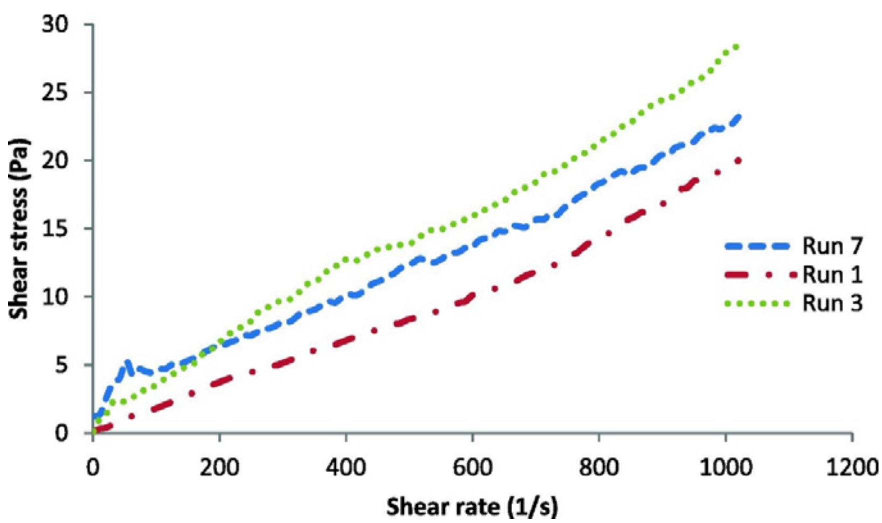

Fig. 10. Rheogram plots for drilling fluid formulations at runs 1, 3 and 7.

3.5. Interactive effect of additives on rheological properties

In order to study the interactive effect of the additives on rheological properties, experimental results in Table 2 were subjected to statistical analysis from which regression models were generated. Two-factor interactions of the additives were presented on 3-dimensional plots while the relative contributions of the additives were plotted on a tornado plot using estimated coefficients from the 2FI models.

3.5.1. Statistical analysis

Summary of the analysis of variance of the fitted linear models at 95 % confidence interval are shown in Table 3. Values of P > F greater than 0.05 indicates model terms are significant. The significance of the regression models and its terms were based on the Fisher value (F-value) and P-statistics. As observed from the ANOVA, R^2 for viscosity at 600 rpm, PV, AV was 0.9999, 0.9267 and 0.9999, respectively, and this value is in good agreement with the fitted linear models except YP whose R^2 = 0.6997. Eqs. (5), (6), (7), (8) are the regression models relating the dependent variables (viscosity at 600 rpm, PV, AV and YP) to independent variables (BMS, BFS, CS and CF). The equations in term of coded factors can be used to make predictions about responses (viscosity at 600 rpm, PV, AV, and YP) for a given level of each factor.

$$\mu_{600rpm} = 20.38 + 3.01A + 1.69B + 2.55C + 0.79D \quad (6)$$

$$PV = 5.84 + 0.068A + 0.80B + 1.29C - 0.67D \quad (7)$$

$$AV = 10.19 + 1.50A + 0.84B + 1.28C + 0.40D \quad (8)$$

$$YP = 9.66 + 0.63A + 0.87B + 0.76C - 0.10D \quad (9)$$

Table 3. Statistical Summary from Analysis of Variance for DF developed using Uturu clay.

Parameters	μ_{600rpm} (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	4154.44	0.0002	6.33	0.1412	4154.44	0.0002	1.17	0.5104[a]
A = BMS	11512.46	<0.0001	0.051	0.8421[a]	11512.46	<0.0001	0.89	0.4458[a]
B = BFS	3615.31	0.0003	7.09	0.1169	3615.31	0.0003	1.69	0.3236[a]
C = CS	8277.14	0.0001	18.28	0.0506	8277.14	0.0001	7.18	0.0750
D = CF	800.62	0.012	4.98	0.1553	800.62	0.012	0.023	0.8929[a]
R^2	0.9999		0.9267		0.9999		0.6997	
Adjusted R^2	0.9996		0.7802		0.9996		0.0992	

a

Insignificant model terms.

3.5.2. Sensitivity analysis

Surface response and contour plots showing the effect of two-factor interaction on viscosity at 600 rpm, PV and YP are illustrated in Figs. 11a–d, 12a–d and 13a–d. For understanding the interaction, BFS, BMS and CS were fixed at 5.5 g and CF was fixed at 1.125 g. Viscosity at

600 rpm increases with the simultaneous increase of all additives (Fig. 11a–d). In Fig. 12a and b, PV increased as BMS and BFS; CS and BMS were increased simultaneously. However, increasing CF simultaneously with either BMS or CS tend to reduce the PV (Fig. 12c and d).At low amount of CF (Fig. 12a and b), PV increased as BMS and BFS; CS and BMS were increased simultaneously. However, increasing CF simultaneously with either BMS or CS did not significantly increase the PV (Fig. 12c and d). At low amount of BMS and BFS (4 g), YP of 8.87 lb/100ft^2 was obtained. Increasing BMS to 7 g while BFS remained at 4 g gave YP of 8.84 lb/100ft^2. However, increasing both BFS and BMS to 7 g significantly increases the YP to 11.8 lb/100ft^2 (Fig. 13 a). This result indicated that increasing only BMS even beyond 7 g will only increase the viscosity and not YP. However, it is noteworthy to state that increasing the amount of BFS will significantly increase the YP as this was indicated in the coefficient of BFS (B) in Eq. (9).

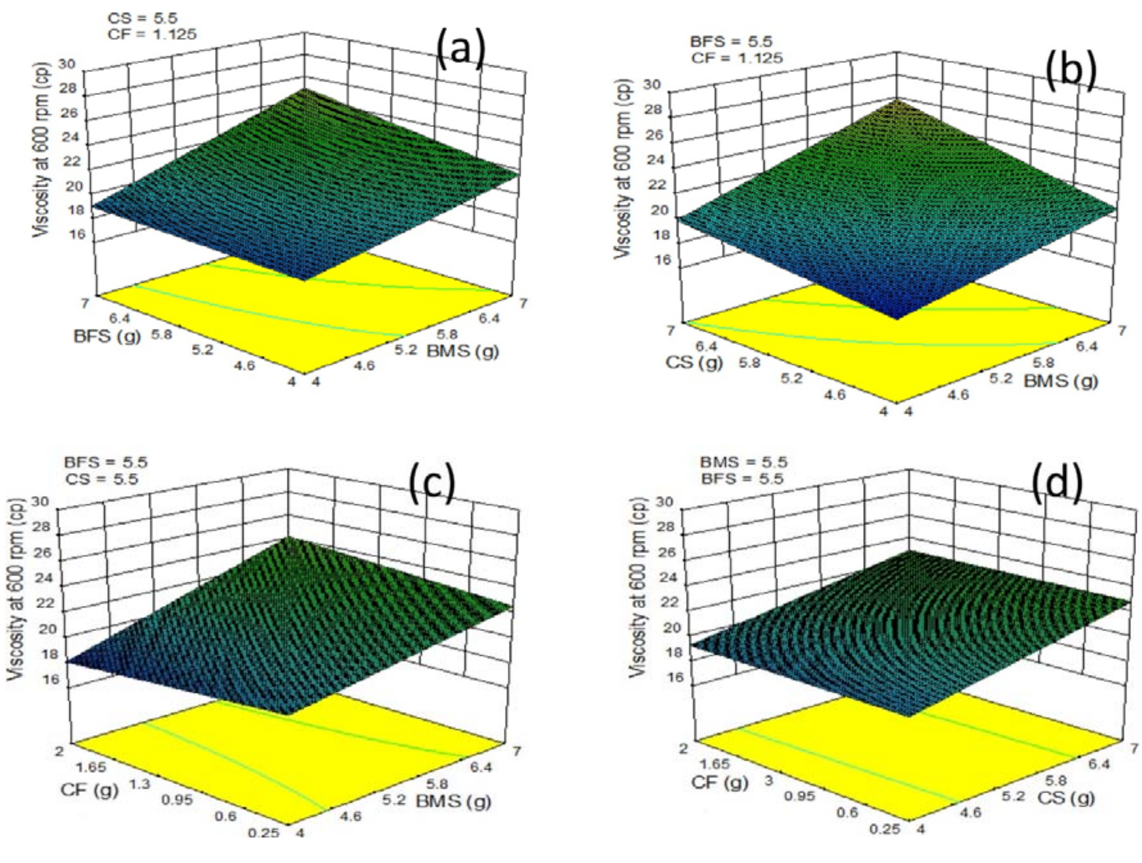

Fig. 11. 3-D plots showing the interactive effect of the additives on viscosity at 600 rpm for Uturu clay: (a) Effect of BMS and BFS on viscosity (b) Effect of BMS and CF on viscosity (c) Effect of CF and BMS on viscosity (d) Effect of CF and CS on viscosity.

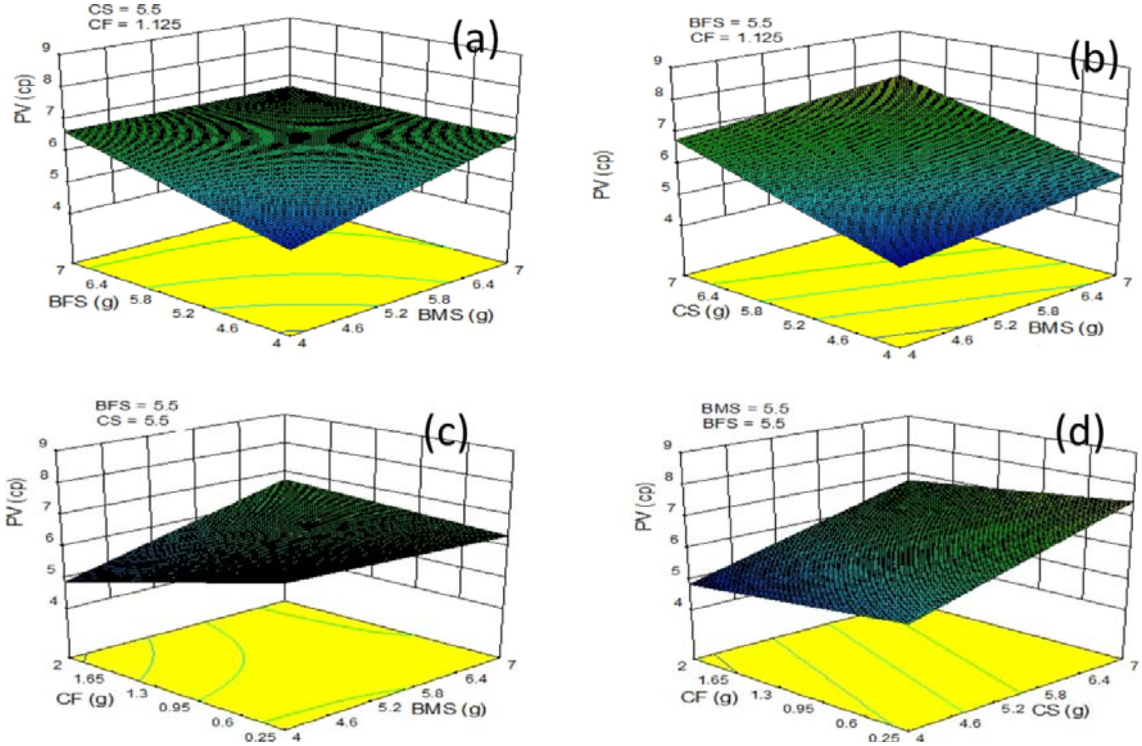

Fig. 12. 3-D plots showing the interactive effect of the additives on PV Uturu clay: (a) Effect of BMS and BFS on viscosity (b) Effect of BMS and CF on plastic viscosity (c) Effect of CF and BMS on plastic viscosity (d) Effect of CF and CS on plastic viscosity.

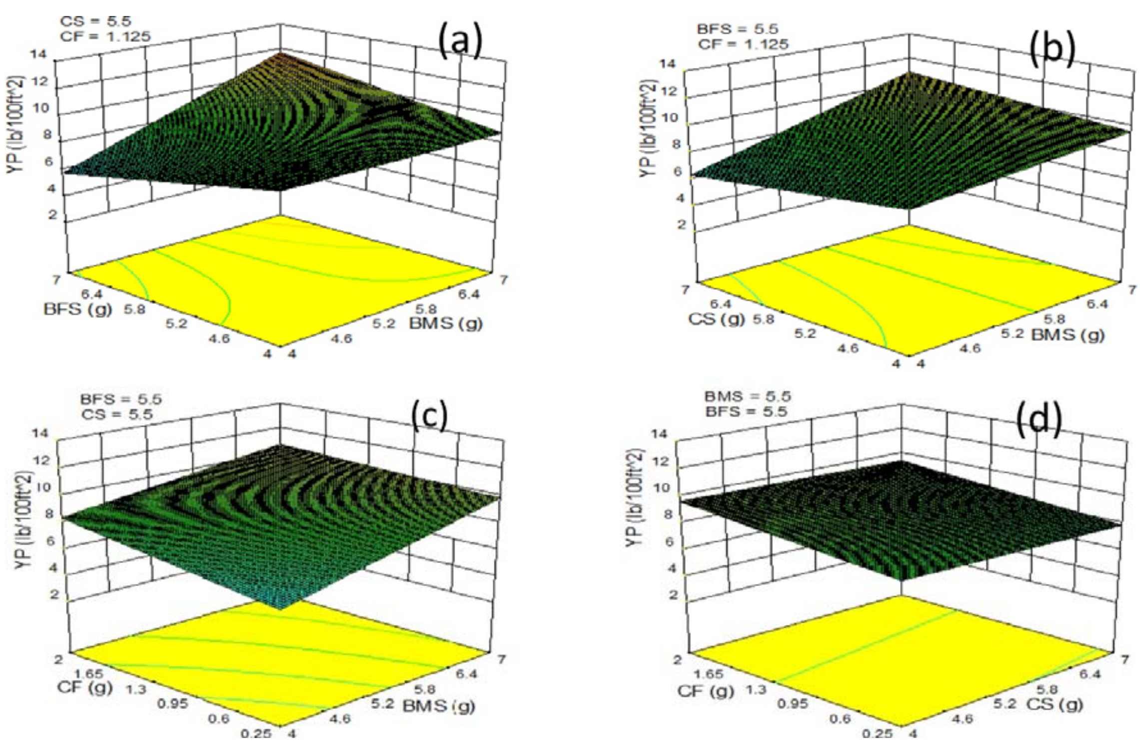

Fig. 13. 3-D plots showing the interactive effect of the additives on YP for Uturu clay: (a) Effect of BMS and BFS on yield point (b) Effect of BMS and CF on yield point (c) Effect of CF and BMS on yield point (d) Effect of CF and CS on yield point.

The sensitivity of the additives was further tested using a tornado plot as shown in Fig. 14. Relative importance of the additives was compared based on the estimated coefficients of ANOVA of 2FI. Individually, all additives contributed positively to viscosity at 600 rpm with BMS being the most influential and CF the least. CS, BFS and BMS contributed significantly to PV with CS having the most significant contribution. On the contrary, addition of CF has a negative effect on PV. Combined effect of BMS and BFS significantly increases the YP while a reverse effect of was observed on PV. This observation explains a possible shear thinning effect induced by the BFS, and hence prevents excessive viscosity which may arise from the use of BMS. Excess viscosity in drilling fluid during drilling operation may cause stuck pipe and reduce penetration rate [2]. A similar trend was observed for the combined effect of BMS and CS. Based on this observation; it can be recommended that more BFS should be used in situations where PV reduction is required.

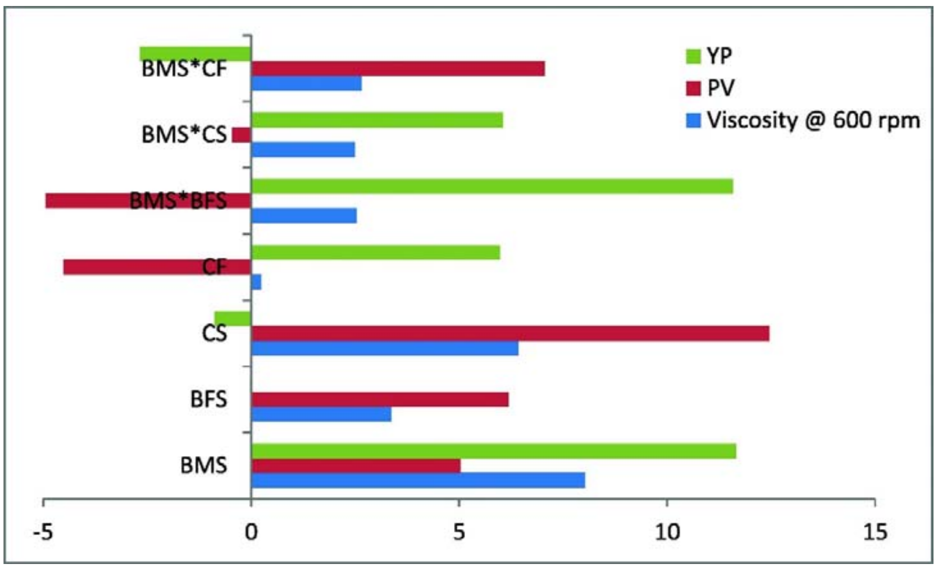

Fig. 14. Tornado plots showing the relative contribution and importance of additives on rheological properties.

4. Conclusion

A novel water-based drilling fluid was successfully developed using Uturu bentonite and a combination of natural polymers (cassava starch, breadfruit starch, bush mango seed and corn fibre). Experimental results showed that the developed fluid exhibited non-Newtonian flow properties and is best described by Herschel-Bulkley model. Due to the different properties and nature of the additives, it can be concluded that additives played complimentary roles in adjusting the rheological properties of the developed drilling fluid. All the additives contributed significantly to the rheological and flow properties of the drilling fluid and hence can be used as total substitute for imported synthetic drilling fluid additives. The novel fluid can be used for drilling in oil and gas exploration due to its excellent rheological properties and economic viability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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