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Experimental Evaluation on Suitability of African Oil Bean Husk as a Fluid-Loss Control Agent in Water-Based Drilling Mud

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Abstract
Filtrate loss determines the efficiency of drilling mud. Research on the suitability of African oil bean husk (AOBH) as a fluid loss control additive for water-based drilling mud (WBM) is presented in this article. AOBH was crushed into particle sizes of 63 µm, 125 µm, and 250 µm. The morphology and chemical properties of AOBH were studied with a Fourier Transform Infrared Spectrophotometer (FTIR) and a Phenom Prox model of the Scanning Electron Microscope energy dispersive X-ray spectroscopy (SEM-EDS). WBM samples containing the various sizes of AOBH as fluid-loss control additives were prepared. Samples containing industrial-grade additives (Grel Alphatex) were prepared. Basic mud tests were carried out on samples. Comparisons of results from the various samples were made. Rheology of mud samples was modeled with the Power Law Model and Herschel-Bulkley Models. Results show that AOBH contains mainly carbon and asphaltic compounds. Mud tests show that the performances of AOBH and industrial grade are comparable. Filter cake thickness was 2.3 mm–2.9 mm for AOBH-additives mud but 2.3 mm for industrial-additives mud. Filtrate loss was 2.3 ml–3.3 ml for AOBH-additives mud but 2.3 ml for industrial-additives mud. The apparent viscosity for AOBH-additives mud was 28-29.5 cp, but 29 cp for industrial-additives mud. Plastic viscosity for AOBH-additives mud was 22-23 cp, but 22 cp for industrial-additives mud. The yield point for AOBH-additives mud was 12-15, but 14 for industrial-additives mud. Use of AOBH did not affect the final gel strength. Both models show that the efficiency of the mud containing AOBH in cleaning the hole increased as the grain size of AOBH reduced. The chemistry of AOBH shows that it is biodegradable and eco-friendly.

Keywords: ***Oil-Bean, Fluid-Loss, Control-Agent, Water-Based, Drilling-Mud, Eco-friendly***

1. Introduction

The cost of drilling a wellbore is the most expensive single activity in the petroleum industry. Expenditures represent about 25% of the total oil field exploitation cost and are concentrated mostly in exploration and development in well drilling (Mohammed *et al.*, 2019). The cost of drilling fluid represents about 15-18% of the total cost of petroleum well drilling. WBM is recommended as a less expensive and environmentally harmless drilling. Though as a conflict, WBM is reactive with shale formations. Therefore, its use as a drilling fluid is restricted by the geochemistry of the service environment. For a drilling fluid to be satisfactory, it must satisfy three important requirements, which are that it must be very easy to use, it must not be too expensive, and it must be environmentally friendly.

Research continues in improving the properties of drilling towards meeting these requirements. In designing a drilling fluid, different types of chemicals and polymers are used to meet functional requirements such as appropriate mud rheology, density, fluid loss control property, and pH (Amanullah *et al.* 1997). Fluid-loss control property is determined by the filtration rate. Filtration rate (particle invasion) and improved characteristics of the mud cake can be achieved by using various types of flocculating materials. Water-soluble polymers are used when clays cannot be used effectively as a flocculating material. The use of polymers reduces water loss, thereby increasing effective water viscosity (API, 2001). Today, several polymers that may be natural, such as starch, and synthetic starches, like carboxymethyl cellulose (CMC), are used to control fluid loss and viscosity of drilling fluids (Nwosu and Ewulona, 2014). However, most of these polymers and chemicals that are used in formulating the drilling mud are costly and toxic to the environment; hence, the need to source cheaper local additives. Patidar *et al*. (2020) reported that though the technical performance of the drilling fluid cannot be overlooked, a vital role is played by the environmental impact of this mud and its additive as it determines the application of the mud.

A review of the literature shows that polymer reagents are the primary viscosifiers in contemporary drilling fluids. Their origin and structure, which affect their features, vary (Liu *et al*. 2020). Zausa *et al*. (2018) stated that the contribution of drilling mud in terms of the overall cost of drilling may be 15%, but it may cost 100% of the drilling problems. The choice of drilling fluid is based on four (4) factors: type of formation, temperature and pressure of formation, nature of the formation fluid, and operational factors (Medhi *et al.,* 2021). Due to their comparative advantage over other alternatives, about 80% of all wells were drilled with water-based mud (Ahmed and Ekreem, 2019). However, the use of WBM poses many challenges, such as fluid loss from mud into the formation and rheological retrogression. In the industry, polymeric materials and starches are added to the mud to enhance its performance (Intiaz *et al*. 2022). Commercial bentonite may be added to help in fluid loss control and enhance hole cleaning effectiveness. Attapulgite clay is used in brine formation as it prevents clay swelling. The filtration of drilling fluid into the drilled formation is influenced by a variety of parameters. Fluid loss into the formation leads to formation damage, decline in productivity of the well, additional drilling costs, and hydrostatic imbalance of drilling mud (Bock *et al.* 2012).

There has been a concerted research effort to find effective ways to reduce the volume of mud filtration and solid invasion (Bageri *et al*. 2020). Fluid loss control agents or materials are a group of additives specially designed to lower the volume of the filtrate that passes through the filter medium (mesh and filter paper). Specific materials are available for all types of water- and oil-based mud systems and are evaluated in static filtration tests or in various dynamic filtration tests. Fluid loss control is maintained by the viscosity of mud and an ultra-low permeability filter cake by reducing the mobility of fluid to and fro the filter cake. Additionally, the spurt loss must be close to zero to minimize base fluid invasion into the reservoir (fluid loss). The cake must be thin, tough, and easily removable. In minimizing the depth of invasion of the filtrates, filtrate viscosity plays an important role. The research of Ahmad *et al.* (2019) demonstrated how completely synthesized Gemini compound surfactants with a high molecular weight can reduce formation damage and borehole instability.

Moreover, a sealing agent is required in special situations such as vugs and fracture formations, as these non-damaging lost circulation control materials such as micronized cellulose, low-viscosity carboxymethylcellulose (CMC), and starch can improve fluid loss conditions for better results (Idress and Hasan, 2020). The filter loss may be static or dynamic. Some examples of fluid-loss control additives are polyacrylamide, polyethyleneimine, carboxymethyl cellulose (CMC), and hydroxyethyl cellulose (HEC). The latter is sometimes employed but has high foaming during mixing with slurry and is expensive (Andersen *et al*., 2019). The high cost of these fluid-loss control additives is contributed to by the cost of importation. Use of locally sourced fluid-loss control material that can offer comparatively similar performance would be a cheaper substitute. Some of these materials are environmental pollutants, toxic, and not biodegradable. Therefore, while sourcing for local material because of economic advantage, eco-friendliness should also be borne in mind.

Starch from various crops such as cassava, corn, potatoes, etc., has been used as a fluid-loss control additive (Harry *et al.* 2017; Assi, 2018; Elkatatny, 2019a; Dankwa *et al*., 2018; Elkatatny, 2019b). Al-Hameedi *et al*. (2020) used powder made from sunflower seeds as a fluid-loss control additive. Igwe and Kinate (2015) experimentally assessed the suitability of ash formed from shells of periwinkle (PSA) for use as a fluid-loss control additive in water-based drilling mud. The addition of PSA to the various mud samples improved the filtration characteristics of the formulated water-based mud. Igwilo and Zaka (2014) used local materials: “offor” (*Detariummicrocarpum*), “achi” (*BrachystegiaEurycoma),* and Pleurotus. The *Detariummicrocarpum* was used as a viscosifier, while the *BrachystegiaEurycoma* and Pleurotus were used as fluid loss control agents with slight effect on viscosity. Furthermore, the African oil bean (*Pentaclethra macrophylla Benth*) plant is a popular plant in Nigeria locally called “Ugba” by the Igbos, “Apara” by the Yorubas, and “Ukana” by the Efik. It is a tropical tree in the family Leguminosae (Mimosoideae). The tree thrives in the Eastern and Southern parts of Nigeria and has pods (husks) containing up to 10 seeds. When matured, the seed pod explosively split open, scattering its seed up to a distance of 20 m from the tree (Achinewhu, 1982). The pod (husk) is brown and woody when mature.
Therefore, the aim of this study is to investigate the potential of African Oil Bean Husk (AOBH) as a fluid loss control additive in a water-based mud.

2. Materials and Method

2.1 Materials

The materials used and their function in the WBM are presented in Table 1.

Table 1: Materials used for WBM

Materials	Function
De Ionized water	Continuous phase
Bentonite	Primary viscosifier for WBM
Barite	Weighing material
Lime	pH enhancer
Starch	Viscosifier for WBM
Grel Alphatex	Industrial fluid-loss control agent for LPLT drilling
AOBH	Test fluid-loss control additive
KCl	Shale inhibitor for WBM

The equipment used and their function(s) are presented in Table 2.

Table 2: Equipment used in testing WBM

Equipment	Function
LPLT filter press machine	Filtration property at ambient for WBM drilling condition
Baroid Mud balance	Mud density
Fann LPLT rheometer	Mud rheology of WBM
Marsh funnel viscosity	Quick viscosity measurement
FT-IR	For functional group and bond type identification
SEM-EDS	Morphology and elemental composition of AOBH

2.1.1 **Preparation and Characterization of AOBH**

AOBH was air-dried for six (6) days and pulverized with a grinder to smooth the mixture. Then the ground husks were further dried. Sieve sizes of 63 µm, 125 µm, and 250 µm were used to recover the various particle sizes. Fourier transform infrared test and SEM EDS of the sample were analyzed to ascertain the chemical and physical properties of the AOBH. A Shimadzu spectrophotometer (FTIR 8400S) was used to classify the functional groups present in AOBH. A Graseby Specac fitted with a vacuum hydraulic was used to press the sample at 1.2 psi pressure. The samples were made to pass through an infrared detector connected to a computer. With an adsorption range of 600 to 400 cm^{-1}, the sample was scanned, and the reflectance of the sample was interpreted to obtain the dominant functional group and its bond structure/type. The Phenom Prox model of the scanning electron microscope energy dispersive X-ray spectroscopy (SEM-EDS) was used to determine the morphology and elemental composition of the AOBH.

2.1.2 Mud Formulation and Preparation

Samples of WBM were formulated without fluid loss material as blank mud (Sample A). Other samples (Sample B) of WBM were formulated with 1.0 wt% of Grel Alphatex as fluid-loss additives. Also, samples (samples C, D, E, F, G, and H) of WBM were formulated with either 1.0 wt% or 2.0 wt% AOBH material made from the various particle sizes (63 µm, 125 µm, and 250 µm), respectively. The weight percent is based on the density of the base fluid; for WBM, 350 g of the 350 mL of the continuous phase. The composition of samples is presented in Table 3.

Table 3: Composition of WBM

Sample	Water (ml)	Bentonite (g)	Barite (g)	CaOH (g)	KCL (g)	Starch (g)	Fluid loss additive (g)
A	350	21.00	12.00	2.50	2.00	2.40	Nil
B	350	21.00	12.00	2.50	2.00	2.40	1.0wt% Grel Alphatex
C	350	21.00	12.00	2.50	2.00	2.40	1.0wt% 63µm AOBH
D	350	21.00	12.00	2.50	2.00	2.40	2.0wt% 63µm AOBH
E	350	21.00	12.00	2.50	2.00	2.40	1.0wt% 125µm AOBH
F	350	21.00	12.00	2.50	2.00	2.40	2.0wt% 125µm AOBH
G	350	21.00	12.00	2.50	2.00	2.40	1.0wt% 250µm AOBH
H	350	21.00	12.00	2.50	2.00	2.40	2.0wt% 250µm AOBH

2.2 Measurement of Mud Properties

The filtration properties at ambient conditions for WBM were studied. Compatibility tests (rheological property, mud density, marsh funnel viscosity, and mud pH) of these drilling fluids under the influence of the fluid loss control agent were also determined following standard procedures (API, 2001).

3. Results and Discussion

3.1 Characterization of AOBH using Fourier Transform Infrared (FTIR)

4. The data obtained from the FT-IR is presented in Table 4. As shown in the table, the FTIR spectrum analysis revealed the functional group compositions present in the sample at wavelengths spanning from 4000 to 750 cm^{-1}. The dominant functional groups present are C-H and N-H groups with wavelengths of 2924.18 cm^{-1} and 3340.82 cm^{-1}, respectively. Others include carboxylic acid, alcohols, alkenes, and thiols. The N-H is found also in primary amine. Primary amine possesses outstanding shale stability in WBMs (Muhammed *et al*. 2021; Ismail *et al*. 2015).

Table 4: Functional groups obtained from FT-IR analysis of AOBH

Group	Molecular motion	Type of vibration	Intensity	Band (cm^{-1})	Area
Benzene	$C-C$	bending	strong	709.83	16.04
Anhydride	$CO-O-CO$	stretching	strong	1018.45	5.404
primary alcohol	$C-O$	stretching	strong	1087.89	2.794
aromatic ester	$C-O$	stretching	strong	1373.36	4.09
carboxylic group	$-OH$	bending	medium	1458.23	4.709
Alkene	$C=C$	stretching	strong	1643.41	4.601
Azide	$N=N=N$	stretching	strong	2160.35	2.336
Thiol	$S-H$	stretching	weak	2522.98	1.477
Alkane	$C-H$	stretching	medium	2924.18	29.244
aliphatic primary amine	$N-H$	stretching	medium	3340.82	29.076
aliphatic primary amine	$N-H$	stretching	medium	3441.12	22.478
Alcohol	$-OH$	stretching	medium	3780.6	2.892
Alcohol	$-OH$	stretching	medium	3896.34	2.929
Alcohol	$-OH$	stretching	medium	3958.06	1.235

3.2.SEM-EDX analysis of AOBH

The SEM-EDS results obtained are presented in Figure 1. As shown in Figure 1(a), it can be seen that AOBH contains grains that are randomly and poorly bonded together with similar orientation. A non-destructive technique applied to study the morphology and chemical composition (elements) present in AOBH. As shown in Figure 2(b), The material tends to possess high amount of carbon with a weight concentration of 93.96%, other elements in the material include, potassium, copper, zinc, sodium, magnesium, silicon and calcium. Elements present and their concentration are shown in Table 5.

As shown in Table 5, the elements present in AOBH constitute mainly alkali metals. These alkali metals are responsible for keeping the pH of the drilling muds higher than that of the blank mud. It was also observed from the characterization of AOBH that it is non-toxic, biodegradable, and lack bacterial habitation. Hence, AOBH is eco-friendly. Since AOBH is eco-friendly, it can be recommended as suitable for various green product development for petroleum industry operations. Also, unlike salts, polymers, CMC that require treatments before disposing into the environment, AOBH does not require treatment before disposal. Additional cost needed for treatment before disposal can be avoided thereby making AOBH more economical (Ahmed *et. al*. 2019; Akinwumi, 2015).

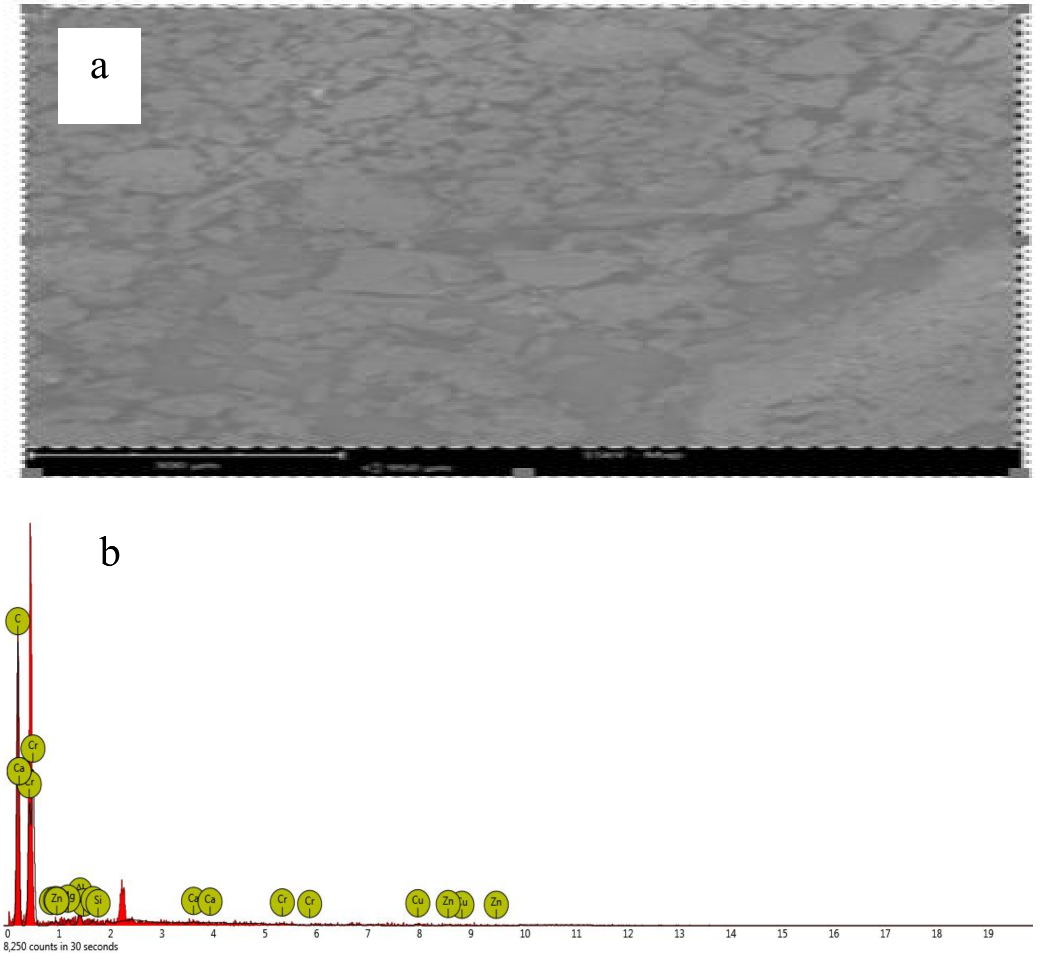

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Figure 1: SEM EDX analysis of AOBH

(a): Scanning electron microscopy. (b): Energy dispersive X-ray spectroscopy

Table 5: Elements present and their concentration

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	96.56	93.96
19	K	Potassium	1.84	1.73
29	Cu	Copper	0.73	3.55
30	Zn	Zinc	0.64	3.19
11	Na	Sodium	1.44	1.77
12	Mg	Magnesium	0.41	0.76
14	Si	Silicon	0.21	0.45
20	Ca	Calcium	0.06	0.18

3.3 Characterization of Drilling Mud

3.3.1. Filtration Property

This property of the mud is vital in ensuring that a safe and reliable filter cake is deposited on the formation wall. The thickness of the deposit must be controlled so as to maintain hole size. A very thick filter cake signifies a reduction of actual hole size, and difficulties in running tubular members in and out of the well will become inevitable. Figures 2 and Table 5 show the filtration property of WBM samples: filter cake thickness (FCT) and fluid loss (FL).

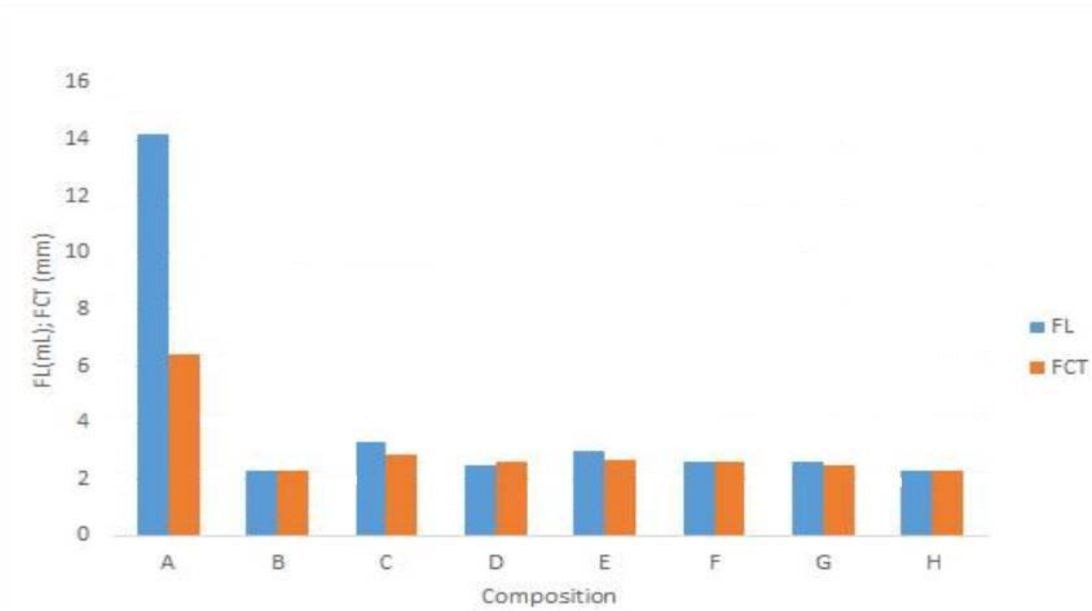

Figure 2: Filtration property of WBM: filter cake thickness (FCT) and fluid loss (FL)

Table 5: Filtration properties of WBM

Composition	WBM FL (mL)	FCT (mm)
A	14.2	6.4
B	2.3	2.3
C	3.3	2.9
D	2.5	2.6
E	3.0	2.7
F	2.6	2.6
G	2.6	2.5
H	2.3	2.3

As shown in Figure 2, drilling mud without a fluid-loss control additive has a significant amount of fluid loss to the formation (14.2 ml) with a thick filter cake (6.4 mm). The results indicate that the filter cake thickness reduced to 2.3 mm (64.1% reduction) and 2.6 mm (59.4% reduction) for commercial additive and AOBH, respectively. The results revealed that AOBH, as a fluid-loss control agent, had a closer wall-building capacity, especially with sample H.

The amount of fluid loss from the mud sample represents invasion of clear filtrate from the mud into the formation. It is a significant parameter that must be controlled so that such fluid invasion does not cause peculiar challenges. These challenges are poor logging data and not observing hydrocarbon zone and formation damage (Nwanekezie and Ogbeide, 2017). Poor logging data can result if logging tools record mud filtrate instead of in-situ fluids from the formation. Hydrocarbon zones may not be observed and hence are ignored if reservoir fluids in such zones are pushed further from the wellbore. Formation damage results if fluid invasion causes a reduction in the permeability of the formation.

Based on data presented in Figure 2 and Table 5, there was a significant loss in volume of mud. The reduction in the volume of mud is due to filtrate loss. The reduction in volume of mud by 2.3 ml represents an 83.8% reduction in the volume of the mud containing commercial fluid-loss control agent. Reduction in volume of mud by 2.7 ml, representing an 80.1% reduction in volume of the mud containing AOBH as a fluid-loss control agent. Composition H has shown similar performance with the industrial additives. From the results, the filtration property of AOBH material is acceptable because the fluid loss from all the compositions was within the acceptable range for drilling operations since the fluid loss was below or equal to 5 ml (Igwilo *et al*. 2021).

This performance could be due to larger particles of the AOBH adhering to the pore throats of the formation, thereby minimizing the spurt loss (reduced mud permeability into the formation) and proving a moderate filter cake on the formation wall (Bayat *et al*. 2018). The filtration property of AOBH is dissimilar to the use of orange peel and sunflower seed as fluid-loss control additives, where reduction of fluid loss was prominent with finer particles (Idress and Hasan 2020). The filtration property performance of the AOBH may also be due to the presence of dual strong double bond stretching of carbon/carbon and nitrogen/nitrogen/nitrogen, signifying alkene and azide, respectively, supporting the formation of thin-layered filter cake in the muds.

Moreover, the presence of a strong bending carbon-carbon single bond (C-C) on a medium stretching carbon-hydrogen single bond (C-H) representing benzene rings and alkanes, respectively, possesses the property of an asphalt, according to Ding *et al*. (2021). This possibly led to the formation of a thin plaster in the form of filter cake and also resulted in a low fluid loss from the mud.

3.3.2. Mud Density

The drilling mud density helps to control formation pressure while drilling. From the data presented in Table 6, it can be seen that the fluid loss control agent made from AOBH caused little or no reduction in the density of the drilling mud. The results are satisfactory because conspicuously high or low reduction in mud density, caused by adding mud additive, would require alteration in the drilling design. The reduction in mud density observed by adding AOBH as a fluid-loss additive is similar to that reported by Ghazali *et al*. (2015), where mud density values were almost flattened under the effect of a fluid-loss control additive made from cornstarch. For most drilling operations, the mud density values are within the range of 8.65 ppg and 9.6 ppg (Akinwumi, 2015).

Table 6: Mud Density, pH and Marsh Funnel Time of the WBM samples

Composition (WBMs)	A	B	C	D	E	F	G	H
Mud Density (ppg)	8.90	9.10	8.85	8.90	8.80	8.80	8.75	8.80
pH	8.2	8.31	8.50	8.64	8.52	8.68	8.52	8.69
Marsh Funnel Time (sec)	46.14	47.21	46.58	45.57	45.10	45.08	44.54	44.36

3.3.3. Mud pH

The hydrogen ion concentration of the WBM is presented in Table 6. The pH of the various muds tends to increase when fluid-loss agents are added. Higher pH values were obtained for mud that had AOBH as a fluid-loss additive than for mud that had the commercial fluid-loss additive. The increase in pH of the WBM that had

AOBH was due to the presence of aliphatic primary amine in the AOBH material, as revealed by FTIR data presented in 4. The aliphatic primary amine is the dominant component of the AOBH with pH values of 11-12. The aliphatic primary amine in AOBH makes the mud more alkaline. Alkalinityes not pose a serious operational challenge. Unlike acids, alkaline is non-reactive with components of the drill string. Alkaline mud will not pose a serious threat to the environment when disposed of after use.

3.3.4. Marsh Funnel Viscosity (MFV)

MFV is a quicker method adopted in observing the change in the viscosity of drilling mud. From Table 6, it can be seen that there was a proportionate slight reduction in marsh funnel viscosity and mud density under the influence of AOBH; this is in agreement with Bayat *et al*. (2018), who stated a direct relationship between viscosity and hydrostatic pressure. These reductions in marsh funnel viscosity under the influence of AOBH will cause a slight reduction in the wellbore cleaning and cutting-carrying capacity of the drilling muds, thus leading to a slightly reduced rate of penetration (ROP).

3.4.Rheological Properties of the Drilling Fluids

The rheological properties of the drilling fluids such as Average Viscosity (AV), Plastic Viscosity (PV), and Yield Point (YP) of WBM are presented in Figure 3.

3.4.1. Plastic viscosity

The PV of drilling fluid should be designed such that it will become possible for the fluid to be pumped with relative ease by the circulating equipment (mud pump). The plastic viscosity of samples is presented in Figure 3 and Appendix I. From the results presented, it can be seen that there was a reduction in PV values under the influence of a fluid-loss control agent. The AOBH possesses similar values to the commercial grade; this performance signified that the AOBH acted as a reliable solid control agent in the WBM with excellent PV values within the API range (less than 35 cp). This is in agreement with Sulaimon *et al*. (2017). The WBM formulated with the AOBH also portrayed a small reduction in rheological values (PV) similar to Patidar *et al.* (2020), where husk material made from groundnut had a moderate reduction in rheological values. The little drop in PV of the mud also signifies that the AOBH additives enhance the pumping ability of the WBM by a mud pump. This will in turn lead to a moderate reduction in the rate of annular transport of drill cuttings in the drill string annulus.

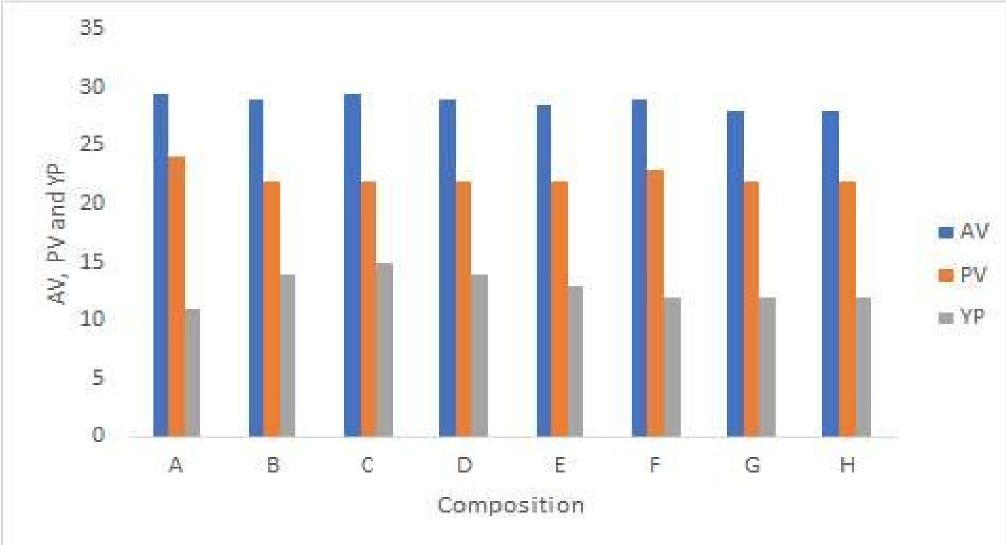

Figure 3: Average Viscosity, Plastic Viscosity and Yield Point of WBM samples**.**

3.4.2. Apparent viscosity

The apparent viscosity of a drilling fluid signifies half of a viscometer reading at 600 rpm. From the results presented in Appendix I, the AV values tend to reduce under the influence of both fluid-loss control additives. An increase in the particle size of the AOBH in the muds resulted in a further reduction in the AV values of all the drilling fluid compositions; this is in agreement with Nascimento *et al*. (2019).

3.4.3. Gel strength

The gel strength of a drilling fluid is the behavior of the mud at a time when drilling is halted and you need to initiate circulation. Drilling muds with higher gel strengths require more pressure to initiate their pumping. From Figure 3 and Appendix I, it was shown that the initial gel strength (10 seconds gel) of the WBM increased with the application of the AOBH. The final gel strength (10-minute gel) of AOBH possesses a slight influence on WBM.

3.5.Modelling the rheology of the drilling fluids

The hydraulic property of a drilling fluid is modeled to understand the behavior of the mud relating to its ability to clean the bottom of the well efficiently under certain rates at which the mud is being sheared. The rheological models adopted in this study are the power law presented in Equation (1) and the Herschel-Bulkley model presented in Equation (2), respectively.

Power law Model

$$\tau = K(\gamma)^n \quad (1)$$

Herschel-Bulkley Model

$$\tau = \tau_y + K(\gamma)^n \quad (2)$$

Where:

τ = shear stress (Ib/100ft^2)

γ = shear rate (s^{-1})

τ_y = yield shear stress

$$\gamma = 1.703 \times \text{rpm setting} \quad (3)$$

$$n = 3.32\log\frac{\emptyset 600}{\emptyset 300} \quad (4)$$

$$K = \frac{\emptyset 300}{511^{n}} \quad (5)$$

3.5.1. The power law model

The power law model is applied to non-Newtonian fluid whose shearing characteristic is a transition between the Newtonian fluid model and the Bingham plastic model. The fluid type this model is applicable to is pseudoplastic fluid, such as drilling mud. The thickness of the mud, also referred to as the consistency index (K), and the fluid behaviour index (n) are constants calculated from the rheometer readings applied in plotting the shear rate of the fluids against shear stress. According to Khamehchi *et al*. (2016), the more n values fall below 1.0, the more the fluid becomes shear-thinned and provides better hole-cleaning ability. Increasing values of K signify improved hole cleaning and suspension of drilled fragments of rock during a drilling break. The power law model plots (PLMP) of the drilling fluids as presented in Figure 4 were generated from the data in Appendix I. The PLMP for all the drilling fluids revealed that all the mud samples are non-Newtonian even under a blend of the AOBH material into the muds. From the results generated by the power law model, it can be observed that the fluid behavior index, being a major factor responsible for the bottom hole cleaning ability of the drilling mud, keeps reducing under the influence of the fluid loss control agents; the larger particle sizes of the AOBH further reduced the hole cleaning ability of the drilling mud. Also, the mud consistency index reduced under the addition of the fluid loss control materials. This signified that the AOBH will retard the hole-cleaning ability of the drilling muds marginally.

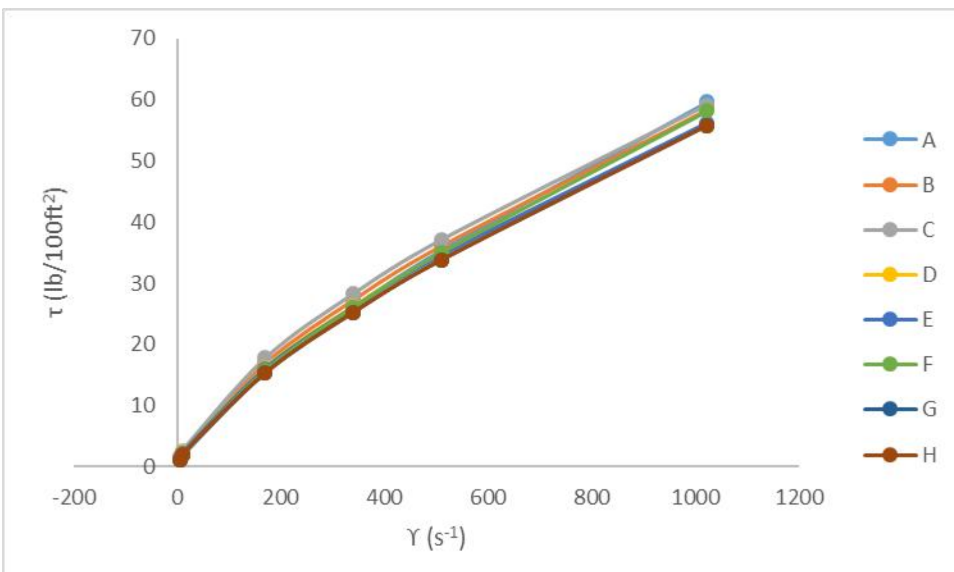

Figure 4: Power Law model plot for samples of mud

From the fitted curve presented in Figure 4 above, the drilling mud Sample A exhibited a very low shear stress at a low shear rate without a fluid loss control agent. This was due to the fact that the fluid behaviour index is higher, resulting in lower cutting removal from the wellbore. At a low rate of shear of the mud Sample B, the shear stress was high; this was attributed to the introduction of a fluid loss control material with a lower fluid behaviour index. This composition will offer a better hole cleaning. The introduction of the finest particles of AOBH (63 µm) in mud Sample C resulted in a drop of over 50% of the needed shear stress at higher shear rates (600 rpm or 1021.8 s^{-1}). This implies that the force acting on the flowing fluid becomes reduced in the presence of the additive. For the increase in the concentration of 63 µm AOBH in Sample D, there was a moderate increase in shear stress when the shearing rate of the mud was low. This was due to an increase in the fluid behaviour index and a slight drop in yield point. The power law plot containing 125 µm AOBH in Sample E portrays similar behaviour with 63 µm size at low shear rates and at high shear rates. Despite the variation of grain sizes and concentrations of AOBH in Sample F, G, and H, the fluids possess similar behaviour of shear stress at low and high shear rates. This was because the YP, n, and K had similar values.

3.5.2. Herschel-Bulkley Model

According to Andaverde *et al*. (2019), the power law model does not accurately describe the behaviour of the drilling fluid at very low shear rates (in the annulus) or the very high shear rate at the bit. The Herschel-Bulkley Model Plots (HBMP) of the drilling fluids are presented in Figure 5. The HBMP for all the drilling fluids revealed that all the mud samples are non-Newtonian even under a blend of the AOBH material into the muds. Also, yield shear stress was found to increase as the particle size of AOBH increased. From Figure 4, it was observed that the fluid behaviour index reduced under the influence of the fluid loss control agents. As the particle sizes of the AOBH increased, the hole-cleaning ability of the drilling mud reduced. Also, the mud consistency index reduced under the addition of the fluid loss control materials. This suggested that the AOBH reduced the hole-cleaning ability of the drilling muds.

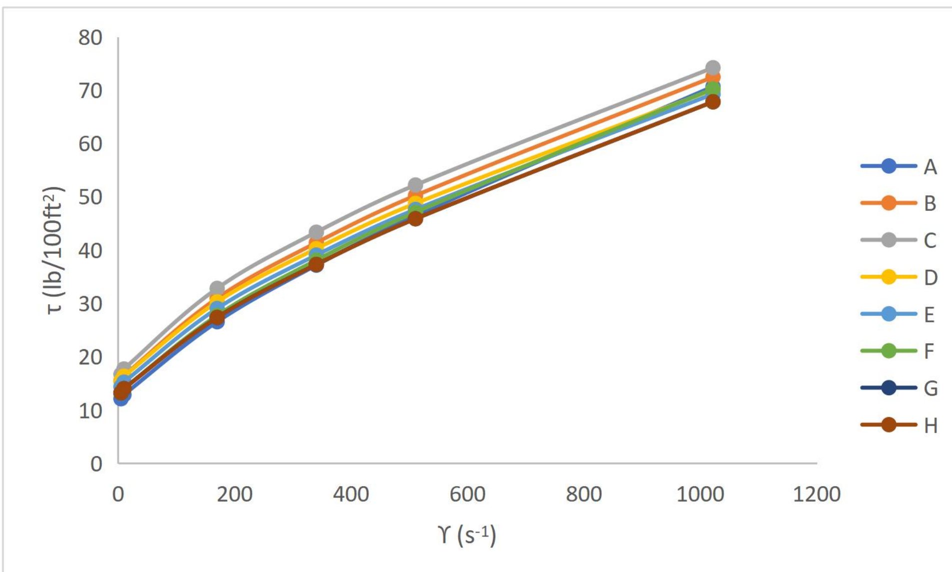

Figure 5: Herschel-Bulkley Model Plot for mud samples

From the fitted curve presented in Figure 5, it was observed that generally all the mud samples revealed a very low shear stress at low shear rate. Trend showed lower values when a fluid loss control agent was added. Also, lower shear stress at lower shear stress were observed as particles size of AOBH was reduced. Fluids exhibiting shear thinning characteristics are easier to pump during drilling (Ajieh *et al*. 2022). For all the models considered, the newly formulated drilling muds exhibited similar characteristics with the contemporary industrial drilling muds, which further suggests that ABOH can effectively function as an additive in drilling mud.

Conclusion

Based on the experimental investigation, the following conclusion can be advanced. The locally sourced material (AOBH) was non-toxic, biodegradable, and lack bacterial habitation. It is cheaper to obtain and eco-friendly. Also, AOBH possesses similar performance with the foreign fluid loss control agent as applied to

WBM. The AOBH is suitable for drilling all formation types based on its filtration properties. The performance of the AOBH yielded excellent performance in filtration property of mud in drilling through all type of formations as regards pressure and temperature. This performance was aattributed to asphalt property observed from the FTIR test result. There was a fractional reduction in the rheology of all the mud samples blended with AOBH.

All the drilling fluids under the influence of this local additive were all non-Newtonian based on the power law model applied in modelling the rheological data obtained from rheometer. The utilization of AOBH tends to reduce the shear stresses in all mud samples at low and high shear rates. The larger the particle sizes, the lower the wellbore cleaning tendency of the drilling fluids. Compatibility rests revealed a reduction in the mud density and marsh funnel viscosity in the presence of AOBH but the mud pH increases. The increase in mud pH leading to a more alkaline mud, this applicable in drilling salt dome formations. All observed values fell within the API approved range. With the performance recorded from these experimental investigations, the AOBH can be applied in wellbore drilling using WBM. Therefore, it could be concluded that AOBH can be recommended as an additive in WBM.

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Appendix I: Rheological properties of the WBM

Composition (WBMs)	A	B	C	D	E	F	G	H
ϴ600	59.0	58.0	59.0	58.0	57.0	58.0	56.0	56.0
ϴ300	35.0	36.0	37.0	36.0	35.0	35.0	34.0	34.0
ϴ200	24.0	23.0	24.0	23.0	24.5	24.0	23.5	23.0
ϴ100	14.0	15.0	15.5	14.5	14.0	13.5	13.0	13.0
ϴ6	9.0	10.0	10.0	10.5	10.0	9.0	9.5	9.0
ϴ3	3.0	3.5	4.0	3.0	3.5	3.0	3.0	2.8
10sec Gel	2.0	2.3	2.5	3.0	2.5	2.5	2.7	2.5
10 min Gel	6.0	6.0	5.0	6.0	5.7	5.6	5.8	6.0
AV	29.5	29.0	29.5	29.0	28.5	29.0	28.0	28.0
PV	24.0	22.0	22.0	22.0	22.0	23.0	22.0	22.0
YP	11.0	14.0	15.0	14.0	13.0	12.0	12.0	12.0
n	0.75	0.69	0.67	0.69	0.70	0.73	0.72	0.72
K	0.33	0.49	0.57	0.47	0.44	0.37	0.38	0.38