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Review Article

Assessing the Rheological and Filtration Loss Control Potential of Selected Plant-Based Additives in Oil-Based Mud

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Abstract

In drilling operations, chemical additives pose environmental concerns during mud disposal. This study evaluated three plant-based additives, namely rice husk (RH), *Detarium microcarpum* (DM), and *Brachystegia eurycoma* (BE), in oil-based mud at low-pressure, low-temperature conditions. The mud's rheological profile followed Herschel Bulkley's model. With 8 g additive content, RH increased the mud's apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) by 62.5%, 51.25%, and 34.38%, respectively. DM showed higher increases of 200.0%, 195.0%, and 162.5%, while BE exhibited the most significant improvements of 287.5%, 272.5%, and 250.0%. The filtration tests indicated that RH reduced spurt loss and fluid loss volumes by 83.33% and 62.35%, while DM decreased by 82.41% and 47.94%, as BE had the highest reduction of 94.44% and 51.18%. Again, the filter cake thickness of RH, DM, and BE muds increased by 210.29%, 273.53%, and 79.41%, respectively, with permeabilities of 8.90×10^{-3} mD, 11.87×10^{-3} mD, and 7.35×10^{-3} mD. Furthermore, the mud susceptibility to NaCl showed that AV decreased for RH, DM, and BE, while YP decreased significantly. The filter cake thickness and permeability increased by 62.38 and 359.55% for RH, as the DM decreased by 93.80% and 84.37% and the BE by 96.68% and 96.62%, which indicates that RH is more susceptible to NaCl than DM and BE in the mud. Also, these plant-based additives in mud exhibited fragile gel strength and commendable cake characteristics: firm, smooth, and soft/slippery, which make them potentially suitable for oil well drilling.

Keywords

Rice Husk, *Detarium Microcarpum*, *Brachystegia Eurycoma*, Rheological Properties, Filtration Loss Properties, Salt Contamination, Drilling Mud

1. Introduction

In oil and gas exploration, one of the components of the hydrocarbon well drilling operation is the drilling fluid. In the petroleum industry, drilling fluid is called drilling mud, which functions as "the blood of the drilling process" [1]. According to Agwu et al. [2], drilling fluid is the 'architect' that makes the drilling operation achievable. Villada et al. [3] posited that

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its design and formulation are necessary for a successful drilling operation and performance. Hence, the success of drilling a well to the desired depth/targets depends on the functionality of the drilling fluid used. There are four distinct drilling fluids: water-based, oil-based, pneumatic and synthetic-based [4]. Over the years, the petroleum industry has stuck to the use of water-based and oil-based drilling muds. Conventionally, drilling fluids are applied to achieve the proper functioning of the drilling process by performing some roles [5]. These functions include but are not limited to transporting the drill cuttings to the surface, cooling and lubricating the drilling bit, controlling the formation pressure, consolidating the wall of the wellbore, sealing off permeable formations, controlling the formation damage, etc. [2, 5-7]. Among the enumerated drilling fluid functions, lifting the drill cuttings to the surface and sealing the wellbore walls to prevent filtration in the well and stuck pipe while drilling the hole are the major ones [8]. Thus, drilling fluids are tailored to effectively construct a well [9]. Also, Abdo and Haneef [10] reported that careful selection of drilling mud type is essential to avert drilling problems like formation damage, wellbore instability, and drag and torque reduction. Therefore, selecting the appropriate drilling mud requires experience and an understanding of drilling engineering to prevent drilling problems [11]. Besides, Anawe-Paul et al. [12] maintained that the choice of the drilling fluid used for a drilling operation is contingent on many complex factors, namely well design, well pressures, temperature, type of formation to be encountered and cost. For the drilling cost, about 25% of oilfield exploration expenses are on drilling [13], while drilling fluid cost is between 15 and 30 percent of the drilling cost [14].

According to Borah and Das [5], the formulation of drilling fluids with different properties depends on the formations drilled at different depths and conditions. Also, Oseh *et al.* [15] added that an optimal drilling system is achieved when the drilling mud's filtration, viscosity, and density remain unchanged throughout the drilling operation. Therefore, as enumerated earlier, achieving the cardinal functions of drilling fluids involves adding conventional chemical additives to the mud system [16]. Regrettably, the chemical (mostly non-biodegradable) additives pose several challenges because of environmental and personnel safety issues [5, 17]. Al-Hameedi et al. [14] and Borah and Das [5] reported that some of these additives with potential effects include caustic soda, sodium chloride, polyamine potassium chloride and potassium sulfide. Also, Okon et al. [8] reported that most of the additives used for drilling operations are foreign and expensive. Hence, this implies that the high cost of drilling additives would impact the overall well drilling cost. To ameliorate the mentioned drawbacks, biodegradable and eco-friendly materials have been considered alternatives to conventional additives in drilling operations to cushion their toxic impact on the ecosystem and the cost of drilling fluids [18]. The quest for eco-friendly materials that can optimize the drilling process and minimize the cost of drilling fluid is gaining momentum. Extensive research has been conducted on using various plant-based materials as additives in drilling fluids. Agwu and Akpabio [19] and Borah and Das [5] comprehensively review studies on eco-friendly materials as additives in drilling mud, especially water-based mud. Some of these works and recent ones are reported in Table 1. Available works indicate that several plant-based materials have been evaluated for suitability as additives in water-based mud. They serve as pH enhancers, rheology modifiers, and filtration loss controllers in low-pressure, low-temperature (LPLT) conditions, with a few concerns at high-pressure, high-temperature conditions. In the same direction, the limited works available for oil-based mud, as presented by Adebeyo and Chinonyere [20], Anawe-Paul et al. [12] and Katende et al. [13], are evaluated at the mentioned conditions and tests: rheology and filtration properties for water-based mud. The list of these plant-based products is extensive and includes banana peels and trunk, bagasse, coconut shell and fiber, corn cob and starch, cotton, sunflower and date seeds, psyllium, rice and groundnut husks, among others. Okon et al. [8] maintained that these plant-based products are either cellulose or hydrocolloid-based additives with the potential to perform some functions in drilling mud. They evaluated and reported the effectiveness of rick husk (cellulose-based), *Detarium microcarpum* and *Brachysteria eurycoma* seeds (hydrocolloid-based) as additives in water-based mud. To further propagate the potential of these plant-based materials as additives in drilling mud, the forte of this study is to evaluate their rheological and filtration loss control performance and susceptibility to salt contamination in oil-based drilling mud.

Table 1. *Some works on eco-friendly materials as additives in drilling mud.*

	Author	Materials	Content /Concentration	Particle Size	Mud Type	Test	Test Conditions	Findings / Results
i.	Okon et al. [9]	Rice husk	5, 10, 15, and 20 g	125 µm	WBM	Filtration	LPLT: 100 psi and room temp.	A fluid loss reduction of 64.89% was achieved with 20 g additive content.
ii.	Amanullah et al. [21]	Date seed powder	6 g	< 150 µm	Fresh and salty	Fluid loss	HPHT: 500 psi and	Fluid loss reductions of 60.43% and 63.41% were achieved for the fresh and salty WBM, re-

	Author	Materials	Content /Concentration	Particle Size	Mud Type	Test	Test Conditions	Findings / Results
					WBM		100°C	spectively.
iii.	Davoodi et al. [18]	Pistachio shell powder	9 g	> 75 µm 120 – 180 µm	WBM	Filtration loss	LPLT and HPHT	Fluid loss reductions of 44% and 39% were achieved at the LPLT and HPHT conditions, respectively.
iv.	Al-Hameedi et al. [17]	Grass powder and starch	3.5, 7.0 and 10.5 g	N/A	WBM	Filtration loss	LPLT: 100 psi and 75 °F HPHT:500 psi and 250 °F	Fluid loss reductions of 45% and 26% were achieved at the LPLT and HPHT conditions, respectively.
v.	Katende et al. [13]	Nanosilica	0.5, 1.0, and 1.5 ppb	14 µm	WBM and OBM	Fluid loss reducer and Rheological properties	High temp: ambient – 300 °F HPHT filtration test	The nanosilica improves the rheological properties of both WBM and OBM. However, its performance for HPHT fluid loss was not successfully improved.
vi.	Ghaderi et al. [22]	Saffron purple petals	1, 2, and 3 wt.%	N/A	WBM	Rheological, filtration and corrosion	LPLT:100 psi and 25°C	Filtrate volume reductions of 23.7, 36.6 and 45.0% for 1, 2, and 3 wt.% additive, respectively, were achieved.
vii.	Al-Hameedi et al. [14]	Black sunflower seeds' shell powder	0.5 – 3.5 wt.% (i.e., 3.5 – 24.5 grams)	52 – 400 µm	WBM	Rheological and fluid loss measurements	LPLT: 100 psi and 75 °F HPHT:500 psi and 250 °F	Increasing the concentration of the additive increased the yield point with less impact on plastic viscosity. Also, the filtration characteristics of the additive for both LPLT and HPHT were comparable to those of the standard polymer.
viii.	Davoodi et al. [23]	Acorn shell powder	3, 5, 7, and 9 g	100 – 350 µm	WBM	Rheological and filtration	LPLT and HPHT	Filtration reductions of 80.1% and 63.3 for HPHT and LPLT, respectively, were achieved.
ix.	Yalman et al. [11]	Rice husk ash	2 – 15 wt.%	102.39 µm	WBM	Rheological and filtration	LPLT: Room temp and 0.68 MPa	With 4 wt.% content, a fluid loss reduction of 10% was achieved, while apparent viscosity and yield point increased by 60% and 183%, respectively, with 15 wt.% content.
x.	Ebrahimi and Sanati [24]	Alyssum seeds	0.5 and 1.0 wt.%	N/A	Water and brine-based muds	Rheological and filtration	LPLT	Fluid loss reductions of 34.48% for WBM and 35.01% for salty WBM were achieved.
xi.	Boyi and Amadi [25]	'Ukpo', 'Achi' and 'Ofor'	5, 10, 15, and 20 g	N/A	WBM	Rheological properties	N/A	The local additives showed potential to be used as a substitute for standard viscosifier (PAC-R)
xii.	Ajiri et al. [26]	Sawdust and Coconut fiber	2.5 and 5.0 g	N/A	WBM	Fluid loss	LPLT	A fluid loss reduction of 23.68% was achieved with 50:50 composite additives.
xiii.	Ali et al. [27]	Potato powder	0.5, 1.0, and 2.0 wt.%	5 – 600 µm	WBM	Filtration, Rheological & Morphological	LPLT: 100 psi and 25, 50 & 75°C, HPHT:1800 psi and 500 °F	The potato powder provides better filtration and rheological properties with fluid loss reduction of about 43.5% at the additive concentration of 1 wt.%

2. Materials and Methods

2.1. Samples Collection and Preparation

Figure 1 shows the experimental procedures for preparing the plant-based materials (i.e., pre-experimental processes) and the steps to execute the study. Okon et al. [8] reported an overview of the plant-based materials. The rice husk (Figure 2) was from a mill in Ini Local Government Area as the *Brachystegia eurycoma* and *Detarium microcarpum* seeds (in Figures 3 and 4) were bought from a market in Uyo Local Government Area, both locations in Akwa Ibom State, Nigeria. The pre-experimental procedures (namely drying, grinding and sieving) involved in the sample preparation are as reported in the earlier work by Okon et al. [8]. Figures 5 through 7 depict the ground samples of the plant-based products.

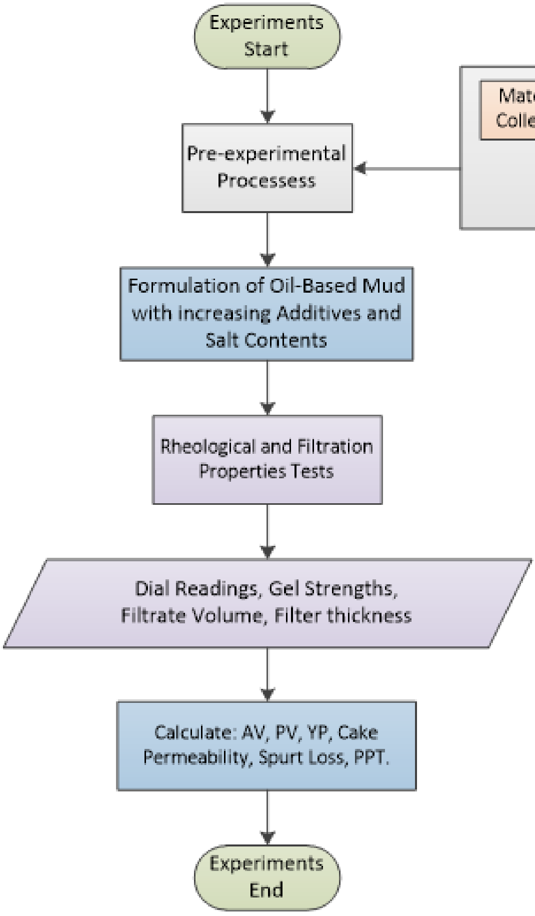

Figure 1. *Flowchart of the experimental procedures of the study.*

Figure 2. *Rice husk.*

Figure 3. *Brachystegia eurycoma.*

Figure 4. *Detarium microcarpum.*

Figure 5. *Ground* Rice husk.

Figure 6. *Ground Brachystegia eurycoma.*

Figure 7. *Ground Detarium microcarpum.*

2.2. Mud Samples Preparation

Seventy-eight (78) mud samples were formulated based on the American Petroleum Institute (API) specification API B-12 and standard for non-treated bentonite (i.e., 25 g to 350 ml base fluid). The API B-12 recommended oil-to-water ratio is 60 to 40, meaning 240 ml of diesel oil to 110 ml of distilled water, as shown in Table 2. The four types of mud formulated were blank mud (BM), rice husk mud (RH), *Brachystegia eurycoma* mud (BE) and *Detarium microcarpum* mud (DM). Based on these muds' additives content (in grams), the RH, BE, and DM mud samples were divided into four sets and labelled SET-1, SET-2, SET-3 and SET-4 for 2, 4, 6 and 8 g content. The composition of the mud samples is in Table 2. Using a high-speed mud mixer (Hamilton Beach, in Figure 8), a homogeneous mixture of the mud samples (Figures 9 and 10) was obtained and allowed to age for twenty-four (24) hours. Then, the mud samples' rheological properties and filtration loss characteristics were determined. The mud rheological properties were apparent viscosity (AV), plastic viscosity (PV), yield point (YP) and gel strength. The filtration characteristics were spurt loss volume, fluid loss volume, filter cake thickness, mud cake permeability, static filtration rate and permeability plugging test volume. The mud's rheological properties and filtration performance were determined using the API-recommended practice for field testing for drilling fluids. Thus, the API low-pressure low-temperature (LPLT) filtration test standard is one hundred (100) psi and thirty (30) minutes.

Table 2. *Basic mud components.*

Mud components	Additive function	Content	Mixing order	Mixing during (min)
Diesel and distill water (ml)	Base fluids	350	1	--
Bentonite, (g)	Primary viscosifier	25	2	5
Barite, (g)	Densifier	10	3	5
Soda ash, (g)	pH control	0.25	4	2
Emulsifier, (ml)	Proper mixing of the base fluids	2.0	5	5
Rice husk, (g)	Fluid loss control additive	2, 4, 6, 8	6a	5

Mud components	Additive function	Content	Mixing order	Mixing during (min)
Detarium microcarpum, (g)	Fluid loss control additive	2, 4, 6, 8	6b	5
Brachystegia eurycoma, (g)	Fluid loss control additive	2, 4, 6, 8	6c	5
Sodium Chloride, (g)	Contaminant for the mud salinity susceptibility test	1, 2, 3, 4, 5	7	5

Figure 8. *High-speed mud mixer.*

Figure 9. *Some mud samples (side view).*

Figure 10. *Some mud samples (plan view).*

In practice, drilling through a formation to several thousand feet, the possibility of encountering a salt dome (i.e., salty formation) with salt cations of sodium, calcium and magnesium cannot be rolled out [7]. The formation's salt content will undoubtedly affect the drilling mud's rheological and filtration loss performances directly or indirectly [7, 28]. With this in mind, the mud samples were assessed at varied salt contents (1, 2, 3, 4, and 5 g) to determine these selected plant-based additives' rheological and filtration loss control capability in oil-based mud. The results obtained from the various tests were noted and recorded.

2.3. Mud Rheological Properties Measurement

Udoh and Okon [29] stated that the mud rheological properties determined from rotational viscometer (Fann V-G) are more reliable than those from marsh funnel. In this study, Fann V-G in Figure 11 was used to determine the mud samples' rheological trend and parameters, like apparent viscosity (AV), plastic viscosity (PV) and yield point (YP), from their dial readings at different rotational speeds (revolution per minute, rpm). Before determining mud properties, the Fann V-G viscometer was calibrated/standardized using distilled water to ensure consistency in its measurement. Then, the viscometer cup was filled to the scribed position with the mud sample to be measured and placed on the viscometer base. Afterward, the cup was raised to immerse the rotary sleeve to the "fill line" mark and clamped to the viscometer stand at that position. The power button was on to set the speed selector knob to 600 rpm. Its dial reading was recorded at a stable dial reading for the mentioned speed. Also, the 300-rpm dial reading was determined by adjusting the selector knob. From the values (dial readings) obtained, the mud samples' apparent viscosity, plastic viscosity and yield point were determined using Equations 1 through 3 [9].

$$AV = \left(\frac{\theta_{600}}{2}\right) \tag{1}$$

$$PV = \left(\theta_{600} - \theta_{300}\right) \tag{2}$$

$$YP = \left(\theta_{300} - PV\right) \tag{3}$$

Figure 11. *Fann V-G viscometer.*

Another significant mud rheological property is its gel strength (thixotropy). Therefore, the potential of the selected plant-based additives to suspend drill cuttings was determined using 10 seconds and 10 minutes of gel strength. For the 10-second gel strength determination, the rotary sleeve was set at 600 rpm to spin the mud sample to be measured for 10 seconds. Then, the selector knob was regulated to 3 rpm, and the viscometer was turned off to enable the mud sample to settle for 10 seconds. With the flip toggle reversed to the low position, the highest dial reading was the 10 seconds or initial gel strength. Again, the same procedure was implemented for 10 minutes of gel strength, only for the mud sample to settle for 10 minutes. With the flip toggle switched to the rear position, the maximum deflection on the viscometer was the 10-minute gel strength.

2.4. Mud Filtration Loss Test Procedure

As earlier alluded, the filtration loss control test of the selected plant-based additives in oil-based mud was based on the API specification for the LTLP static filtration test. The Ofite filter press stack (Figure 12) has six (6) test cells (cylinders) that contain the mud samples placed on it. The filter papers – Whatman No. 50, were fixed to the bottom of the test cells using rubber gaskets. The mud samples to be tested were put into the cylinders and covered (firmly) with the appropriate top rubber gasket to ensure no pressure losses during the test. The necessary connections from the cylinder cover to the filter press stack to the 2.5 horsepower air compressor (Figure 13) were made to pressurize the filter press. The T-valve on the filter stack was released to allow airflow into the various test cells as the pressure in the cells was monitored through the pressure gauge. When the required pressure of 100 psi was established in the test cells, the airflow to the cylinders was cut off at the T-valve. The test cells were allowed to stand, and then the mud filtrates from the cells were collected using calibrated cylinders placed under the test cells. The filtrates (fluid loss) volume (in millilitres, ml) for 5, 7.5, 10 and 30 minutes were recorded as the mud samples' fluid loss volume. After 30 minutes, the pressure in the cells was released through the passive valve on the test cells. Afterward, the test cells were opened to access the filter papers. The thickness of mud residues on the filter papers was measured using a vernier caliper and recorded (in millimeters, mm) as the mud samples' cake thickness.

Other filtration and bridging analyses of the selected plant-based additives were their spurt loss volume, permeability plugging test (PPT) volume, static filtration rate, and mud cake permeability determination. The spurt loss volume (V_{sp}) of the mud samples was determined using Equation 4.

$$V_{sp} = 2\left[2V_{7.5} - V_{30}\right] \tag{4}$$

where V_{sp} is the spurt-loss volume, and $V_{7.5}$ and V_{30} denote filtrate volumes obtained at 7.5 minutes and 30 minutes, respectively. Equations 5 and 6 were used to determine the mud sample's PPT volume and static filtration rate.

$$V_{PPT} = 2V_{30} \tag{5}$$

$$q_{sf} = 0.7302\left[V_{30} - V_{7.5}\right] \tag{6}$$

where V_{PPT} is the permeability plugging test volume, q_{sf} represents the static filtration rate and $V_{7.5}$ and V_{30} are as denoted in Equation 4. Again, to estimate the mud sample cake permeability, the mud filtrate (in Figure 14) viscosity was determined using a kinematic viscosity bath (Figure 15). Then, the mud samples' cake permeability was determined using Equation 7. Further details for the development of Equation 7 are available in the works of Rautela [30], Lomba [31] and Okon et al. [8].

$$k = 8.95 \times 10^{-5} q_w \varepsilon \mu \tag{7}$$

where k is the cake permeability in millidarcy (mD), q_w denotes the fluid loss volume in a cubic centimeter (cm^3), ε represents the filter cake thickness in millimetre (mm) and μ is the mud filtrate viscosity in centipoise (cP) [8].

Figure 12. *Ofite filter press stack.*

Figure 13. *Air compressor pump.*

Figure 14. *Some mud samples filtrate.*

Figure 15. *Kinematic viscosity bath.*

3. Results and Discussion

3.1. Rheological and Filtration Loss Control Properties Performance of the Local Materials

3.1.1. Rheological Properties Performance

The rheological properties of the various muds with the local additives are presented in Figures 16 through 18 and Table 3. Figures 16 through 18 show the rheological trends: shear stress versus shear rate profiles of the various formulated mud samples. From these figures, the mud samples: blank mud, rice husk mud, *Detarium microcarpum* mud, and *Brachystegia eurycoma* mud, with different additives content, exhibited the Herschel Bulkley rheological model. This characteristic of the mud samples implies that they are yield point dependent. This rheological parameter of the mud samples means they would require some forces to initiate their flow during the drilling operation. These mud rheological trends improved as the additive concentrations in the mud samples increased. Again, looking at these mud rheological profiles, the rice husk mud with an additive content of 6 g was higher than the blank mud (Figure 16). The same was true for the *Brachystegia eurycoma* muds' rheological trends, which were higher than the control mud from the 2 g additive contents (Figure 18). Also, the *Detarium microcarpum* mud rheological trend was higher than the blank mud profile, except for the 2 and 4 g, which was close to the control mud trend at the low shear rate (Figure 17). Therefore, the additive content of these selected plant-based materials in the formulated mud samples has improved the viscosity (rheology) of the mud samples.

Table 3 presents the rheological parameters: plastic viscosity (PV) and apparent viscosity (AV) at varying additive contents of the mud samples. The table showed increases in the mud samples' PV and AV as their additive contents increased. Thus, the muds' PV and AV increase at 8-gram additive content showed a PV increase of 62.5% for rice husk mud, 200% for *Detarium microcarpum* mud, and 287.5% for *Brachystegia eurycoma* mud, and AV of 51.25%, 195.0% and 272.5% for rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud, respectively. The results showed that these local additives *Detarium microcarpum* and *Brachystegia eurycoma*, which are hydrocolloid-based materials, are more effective than rice husk – cellulose-based materials. The mud viscosity improvement further increased the yield point (YP), as presented in Table 3. At 8 g additive content, the mud samples YP resulted in 34.38%, 162.5% and 250.0% increase for rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud, respectively. The yield point to plastic viscosity ratio (YP/PV) of the various mud samples was within the American Petroleum Institute (API) specification of less than 3 lb/100ft^2/cP, as indicated in Table 3. The YP/PV values of the mud samples mean that the mud is stable [32] and would be pumpable with good hole cleaning [33, 34]. Therefore, it is noted that the rheological trend and parameters of the muds increase as their additive concentrations increase. This observation is because the increased additive contents enhance the attractive forces among the mud particles that improve viscosity and high yield point [35]. This outcome is in line with the findings from the works of Okon et al. [8] and Veisi et al. [36], which mentioned that increased additive concentration increases mud rheological characteristics.

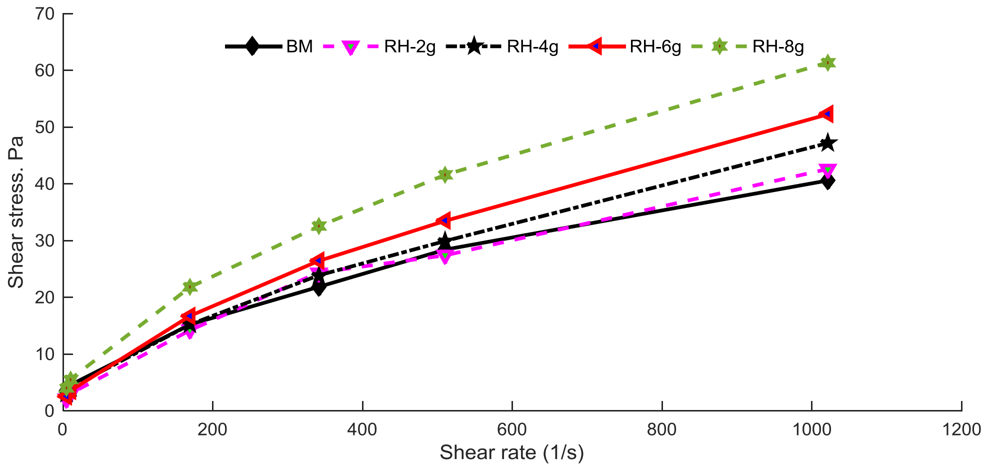

Figure 16. *Shear stress-shear rate profile of the rice husk muds with the blank mud.*

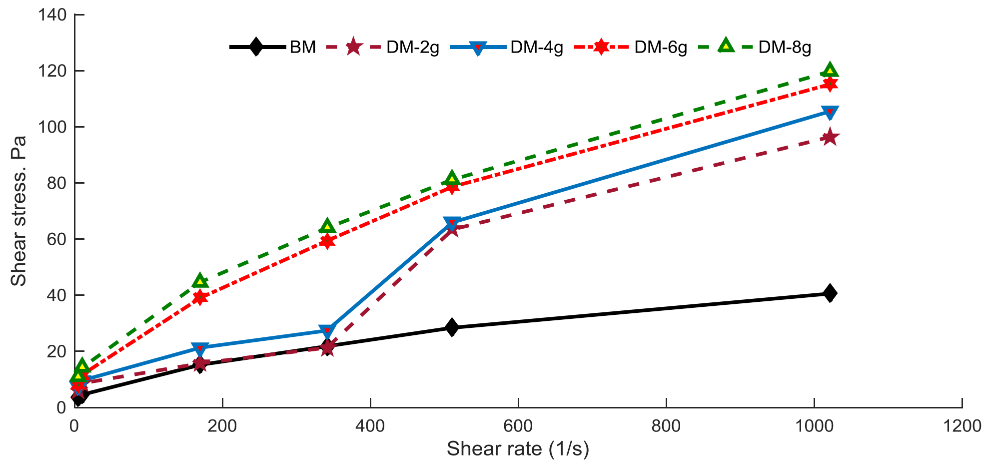

Figure 17. *Shear stress-shear rate profile of the Detarium microcarpum muds with the blank mud.*

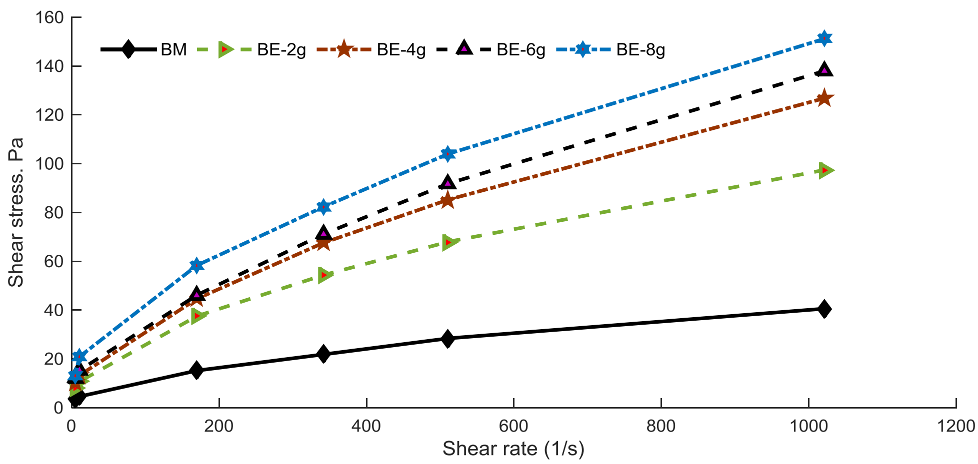

Figure 18. *Shear stress-shear rate profile of the Brachystegia eurycoma muds with the blank mud.*

Table 3. Rheological properties of the various mud samples at different additive concentrations.

Mud Samples Type	BM	RH mud				DM mud				BE mud			
Additives Content		**2g**	**4g**	**6g**	**8g**	**2g**	**4g**	**6g**	**8g**	**2g**	**4g**	**6g**	**8g**
Plastic viscosity, cP	24.0	30.0	34.0	37.0	39.0	65.0	78.0	72.0	76.0	58.0	82.0	91.0	93.0
Apparent viscosity, cP	40.0	42.0	46.5	51.5	60.5	95.0	104.0	113.5	118.0	96.0	125.0	136.0	149.0
Yield point, Ib/100ft^2	32.0	24.0	25.0	29.0	43.0	52.0	60.0	83.0	84.0	76.0	86.0	90.0	112.0
YP/PV ratio	1.33	0.80	0.74	0.78	1.10	0.92	0.67	1.15	1.11	1.31	1.05	0.99	1.20

On the other hand, Table 4 presents the 10-second-10-minute gel strength performance of the various mud samples at different additive contents and varying viscometer (rotor) speed combinations. The results revealed that the mud's gel strength increased as its additive contents increased. The reason for this increase in the mud gel is observed in the mud samples' plastic viscosity and yield point. At 8 g additive content, the mud samples' 10 seconds gel strength increased on average 41.30% for rice husk mud, 76.09% for *Detarium microcarpum* mud and 184.07% for *Brachystegia eurycoma* mud. In contrast, the 10-minute gel strength increase was 35.48%, 70.95% and 180.63% for rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud. After a look at these results and the values in Table 4, it is noted that most of the various mud samples have flat or fragile gel strength, as the difference between the 10-minute and 10-second gel strength values is not high. Practically, this observation implies that these muds' gel strength during mud circulation will not increase significantly after tripping out of the hole. Thus, the flat-gel characteristic of the mud samples is desirable for minimal mud pump power requirement and to avoid pipe sticking after no mud circulation period. Furthermore, the results in Table 4 revealed that the mud gel strength values obtained are less dependent on the rotor speed combinations used for the determination. Again, the gel strength performances of these selected plant-based materials showed that the hydrocolloid-based additives, *Detarium microcarpum* and *Brachystegia eurycoma*, are higher than the cellulose-based additive – rice husk.

Table 4. Gel strength results for the various mud samples at different viscometer speed combinations.

Viscometer Speed (rpm)	Additive Content	10 seconds / 10 minutes Gel Strength				
			2g	**4g**	**6g**	**8g**
600/300	BM	47/53				
	RH		48/54	47/50	50/55	65/70
	DM		60/75	75/90	90/100	88/95
	BE		86/97	80/97	102/110	140/160
200/100	BM	46/52				
	RH		47/52	45/50	50/55	60/65
	DM		55/73	55/60	75/85	80/90
	BE		80/90	75/95	100/105	132/145
6/3	BM	45/50				
	RH		45/50	50/55	55/60	70/75
	DM		50/70	45/50	70/80	75/80
	BE		85/95	70/90	90/100	120/130

3.1.2. Filtration Loss Control Properties Performance

Drilling mud filtration characteristics are determined to establish the fluid loss (filtrate) and bridging potential of the mud. This assessment is necessary to avert formation damage and pipe sticking during drilling operations. Thus, Table 5 shows the fluid loss results of the variously formulated muds at different control additive concentrations. From these results, the fluid loss volume of the mud samples decreased as the control additive contents increased, which is inconsistent with the work by Okon et al. [8]. The fluid loss control improved as the additive contents increased because more particles were available in the mud to interact, bind and become cohesive to reduce filtrate losses. The API filtration and bridging performance of the mud samples at various additive concentrations are in Table 6. From these results, the spurt loss that expressed the filtrate volume through the filter medium before the fluid-controlling filter cake is formed exhibits a decreasing tendency as the additive contents increase. Also, the API fluid loss of the muds exhibited the same trend as the spurt loss volume. Of course, this observation is necessary as these filtration parameters are mutual. Again, the permeability plugging test (PPT) volume and static filtration rate of the mud samples depict the same tendency as spurt loss and fluid loss volumes. In other words, these filtration properties of the mud samples are directly dependent on the control additive concentration. At 8 g additive concentration, the rice husk mud fluid loss volume was 12.8 ml, less than the API specification of 15 ml. However, the *Brachystegia eurycoma* mud and *Detarium microcarpum* mud resulted in fluid loss volumes of 16.6 ml and 17.7 ml, respectively, slightly above the API standard. The formulated muds' spurt loss and fluid loss (filtrate) volumes were reduced by 83.33% and 62.35% for rice husk mud, 82.41% and 47.94% for *Detarium microcarpum* mud, and 94.44% and 51.18% for *Brachystegia eurycoma* mud. Furthermore, the static filtration rate of the muds resulted in 52.54%, 31.88% and 31.05% reduction for rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud, respectively. From these analyses, it is expedient to state that the spurt loss of the mud would be minimal with *Brachystegia eurycoma* than with rice husk and *Detarium microcarpum*, as rice husk is a more effective fluid loss control additive than *Detarium microcarpum* and *Brachystegia eurycoma*.

Table 5. *Fluid loss volume of the various mud samples at different additives content and test time.*

Mud sample type	BM mud	RH mud				DM mud				BE mud			
Additives content		2g	4g	6g	8g	2g	4g	6g	8g	2g	4g	6g	8g
Time (min)	Fluid loss volume (ml)												
5.0	20.4	16.4	10.5	8.0	5.8	14.7	10.4	9.8	7.8	14.2	10.4	7.4	6.8
7.5	22.4	18.6	14.2	10.6	7.3	17.6	12.4	11.6	9.8	18.2	12.6	9.2	8.6
10.0	26.4	24.0	18.8	12.8	8.0	23.0	18.8	17.2	16.0	20.4	18.8	10.4	9.8
30.0	34.0	30.0	24.6	18.4	12.8	29.6	21.5	20.6	17.7	30.0	22.0	17.4	16.6

Table 6. *Filtration and bridging performance of the various mud samples at different additive contents.*

Mud samples type	BM mud	RH mud				DM mud				BE mud			
Additives content		2g	4g	6g	8g	2g	4g	6g	8g	2g	4g	6g	8g
Spurt loss, ml	21.60	14.40	7.60	5.60	3.60	11.20	6.60	5.20	3.80	12.80	6.40	2.00	1.20
API fluid loss, ml	34.0	30.0	24.6	18.4	12.8	29.6	21.5	20.6	17.7	30.0	22.0	17.4	16.6
Perm. plugging test, ml	68.0	60.0	49.2	36.8	25.6	59.2	43.0	41.2	35.4	60.0	44.0	34.8	33.2
Filtration rate, ml/min$^{1/2}$	8.47	8.32	7.59	5.70	4.02	8.76	6.64	6.57	5.77	8.62	6.86	5.99	5.84
Filter cake thickness, mm	0.68	1.02	1.04	1.37	2.11	1.32	1.75	1.93	2.54	3.40	2.99	2.77	1.22
Mud cake perm., 10^{-3} mD	8.06	10.80	9.53	9.03	8.90	14.18	12.54	12.33	11.87	37.04	23.88	17.50	7.35

Other filtration parameters of the mud samples that depict the mud bridging characteristics are their filter cake thickness and mud cake permeability. These filtration potentials are essential to ascertain the sealing capacity of the mud samples. In Table 6, the filter cake thickness of rice husk and *Detarium microcarpum* muds increased as their control additive concentrations increased. The rationale behind this observation is that the number of particles (solids) in the mud system has increased to form a filter cake that controls filtrate escape from the drilling mud. Thus, the increase in the filter cake thickness of the rice husk and *Detarium microcarpum* muds resulted in a decrease in their fluid loss control performance. An exception to the mentioned observation was *Brachystegia eurycoma* mud, whose filter cake thickness reduces as the additive contents increase. An explanation for this is the hydrocolloid (i.e., thickening) nature of *Brachystegia eurycoma* that thickens the mud more than deposits solid content, as in the case of rice husk and *Detarium microcarpum* muds. At 8 g additive content, the mud filter cake thickness was 2.11 mm for rice husk mud, 2.54 mm for *Detarium microcarpum* mud, and 1.22 mm for *Brachystegia eurycoma* mud. These results were close and slightly above the API specification of 2 mm for mud filter cake thickness. Comparing these results with the blank mud filter cake thickness showed a 210.29%, 273.53% and 79.41% increase for rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud, respectively. The mud cake permeability of the formulated mud samples exhibited an indirect trend with the additive concentrations. This implies that the filter cake permeability of the various mud samples reduces as the additive contents in the mud samples increase. Also, the mud cake permeability of the mud samples at 8 g additive concentration was $8.90x10^{-3}$ mD for rice husk mud, 11.87×10^{-3} mD for *Detarium microcarpum* mud, and 7.35×10^{-3} mD for *Brachystegia eurycoma* mud. These results indicated that the rice husk and *Detarium microcarpum* muds depict increased mud cake permeability, as *Brachystegia eurycoma* mud has reduced cake permeability.

Filter cake thickness measurement and permeability determination are qualitative characteristics of mud filter cakes [8]. They are either thin or thick in terms of cake thickness and either highly permeable or low in terms of cake permeability. For the qualitative characteristic, API describes mud filter cakes as soft, slippery, firm, smooth and sticky [8, 37]. Figure 19 presents some filter cakes obtained for the various formulated mud samples. According to Agwu et al. [37], there is no established approach to assessing the qualitative characteristics of mud cakes; instead, researchers apply subjective judgment. From the mud filter cakes obtained, rice husk cakes are firm, smooth and soft, while *Detarium microcarpum* and *Brachystegia eurycoma* mud filter cakes are soft, smooth and slippery. Okon et al. [8] reported that these qualitative characteristics of the mud filter cakes are desirable to prevent pipe sticking during drilling operations. Therefore, these control additives in the oil-based muds exhibited good filter cake potentials for oil well drilling purposes.

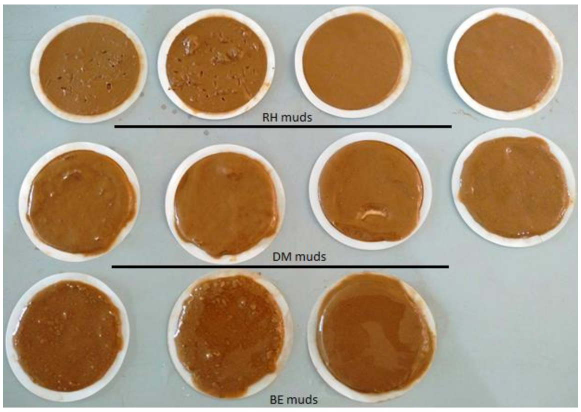

Figure 19. *Some filter cakes obtained from the various mud samples.*

3.2. Effect of Salinity on the Additives Rheological and Filtration Loss Control Properties Performance

Oseh et al. [38] reported that it is necessary to understand the salinity effect (i.e., salt contamination) on the drilling mud used for drilling operations. Also, Ali et al. [35] added that drilling muds' filtration characteristics, rheological properties, density, etc., are sensitive to salt contamination and temperature changes. Thus, examining the salinity susceptibility of the selected plant-based materials as additives in oil-based mud was imperative.

3.2.1. Salinity Effect on the Muds' Rheological Properties

According to Luo et al. [4] and Kök and Bal [39], plastic viscosity, apparent viscosity, yield point and gel strength are among the essential rheological parameters of drilling fluids. In this regard, Tables A1 and A2 present the effect of salt (NaCl) concentrations on the mentioned drilling mud rheological properties. In Table A1, the results obtained for the various mud samples' apparent viscosity, plastic viscosity and yield point showed that these rheological properties slightly increased as the salt concentration increased in the mud samples. These results are in sync with the ones reported by Hassiba and Amani [40], Sami [41] and Ali et al. [35]. The blank mud yield point and apparent viscosity were an exception, as these rheological parameters increased with salt content in the mud system. These observations are because salt content in the various mud samples reduced their water activity [42]. Therefore, it hindered the flocculation (i.e., deflocculates) of the mud's solid particles (additives) content. In drilling operations, mud's flocculation, dispersion and hydration potential are affected by salt [41]. Thus, the rheological characteristics of the various formulated mud samples were reduced.

On the other hand, Table A2 presents the salt (NaCl) effect on the gel strength of the mud samples at varying concentrations. As observed for the other rheological parameters, the 10-second and 10-minute gel strength of the various mud samples slightly decreased or increased (in some cases) as the salt concentration increased. The reason for this observation is not far-fetched from the submission for the other rheological characteristics: apparent viscosity, plastic viscosity and yield point. Therefore, it is necessary to establish the magnitude of the effect of salt on the rheological performance of the additives' muds. Thus, using the 8 g additives content muds, salt content muds and without salt were compared to assess their rheological properties. The results of the comparison are visible in Figures 20 through 25. Figures 20 through 22 show that a gram of salt content in the mud samples was sufficient to cause a significant reduction or slight increase of the plastic viscosity, apparent viscosity and yield point of the mud. Figure 20 presents the apparent viscosity of the various formulated mud samples. The mud's apparent viscosity reduction is 8.75%, 38.02%, 51.27% and 4.03% for the blank mud, rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud. These values implied that the *Detarium microcarpum* and rice husk muds experienced reduced apparent viscosity more than the blank and *Brachystegia eurycoma* muds. Again, the plastic viscosity and yield point are in Figures 21 and 22. The plastic viscosity of the rice husk and *Detarium microcarpum* muds decreased by 33.33% and 40.79%, as the blank and *Brachystegia eurycoma* muds increased by 33.33% and 4.30%, respectively. Also, the yield point of the mud samples decreased by 71.88% for the blank mud, 46.51% for the rice husk mud, 70.24% for the *Detarium microcarpum* mud, and 17.86% for the *Brachystegia eurycoma* mud. These analyses implied that the rice husk and *Detarium microcarpum* muds were more susceptible to salt (NaCl) than the *Brachystegia eurycoma* mud. Even with the unsettling of the samples' rheological properties by the salt content, the YP/PV values indicated that the mud samples are still pumpable. In Figure 23, for the 5 g salt content, the blank mud PY/PV ratio increased by 4.62%, whereas rice husk mud, *Detarium microcarpum* mud and *Brachystegia eurycoma* mud decreased by 32.72%, 44.55% and 31.67%, respectively. Figures 20 through 22 further revealed that the mud's rheological characteristics variations from the 2 g salt content were not much. The closest was for the *Brachystegia eurycoma* muds. This observation implied that the additives adjusted to the salinity sensitivity of the mud system as the salt content increased.

Furthermore, Figures 24 and 25 depict the blank mud and the 8 g additives content mud 10 seconds and 10 minutes gel strength at varying salt concentrations. Again, the variously formulated mud samples' gel strength responded to the mud system's salinity effect. At 1 g salt content, the 10 seconds and 10 minutes gel strength of the mud samples dropped by 23.08% and 21.43% for the rice husk mud, 31.82% and 31.58% for the *Detarium microcarpum* mud sample and 14.29% and 18.75% for the *Brachystegia eurycoma* mud. The blank mud sample had slightly increased by 6.38% and 3.77% for 10 seconds and 10 minutes of gel strength, respectively. As observed for the other rheological properties in Figures 20 through 22, the mud samples' gel strength changes from 2 g salt content were less even as the salt content increased. This observation was earlier alluded to for other rheological parameters of the mud samples. Thus, the salinity susceptibility of the selected plant-based materials as additives in the oil-based mud revealed that the *Brachystegia eurycoma* rheological characteristics were less sensitive to the salt (NaCl) variations.

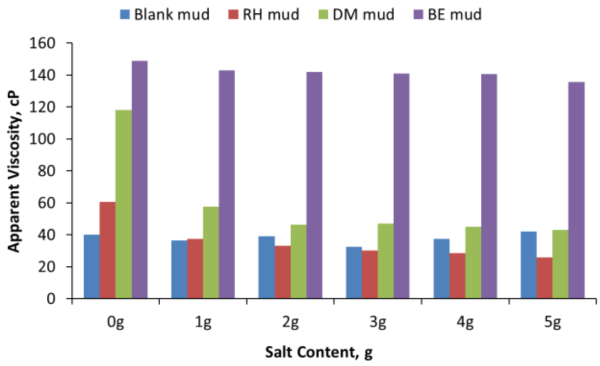

Figure 20. *Comparing the apparent viscosity of the 8 g additives muds with blank mud at varying salt concentrations.*

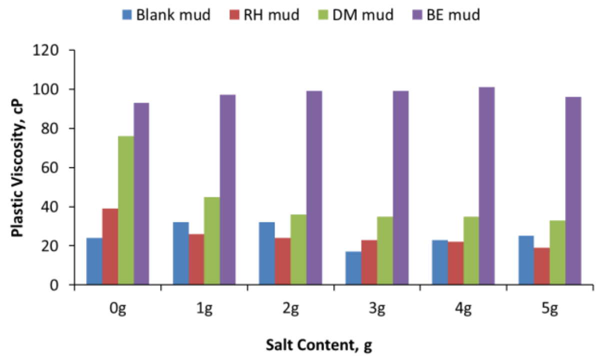

Figure 21. *Comparing the plastic viscosity of the 8 g additives muds with blank mud at varying salt concentrations.*

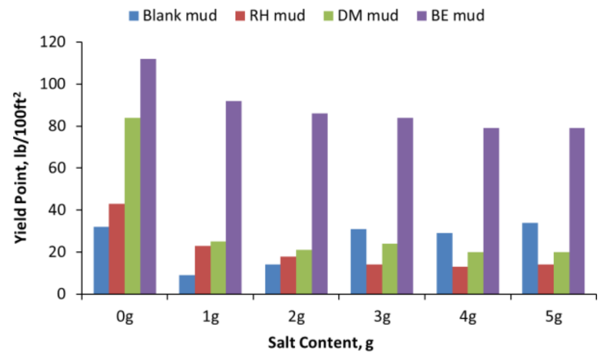

Figure 22. *Comparing the yield point of the 8 g additives muds with the blank mud at varying salt concentrations.*

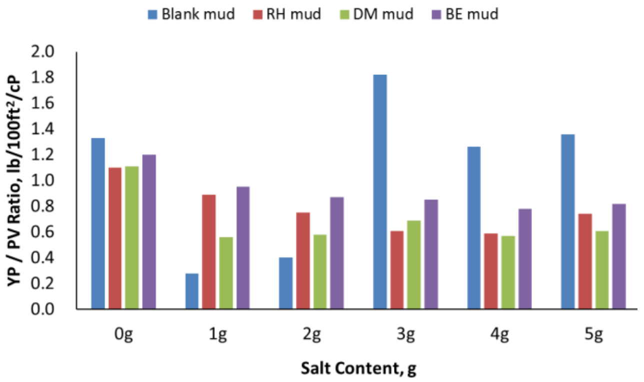

Figure 23. *Comparing the YP/PV ratio of the 8 g additives muds with the blank mud at varying salt concentrations.*

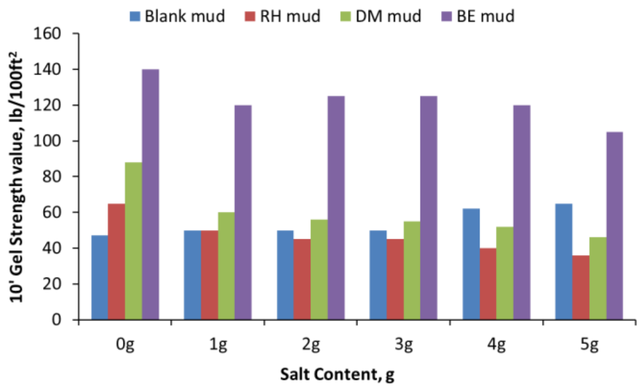

Figure 24. *Comparing the 10-second gel strength of the 8 g additives muds with blank mud at varying salt concentrations.*

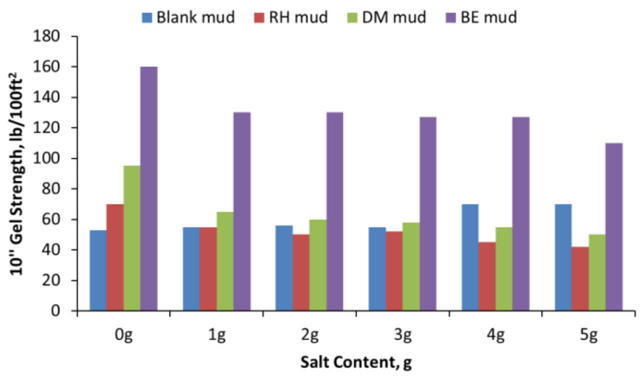

Figure 25. *Comparing the 10-minute gel strength of the 8 g additives muds with blank mud at varying salt concentrations.*

3.2.2. Salinity Effect on the Muds' Filtration Loss Properties

Some works in the literature by Basirat et al. [43] and Kuma et al. [6] posited that salt in the drilling mud system increases filtration loss characteristics. Table A3 presents the susceptibility of the variously formulated mud samples to varying salt (NaCl) concentrations. From the results, the various mud samples' filtration loss and bridging properties, spurt loss volume, API fluid loss volume, filter cake thickness, mud cake permeability, and permeability plugging test volume increased as the salt concentration increased in the mud samples. The reason is that the salt in the mud system deflocculates the additives that enhance fluid flow through the developed weak or loose filter (mud) cake. An exception to the mentioned observation was the static filtration test volume that was in reverse, which decreased as the salt content increased in the mud. These results obtained for the various mud samples are inconsistent with the works available in the literature. Furthermore, it is imperative to establish the salt susceptibility of the blank and the 8 g additives content muds on their filtration characteristics.

Figures 26 through 28 depict the spurt loss, API fluid loss and permeability plugging test volume results of the various mud samples. Comparing these muds' salinity sensitivity performance, it is clear that the additives muds were more susceptible to salt contamination than the blank mud at the 1 g salt content. This assertion is based on the significantly increased filtration loss characteristics. The spurt loss volume increased by 75.93% for blank mud samples, 566.67% for rice husk mud, 531.58% for *Detarium microcarpum* mud, and 400% for *Brachystegia eurycoma* mud, as API fluid loss and permeability plugging test volumes increased by 85.29%, 165.63%, 171.19% and 2.41% for the blank mud sample, rice husk mud, *Detarium microcarpum* mud, and *Brachystegia eurycoma* mud, respectively. This analysis for the API fluid loss volume showed that the *Brachystegia eurycoma* mud exhibited less sensitivity to the salt (NaCl) content than the other additives. Figures 26 through 28 further revealed that the additives muds from the 2 g salt content adjusted to the salt present in the mud system than the blank mud. The observation is the progressive increase of the blank mud filtration loss parameters to the additives' muds. During drilling operations, the implementation of the additive muds' less progressively filtration loss performance that they can be treated easily after salt contamination to retain their filtration characteristics.

Figures 29 and 30 present the various mud samples' bridging capacities (i.e., mud cake thickness and permeability). These figures show that the blank and rice husk muds exhibited a similar mud filtrate bridging trend. Their mud cake thicknesses and permeabilities increased as the salt concentrations increased in their system. These muds increased cake thicknesses and permeabilities at 1 g salt content, resulting in 230.16% and 466.63% for the blank mud sample and 62.38% and 359.55% for rice husk mud. The results further revealed that the rice husk mud from 2 g salt content had a less progressive increased filtrate bridging capacity than the blank mud. Also, in Figures 29 and 30, the *Detarium microcarpum* and *Brachystegia eurycoma* muds' filtrates bridging potential depicted similar characteristics that were reverse of that of blank and rice husk muds. Thus, the *Detarium microcarpum* and *Brachystegia eurycoma* mud filtrate bridging properties decreased as the salt content in their system increased. At 1 g salt content, their mud cake thicknesses and permeabilities decreased by 93.80% and 84.37% for the *Detarium microcarpum* mud and 96.68% and 96.62% for the *Brachystegia eurycoma* mud. Again, the static filtration rate of the additive muds, as presented in Figure 31, showed slight increases as the salt concentrations increased in their system compared to the blank mud. This observation reflects why the additives muds had less progressive filtration characteristics than the blank mud sample, as visible in Figures 26 through 28.

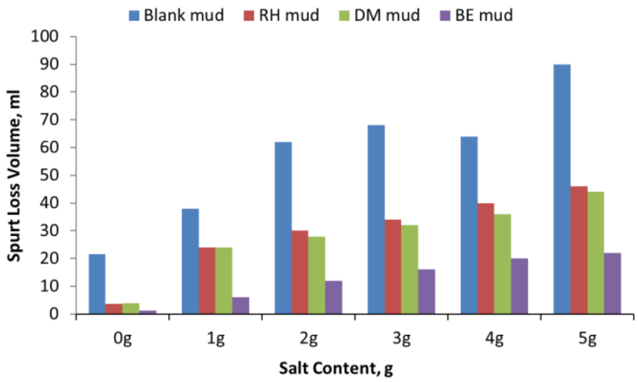

Figure 26. *Comparing the spurt loss volume of the 8 g additives mud samples with the blank mud at varying salt concentrations.*

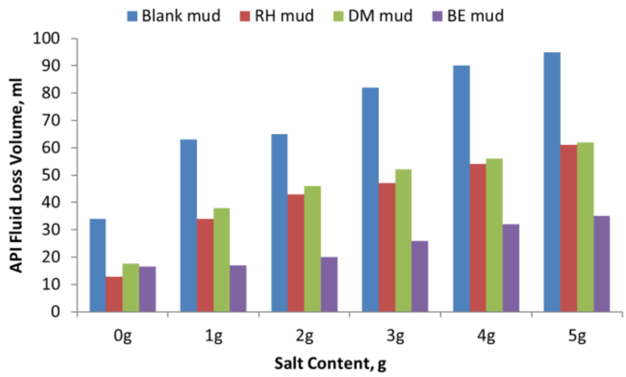

Figure 27. *Comparing the API fluid loss volume of the 8 g additives mud samples with the blank mud at varying salt concentrations.*

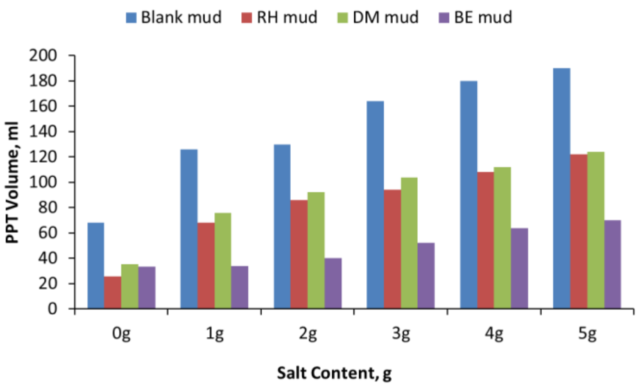

Figure 28. *Comparing the permeability plugging test volume of the 8 g additives mud samples with the blank mud at varying salt concentrations.*

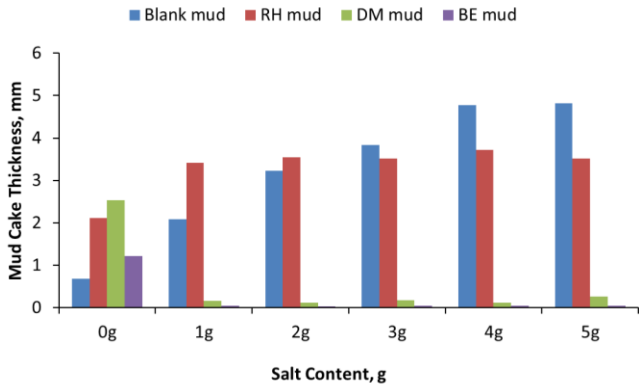

Figure 29. *Comparing the mud cake thickness of the 8 g additives mud samples with the blank mud at varying salt concentrations.*

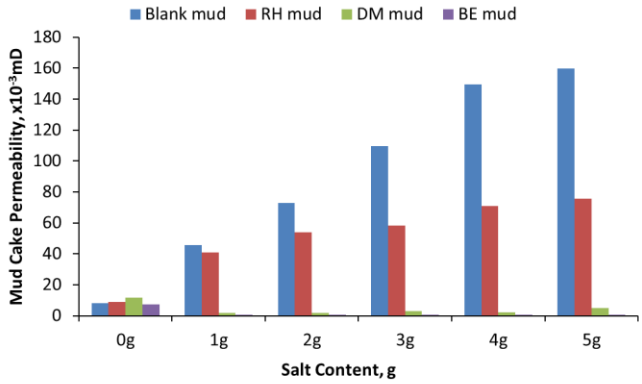

Figure 30. *Comparing the mud cake permeability of the 8 g additives mud samples with the blank mud at varying salt concentrations.*

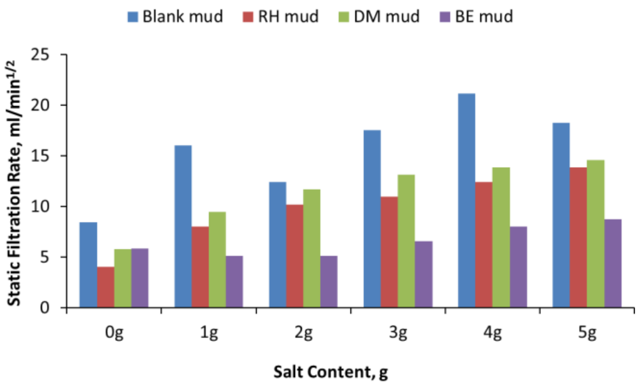

Figure 31. *Comparing the static filtration rate of the 8 g additives mud samples with the blank mud at varying salt concentrations.*

In summary, the rheological and filtration loss control properties of the plant-based additives, rice husk, *Detarium microcarpum*, and *Brachystegia eurycoma* in oil-based drilling fluids are desirable and meet the accepted API standards. These additives have demonstrated remarkable resistance to salt contamination, maintaining their properties even when compared with non-contaminated mud samples. This robust performance underscores the potential of these plant-based materials as additives in oil-based drilling mud for oil well drilling, a significant and promising outcome of this study.

3.3. Cost Comparison of the Plant-Based Additives with Some Conventional Additives

Table 7 and Figure 32 present a compelling comparison between the cost of plant-based additives and conventional additives for rheological and filtration loss control in drilling mud. The cost of procuring a tonne of plant-based additives is significantly lower than the conventional ones, demonstrating their potential cost-effectiveness and promising future. However, it is important to note the content or concentration at which the plant-based additives are comparable with the conventional additive, which is a limitation of this study. This observation is pivotal in determining the practicality of plant-based additives. In a previous study by Okon et al. [8], it was found that 15 g of rice husk and *Detarium microcarpum* and 20 g of *Brachystegia eurycoma* content were comparable with 4 g CMC as additives in water-based mud. Using drilling data provided by Davoodi et al. [18], the drilling mud cost of applying the plant-based additives was evaluated.

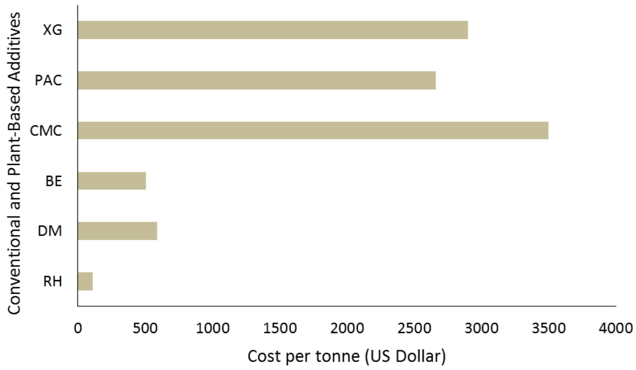

Figure 32. *Cost comparison of the plant-based and conventional additives for rheological and filtration loss control in drilling mud.*

Table 7. *Cost comparison of the plant-based and conventional additives for rheological and filtration loss control in drilling mud.*

	Additive materials	Minimum cost (kg/$)	Maximum cost (kg/$)	Average cost (kg/$)	Average cost (tonne/$)
i.	Rice husk (RH)	0.096	0.12	0.108	108
ii.	*Detarium microcarpum* (DM)	0.67	1.34	1.005	1005
iii.	*Brachystegia eurycoma* (BE)	0.81	1.61	1.21	1210
iv.	Carboxymethyl cellulose (CMC)	2.33	4.67	3.50	3500
v.	Polyanionic cellulose (PAC)	2.27	3.05	2.66	2660
vi.	Xanthan gum (XG)	2.80	3.00	2.90	2900

Tables 8 and 9 present the cost analysis of preparing and implementing 840 barrels of the drilling mud. The results in Table 9 showed that the cost of using the plant-based additives in 840 barrels of drilling mud is 15,472.8, 16,842.0, and 17,077.2 US dollars for rice husk (RH), *Detarium microcarpum* (DM) and *Brachystegia eurycoma* (BE), respectively. At the same time, the cost of conventional additives is 17,824.8, 17,178.0, and 17,362.8 US dollars for carboxymethyl cellulose (CMC), polyanionic cellulose (PAC) and xanthan gum (XG), respectively. Comparing the cost of applying the planted-based additives, it is observed that there will be a cost reduction of 13.20%, 5.51%, and 4.19% for rice husk (RH), *Detarium microcarpum* (DM) and *Brachystegia eurycoma* (BE), respectively, when compared with CMC. Also, the cost comparison with PAC and xanthan gum showed that the plant-based additives reduced 9.93%, 1.96%, and 0.59% for PAC and 10.89%, 3.0%, and 1.65% for xanthan gum. Besides the cost reduction of implementing the plant-based additives, their low environmental footprint is a factor to consider in achieving eco-friendly mud for drilling operations. Therefore, using these plant-based substitutes for conventional additives in oil and gas operations would be a way to reduce the total cost of oil well drilling in the petroleum industry.

Table 8. Cost of additives for 840 barrels of oil-based mud.

Additives	Additive (ppb)	Cost per tonne ($/t)	Cost per bbl ($/bbl)	Cost for 840 bbl
Sodium chloride*	90	55	2.25	1890
Potassium chloride*	20	75	0.68	571.2
Limestone*	60	350	9.50	7980
XC polymer*	0.6	1500	0.41	344.4
Starch*	9.0	1200	4.90	4116
Caustic soda*	0.5	300	0.10	84.0
Soda ash*	0.5	900	0.20	168.0
CMC	2.0	3500	3.18	2671.2
PAC	2.0	2660	2.41	2024.4
XG	2.0	2900	2.63	2209.2
RH	7.5	108	0.38	319.2
DM	7.5	590	2.01	1688.4
BE	10	505	2.29	1923.6

* Values are extracted from Davoodi et al. [18]

Table 9. Various mud costs and percentage reduction.

Additives	Cost of 840 bbl mud (USD)	Percentage Cost Reduction (%)		
		CMC	PAC	XG
CMC	17824.8	-	-	-
PAC	17178.0	-	-	-
XG	17362.8	-	-	-
RH	15472.8	13.20	9.93	10.89
DM	16842.0	5.51	1.96	3.00
BE	17077.2	4.19	0.59	1.65

4. Conclusion

Oil-based muds are the most desirable drilling fluids for oil well drilling operations, especially in complex and challenging zones. Its properties are enhanced using chemical additives to achieve the desired goal. However, the toxicity and disposal issues of the base fluid (i.e., diesel oil) and its additives on the environment are a concern. Hence, eco-friendly drilling fluid is necessary for drilling activities. This study evaluates the rheological and filtration loss control potential of rice husk, *Detarium microcarpum*, and *Brachystegia eurycoma* as additives in oil-based drilling mud. Also, the study investigates the susceptibility of the plant-based additives to salt (NaCl) at varying concentrations in the drilling fluid. Thus, the following conclusions are underlisted:

1. The mud exhibited a yield point-dependent rheogram that fits the Herschel Bulkley shear stress-shear rate profile model.
2. At 8 g content, the plant-based additives rice husk, *Detarium microcarpum*, and *Brachystegia eurycoma* achieved significant yield point increases of 34.38%, 162.5% and 250.0%, respectively.
3. Fluid loss control volumes comparable with the API recommended specification or standard for convention-

al additives were achieved with 8 g plant-based additives in the oil-based mud.

4. Mud cake permeability of 8.90×10^{-3} mD for rice husk, 11.87 × 10^{-3} mD for *Detarium microcarpum* and 7.35×10^{-3} mD for *Brachystegia eurycoma* was established with 8 g additives content in the mud samples.
5. The plant-based additives' rheological and filtration loss control performance or potential were not adversely affected by the salt (NaCl) contamination in the mud system.
6. The plant-based additives mud cake characteristics are firm, smooth and soft gel strength for rice husk, while *Detarium microcarpum* and *Brachystegia eurycoma* have soft, smooth and slippery characteristics.

Thus, it is recommended that a study be conducted to determine the performance of the plant-based additives in drilling mud at elevated temperatures and as composite additives. Also, it would be important to establish the proportion of the plant-based additives to conventional (standard) additives in drilling mud mixing to propagate their applicability in oilfield mud formulations.

Abbreviations

API	American Petroleum Institute
AV	Apparent Viscosity
BE	*Brachystegia Eurycoma*
BM	Blank Mud
CMC	Carboxymethyl Cellulose
cP	Centipoise
DM	*Detarium Microcarpum*
g	Gram
HPHT	High-Pressure High-Temperature
k	Permeability
LPLT	Low-Permeability Low-Temperature
mD	Millidarcy
mm	Millimetre
MPa	Mega Pascal
NaCl	Sodium Chloride
OBM	Oil-Based Mud
°C	Degree Celcius
PAC	Paloanionic Cellulose
PAC-R	Polyanionic Cellulose – Rheology
pH	Hydrogen Ion Potential
PPT	Permeability Plugging Test
PV	Plastic Viscosity
q_{st}	Static Filtration Rate
RH	Rice Husk
rpm	Revolution Per Minute
XG	Xanthan Gum
USD	United State Dollars
V_{PPT}	Permeability Plugging Test Volume
WBM	Water-Based Mud
wt.%	Weight Percent
µm	Microns
YP	Yield Point
θ_{300}, θ_{600}	300 and 600 Dial Reading

Data Availability

All the data used in this study were obtained from the experimental and reported or presented in the paper.

Materials Statement

The authors declare that all the materials used in this study were not in any competing interest and do not violate any content.

Authors Contributions

Idara George Bassey: Data curation, Investigation, Methodology, Writing – original draft

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Anselm Iuebego Igbafe: Supervision, Validation, Visualization, Writing – review & editing

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Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Appendix I: Plastic Viscosity, Apparent Viscosity and Yield Point Performance of the Mud Samples at Various Salt Concentrations

Table A1. *Some rheological performance of the mud samples at varying salt concentrations.*

Additive Content	**Blank Mud**					**Rice Husk Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
Plastic Viscosity, cP	32.0	32.0	17.0	23.0	25.0	20.0	28.0	31.0	33.0	35.0	25.0	23.0	24.0	21.0	24.0	23.0	23.0	22.0	22.0	23.0	26.0	24.0	23.0	22.0	19.0
Apparent Viscosity, cP	36.5	39.0	32.5	37.5	42.0	33.5	41.0	43.5	40.0	41.5	34.0	30.5	3.0	27.5	27.0	35.0	31.0	29.5	29.0	26.5	37.5	33.0	30.0	28.5	26.0
Yield Point, lb/100ft^2	9.0	14.0	31.0	29.0	34.0	27.0	26.0	25.0	14.0	13.0	18.0	15.0	12.0	13.0	6.0	24.0	16.0	15.0	14.0	10.0	23.0	18.0	14.0	13.0	14.0
YP/PV ratio	0.28	0.40	1.82	1.26	1.36	1.35	0.93	0.81	0.42	0.37	0.72	0.65	0.50	0.62	0.25	1.04	0.70	0.68	0.64	0.44	0.89	0.75	0.61	0.59	0.74

Additive Content	**Blank Mud**					***Detarium microcarpum* Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
Plastic Viscosity, cP	32.0	32.0	17.0	23.0	25.0	50.0	33.0	33.0	30.0	24.0	38.0	33.0	23.0	22.0	29.0	40.0	52.0	49.0	51.0	41.0	45.0	36.0	35.0	35.0	33.0
Apparent Viscosity, cP	36.5	39.0	32.5	37.5	42.0	63.0	44.0	42.5	40.0	36.0	47.5	42.5	36.0	30.5	39.0	75.0	70.0	69.0	68.5	56.0	57.5	46.5	47.0	45.0	43.0
Yield Point, lb/100ft^2	9.0	14.0	31.0	29.0	34.0	26.0	22.0	19.0	20.0	24.0	19.0	19.0	26.0	17.0	20.0	70.0	36.0	40.0	35.0	40.0	25.0	21.0	24.0	20.0	20.0
YP/PV ratio	0.28	0.40	1.82	1.26	1.36	0.52	0.67	0.58	0.67	1.00	0.50	0.58	1.13	0.77	0.69	1.75	0.69	0.82	0.69	0.98	0.56	0.58	0.69	0.57	0.61

Additive Content	**Blank Mud**					***Brachystegia eurycoma* Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
Plastic Viscosity, cP	32.0	32.0	17.0	23.0	25.0	41.0	42.0	42.0	41.0	40.0	69.0	62.0	60.0	58.0	55.0	73.0	74.0	70.0	74.0	60.0	97.0	99.0	99.0	101.0	96.0
Apparent Viscosity, cP	36.5	39.0	32.5	37.5	42.0	58.5	57.0	56.0	55.0	54.0	85.0	75.0	70.0	67.5	65.5	110.0	109.0	106.0	99.0	90.0	143.0	142.0	141.0	140.5	135.5
Yield Point, $lb/100ft^2$	9.0	14.0	31.0	29.0	34.0	35.0	30.0	28.0	28.0	28.0	32.0	26.0	20.0	19.0	21.0	74.0	70.0	72.0	50.0	60.0	92.0	86.0	84.0	79.0	79.0
YP/PV ratio	0.28	0.40	1.82	1.26	1.36	0.85	0.71	0.67	0.68	0.70	0.46	0.42	0.33	0.33	0.38	1.01	0.95	1.03	0.68	1.00	0.95	0.87	0.85	0.78	0.82

Appendix II: Gel Strength Performance of the Mud Samples at Various Salt Concentrations

Table A2. *Gel strength performance of the mud samples at varying salt concentrations.*

Additive Content	**Blank Mud**					**Rice Husk Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
600/300 rpm	50/55	50/56	50/55	62/70	65/70	45/54	50/55	50/55	50/55	50/55	45/50	40/50	40/45	35/45	40/45	45/50	40/45	45/50	40/45	36/42	50/55	45/50	45/52	40/45	36/42
200/100 rpm	37/40	40/47	48/52	55/60	62/67	43/52	45/50	46/52	45/50	40/45	45/48	40/45	30/35	30/40	37/42	40/48	45/50	35/45	35/40	35/40	42/48	40/48	45/50	42/46	35/40
6/3 rpm	45/45	50/50	54/55	50/55	60/65	40/45	40/46	45/50	40/45	40/52	40/50	45/48	35/40	40/45	35/40	45/50	40/45	40/45	35/38	35/40	45/50	45/50	40/48	40/44	35/40

Additive Content	**Blank Mud**					***Detarium microcarpum* Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
600/300	50/	50/	50/	62/	65/	30/	45/	45/	15/	20/	50/	45/	35/	25/	20/	85/	68/	56/	50/	65/	60/	56/	55/	52/	46/

Additive Content	Blank Mud					***Detarium microcarpum* Mud** 2g					4g					6g					8g				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
rpm	55	56	55	70	70	36	50	48	20	30	60	48	40	30	30	90	74	65	65	70	65	60	58	55	50
200/100 rpm	37/40	40/47	48/52	55/60	62/67	25/30	35/40	40/42	7/15	10/18	40/50	30/42	30/35	20/25	20/25	70/80	65/70	55/60	50/55	65/70	55/58	55/58	52/55	47/53	42/47
6/3 rpm	45/45	50/50	54/55	50/55	60/65	20/25	25/30	20/25	15/17	10/15	35/40	25/30	35/30	5/15	10/20	65/70	50/65	50/55	45/50	50/55	50/54	50/55	45/50	45/50	40/45

Additive Content	Blank Mud					***Brachystegia eurycoma* Mud** 2g					4g					6g					8g				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
600/300 rpm	50/55	50/56	50/55	62/70	65/70	65/72	55/62	55/60	53/62	52/60	70/75	60/65	55/60	55/57	50/55	90/95	86/92	85/90	80/85	75/78	120/130	125/130	125/127	120/127	105/110
200/100 rpm	37/40	40/47	48/52	55/60	62/67	62/70	57/61	60/65	55/60	50/54	62/67	50/56	55/60	50/55	46/50	85/90	80/85	80/84	70/80	70/74	120/125	120/125	116/120	115/120	107/115
6/3 rpm	45/45	50/50	54/55	50/55	60/65	60/68	55/60	50/60	50/55	45/50	60/65	55/60	55/55	50/55	45/46	80/90	75/80	75/80	70/75	70/75	115/120	110/115	110/115	107/112	105/110

Appendix III: Filtration Loss Control Performance of the Mud Samples at Various Salt Concentrations

Table A3. Filtration and bridging performance of the mud samples at varying salt concentrations.

Additive Content	Blank Mud					**Rice Husk Mud** 2g					4g					6g					8g				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
Spurt loss, ml	38.0	62.0	68.0	64.0	90.0	38.0	44.0	50.0	62.0	70.0	32.0	36.0	42.0	48.0	54.0	30.0	36.0	40.0	46.0	54.0	24.0	30.0	34.0	40.0	46.0

Additive Content	Blank Mud					Rice Husk Mud																			
						2g					4g					6g					8g				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
API fluid loss, ml	63.0	65.0	82.0	90.0	95.0	51.0	62.0	71.0	79.0	85.0	44.0	50.0	61.0	68.0	75.0	37.0	46.0	54.0	57.0	63.0	34.0	43.0	47.0	54.0	61.0
Perm. plugging test, ml	126.0	130.0	164.0	180.0	190.0	102.0	124.0	142.0	158.0	170.0	88.0	100.0	122.0	136.0	150.0	74.0	92.0	108.0	114.0	126.0	68.0	86.0	94.0	108.0	122.0
Filtration rate, ml/min $^{1/2}$	16.06	12.41	17.52	21.18	18.25	11.68	14.60	16.79	17.52	18.25	10.22	11.68	14.60	16.06	17.52	8.03	10.22	12.41	12.41	13.14	8.03	10.22	10.95	12.41	13.87
Filter cake thickness, mm	2.08	3.22	3.83	4.77	4.82	3.55	3.52	3.52	3.50	3.47	3.68	3.40	3.32	3.02	3.02	3.76	3.95	3.93	3.64	4.62	3.41	3.55	3.52	3.72	3.52
Mud cake perm., 10^{-3} mD	45.7	72.9	109.5	149.6	159.6	63.89	77.02	88.20	97.58	104.09	57.14	59.99	71.47	72.47	79.93	49.1	64.12	74.89	73.22	102.71	40.92	53.87	58.38	70.89	75.77

Additive Content	Blank Mud					*Detarium microcarpum* Mud																			
						2g					4g					6g					8g				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
Spurt loss, ml	38.0	62.0	68.0	64.0	90.0	44.0	54.0	56.0	62.0	66.0	36.0	40.0	42.0	50.0	56.0	28.0	32.0	42.0	46.0	54.0	24.0	28.0	32.0	36.0	44.0
API fluid loss, ml	63.0	65.0	82.0	90.0	95.0	62.0	69.0	72.0	83.0	87.0	56.0	54.0	63.0	69.0	76.0	42.0	48.0	51.0	57.0	65.0	38.0	46.0	52.0	56.0	62.0
Perm. plugging test, ml	126.0	130.0	164.0	180.0	190.0	124.0	138.0	144.0	166.0	174.0	112.0	108.0	126.0	138.0	152.0	84.0	96.0	102.0	114.0	130.0	76.0	92.0	104.0	112.0	124.0
Filtration rate, ml/min	16.06	12.41	17.52	21.18	18.25	14.60	15.33	16.06	18.99	19.72	13.87	12.41	15.33	16.06	17.52	10.22	11.68	10.95	12.41	13.87	9.49	11.68	13.14	13.87	14.60

Additive Content	**Blank Mud**					***Detarium microcarpum* Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
1/2																									
Filter cake thickness, mm	2.08	3.22	3.83	4.77	4.82	0.171	0.222	0.268	0.202	0.251	0.164	0.176	0.179	0.269	0.305	0.101	0.098	0.133	0.126	0.116	0.155	0.124	0.182	0.118	0.257
Mud cake perm., 10^{-3} mD	45.7	72.9	109.5	149.6	159.6	3.34	4.83	6.09	5.29	6.89	2.90	3.00	3.56	5.86	7.31	1.34	1.48	2.14	2.27	2.38	1.86	1.80	2.99	2.08	5.03

Additive Content	**Blank Mud**					***Brachystegia eurycoma* Mud**																			
						2g					**4g**					**6g**					**8g**				
Salt Content	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**	**1g**	**2g**	**3g**	**4g**	**5g**
Spurt loss, ml	38.0	62.0	68.0	64.0	90.0	10.0	32.0	32.0	44.0	50.0	12.0	20.0	28.0	32.0	36.0	10.0	18.0	20.0	26.0	32.0	6.0	12.0	16.0	20.0	22.0
API fluid loss, ml	63.0	65.0	82.0	90.0	95.0	75.0	52.0	50.0	52.0	55.0	27.0	32.0	33.0	36.0	39.0	23.0	30.0	37.0	41.0	44.0	17.0	20.0	26.0	32.0	35.0
Perm. plugging test, ml	126.0	130.0	164.0	180.0	190.0	150.0	104.0	100.0	104.0	110.0	54.0	64.0	66.0	72.0	78.0	46.0	60.0	74.0	82.0	88.0	34.0	40.0	52.0	64.0	70.0
Filtration rate, ml/min 1/2	16.06	12.41	17.52	21.18	18.25	25.56	13.14	12.41	10.95	10.95	7.67	8.03	6.94	7.30	7.67	6.57	7.67	9.86	10.22	10.22	5.11	5.11	6.57	8.03	8.76
Filter cake thickness, mm	2.08	3.22	3.83	4.77	4.82	0.134	0.118	0.109	0.048	0.199	0.208	0.179	0.166	0.185	0.128	0.103	0.107	0.124	0.112	0.114	0.041	0.038	0.042	0.047	0.048
Mud cake perm., 10^{-3} mD	45.7	72.9	109.5	149.6	159.6	3.65	2.23	1.98	0.91	3.97	2.04	2.08	1.99	2.42	1.81	0.86	1.17	1.67	1.67	1.82	0.25	0.28	0.40	0.55	0.61

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