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Formulation and Performance Evaluation of Environmentally Friendly Oil Based Mud Using Palm Kernel and Limonene Oils

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ABSTRACT

Drilling operations are impossible without the use of drilling mud. However, the commonly used oil for oil-based mud is diesel, but studies have shown it is toxic, which adversely impacts the environment. Hence the need for alternative oils which possess low toxicity and are biodegradable. Past works have shown that plant oil can be used to formulate competent environmentally friendly oil-based muds. In this study, three different oil samples were investigated; Palm kernel oil (PKO), a blend of Limonene oil with PKO and diesel oil which was our control sample. The physiochemical properties, rheological properties, sand content, pH, fluid loss, cake thickness and cutting carry index (CCI) of the formulated mud samples were tested and compared. The blend of limonene oil with palm kernel oil influenced the physiochemical properties of palm kernel oil, as its density and viscosity were increased. The Rheological behavior of the three mud samples were characterized using the Power Law Model where the Flow behavior index (n) were all less than 1, thus indicating that they were all pseudo plastic fluids, which is desirable for drilling fluids. PKO mud and the blend of limonene/PKO mud had better results when compared to diesel-based mud. The former had higher mud densities of 8.9ppg each, less than 0.25% sand content, pH level of 8 and 9 respectively, which is within the required API standard range, filtrate volumes of 37ml and 32ml, lesser mud cake thickness of 1.5mm and 1.2mm respectively, and a higher CCI. Limonene/PKO mud gave the best result, proving that blends of plant oils can be combined in formulating a competent drilling fluid. Finally, this study has proven that PKO and a blend of limonene with PKO are suitable for drilling and can be used in place of diesel oil.

KEYWORDS: oil-based mud, limonene oil, palm kernel oil, diesel oil, power law model.

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1. INTRODUCTION

Drilling fluid or drilling mud are nomenclatures used to refer to fluids that assist in well control and, in the removal of drill cuttings from the bottom of the hole to the surface during oil drilling operations. Before now, in the early days of oil and gas exploration, the primary function of drilling mud was just to carry cuttings from the bottom of the hole to the surface. Whereas, as of today it has been recognized that drilling mud has many more essential functions (Caen & Chillingar, 1996).

Drilling mud is usually a mixture of oil or water, weighing materials, clay and selected additives and chemicals as required. For a successful drilling operation, a competent drilling mud is needed.

According to Fadairo *et al.* (2012) there are three key factors that must be considered when selecting a competent drilling mud in other to achieve a successful drilling operation, these factors are: The cost of formulating the mud, The mud technical performance and the environmental impact of the mud. Also, the drilling mud properties must be carefully calibrated and measured in relation to the formation lithology, pressure, temperature, chemical properties, and rock properties. A mud engineer is charged with the task of selecting the best range of characteristics such as viscosity, density, and composition ratio of the drilling mud. (Bland *et al.*, 2006).

Drilling mud is categorized into three types; Air based mud, Oil based mud and Water based mud. Oil based mud is a drilling fluid with diesel, bio diesel or mineral oil as the major component. Over time it had been discovered that oil-based mud achieved better productivity than its counterparts (Air based mud and Water based mud). It is also considered to be more favorable in specific formations such as deep waters, high temperature/high pressure wells, clay and shale formations, formation with salt and sour borehole**.** (Olaitan *et al.*, 2017)**.** All these have enabled the upstream petroleum industry to thrive on the use of oil-based mud. (Ananwe *et al.*, 2014. Oseh., 2019)

However, the preferred and commonly used oil in the formulation of oil-based mud is diesel, which studies have shown that diesel have nephrotoxic and high aromatic content. This adversely impacts the environment especially in sensitive areas such as offshore. Hereby resulting in strict regulations and an increase in disposal costs which has elevated its cost significantly. (Cripps, *et al.*, 1998). Cuttings must be put under significant processing before they can be disposed of (Hussein & Amin, 2010)**.** Disposal methods are numerous, ranging from burying, landfills, thermal desorption, recycling etc. But these methods are very expensive to operate especially for cuttings gotten using diesel oil-based mud.

Oil companies therefore due to the problems mentioned above were tasked to search for alternative oils that can be used in the formulation of oil-based mud with reduced handling cost and environmental impacts, but still be competent to perform its basic functions. Hence oil from plants were discovered, which possess low toxicity and high biodegradability. Utilization of oils from plants as an alternative to diesel oil has been found to be very environmentally friendly and cost efficient. Common among the plant oil being Soybean oil, Palm oil, Sesame oil, Jatropha oil, Groundnut oil, Castor oil, Almond oil, Rubber oil, Walnut oil, Moringa oil, Canola oil, Limonene oil etc. This work is focused on formulating an oil-based mud from PKO and a blend of limonene oil with PKO to ascertain if combinations of plant oils will yield desirable results.

2. MATERIALS AND METHODS

The experiments were conducted at The Petroleum Engineering Laboratory in Rivers State University and The Petroleum Engineering Drilling Fluids/Cement Laboratory Workbook (Chimezie-Nwosu, Temple, & Leebee, 2015) was used as guide for all the experiments.

2.1 Materials

The materials used include Diesel oil, Palm kernel oil, Limonene oil, n-Hexane, Barite, Bentonite, Caustic soda (NaOH), Soda Ash (Na_2CO_3), Poly Anion Cellulose (PAC), Potassium Chloride (KCL), Xanthan gum, Borax, CO_2 pressure cartridge, Water, Universal pH Paper Strips, Filter paper, Threads, Soap, Tissue.
The apparatus used includes; Electronic weighing scale, Soxhlet extractor, Thimble, Retort stand, Condenser, grinding machine, Electronic mixer, Mud balance, Beaker, Round bottom flask, Rotary viscometer, API filter press, Thermometer, Hot plate, Vernier caliper, Reagent bottles, Plastic storage container, Nylon bags, Distillation column, Test jar, Air cooler, Penksy Martens Flash Point Tester, Mixing container, Pycnometer, Viscometer, Marsh Funnel, Cylinder, Stopwatch, Electronic Oven, 200-mesh (74-micron) Screen, Funnel, Graduated sand content measuring glass tube, Scientific Calculator.

2.2. Limonene Oil Extraction

The lemons were obtained in bulk. Then washed, peeled and oven dried, after which it was grounded using a grinding machine and stored.

The oil extraction method employed was the solvent extraction method as it is best for extracting essential oils because it can perform a large number of extractions on a liquid or solid sample with minimal effort and with minimum amount of solvent (Kasiramar, 2018). Before extraction, the sample was weighed and placed into a thimble and then loaded into the main chamber of the apparatus. Each thimble contained 100g of sample. The extraction solvent of choice was (n-hexane). The solvent was heated to reflux using a hot plate heater. When the Soxhlet chamber was full it automatically emptied by a siphon side arm, with the solvent running down to the round bottom distillation flask. This cycle was repeated over days until the entire sample had been exhausted. The product obtained was distilled. 2kg of grinded lemon peels yield 20ml of oil. The oil was observed to be highly dense and more viscous than PKO, so a blend of (20ml) of limonene oil was mixed with (380ml) of PKO, to get Limonene/PKO. This was done to determine the feasibility of using blends of plant oils in formulating oil-based mud.

2.3. Physiochemical Properties of the Oils

Five key physiochemical properties were analyzed; Density, Viscosity, Flash point, Pour point and Cloud point

2.3.1. Density (ppg)

The following steps were taken to determine the oil densities.

i. The volume of the pycnometer was calibrated using water.
ii. The pycnometer was weighed.
iii. The oil samples were poured into the pycnometer and weighed in grams.

Oil densities were calculated using equation 1 below.

$$\rho = m/v \qquad (1)$$

Where, m = mass, v = volume

2.3.2. Viscosity (Cp)

The following procedure was conducted using the Redwood viscometer.

i. The oil cup was filled with oil to the required oil level indicated by the marker point.
ii. The ball was lifted above the orifice hole, which allowed the oil flow through at room temperature.
iii. The stopwatch was started. As soon as 150ml of oil was collected, the stopwatch was stopped.
iv. The time measured in seconds represents the viscosity of the oil. This was converted to kinematic viscosity unit in centipoise, using equation 2

$$KV = At - \left(\frac{B}{t}\right) \qquad (2)$$

Where, A and B are constants,
A = 0.26 and B = 1.71
t = time taken to recover a given volume (150ml) of oil.

2.3.3. Flash Point (˚C)

The Pensky Martens flash point tester was used to determine the flash point of the oil samples.

2.3.4. Pour Point and Cloud Point

The following procedure was employed.

i. The oil sample was poured into the test jar to the marked level.
ii. The test jar was closed with a cork carrying a thermometer. The thermometer was adjusted so that its bulb rested on the bottom of the test jar. Then placed in the jacket inside the Air cooler.
iii. At each test thermometer reading (in multiples of 1˚C), the test jar was removed from the jacket quickly but without disturbing the oil, to inspect for any movement and then replaced back into the air cooler, for the Pour point test.
iv. At each test thermometer reading (in multiples of 1˚C), the sample was removed from the jacket quickly but

without disturbing the oil, to inspect for any cloud or haziness and then replaced back into the air cooler, for the Cloud point test.

v. Steps 4 and 5 were repeated, until the pour point and cloud point were ascertained.

2.4. Mud Preparation

The derived oil was used to formulate oil-based mud, using standard API laboratory procedures: Table 1 shows the composition of the formulated mud samples. 350ml of oil was soaked with barite for 24hours. Other compounds were weighed and added appropriately.

Table 1: Composition of Formulated Oil Based Mud

Additives	Conc	Mix Time	Mix Order	Functions
Oil Sample	350ml	5	1	Based fluid
Barite	76.8g	10	2	Weighting agent
Bentonite	2.8g	10	3	Viscosifier
Caustic Soda	0.2g	5	4	pH and Alkalinity control
Soda Ash	0.2g	5	5	CaCo$_3$ Inhibitor
PAC	2.0g	5	6	Fluid loss control
Potassium Chloride	18g	5	7	Corrosion control
Xanthan Gum	2.8g	5	8	Thickener
Borax	0.2g	5	9	Preservative

2.5. Mud Properties

The following properties were analyzed for the formulated mud samples. They include.

2.5.1. Mud Density

This was done using the Mud Balance.

i. The lid was removed, and the cup was filled with the mud.

ii. The lid was replaced and rotated until firmly seated, making sure some mud was expelled through the hole in the lid.

iii. The cup was placed on the knife-edge and the rider was moved along the arm of the balance until equilibrium was obtained.

iv. The reading was taken from the left-hand edge of the rider, in pounds per gallons (ppg).

2.5.2. Rheology

The following were the procedures that was taken using the Rotary Viscometer:

i. The muds were placed in a sample cup and the rotor sleeve was immersed to the fill line on the sleeve by raising the platform.

ii. The lock nut was tightened to stabilize the platform and the power outlet/power switch on the back panel were turned on.

iii. The knob was turned to Stir setting to agitate the sample for some seconds.

iv. Then, the knob was rotated to 600 RPM setting and waited for a stabilized dial reading and recording the value of the 600RPM reading was recorded.

v. Step 5 was repeated for 300RPM, 200 RPM, 100RPM, 60RPM, 30RPM and 6RPM, their dial readings were recorded.

The results derived from the rotary viscometer was used to calculate for, apparent viscosity, plastic viscosity, yield point, shear rate and shear stress:

Apparent viscosity:

$$\frac{Dial\ reading@600rpm}{2} \tag{3}$$

Plastic viscosity:

$$Dial\ reading@600rpm - Dial\ reading@300 \tag{4}$$

Yield Point:

$$Dial\ reading@600rpm - Plastic\ viscosity \tag{5}$$

Shear Rate (ɤ):

$$Viscometer\ rotational\ Speed \times 1.703 \tag{6}$$

Shear Stress (τ) using the Power Law Model:

$$K \times (Shear\ Rate)^n \tag{7}$$

2.5.3. Gel Strength

The gel strength of the formulated mud samples was measured using the Rotary Viscometer. They were done after 10 seconds of agitation and 10 minutes (600 seconds) after relative calmness.

2.5.4. Mud Filtration Properties

This test is undertaken to determine the filtration properties of the formulated muds namely the thickness of mud cake and the fluid loss. This was done using an API filter press.

2.5.5. Hydrogen ion Potential Concentration (pH)

i. pH litmus paper was dipped into the formulated oil-based mud.
ii. Then it was left to dry out and the color observed indicated the pH level.

2.5.6. Sand Content

Steps taken.

i. The glass measure tube was filled to "mud" line with mud sample. Water was added to the next scribed mark. The thumb finger was placed over the mouth of the tube, and it was shaken vigorously.
ii. Then the mixture was poured onto a clean screen. More water was added to the tube, shook, and poured onto the screen. It was repeated until the wash water was clean.
iii. A funnel was placed on top of screen assembly. The setup assembly was slowly inverted, and the tip of the funnel was inserted into the graduated glass tube. The sand was washed back into tube with a fine spray of water.
iv. The sand was allowed to settle. The volume percent sand content from graduations on the glass measuring tube was read and recorded.

2.5.7. Cutting Carrying Index (CCI)

The method called Cutting Carrying Index (CCI) was utilized to get a good idea of how good the hole cleaning is. The Cutting Carrying Index is a mathematical equation from real data:

$$CCI = \frac{K \times AV \times MW}{400{,}000} \tag{8}$$

The Power Law constant (K) was calculated using the equation below:

$$K = 511^{1-n} \times (Pv + YP) \tag{9}$$

The flow behavior index (n) was determined using the following equation:

$$n = \frac{3.322\log(2Pv + YP)}{(Pv + YP)} \tag{10}$$

Were.
AV = annular velocity in ft/min.
MW = mud weight in ppg.
K = Power Law Constant.
PV = plastic viscosity in centipoises.
YP = yield point in lb/100sqft
n = flow behavior index.

3. RESULTS AND DISCUSSION

3.1. Physiochemical Properties

i) Density of Oils:

The oil densities were calculated after substitution of the necessary parameters into equation 1. The density of Limonene/PKO was slightly higher than that of PKO. The combination of 20ml Limonene oil with 380ml PKO made the original density of PKO to increase from 914Kg/m^3 to 916Kg/m^3. Diesel oil had the lowest density. Oil with high densities provide the advantage of saving cost of formulation, as less weighing agent will be required to achieve higher mud densities.

ii) Viscosity of Oils:

The viscosities of the oil were calculated, and the results are illustrated in Table 2. It is clearly visible that Limonene/PKO is most viscous with a viscosity of 16cP, followed by PKO at 14.8cP, while diesel had the least value of 4cP. The effect of the blend of limonene oil with PKO resulted in having a higher viscosity than PKO. Oil with high viscosities provide the advantage of saving cost of formulation, as less viscosifiers will be required. The higher viscosity of PKO and limonene/PKO prove more desirable than that of diesel oil, as treating oil with higher viscosity is more favorable than treating oil with low viscosity.

iii) Flash point of Oils:

The flash point result is represented in Table 2, and it was in line with the findings of Muhammad (2012) which is expected to be greater than 100°F (82°C). Higher flash point will minimize fire hazards. It was observed that PKO had the highest flash point of 284˚C, followed by Limonene/PKO at 233˚C. This is good, as oil with high flash point means it can minimize fire hazards. Diesel had the lowest flash point at 70˚C, meaning it is more flammable. From literature, limonene oil has a flash point ranging between 60 - 70 ˚C. The blend of limonene oil with PKO had a significant impact on its flash point, as it reduced the original flash point of PKO from 284˚C to 233˚C.

iv) Pour point of Oils:

Table 2 illustrates the pour point of the oil samples. It is observed that diesel oil had the least pour point with a temperature of -18˚C. Followed by limonene/PKO at 21.8˚C, while PKO had the highest pour point temperature of 22.1˚C. The pour point should be lower than the ambient temperature to allow pumpability of mud. The pour points of the three oil samples were below the laboratory ambient temperature of 31.5°C. PKO and Limonene/PKO had higher levels and as such is not advised to be used in cold environments.

v) Cloud point of Oils:

PKO had the highest cloud point of 26.6˚C, while Diesel had the lowest cloud point temperature of -13˚C. As illustrated in Table 2, PKO and Limonene/PKO had higher levels. This is because PKO is highly saturated. As such PKO and the blend of Limonene/PKO is not advisable for use in extremely cold environments.

Table 2: Physiochemical properties of oil samples

Physiochemical Properties	Unit	PKO Oil	Limonene/PKO Oil	Diesel Oil
Density	kg/m^3	914	916	855
Viscosity	cP	14.8	16	4
Flash Point	˚C	284	233	70
Pour Point	˚C	22.1	21.8	-18
Cloud Point	˚C	26.6	23	-13

3.2. Mud Density

Fig 1 shows the mud densities of the formulated mud samples.

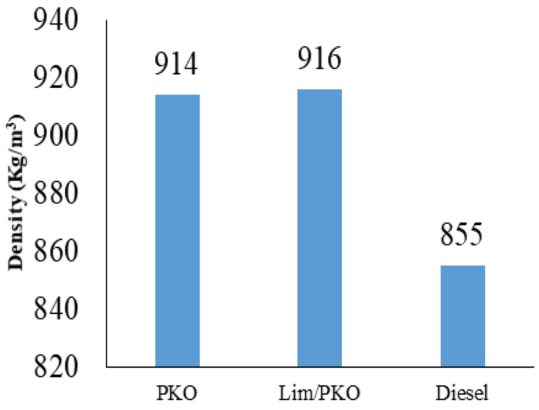

Fig 1: Mud Density of Mud Samples

The result shows that Palm kernel oil-based mud and Limonene/Palm kernel oil-based mud had same results with a mud weight of 8.9ppg, while Diesel oil-based mud had the least mud density at 7.1ppg. The density of the oil-based mud to be used is dependent on the reservoir conditions and the advantage of oil with high densities is that less barite would be used, saving the cost of formulation. It can be seen from Table 1 that equal amount of barite was added to the formulated mud samples. However, Diesel based mud had the least mud density, indicating that for Diesel oil-based mud to attain a higher mud density, greater quantities of barite is required, thereby increasing the cost of formulation. This result implies that oil with high density will require less quantities of barite to achieve higher mud density. According to Chikwe *et al.* (2019) higher the density of the drilling mud is, the better it helps to maintain hydrostatic pressure and suspend cuttings in the mud leading to better cleaning of the bore hole. Also, denser drilling mud like PKO based mud and Limonene/PKO based mud are required for some reservoirs, especially when faced with problems like influx of other fluids into the well bore.

3.3. Rheological Properties:

Fig 2 shows a plot of the viscosity variation vs Speed of viscometer (RPM) obtained using a rotary viscometer.

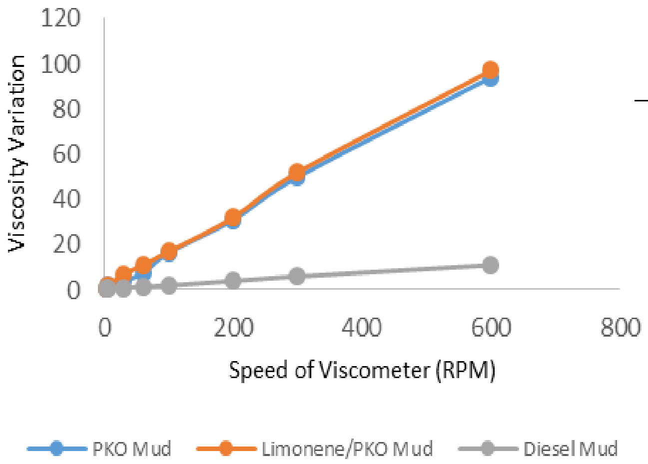

Fig 2: Plot of Viscosity Variation of Mud Samples Vs Speed of Viscometer (RPM) using a Rotary Viscometer.

The plot is like the Newtonian model and the Power Law model. This is because the flow index behaviour (n) is very close to 1. Hence the weak curve and almost a straight-line plot like a Newtonian model. However, if the value of the flow index behaviour (n) was closer to 0, the power law model flow curve would have been stronger and visible.

Table 3: Rheological Results of Mud Samples

Rheological Parameters	**PKO Mud**	**Limonene / PKO Mud**	**Diesel Mud**
Apparent viscosity (cp)	47	48.5	5.5
Plastic viscosity (cp)	44	45	5
Yield point (lb/100ft^2)	6	7	1
Gel strength (10secs) (lb/100ft^2)	2	2	1
Gel strength (10mins) (lb/100ft^2)	1	1	1
Power Law Constant (K) (lbs.sn/100ft^2)	87.2349	97.32	13.1247
Flow Behavior Index (n)	0.91075	0.89949	0.8745

The plastic viscosity should be as low as possible, and the yield point must be high enough to carry cuttings out of the hole for optimum drilling. The results after calculating using equation 3 is tabulated in Table 3, it was observed that the plastic viscosities of PKO mud and Limonene/PKO Mud were 44cP and 45cP respectively, which is quite high. Excess colloids in a viscous fluid causes high plastic viscosities. Lower plastic viscosity can be achieved through reduction in solid content by diluting the mud (Schlumberger, Oilfield Glossary, 2021). The plastic viscosity of Diesel Mud was 5cP, which is desirable. The lower the plastic viscosity of a mud is, then the advantage of it being less resistant to flow (Fakharany *et al.*, 2017), hence increasing its capability of drilling rapidly. Drilling operations with mud that possesses lower plastic viscosities may require less circulation pressure. Lower circulation pressure will lead to lower pumping costs and reduce the chances of losing circulation during operation and reduced wear in the drill string.

The yield point evaluates the ability of mud to lift cuttings out of the well bore. Fluids of the same density can have varied yield points. However, a fluid with a higher yield point means that it can carry drill cuttings better than that with a lower yield point. After calculations, the formulated oil-based mud from PKO and Limonene/PKO had higher yield points of 6 lb/100ft^2 and 7 lb/100ft^2 respectively. Diesel based mud achieved a yield point of 1 lb/100ft^2 which is low and unpleasing. The yield point must be high enough to carry cuttings out of the hole, but not so large to avoid excessive pump pressure when starting mud flow (Ceann, Darley, & George, 2011). The yield point of a mud can be increased with additives. PKO mud and Limonene/PKO mud will cost less to achieve this, as their yield points were higher.

The gel strength of the formulated muds is represented in Table 4. There were the same at ten minutes, with a viscometer reading of 1 lb/100ft^2. At 10 seconds; the gel reading of Palm kernel oil and Limonene/PKO muds where slightly higher, with a reading of 2 lb/100ft^2, while that of diesel base mud remained as 1 lb/100ft^2. For an increased gel strength more quantities of viscosifier (bentonite) and thickener (xanthan gum) are required. It will cost more to increase the gel strength of diesel oil-based mud, as larger quantities of this additives will be needed during formulation. Okie-Aghughu *et al.* (2013) *advised that* proper gel strength is required, as solids will be well suspended in the hole and allowed to settle out on the surface. Also, excessive gel strength should not be encouraged either, as they can cause a number of drilling problems.

3.4. Shear Rate and Shear Stress Plots:

The shear rate and shear stress were calculated using equations 6 and 7.
Fig 2 illustrates the combined plot of Shear Stress vs Shear Rate of the various mud samples.

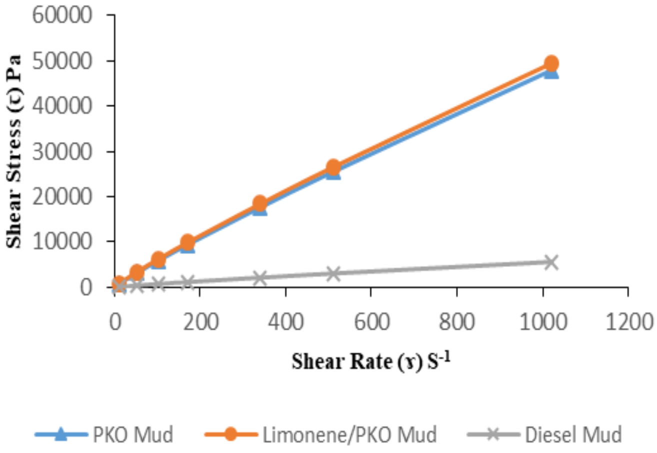

Fig 3: Combined Shear Stress Vs Shear Rate Plot for PKO Mud, Limonene/PKO Mud and Diesel Mud

The Power Law Model was used to calculate for shear stress, using equations 6 and 7. The Power Law Constant (K) also known as Consistency Factor and the Flow Behavior Index (n) are the two parameters used here to describe the flow characteristics. K describes the thickness or pump ability of the fluid. As a fluid becomes more viscous, K increases, as the fluid becomes more shear thinning (n) decreases. If $n > 1$ the fluid flow is dilatant, if $n = 1$ then it is a Newtonian fluid, whereas if $n < 1$ the fluid flow is pseudo plastic. This means the fluids viscosity decreases when stress is applied. The power law constant (K) for PKO Mud, Lim/PKO Mud and Diesel Mud were 87.2349 lbs.sn/100ft^2, 97.32 lbs.sn/100ft^2, 13.1247 lbs.sn/100ft^{2,} respectively. While their flow behavior index (n) was respectively 0.91075, 0.89949, 0.8745 and they were all less than 1 (< 1), this implies that they are pseudo plastic fluids, which is desirable for every drilling fluid. A typical Power law model plot gives a strong flow curve (i.e., a very visible curve), but due to the high value of n, the flow curve was weak (i.e., having a less visible curve or almost linear plot) as shown in Fig 3. However, the high values of n can be adjusted/reduced by adding a polymer able to form a gel network and is characterized by shear thinning properties. This will produce a stronger Power law model flow curve. Examples of such substances are geltone, xanthan gum, guar gum etc. (Kopeliovich, 2013).

3.5. Marsh Funnel Viscosity

Fig 4 represents the viscosities of the formulated muds using the Marsh funnel. Limonene/PKO mud was most viscous, followed by PKO mud, while Diesel mud was the least viscous.

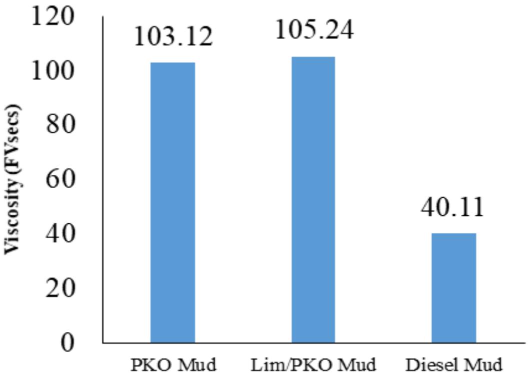

Fig 4: Marsh Funnel Viscosity of Mud Samples

Mud with high viscosity can suspend and carry cuttings to the surface more than mud with lower viscosity. However, Fadairo *et al.* (2012) pointed out that mud with low viscosity will prove better for a reduced friction during drilling because of low resistance to flow, in turn leads to reduction in the wearing and tearing of drill string while increasing rate of penetration.

3.6. Filtration Properties

Table 4 illustrates the filtration properties of the formulated mud samples i.e., fluid loss and mud cake thickness. Diesel oil-based mud had the highest fluid loss of 116ml, Palm kernel oil-based mud had a fluid loss of 37ml, while Limonene/Palm kernel oil-based mud had the least with 22ml. It can be inferred that Limonene/PKO mud has a better filtration property compared to other formulated samples. Fadairo *et al.* (2012) work explained that many problems can result from mud with excessive filtration volume loss, which include; formation damage due to filtrate and solids invasion, swelling of in-situ clays, measuring filtrate altered properties rather than reservoir fluid properties and the oil and gas zones may be overlooked because the drilling fluid is flushing hydrocarbons further from the bore hole, this in turn makes detection much more cumbersome. Hence, mud with lesser filtrate volumes is desired.

Diesel oil-based mud had the highest cake thickness of 2.2mm, Limonene/Palm kernel oil-based mud had the least cake thickness of 1.2mm, while Palm kernel oil-based mud was slightly higher with a cake thickness of 1.5mm as shown in Table 4. It is important to point out that there are a lot of problems caused because of mud with excessive thickness. These include tight spots in the hole, differential sticking of the drill string due to increased contact area. Others are difficulties in running casing and cementing because of the poor displacement of mud cake in the well bore etc. (Fadairo *et al.*, 2012). Therefore, PKO based mud and Limonene/PKO based mud with lesser mud cake thickness proves to be better.

Table 4: Filtration Properties of Mud Samples

Filtration Properties	PKO Oil	Limonene /PKO Oil	Diesel Oil
Fluid Loss	37ml	22ml	116ml
Mud Cake Thickness	1.5mm	1.2mm	2.2mm

3.7. Hydrogen ion Concentration (pH)

According to Chikwe *et al.* (2019) the mud pH will affect viscosity, bentonite is least affected if the pH is in the range of 7 to 9.5. A pH of 8.5 to 9.5 gives minimal shale problems, good borehole stability and better control over mud properties. A high pH (10+) causes shale problems. Drilling muds are normally expected to be on the alkaline side, as acidic muds corrode the metal fittings in the borehole like the drill strings and damages subsurface formations. Both PKO based mud and Limonene/PKO based mud met these criteria, with PKO based mud having a pH level of 8, Limonene/PKO based mud with a slightly higher pH level of 9, while diesel oil-based mud did not meet the criteria with a pH level reading of 6.

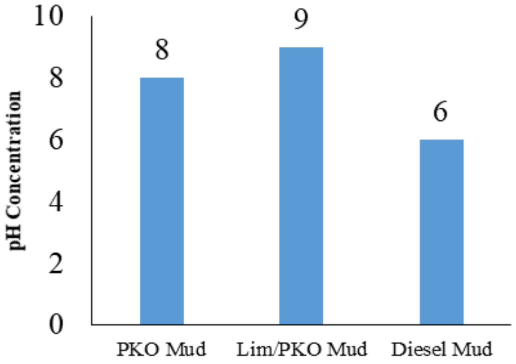

Fig 5: Hydrogen Ion Concentration (pH) of Mud Samples

3.8. Sand Content

This test is used to determine the volume percent sand-sized particles in a mud. Fig 5 shows that all the formulated oil-based mud met the criteria of having less than 1% sand content.

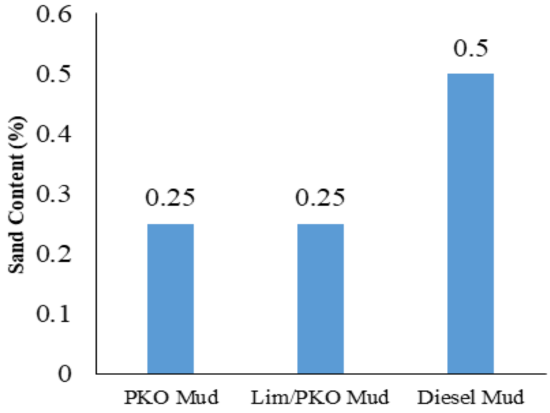

Fig 5: Sand Content of Mud Samples

Palm kernel oil-based mud and Limonene/Palm kernel oil-based mud had less than 0.25% and diesel oil-based mud had 0.5%. This is used to adjust the mud, as sand content is expected not to surpass 1%. The lesser the sand content the better the mud is for drilling. High percentage of sand causes excessive wear on mixing equipment, drill string and on pump parts (Fann Instrument Company, 2015).

3.9. Cutting Carrying Index

This is a measure of a drilling fluid's ability to conduct drilled cuttings in the hole. Higher cutting carrying index mean better hole cleaning capacities. Values of CCI are indicative of the extent or quality of hole cleaning. If CCI is equal to 0.5 or less, the hole cleaning is poor, but if CCI is equal to 1.0 or greater, it indicates that the hole cleaning is good. The CCI of PKO mud and Limonene/PKO mud were higher than that of Diesel mud, but they were all lesser than 1 (<1) which signifies poor hole cleaning capacity. Factors that influence CCI are mud weight, plastic viscosity, yield point and the annular velocity. It is recommended to keep the annular velocity above 150ft/min. Smith & Watts (2015) advised from experience that a minimum liquid-phase annular velocity of 180 to 200 ft/min is required in wellbore with a deviation of 10^{o} and greater. Extremely high or low velocity speeds are not desirable, as it could damage the well bore. The CCI was recalculated using a higher annular velocity of 250ft/min. Though the results improved, but it was still less than 1, these results can be found in Table 5. To achieve a good/high CCI, the yield point of the mud needs to be high while the plastic viscosity should be low. The poor CCI result is due to the plastic viscosity and yield point results of the formulated mud samples.

Table 5: Cutting Carrying Index Result

Mud Sample	PKO Mud	Limonene/PKO Mud	Diesel Mud
CCI with an Annular velocity of 150ft/min	0.29	0.34	0.03
CCI with an Annular velocity of 250ft/min	0.49	0.54	0.06

4. CONCLUSION

PKO and a blend of Limonene oil with PKO are technically feasible to substitute diesel in the formulation of oil-based mud as.

i. PKO and Limonene/PKO had better physiochemical properties result. Higher flash points, proving their fire-resistant capabilities, higher densities and viscosities which reduces cost of mud formulation.
ii. The rheological properties of PKO based mud and Limonene/PKO based mud were better than that of diesel oil-based mud.
iii. The mixture of Limonene/PKO based mud possessed the lowest fluid loss and cake thickness. It can be inferred that it has better filtration properties compared to the other formulated mud samples.

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