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Advancing Sustainability of Drilling Fluid: Coconut and Shea Butter Oils as Alternative to Diesel

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Drilling fluid is a key element in the drilling process because it lifts cuttings to the surface, maintains a stable wellbore, and generates sufficient hydrostatic pressure to prevent the influx of formation fluids into the wellbore. While oil-based drilling fluids offer advantages like wellbore stability, lubrication, and temperature resistance, disposing of oil-contaminated cuttings, particularly those using diesel, harms the environment. This study explores the use of coconut oil and shear butter oil, a renewable and biodegradable resource, as the base for oil-based drilling fluids.

Two samples of coconut oil and shea butter oil-based mud samples were formulated and tested in the laboratory against the conventional crude oil-based mud. Laboratory tests compared each sample of coconut oil and shea butter oil-based mud against conventional diesel-based mud. Tests

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included FTIR characterization of additives, and evaluation of gel strengths, yield point, viscosity, and emulsion stability at 120°F and 300°F. Filtration loss and mud thickness were also measured. Results indicate that coconut oil and shea butter oil-based drilling fluids offer promising rheological properties and environmental benefits. Coconut oil-based sample (VCO I) exhibited superior viscosity and emulsion stability, though it produced a thicker mud cake, indicating a need for optimization. These alternatives present a viable solution to reduce the environmental impact of drilling operations. Further research and field trials are recommended for practical application.

Keywords: Rheology; drilling fluid; oil-based mud; temperature; environmentally friendly.

1. INTRODUCTION

Drilling fluid is essential for successful drilling operations, as it transports cuttings, maintains borehole pressure, lubricates the drill bit, and reduces its temperature (Nasser et al., 2013). The choice of appropriate drilling fluid types is critical for ensuring efficient drilling procedures and ultimately determining the success rate of operations (Kanesan & Jamaludin, 2020). The different characteristics of a drilling fluid vary from rheological properties, filtration and lost circulation control, and lubrication to differential sticking tendencies, and thermal and microbial inhibition abilities (Nairy, Farhan Jameel, Susan Matthew, N, & Jyoti Gogoi, 2008). Similar to other non-Newtonian fluids, drilling fluids exhibit shear-thinning behaviour, maintaining high viscosity at low shear rates (R. Caenn, Darley, & Gray, 2017; Oseh et al., 2020) to effectively carry and suspend cuttings while displaying low viscosity at high shear rates for efficient pumping downhole (M. C. Li et al., 2018). They are generally classified as one of two types; Water Base Mud (WBM) – Fluids/Muds having water as their continuous phase, and Oil Base Mud (OBM) – Fluids/Muds systems with oil as its continuous phase.

The efficacy of oil-base muds in mitigating drilling challenges stemming from shale swelling, borehole instability, lubricity, thermal instability, intolerance of contamination, ease of maintenance, differential pressure sticking, corrosion, and elevated formation temperatures has been unequivocally demonstrated by Field performance worldwide (Abduo, Dahab, Abuseda, AbdulAziz, & Elhossieny, 2016; Okorie E. Agwu, Okon, & Udoh, 2015; Simpson, 1979; Sulaimon, Adeyemi, & Rahimi, 2017).

Despite being lauded by industry operators for its exceptional rheological properties at high temperatures exceeding 300°F, oil-based muds (OBM) has garnered significant criticism, primarily due to their detrimental environmental impact (Okorie E. Agwu, Isemin, & Akpabio, 2015). This critique extends beyond their costliness, highlighting concerns about their adverse effects on the ecosystem (Dardir, Ibrahime, Soliman, Desouky, & Hafiz, 2014; Yassin, Kamis, & Abdullah, 1991). While the primary focus of many petroleum companies' projects lies in enhancing production performance and technologies to maximize profits and minimize cost, there is an increasingly recognized imperative to confront environmental apprehensions to ensure enduring sustainability (Ahmed & Kalkan, 2019). As such, projects focusing on environmental considerations are crucial for fostering a sustainable future alongside petroleum operations.

Because of their toxicity, persistency, and bioaccumulation, the use of diesel and mineral oil-based drilling fluids in offshore operations is highly limited or outright prohibited in many regions of the world today, including the USA, UK, Holland, Norway, Nigeria, and Australia. (Dosunmu & Ogunrinde, 2010b). The use of oil base mud has the potential to cause detrimental chemical seepage into the soil from carried cuttings, endangering aquatic life and contaminating groundwater (Ryen Caenn, Darley, & Gray, 2011). Cuttings produced in the course of drilling operations involving OBM often include higher amounts of heavy metals than naturally occurring sediments, which can lead to phytotoxicity, bioaccumulation, and unfavourable environmental consequences (Sonatrach et al., 2010). Thus, cuttings produced during drilling must be cleaned using a costly procedure before being discarded into the ocean. Following use, the oil mud must be transferred to a landfill. The use of oil-based mud in particular environmentally sensitive locations is strictly forbidden (Hinds, Smith, & Morton, 1983).

Within this context, the imperative for sustainable drilling practices becomes paramount, guiding

the exploration of alternative solutions to mitigate environmental impacts while maintaining operational efficiency. In response to these challenges, projects focusing environmental considerations on drilling fluid formulation and use have become increasingly crucial in shaping a sustainable future alongside petroleum operations, the current approach to mitigate the environmental hazard of OBM includes the use of vegetable oil and synthetic fluids as a replacement for diesel oil in drilling mud formulation (Hinds et al., 1983; Kanesan & Jamaludin, 2020).

Recognizing the intricate interplay between drilling fluid design and environmental impact, such projects aim to balance various factors, including well design, anticipated formation pressures and rock mechanics, formation chemistry, temperature variations, and adherence to environmental regulations, logistics, and economic feasibility. Central to this endeavour is the acknowledgment that the rheology of the drilling fluid significantly influences its effectiveness in executing drilling operations.

The primary component of vegetable base OBM is vegetable oil, which is made up of triglycerides with long fatty acid chains that contain unsaturated bonds. Common vegetable oils typically contain up to 12 fatty acids (Fox & Stachowiak, 2007). Notably, vegetable oils are non-toxic, and their combustion produces lower levels of carbon dioxide and carbon monoxide. Additionally, vegetable oils have the unique capacity to degrade in the environment (Okorie E. Agwu, Okon, et al., 2015), with research showing up to 80% possibility in degradability (Sankaranarayanan, N., J., & Krolczyk, 2021; Singh & Gupta, 2006).

The enhanced thermophysical qualities of vegetable-oil-base mud would give it an advantage over regular OBM. Vegetable oils have higher flash and flame points than mineral oils, indicating greater fire resistance. As a result, the transportation, storage, and handling of vegetable OBM is safer, with fewer operational concerns due to low flash and fire spots (Amanullah, 2005). However, there are several limitations, notably due to the higher viscosity of vegetable oils in contrast to diesel oil by 4 to 5 times higher, making it sometime inappropriate for mud formulation, and multiple problems linked to mud rheological qualities (Dosunmu & Ogunrinde, 2010b).

Coconut oil and Shea Butter oil were chosen as the continuous phase for oil-based mud formulation in this study due to their good physical and chemical qualities. The study seeks to investigate the feasibility of replacing diesel oil with coconut oil or Shea Butter in OBM. Diesel will also be tested alongside these vegetable oils to serve as a baseline. Throughout the study, the properties of coconut oil-base mud and shea butter oil-base mud will be carefully evaluated and characterized to determine its potential as a replacement for diesel in OBM formulations, and to evaluate their potential environmental impact and sustainability compared to conventional diesel oil-based fluids.

Globally used refined coconut oil is usually colorless and odorless, albeit it may not always be the purest or best grade. Commonly made from copra, or dry coconut kernels, RBD Coconut Oil (Refined, Bleached, and Deodorized) is another name for it. To extract the oil, the dried copra is pressed in a hydraulic press that is heated to a high temperature. Nearly all of the oil, which makes up more than 60% of the dry weight of the coconut, is efficiently extracted with this technique. But because of contaminants, this "crude" coconut oil is not fit for human consumption and has to be refined further by heating and filtering.

Coconut oil is mostly made of saturated fatty acids (about 94%), with a significant proportion (over 62%) of Medium Chain Fatty Acids. Coconut oil has a high flash or smoke point of 350°F (177°C), indicating that it has good thermal stability. With a Specific Gravity (SG) of 0.9138 and a viscosity ranging from 23 to 28 mPa, coconut oil has proven to be a viable alternative for oil-based muds. By comparison, the American Petroleum Institute (API, 1998) states that at 60°F, diesel oil has an SG of 0.84.

Shea oil is a vegetable oil that is derived from the seeds of the Shea tree (Vitellaria paradoxa), a member of the Sapotaceae family. It is extracted from the comparatively big, oil-rich seed that is encased in a thin, acidic, nutritious pulp that makes up the Shea fruit. Nigeria accounts for approximately 50% of the global shea nut production, as reported in the Journal of Science, Technology, Mathematics and Education (JOSTMED) Volume 8(2), page 67.

Fig. 1. Coconut Kernel before experiments

Honfo et al. (2012) found that Shea butter oil consists of 2-6% palmitic acid (C16), 15- 25% stearic acid (C18), 60-70% oleic acid (C18), less than 1% linoleic acid (C18), and 5- 15% linolenic acid.

Shea butter oil with a greater amount of oleic acid would have superior oxidative stability, which influences positively on thermophysical qualities when compared to the oleic acid content of coconut oil, which is only around 8%, and Palm oil, which has about 50% of oleic acid (Akoh, 1994; Sulaimon et al., 2017).

2. MATERIALS AND METHODS

Apparatus/Equipment: The equipment used in this work include; graduated measuring cylinder, beakers, electronic weighing balance, mud mixer, viscometer, baroid mud balance, water bath, ph meter, stop watch, grinder, api filter press, and variable rheometer.

Materials: The materials used in this work include diesel oil, coconut oil, shea butter oil, CONFI-MUL P, CONFI-MULS, CONFI GEL, sodium hydroxide (NaOH), water, barite, and CONFI-TROL. Next, 6 mud samples are formulated using the following formulation in Table 1. All the parameters of analyses are made in comparison with the conventional mud sample (S1).

Coconut oil extraction: Hot extraction process was employed in the extraction of oil from the Virgin Coconut. The Coconuts were broken, grated and pressed to get coconut milk. Coconut oil was then extracted from coconut milk by heating it. To extract virgin coconut oil (VCO), the coconut milk was heated at 100-120°C for 60 minutes until all the water completely evaporated. Heating the coconut milk denatured and destabilized the proteins within the milk emulsion. Proteins are then coagulated by slowly heating them in a VCO cooker. This coagulation releases the oil, which separates from the pertinacious residue. Filter the mixture through a muslin cloth to remove any remaining residue. Any residue that remains is further heated to remove more oil. The collected oil is then trans-esterified.

Shea butter oil extraction: Shea butter (Butyrospernum parkii) seeds (nuts) were collected. The seeds were dehulled, cleaned and dried under the sun for a day and later dried in the oven for three hours at 50 °C to ensure that moisture content was reduced to the barest minimum. The prepared seed were oven dried at 70 °C until a constant weight was obtained, then grinded into sizes. The extractor used was soxhlet apparatus with n- hexane as solvent. After extraction, the mixture of the solvent and extract was allowed to cool and then filtered to remove solid particles. The filtrate was concentrated under vacuum in a rotary

evaporator (Akpan et al., 2005). The results obtained were noted. The extracted oil was analyzed for the physical and chemical properties. All reagents used were of analytical grade.

2.1 Trans-Esterification Process

The purpose of alkali trans-esterification was to convert the vegetable oil to methyl ester so that it can be used as base fluid for drilling mud. Already extracted oil was measured into three-necked 250 ml round bottom flask equipped with reflux condenser. The flask was placed on electric heater with temperature controller and magnetic stirrer. Potassium hydroxide (KOH) pallets as catalyst was mixed with methanol. The mixture was transferred into flask containing the extracted oil and stirred vigorously at 350 rotation per minute at 60 °C for one hour. The mixture was transferred into separating funnel and allowed rest for four hours. The lower layer of glycerin was drained off by gravity while the upper layer was a mixture of methanol and methyl ester. The methanol was removed by vacuum distillation. The methyl ester was purified by washing it with 1000 ml of warm water at 60 °C until the pH was 7 (seven). The water was drained off and the oil was heated in hot plate to 100 °C with medium stirring for 20 min. Then the methyl ester was collected and stored at room temperature.

Table 1. Mud composition

Additives	Units	S.G	Control (Diesel)	Virign Coconut Oil		Shea Butter Oil	
				Sample 1	Sample 2	Sample 1	Sample 2
Base fluid	ml	0.87	195.7	169	195.7	195.7	196.7
primary emulsifier	ml	0.9	3.5	3.5	3.5	4	3.5
secondary emulsifier	ml	0.88	6	6.5	6.5	8	6.5
viscosifier	g	1.7	0.5	0.5	0.5	0.5	0
fluid loss Agent	g	1.05	8	8	8	8	8
NaOH	g	1.52	6	6	6	6	6
water	ml	1	39.6	34.1	39.6	39.6	39.8
Barite	g	4.2	233.5	394.36	-	233.8	229.18
Crushed barite	g	4.2	-	-	233.5	-	-

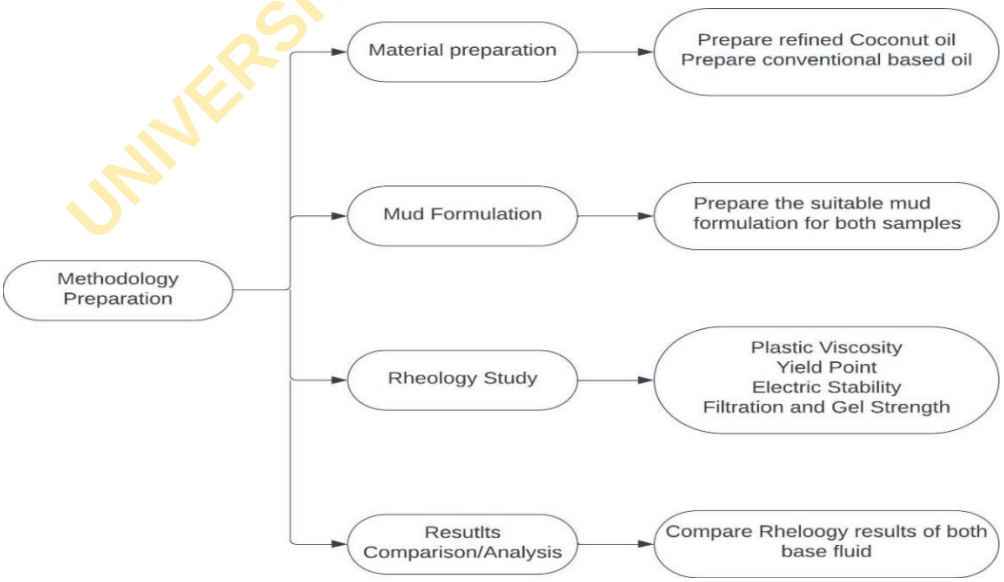

Fig. 2. Process methodology

Plastic Viscosity, $PV = \theta_{600} - \theta_{300}$ (1)
Apparent Viscosity, $APV = \theta_{600}/2$ (2)
Yield Point, $YP = \theta_{300} - PV$ (3)

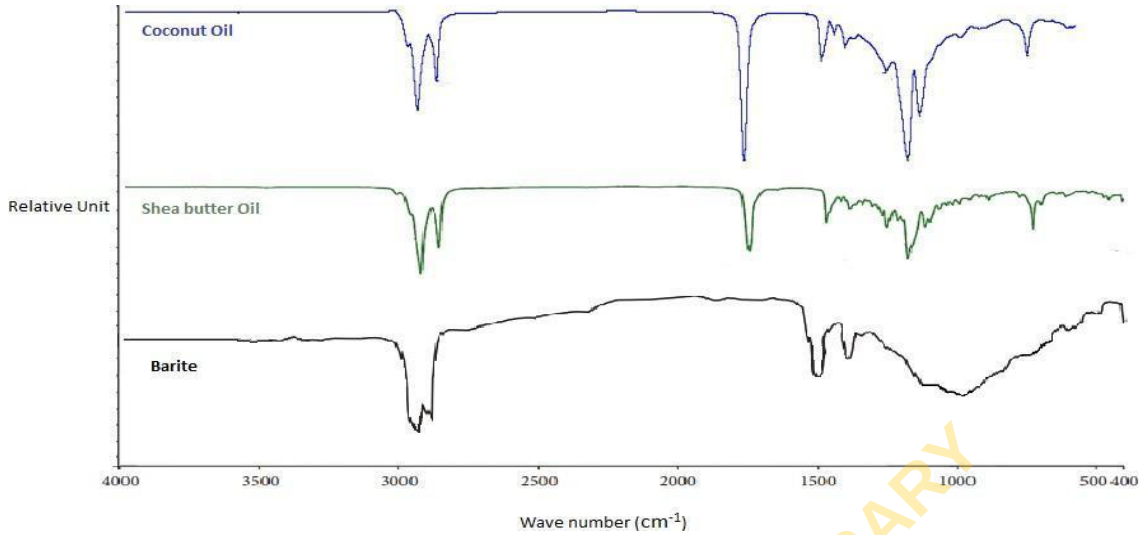

Fig. 3. FTIR Spectra for Coconut oil, Shea butter oil and barite

Gas Chromatography with Flame Ionization Detector (GC-FID) and Gas Chromatography with Mass Spectrometry (GC-MS) were used to examine the components and content of coconut oil and biodiesel, respectively. The instruments used were an Agilent 7890A quadrupole Mass Selective Detector (MSD) with helium as the carrier gas for MS and an Agilent 5975 quadrupole GC with a FID and hydrogen as the carrier gas for GC. With a split ratio of 40:1, separation was accomplished on an HP-5 fused silica capillary column (25 m × 0.25 mm x 0.40 µm). The mass spectrometer scanned from 30 Da to 600 Da while operating in electron impact mode at 70 eV ionization energy. Molecular mass, fragmentation patterns, and comparison with an electronic library were used to identify the products. Data analysis and acquisition were made easier by GC and MSD Chemstation software. 0.8 mL/min was the flow rate, 1µL was the injection volume, and 5.6 psi was the pressure. As per Bello et al. (2013), the analytical technique was followed, and the initial oven temperature was kept at 60°C. Moisture content, and S.G, were determined as with the procedures conducted on shea butter oil.

2.2 FTIR Characterizations

Fig. 3 depicts the comparative experimental spectrum of coconut oil, shea butter oil, and barite, as well as frequency assignments (functional groups and compounds). Tables 2, 3 and 4 give their numerical values. There is a variance in spectrum results across the investigated samples due to functional groups at each wave number. The FTIR spectra of coconut oil triglycerides indicate a stretched C-H bond at 2922.03 cm^{-1}. The normal absorption from triglycerides appears at wave number 1742.91 cm−1, which is an absorption of C=O ester. This is because the C-H aliphatic groups and C=O amide groups are the same component groups in all alkanol amides. Also, at wavenumber 1462.98 C-H bending of the Aliphatic (fatty acids) group is noticed.

Shea butter's peaks ranged from 2921.47 cm^{-1} to 2915.49 cm^{-1}, 2851.88 cm^{-1} – 2849.51 cm^{-1}, and 1745.43 cm^{-1} – 1736.51 cm^{-1}, 1469.65 cm^{-1} to 1464.20 cm^{-1}. These are C-H (CH2) and C-H (CH3) stretching vibrations, -C=O stretching vibrations of acids and esters, -C-H-(CH2CH3) bending vibrations of CH2 and CH3 aliphatic groups, C-O bonds of esters, and bending vibrations of a methylene group, respectively. Furthermore, its physical mixes showed absorption bands from 1734.91 cm^{-1} to 1175.65 cm^{-1}.

The sulfate group in barite exhibits four vibrational modes with frequencies of 1180, 1130, 1090, and 990 cm^{-1}. The peak at 1180 cm^{-1} is related to the asymmetric stretching vibration of the sulphate group, while the 1130 cm−1 peak belongs to the triply S-O stretching mode commonly found in barite groups (Janaki & Velraj, 2011). The 1090 cm^{-1} peak is assigned to the symmetric stretching of the $SO4^{2-}$ group, and the 990 cm^{-1} peak to the symmetric stretching of the $SO4^{2-}$ tetrahedral. These vibrational frequencies fall within the 1197 cm^{-1} - 1076 cm^{-1} range reported by Ramaswamy et al. (2010) for barite, except for the 990 cm^{-1} peak, which may

Table 2. Vibration frequencies and assignment of Coconut oil

Wavelength (cm^{-1})	Functional group	Compounds
2922.03	C-H (Stretching)	Aliphatic group (fatty acids)
2852.56	C-H (Stretching)	Aliphatic group (fatty acids)
1742.91	C=O (ester)	Triglycerides
1462.98	C-H (bending)	Aliphatic group (fatty acids)

Table 3. Vibration frequencies and assignment of Shea butter oil

Wavelength (cm^{-1})	Functional group	Compounds
2951.16	C-H (CH2) (Stretching)	Aliphatic chain
2850.23	C-H (CH3) (Stretching)	Methyl group
1735.42	C=O	Ester (triglycerides)
1470.55	C-H (bending)	Methylene group (CH2)
1385.36	C-O (ester)	Ester (triglycerides)
1113.50	C-O (bending)	C-O stretch in fatty acids

Table 4. Vibration frequencies and assignment of barite

Wavelength (cm^{-1})	Functional group	Compounds
3600	-OH stretching	Alcohol
3410	-OH stretching	Alcohol
2030	Ba-S-O stretching and bending vibrations	
1180	$SO4^{2-}$ (Asymmetric stretching and bending vibrations)	Sulphate
1710	Stretching vibrations of Oxygenous groups	
1130	S-O (Triply asymmetric stretching mode)	Sulphate monoxide
1090	$SO4^{2-}$ (Symmetric stretching)	Sulphate
990	Symmetric stretching of $SO4^{2-}$ tetrahedral	Sulphate
880	Symmetric stretching of $CO4^{2--}$ in calcite	
640	Ba-S-O1,2 polyhedral stretching vibration	

be due to differences in particle size and interactions between the $SO4^{2-}$ tetrahedral and metallic oxides (e.g., Al-O, Si-O) present as impurities in the clay. The spectrum also showed reasonably sharp peaks at 3600 cm^{-1} and 3410 cm^{-1}, which can be attributed to O-H stretching due to crystalline hydroxyl groups and absorbed water (Janaki & Velraj, 2011). Mayer et al. (2006) assigned peaks at 644 cm^{-1} and 630 cm^{-1} to BaO12 octahedral stretching vibrations in supergene and endogen barite samples analyzed with an FTIR spectrometer. This closely aligns with the 640 cm^{-1} peak observed in this study. The peak at 2030 cm^{-1} is assigned to Ba-S-O stretching and bending vibrations, indicating a "sheet" structure for the Ba-S-O bonding, similar to the 2000 cm^{-1} peak reported by Mayer et al. (2006). The peak at 880 cm^{-1} corresponds to symmetric modes of $CO3^{2-}$ stretching, suggesting the presence of calcite traces in the barite clay sample as an impurity.

3. RESULTS AND DISCUSSION

3.1 Results

All tests at 300°F were conducted after 1 hour of aging, thus the effects of temperature, aging and varying concentration for each sample are jointly discussed below. Sample I is Diesel used as the Control Sample. Sample II is Virgin Coconut Oil (VCO I) used as the sample with increased mud density. Sample III is Virgin Coconut Oil (VCO II) used as the sample with fine sized weighting agent. Sample IV is Shear Butter Oil (SBO I) used as the sample with increased emulsifier. Sample V is Shea Butter Oil (SBO II) used as the sample with decreased viscosifier.

Weighting agents, characterized by their high specific gravity, are employed to increase mud density and enhance drilling fluid performance. From Figs. 4 and 5, the impact of increasing temperature on oil based drilling fluids was

marked by the observed increase in mud densities for diesel, VCO I, SBO I, and SBO II, while SBO II shows the most resilience to increase in temperature with 0% change (Fig. 5). Despite these variations, all mud samples maintained effective density levels for controlling high downhole hydrostatic pressure. However, recent studies (Gamal et al., 2019) have showed that excessively high mud weight can cause formation dislodging and create an abnormal downhole pressure. Among all the tested formulations, diesel offered the highest mud density change (2.40%) across varying temperature ranges (Fig. 5) underscoring vegetable oils best suit case for HPHT applications. Fig. 4 shows the percentage change in the weight of the mud sample with change in temperature. The percentage change was highest for diesel mud sample, lowest for VCO II, but for SBO II, there was no change.

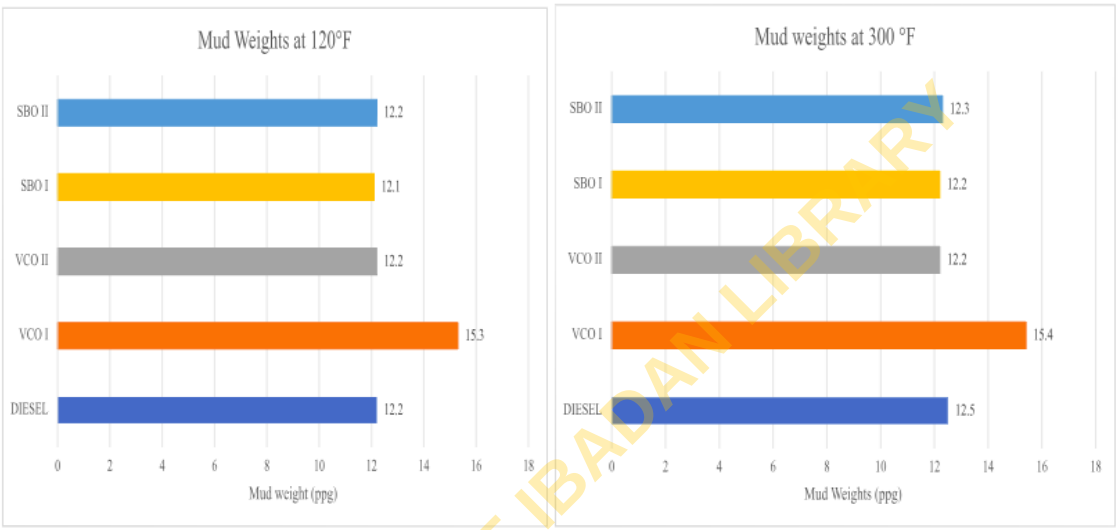

Fig. 4. Plot of sample mud weights at 120 °F and 300 °F

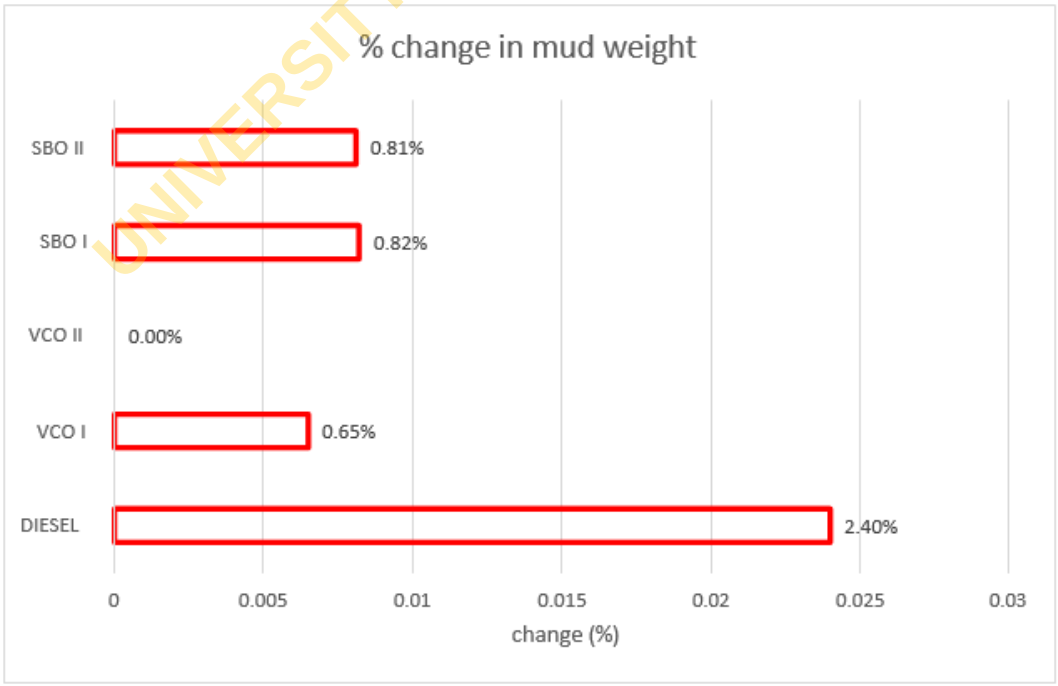

Fig. 5. Plot of % change in mud samples weight

Fig. 6 shows gel strength at both temperatures. All samples experienced increase in gel strength. SBO I and diesel samples had the highest change in gel strength at 120°F while VCO II and diesel had the highest change in gel strength at 300°F. At 120°F, VCO I had the least change in gel strength with time, followed by SBO II. At 300°F, SBO I had the least change in gel strength followed by VCO I. It can be seen from Fig. 7 that the Plastic viscosity, apparent viscosity and yield point of all the mud samples increased with increase in temperature from 120°F to 300°F. From Fig. 8, it can be seen that all the emulsion stability of all the mud samples decreased as temperature increased from 120°F to 300°F. VCO I had the highest percentage decrease in emulsion stability with increase in temperature, followed by SBO II and Diesel, while SBO I had the least percentage decrease followed by VCO II.

Fig. 6. Plot of Mud Sample's 10 sec and 10 mins Gel Strength at 120°F and 300 °F

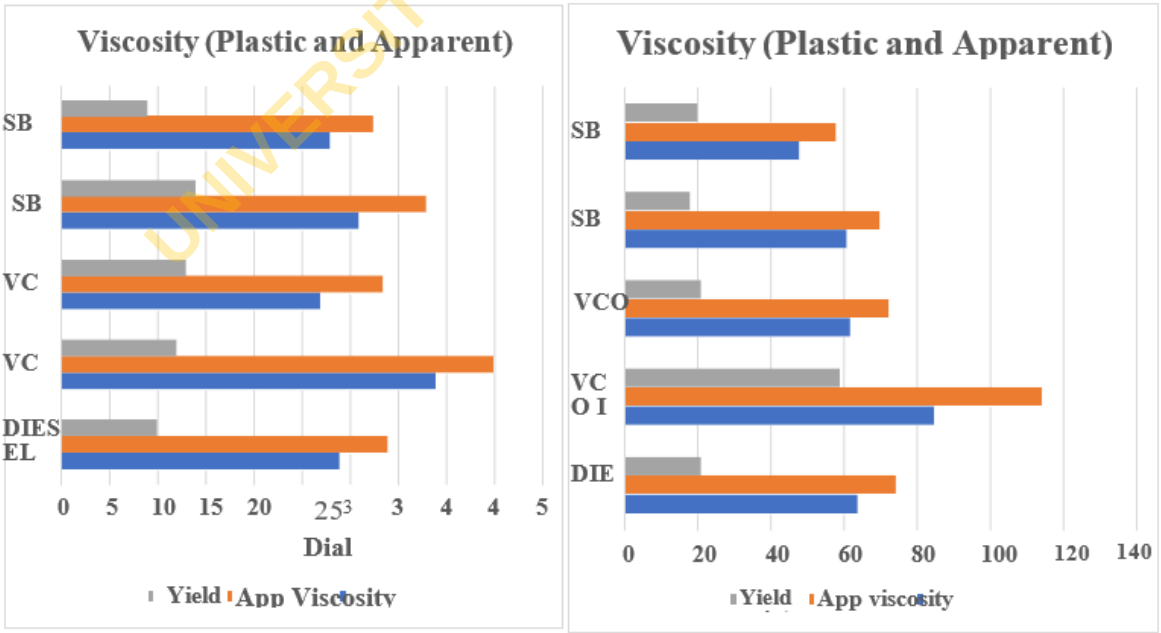

Fig. 7. Plot of Viscosity (Plastic and Apparent) and Yield at 120°F and 300 °F

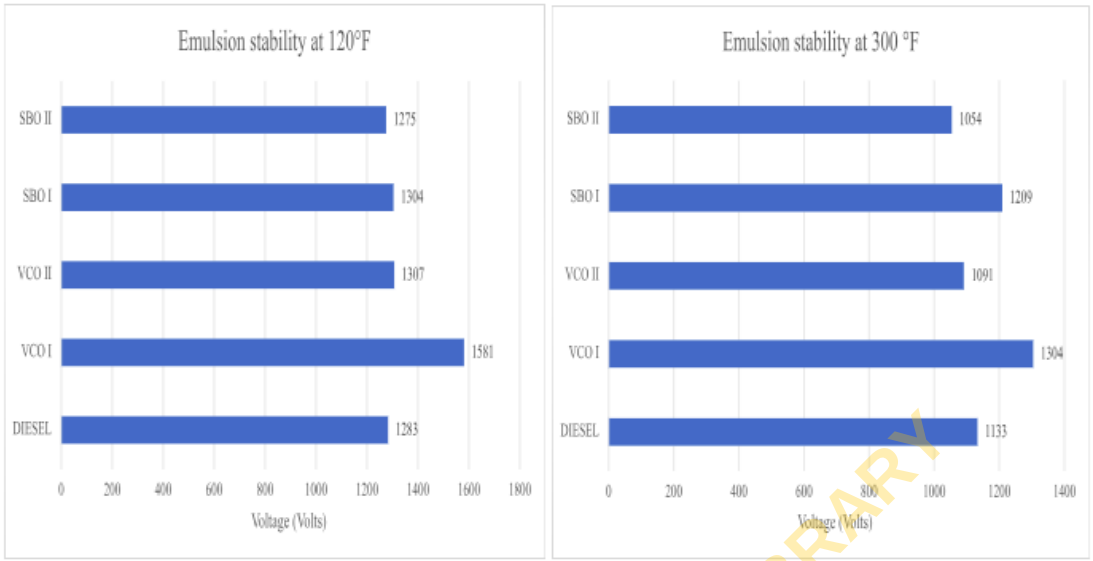

Fig. 8. Plot of Emulsion Stability of Mud Samples at 120°F and 300 °F

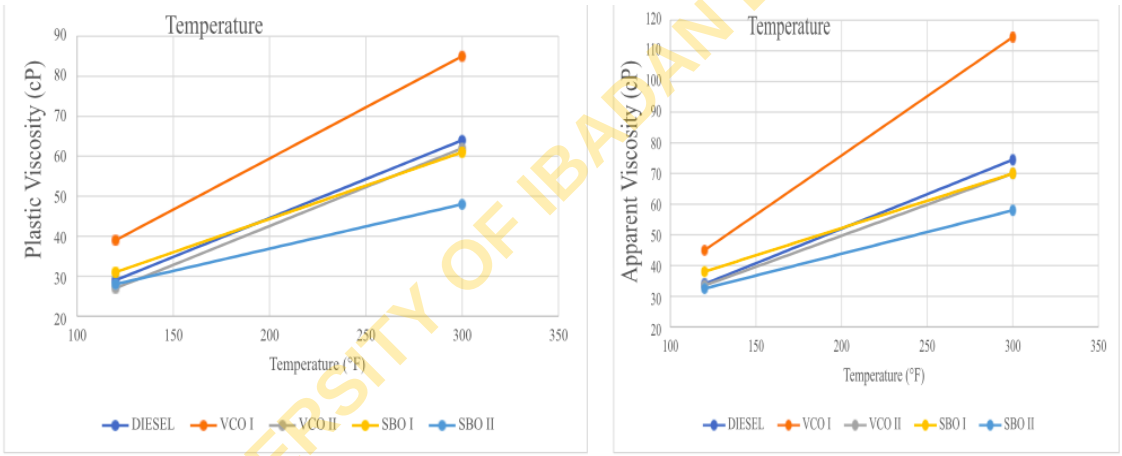

Fig. 9. Plot of Plastic Viscosity and Apparent viscosity vs. temperature

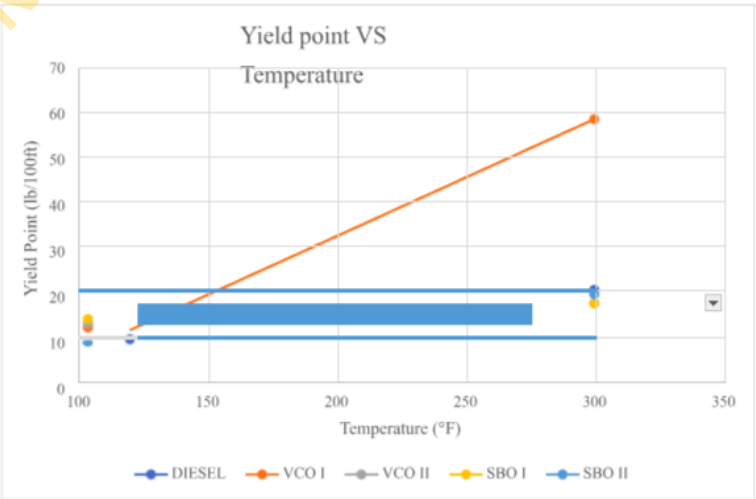

Fig. 10. Plot of Yield points vs. temperature

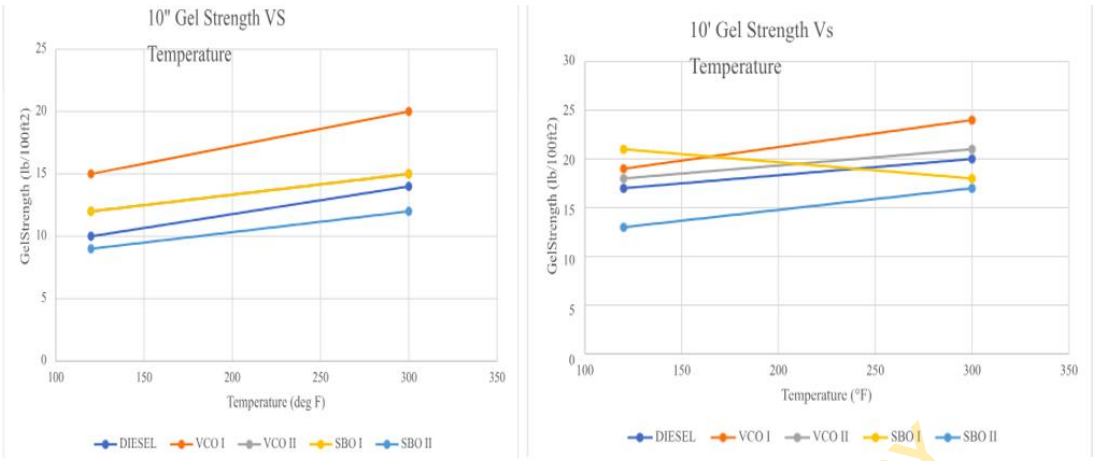

Fig. 11. Plot of (a) 10" and (b) 10' Gel strength's Vs Temperature

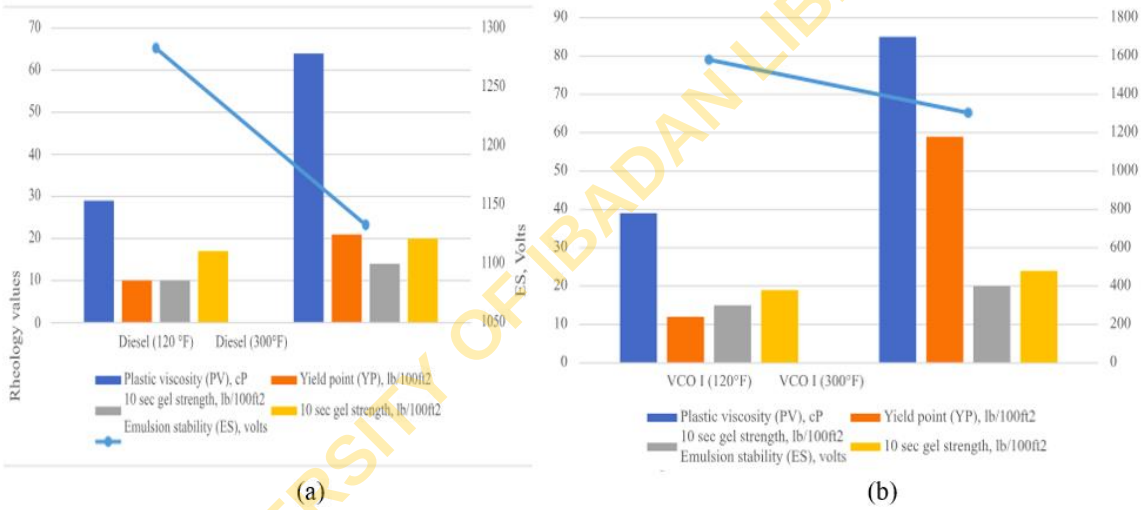

Fig. 12. Rheology based on mud density increment 120°F and 300°F for (a) diesel and (b) VCO I respectively

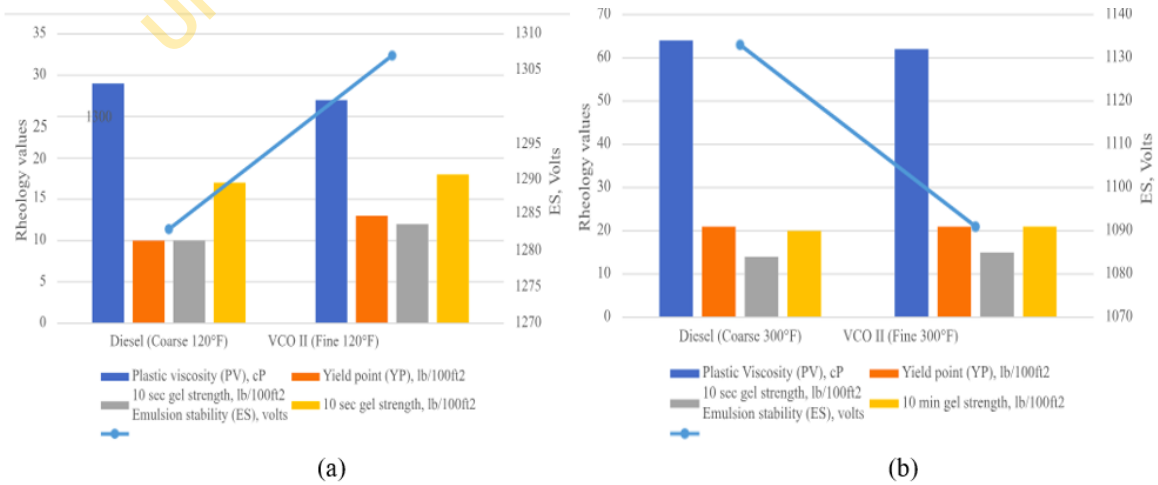

Fig. 13. Rheology behaviour comparison on different barite types at (a) 120°F and (b) 300°F

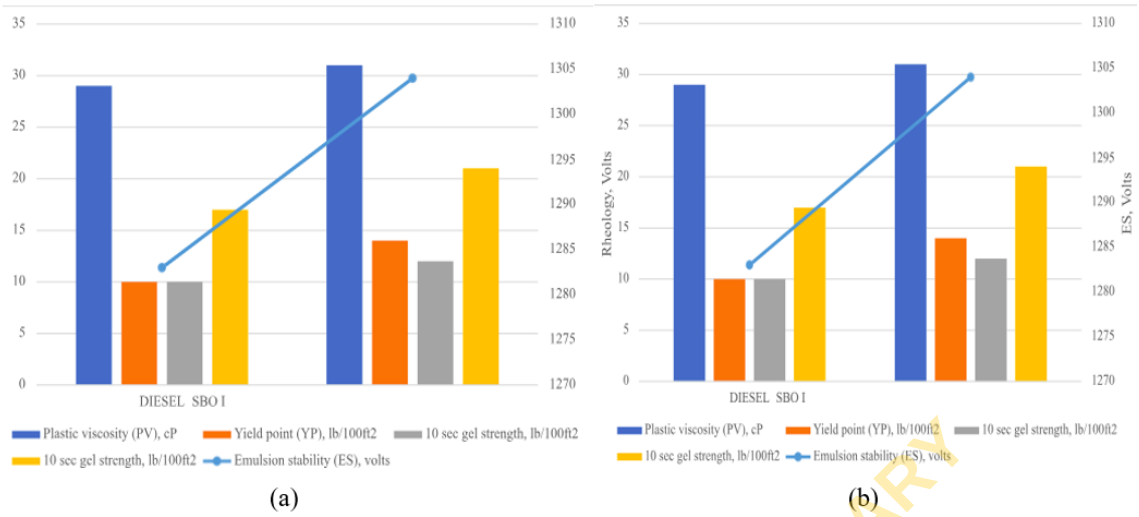

Fig. 14. Rheology behaviour comparison on increased emulsifier (a) 120°F and (b) 300°F

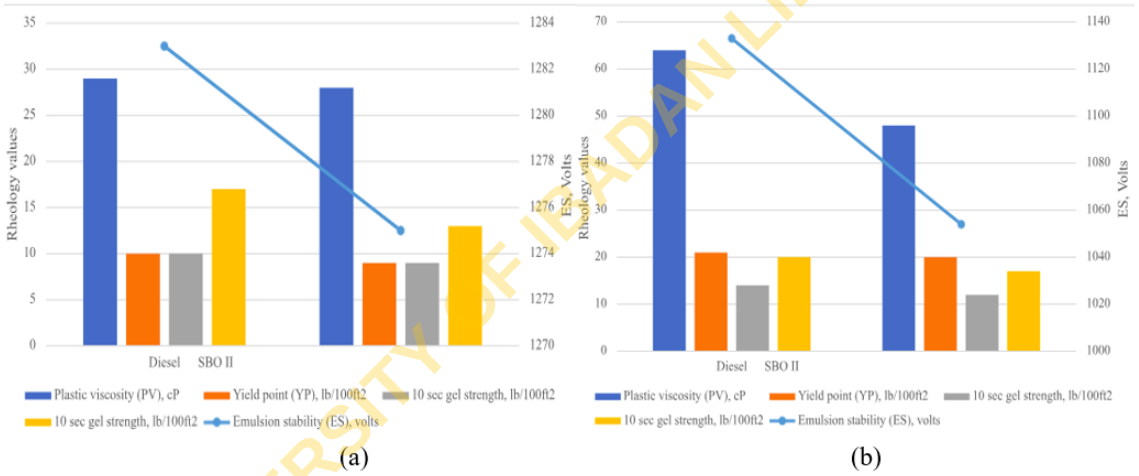

Fig. 15. Rheology behaviour comparison on reduced viscosifier (a) 120°F and (b) 300°F

From Fig. 9, it can be seen that an increase in temperature resulted in an increase in the plastic and apparent viscosities of the mud samples respectively. Fig. 10 showed that VCO I had the highest yield point indicating the strongest gel structure at rest as can be seen from Figs. 11 and 12.

3.2 Discussion of the Mud Density Results

For the control of formation pressure and to maintain adequate overbalance critical to drilling operations, mud density plays a pivotal role. Mud density directly influences the fluid-carrying capacity of drilling mud, crucial for effective drilling. Weighting agents, characterized by their high specific gravity, are employed to increase mud density and enhance drilling fluid performance. From the results presented in Figs. 4 and 5, the impact of increasing temperature on oil based drilling fluids was marked by the observed increase in mud densities for diesel, VCO I, SBO I, and SBO II, while SBO II shows the most resilience to increase in temperature with 0% change. Despite these variations, all mud samples maintained effective density levels for controlling high downhole hydrostatic pressure. However, recent studies (Gamal et al., 2019) have showed that excessively high mud weight can cause formation dislodging and create an abnormal downhole pressure. Among all the tested formulations, diesel offered the highest mud density change (2.40%) across varying temperature ranges (Fig. 5) underscoring vegetable oils best suit case for HPHT applications.

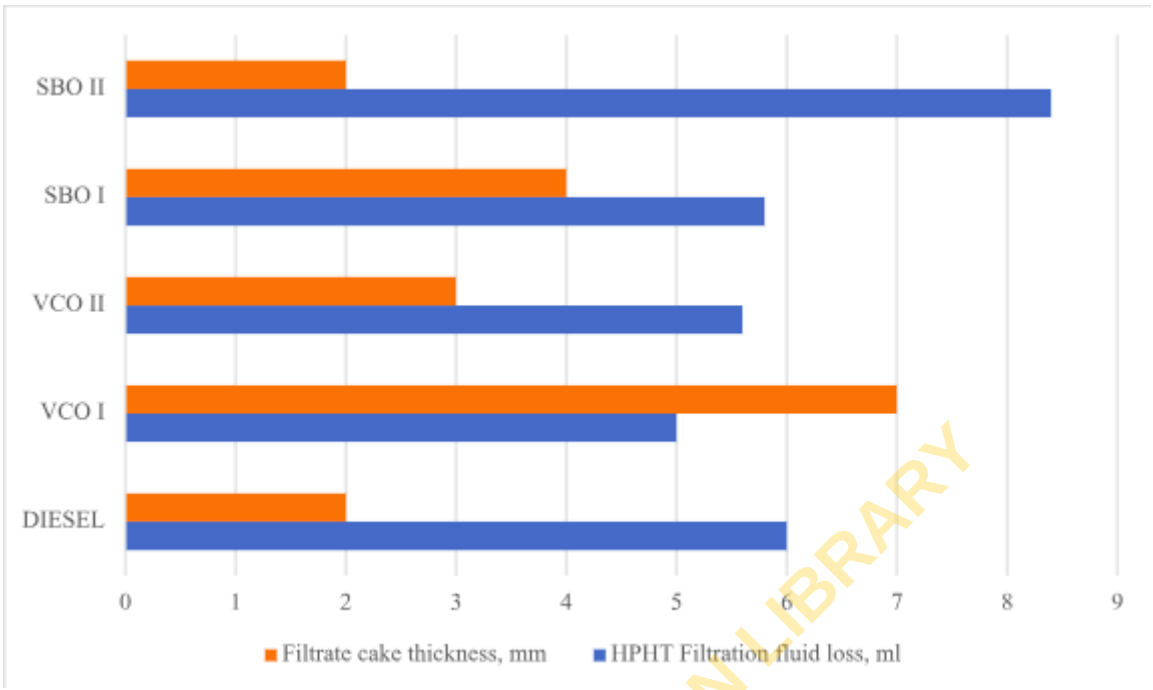

Fig. 16. 300°F filtration characteristics

Two mud samples were tested in an HPHT (High Pressure High Temperature) system; one was based on diesel and the other on coconut oil. The mud weights of the two samples were 12 and 15 pounds per gallon (ppg), respectively. Figs. 13a and 13b show that the fluids' rheological behaviour at 300 rpm showed a noticeable increase in plastic viscosity (PV), yield point (YP), and gel strength (GS), but a decrease in emulsion stability (ES).

Both diesel and VCO I showed notable increases in PV upon reaching the high temperature of 300°F; diesel increased from 29 to 64 cP, while VCO I showed greater increase, from 39 to 85 cP. In a similar vein, the YP values for diesel and VCO I went boosted from 10 to 21 and 12 to 59 lb/100 ft^2, respectively. Furthermore, there was a minor rise in GS, with VCO I rising from 15 to 20 lb/100 ft^2 and diesel base rising from 10 to 14 lb/100 ft^2. Both samples demonstrated emulsion stability in spite of these modifications, with values surpassing 400 Volts both before and after the temperature increase.

Generally, VCO I after ageing and subject to temperature increase showed greater changes. This occurrence is thought to be caused by the extra barite added to the VCO I mud formulation in order to fit the high-density 15 ppg mud system, which increased the mud's overall solid content.

This analysis focuses on the plastic viscosity (PV) behaviours observed in the tested drilling fluid samples (Diesel, VCO I, VCO II, SBO I, and SBO II) as presented in Fig. 7. The observed trend across all samples is the rise in PV with increasing temperature (120°F to 300°F) indicating the possibility of thermal degradation or alteration of the drilling mud components. This aligns with well-established principles in fluid mechanics. As temperature increases, the kinetic energy of the fluid molecules rises. This heightened molecular agitation leads to greater interaction and resistance to flow within the fluid, reflecting a higher PV. Across the temperature range, VCO I consistently have the highest PV (Figs. 7, and 15). This indicates a higher internal resistance to flow within the VCO fluid layers than in other samples.

The apparent viscosity is said to be the viscosity of a material (liquid, gaseous or semi- solid) at a given shear rate and temperature. Similar to plastic viscosity, apparent viscosity (AV) also plays a significant role in drilling fluid performance, and follows a similar trend in this study. It reflects the combined effects of the fluid's internal resistance to flow (plastic viscosity) and the rate at which the shear rate is applied. To better understand each fluid's relative performance, we determined the average AV at all temperatures. VCO I fluids have the highest average AV (79.75 cP), suggesting the greatest

resistance to flow. SBO II fluids have the lowest average AV (45.25 cP), while the other fluids fall between the two extremes.

The yield point (YP), often known as a mud's cutting-carrying ability, is used to assess its ability to raise cuttings out of the annulus. A high YP indicates a non-Newtonian fluid, which carries cuts more efficiently than a fluid of comparable density but lower YP. VCO I has the highest average yield point (35.50 lb/100ft²), indicating the strongest gel structure at rest. SBO II fluids exhibit the lowest average yield point (14.5 lb/100ft²), while the other fluids fall between these two extremes.

Based on YP alone, VCO fluids appear to be favourable due to their strong gel structure, potentially aiding in wellbore stability. However, the risk of pipe sticking also needs to be considered. SBO fluids offer a lower YP, potentially reducing the risk of pipe sticking but might require additional measures for wellbore stability in some formations.

Theoretically, adding more organophilic clay to mud will increase its lifting capacity, strengthen its gel, and improve its suspension qualities. An experiment evaluating the effect of viscosifier concentration on the rheological performance of SBO (Shea Butter Oil) base oil was conducted. SBO II sample mud formulated with no viscosifier in the mud formulation was chosen as the comparative sample.

The results, presented in Fig. 15, indicate that the Diesel base sample exhibited higher plastic viscosity (PV) values compared to SBO II. Specifically, at 120°F, Diesel recorded a PV of 29 cP, whereas SBO II showed a slightly lower PV of 28 cP Similarly, at 300°F, Diesel had a PV of 64 cP, whereas SBO II exhibited a reduced PV of 48 cP. The reduction of organophilic clay content in SBO II led to decreased yield point (YP) and gel strength (GS) values at both 120°F and 300°F. Specifically, YP decreased from 10 to 9 lb/100 ft^2, and GS decreased from 21 to 20 lb/100 ft^2. Similarly, the 10-minute gel strength decreased from 17 to 13 lb/100 ft^2 at 120°F and from 20 to 17 lb/100 ft^2 at 300°F.

These results imply that lowering the amount of organophilic clay in the mud formulation led to decreased rheological characteristics at all stages (before and after temperature increase and aging) when compared to the Diesel base sample.

Diesel oil based mud with 2mm offered the lowest values for mud thickness. This indicates that problems of differential sticking are greatly minimised using them compared to vegetable oils, especially in the case of VCO I with the highest filter cake thickness of 7mm.

In this analysis, the influence of particle size on VCO II mud to counteract barite sag was investigated. VCO II mud was prepared with barite particles of smaller size compared to Diesel mud. The results presented in Table 4 indicate that VCO II exhibited slightly lower plastic viscosity (PV) values at both 120°F and 300°F compared to Diesel. Specifically, at 120°F, VCO II showed PV values of 27 lb/100ft², while Diesel exhibited 29 lb/100ft². At 300°F, VCO II recorded PV values of 62 lb/100ft², slightly lower than diesel's 64 lb/100ft². However, both VCO II and Diesel showed equal yield point (YP) values of 21 lb/100 ft² at 300°F, with VCO II having slightly higher YP than Diesel at 120°F.

The impact of barite particle size on mud can be observed in Figs. 12a and 12b. Larger surface areas and a higher particle count are typically associated with finer particle sizes. Since the larger surface area of colloidal-sized particles attracts more surfactants needed to maintain emulsion stability, a high concentration of these fines can enhance PV. Viscosity may increase erratically as a result of this phenomenon.

These findings indicate that employing smaller-sized barite particles, as observed in the VCO II mud, can indeed affect the rheological characteristics of the mud, especially concerning plastic viscosity. This influence appears to persist both before and after subjecting the mud to increased temperature and aging. Consequently, this adjustment in particle size may play a crucial role in enhancing the mud's ability to counteract barite sag under varying conditions, thereby contributing to improved drilling performance and stability.

Electric stability, commonly referred to as emulsion stability, serves as a fundamental parameter in evaluating the ability of oil-based mud (OBM) to sustain stable emulsions amidst fluctuating temperature conditions. Emulsion stability is critical in drilling operations as it directly influences fluid performance and wellbore stability. This study aims to analyse the electric stability of different OBM samples at 120°F and 300°F to elucidate the impact of

temperature on emulsion stability and its implications for drilling operations.

The electric stability of five OBM samples—Diesel, VCO I, VCO II, SBO I, and SBO II— was assessed using standard testing procedures. Measurements were conducted at temperatures of 120°F, and 300°F. Electric stability, measured in volts, provides insights into the resistance of emulsions formed by the drilling mud to phase separation under varying temperature conditions. The research demonstrates significant trends in electric stability among the evaluated OBM samples. In the case of diesel, electric stability drops from 1283 Volts at 120°F to 1133 Volts at 300°F, demonstrating a decreasing ability to maintain stable emulsions as temperature increases. A similar declining tendency is seen in VCO I, VCO II, SBO I, and SBO II, though with varied degrees of resistance to temperature-induced emulsion instability.

VCO I has relatively higher electric stability than Diesel throughout all temperature ranges, indicating a greater tolerance to temperature influences on emulsion stability, while SBO I with the lowest change of 95volts in ES indicates greater resistance to temperature-induced instability.

From the study, it was found that formulating SBO I with the increased emulsifier resulted in a 37% higher resistance to temperature-induced emulsion instability compared to Diesel, which had a lower emulsifier concentration. This suggests that augmenting the emulsifier concentration enhances the emulsion stability of drilling mud. However, SBO I exhibited a lower plastic viscosity (PV) of 61 cP compared to diesel mud with 64 cP at 300°F. The effect of increasing emulsifier concentration on both mud samples is illustrated in Fig. 14.

Emulsifiers facilitate the formation of water-in-oil emulsions or invert emulsions, reducing the interfacial tension between oil and water. This promotes the formation of stable emulsions with smaller water droplets. Smaller droplet sizes inhibit water content from behaving like a solid, a common occurrence in invert emulsion mud systems. Additionally, secondary emulsifiers serve as wetting agents. However, the presence of excess water that is inadequately emulsified can lead to the formation of larger water droplets, consequently increasing the number of water particles linearly. This exponential increase in water particles ultimately elevates the viscosity of the invert emulsion.

These results indicate that with increase in temperature after aging, SBO I mud is susceptible to degradation negatively affecting its plastic viscosity.

While muds with excellent pH values are needed in zones where mud pH is greatly altered, the same mud is usually subjected to filtration rate test, which is a very important property of any drilling mud. This is very important especially when permeable, carvenous (thief) zones are being drilled or tendencies of the mud pressure exceeding the formation pressure is to be encountered.

Proper control of filtration can prevent or minimize wall sticking and drag and in some areas improve borehole stability (Kok & Alikaya, 2003). Fig. 16 showed filtrate volume from the formulated mud samples collected after 30 minutes in ml. Diesel displayed the highest filtration fluid loss across all samples. This suggests that Diesel allows for the passage of a larger volume of fluid through the filter paper compared to other formulations, while VCO fluids (VCO I and VCO II) generally exhibit lower filtration fluid loss compared to Diesel. VCO I shows slightly lower fluid loss compared to VCO II indicating that VCO fluids form a more effective filter cake that restricts fluid passage to a greater extent.

Shea Butter Based fluids (SBO I and SBO II) exhibits the highest filtration fluid loss throughout the test, thus the least comparable performance with SBO II recording the largest individual sample fluid loss.

The fluid loss and mud cake of the mud sample were examined in the HPHT filtration test for 30 minutes at 300°F and 500 psi of pressure. The majority of the samples from the HPHT test do not pass the API test; SBO II exhibits the largest fluid loss (8.4 ml) and VCO I the lowest (5.0 ml). This suggested that the fluid loss agent was being utilized at an inadequate concentration. The absence of water in the mud filtrate upon looking for the mud cake indicated that the emulsion was stable following HPHT treatment. In terms of mud cake observation, Diesel and SBO II exhibit good mud cake thickness within the specified range of around 2/32 in. for API. A thicker mud cake is seen in other samples (VCO I & II, and SBO I), with VCO I having the thickest mud cake (8/32 in.) because of the higher solid content (due to higher mud weight and barite content).

The gel strength is another important drilling fluid property, as it demonstrates the ability of the drilling mud to suspend drill solid (drilled cuttings) and weighting material when mud circulation is ceased. Across all samples, both 10-second and 10-minute gel strength values increase with rising temperature (from 120°F to 300°F). Fig. 6 indicated that VCO Fluids generally exhibit the highest gel strength for both 10-seconds and 10-minutes at both temperatures. This suggests a stronger and faster development of a gel structure in VCO fluids, potentially due to the gelling properties of some of the fatty acid's components of coconut oil present in these fluids, while Diesel displays moderate gel strength that increases with temperature.

Conversely, the gel strength values of the muds formulated using Shea Butter Oil (SBO I and SBO II) generally exhibit lower gel strength throughout the temperature range compared to VCO fluids. However, SBO II shows gel strength values closer to VCO fluids at higher temperatures (240°F and 300°F).

Therefore, while VCO fluids offer the strongest gel structure, potentially beneficial for wellbore stability, they might require careful monitoring to avoid excessive gelation and the risk of pipe sticking. SBO fluids show a trade-off between gel strength and potential sticking risks. Selecting the optimal drilling fluid based on gel strength necessitates considering the specific wellbore conditions, particularly the presence of weak formations and the likelihood of circulation interruptions

4. CONCLUSION

Vegetable oil base mud (base VCO I & SBO I) showed resilience to temperature-induced changes in rheological properties, with VCO I exhibiting the most stable behavior. It offered higher electric stability compared to diesel across temperature ranges. VCO fluids have higher plastic viscosity and yield point values, indicating stronger gel structures, potentially aiding in wellbore stability; displayed lower filtration fluid loss compared to diesel, indicating better filtration control and show the highest gel strength, suggesting a faster and stronger development of gel structure.

SBO I demonstrated increased emulsion stability with higher emulsifier concentration, albeit with slightly lower plastic viscosity compared to diesel.

SBO II exhibited lower rheological properties compared to VCO II, especially in terms of plastic viscosity (PV), yield point (YP), and gel strength (GS), indicating a weaker gel structure. It demonstrated higher filtration fluid loss compared to VCO II, suggesting less effective filtration control; shows relatively lower emulsion stability compared to VCO II, particularly at higher temperatures and offers moderate gel strength that increases with temperature, but generally lower than VCO II.

VCO II showed slightly lower Plastic Viscosity (PV) compared to diesel, indicating a less viscous fluid. It exhibits comparable or slightly lower Yield Point (YP) values compared to diesel at both 120°F and 300°F, indicating similar or slightly weaker gel structure. It demonstrated slightly lower filtration fluid loss compared to diesel, suggesting better filtration control; offers higher emulsion stability compared to diesel across temperature ranges and displayed higher gel strength compared to diesel, potentially contributing to better suspension of drill solids and weighting materials.

5. RECOMMENDATIONS

Based on these findings, we offer the following recommendations for future drilling operations:

It is recommended that SBO II should be further optimized by adjusting emulsifier concentration and particle size distribution. Also, different additives should be tested to improve the gel strength of SBO II, and optimize the rheological properties of VCO II.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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