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Analysis of the effects of drilling fluid viscosity on hole cleaning in directional well drilling

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ABSTRACT

Hole cleaning is one of the most important aspects of extractive drilling operations. When drill cuttings combine with drilling fluids, a cutting bed gel is created, which becomes extremely challenging to remove while drilling. One of the functions of drilling fluid, when the flow is static, is to maintain the drill bits' suspension. However, the settling of drill bits makes this nearly impossible. In this paper, the influence of fluid viscosity on hole cleaning performance was critically studied through a series of laboratory experiments. The effects of different viscosity levels on hole cleaning were investigated. This paper evaluated the use of lecithin and carboxymethyl hydroxyethyl cellulose (CMHEC) as a viscosifier and fluid loss agent in oil-based drilling fluid. The rheological properties of the formulated drilling fluids were determined at various temperatures according to the API 13B-2 specifications in order to identify the most suitable mud type for high-temperature drilling operations. From this study, it was discovered that Formulation B has the best rheology, with a plastic viscosity (PV) of 12, 7, and 7 cP at 30, 40, and 50 °C, respectively, while its yield point (YP) was found to be 30, 24, and 16, respectively. These values were compared with the generic oil-based formulation (A), which had a plastic viscosity (VP) of 43, 39, and 22 cP at 30, 40, and 50 °C, respectively, while its yield point (YP) was found to be 38, 20, and 26, respectively. The findings show that formulation B has a significant resistance to high temperatures, which means that it can be applied to drilling operations in reservoirs with high temperatures. It is more environmentally friendly. Furthermore, this paper explores the implications of the results in terms of the efficiency of hole cleaning and the drilling process relative to the viscosity of oil-based drilling fluid. This paper concludes by providing suggestions for improving drilling efficiency through the selection of an appropriate drilling fluid viscosity.

Keywords: *Hole cleaning, lecithin, Fluid viscosity, Carboxymethyl hydroxyethyl cellulose.*

1. Introduction

Drilling is a crucial aspect of the extractive industry as it involves creating holes in the earth's surface to extract minerals, oil, and natural gas [1]. Drilling is a complex process and requires a great deal of technical expertise and knowledge. It is important to ensure that the drilling process is done safely and in compliance with all applicable regulations [2]. The oil and gas industry relies on drilling for the exploration and production of both oil and gas. It is a process that involves the use of high-pressure pumps and large drill bits to drill deep into the earth to locate and extract oil and gas reserves. Appropriate selection of drilling fluid helps to maintain the stability of the borehole walls and to reduce the risk of blowouts. The composition of drilling fluid depends on the type of drilling being performed and the type of formation being drilled. It is often tailored to the specific needs of the operation [3]. The critical functions of drilling fluid include carrying cuttings to the surface, controlling formation pressures, sealing permeable formations, maintaining wellbore stability, cooling and lubricating drill bit. [4]. Special additives, such as emulsifiers, filtration additives, foaming additives, lost circulation additives, thinners/dispersants, viscosifiers, wetting agents, surfactants among others are added to a drilling fluid to achieve its basic function [5]. The results of [6] demonstrates that Jatropha-based drilling muds performed better in terms of thermal stability than mud based on standard diesel. According to Udeagbara et al. [7], Castor-based drilling fluid is less acidic, has a lower gel strength (GS), and plastic viscosity (PV) than mud based on diesel. Further works by [8], shows that the rheological and lubricity tests carried out on neem oil biodiesel-based drilling muds are comparable to conventional diesel-based drilling muds. Hole cleaning is necessary to prevent numerous operational problems, such as stuck pipe, reactive formations, lost circulation, and high torque. It is also necessary to maintain high-quality wellbore stability and ensure the accuracy of logging measurements [9]. The viscosity of real-world materials can be greatly affected by variables, such as temperature and pressure, and it is clearly important for drilling fluid engineers to understand how viscosity depends on such variables. For all liquids, viscosity decreases with increasing temperature and decreasing pressure. Viscosity is strongly dependent on temperature, so careful attention must be paid to the temperature control of viscosity measurements in order to obtain accurate results. Liquids with high viscosity are highly temperature dependent, so extra caution is required. [10]. In the vast majority of drilling fluids, viscosity decreases with an increase in shear rate, giving rise to what is now generally called "shear-thinning" behavior, although the terms "temporary viscosity loss" and "pseudoplasticity" have also been employed [11]. In some cases (very few), viscosity increases with shear rate. Such behavior is

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commonly referred to as "shear thickening", although the term "dilatancy" is also used. A study by Sidky et al., [12] establishes that the higher the temperature, the lower the viscosity of the fluid. Also, the viscosity of the mud is affected by the amount of base oil and the particulate matter present in the mud. Zhang et al. [13] also established that when the base oil content increases, the viscosity and yield point of the mud generally increase. Moreover, pressure affects the mud properties, as the application of external pressure increases the viscosity of the mud [14]. According to Onu et al., [8], calocullumінophyllum oil has the potential to be a drilling oil-based mud. However, plant-based mud would need more pump pressure and cost to start flowing than commercial mud. Furthermore, Oseh et al., [15], revealed that the almond seed oil-based drilling mud's rheology, filtration qualities, electrical stability, thermal stability, and ability to inhibit shale swelling are similar to those of diesel OBM. Its high biodegradability is also attributed to its low branching degree and lack of aromatic compounds. For high-temperature operations both water-based mud and oil-based mud have been used; however, in reality, oil-based mud is more widely used to overcome problems in high-pressure high-temperature (HPHT) conditions [16]. The aim of this study is to elaborate on the effects of drilling fluid viscosity on hole cleaning in directional well drilling.

2. METHODOLOGY

2.1. Preparation of Lecithin as Emulsifier

A local variety of egg yolks rich in lecithin was used for this experiment. The phospholipids from the egg yolks were extracted using a solvent named ethanol. The constituents were homogenously mixed, and the phospholipids were allowed to dissolve. The solution was properly filtered to remove any solids or impurities. The solvent was evaporated using a rotary evaporator to obtain a crude lecithin extract. The lecithin extract was purified using a column chromatography apparatus. The purified lecithin was retrieved and allowed to dry under a vacuum to remove any remaining solvent. The purity of the lecithin was tested using in-layer chromatography. The purified lecithin was carefully stored in an airtight container at room temperature, and about 12g was used for this study.

2.2. Preparation of Oil-based drilling fluid samples

The methodology used in this study strongly abides by the Oil Company Materials Association (OCMA), the American Society for Testing and Materials (ASTM), and the API 13B-2 standard for the preparation and evaluation of drilling fluid. An initial quantity of about 150 ml of distilled water and 21.5 g of bentonite were first prepared for each system setup according to the API specification for the preparation of drilling fluid. A quantity of the oil base (diesel about 238 ml) was measured using a measuring cylinder and emptied into the mud cup of the Hamilton Beach mixer. The oil-base drilling fluids were composed of mineral oil, brine (36.8 wt% $CaCl_2$), emulsifiers, lecithin, organo-bentonite, and weighting agent barite. The oleophilic components, such as the emulsifiers, the oil-wetting agent, the fluid-loss additive, the pH control additive, and the viscosifier (organophilic clay), were added slowly and carefully, one after the other, to the oil base while stirring. The resulting mixture was stirred at about 600 revolutions per minute (rpm) using a Hamilton Beach laboratory mixer for approximately 15 minutes. The aqueous phase of the drilling fluid was prepared to the desired ion concentration by dissolving 36.8% by weight of calcium chloride in 77 ml of distilled water. The prepared brine was added to the stirred oil phase, and stirring was continued for about 15 minutes. Barite (barium sulfate), which was used as the weighting agent, was slowly added to the stirred emulsion. Subsequently, stirring was continued for a further 30 minutes to obtain a homogenous mixture. The test analysis was carried out on the fluid samples, which were then allowed to age for 24 hours at room temperature.

2.3. Rheology and Fluid Loss tests

One of the major factors in determining the viscosity properties of good drilling fluids is plastic viscosity (PV) and yield point (YP). The plastic viscosity, yield point, and gel strength of approximately 10 seconds and 10 minutes were carefully recorded at rheometer dial readings of 600 rpm, 300 rpm, 200 rpm, 100 rpm, 60 rpm, 30 rpm, and 6 rpm as specified in the API 13B-2 as specified for the measurement of drilling fluid properties. Following the completion of the experiments at 30 °C, the fluid sample was heated up to about 40 °C and 50 °C, after which the test was repeated. Equations 1 and 2 were used to compute the viscosity properties of the developed fluid. Equation 1 was applied to calculate the plastic viscosity (PV) in mPa.

$$PV = \theta_{600} - \theta_{300} \quad (1)$$

Equation 2 was applied to calculate the yield point (YP) in lb/100ft^2

$$YP = (\theta_{300}) - PV \quad (2)$$

Where: θ_{600} is the 600 revolutions per minute (rpm) dial reading and θ_{300} is the 300 rpm dial reading.

Immediately after the completion of the rheology test, the fluid loss was determined by pouring the control and the bentonite mud with specific weights of carboxymethyl hydroxyethyl cellulose (CMHEC) into the API filter press fluid cell. The pressure was then increased to 250 psi, as recommended in the API 13B-2.

3. Results and Discussion

In order to ensure the validity of the conducted experiment, the data analysis was based on comparative analysis using a control fluid sample, the American Petroleum Institute (API) specification standard for drilling fluid, as well as previously conducted research that had been validated. The range of numerical values for estimating the quality of the properties of oil-based drilling fluid, which is fundamental to ensuring a successful drilling operation, is outlined in Table 1. The rheological requirements for the drilling fluid sample preparation in accordance with the API 13B2 specification are listed in Table 2.

Table 1. API standard range for oil-based drilling fluids.

Mud Properties	Oilfield Units
Plastic Viscosity (PV)	<65 (cp)
Yield point (YP)	5-45 (lb/100ft²)
Gel strength @ 10 seconds	3 - 20 (lb/100ft²)
Gel strength @ 10 minutes	8 - 30 (lb/100ft²)
API Fluid loss	15.0 ml (max)

Table 1. The results for PV, YP, Gel Strength, and Dial Readings of the Samples of mud gotten from the Laboratory Test.

Sample	Parameters	Temperature		
		30°C	40°C	50°C
	θ_{600}	124	98	70
	θ_{300}	81	59	48
	θ_{200}	50	40	30
OBM	PV	43	39	22
	YP	38	20	26
	Gel Strength @ 10secs	4	3	3
	Gel Strength @ 10mins	10	13	13

Table 4 shows a significant decrease in fluid loss after the subsequent addition of 2g of lecithin. There was a 25% reduction in fluid loss at the 1-minute mark, going from 1.2 mL to 0.9 mL. The fluid loss dropped to 5.0 mL at the 9-minute mark, a 23% reduction from 6.5 mL. These findings imply that lecithin effectively improves the fluid retention properties of oil-based drilling mud, likely due to improved emulsion stability and a more uniform filter cake formation. According to Jones and Patel [17], the surfactant qualities of lecithin, which enhance the dispersion of the water and oil phases in the mud and produce a more stable emulsion and less permeability of the filter cake, are responsible for the decrease in fluid loss that occurs when lecithin is added.

Lecithin acts as an emulsifier that prevents the agglomeration of solid particles, resulting in a thinner and more uniform filter cake. Table 5 shows a decrease in filter cake thickness with an increasing lecithin concentration of 2.0 g from an initial filter cake thickness of 2 mm to 1.3 mm. While higher concentrations of lecithin improve the flow properties of the mud, they also reduce its viscosity and enhances its filtration characteristics.

Table 3. Sample with Lecithin.

Sample	Parameters	Temperature		
		30°C	40°C	50°C
	θ_{600}	60	55	50
	θ_{300}	48	45	41
	θ_{200}	45	30	25
OBM (Lecithin)	PV	12	10	9
	YP	36	35	32
	Gel Strength @ 10secs	7	6	5
	Gel Strength @ 10mins	15	13	11
OBM + 2g Lecithin	θ_{600}	54	38	30
	θ_{300}	42	31	23
	θ_{200}	40	23	17
	PV	12	7	7
	YP	30	24	16
	Gel Strength @ 10secs	9	8	7
	Gel Strength @ 10mins	20	18	15

Table 4. gives the result of the fluid loss test while Table 5 shows the Cake thickness.

Time (mins)	Fluid Loss (ml)	
	OBM	OBM + 2g Lecithin
1	1.2	0.9
3	2.1	1.4
5	3.9	2.1
7	5.1	2.8
9	6.5	3.9

Table 5. The measurement of filter cake.

Mud Sample	Thickness of Cake(mm)
Oil based Mud	2
OBM with 2g Lecithin	1.3

3.1. The Effect of Lecithin on Mud Plastic Viscosity

There is a gradual decrease in the plastic viscosity of the oil-based drilling fluid relative to an increase in its solid content, as seen in Figure 1. At a temperature of 30 °C, an increase in the concentration of lecithin results in a decrease in the plastic viscosity of the drilling fluid samples (A and B) at 12 and 7 cP, respectively. As the temperature of the drilling mud increased from 30°C to 50°C, a further decrease in plastic viscosity was observed. Generally, the plastic viscosities of the oil-based drilling muds are believed to be higher than those of the water-based mud samples.

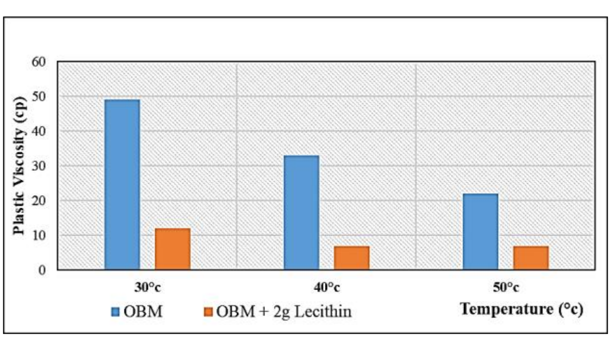

Figure 1. Plastic Viscosity of Oil-Based Drilling Fluid at Varying Temperature.

Due to the fact that increasing the temperature of the mud sample results in a reduction in the drilling mud's liquid phase and a consequent increase in the solid phase, the plastic viscosity of the mud sample decreases. This agrees with previous research by Ali et al., [18] and Rafieefar et al., [19] though other viscosifiers were used. The drastic reduction in plastic viscosities of the oil-based drilling mud dosed with lecithin and carboxymethyl hydroxyethyl cellulose (CMHEC) to 12, 7, and 7cp at different temperatures compared to the generic oil-based drilling fluid at 43, 39, and 22cp, respectively, can be attributed to the effective performance of these additives in altering the rheological properties of the drilling fluid. Lower plastic viscosity enhances the fluid's ability to transport cuttings from the borehole to the surface. With the inclusion of lecithin, the reduced viscosity allows for smoother flow and better suspension of drill cuttings, facilitating their removal from the hole. This improvement in hole cleaning efficiency can prevent issues, such as stuck pipe and improve overall drilling performance.

3.2. Effect of Lecithin on Mud Yield Point

The yield point can be referred to as a determinant of the attractive forces present in a drilling mud when it is subjected to a specific flow [2]. The force of attraction between colloidal particles or fragments found in drilling fluids is frequently referred to as the yield point. From Figure 2, the base mud exhibits a yield point of 38 lb/100ft² at 30°C, which significantly drops to 20 lb/100ft² at 40°C and then increases slightly to 26 lb/100ft² at 50°C. This fluctuation indicates that while the base mud has good suspension capabilities at lower temperatures, its performance becomes less predictable at higher temperatures. However, the lecithin-based mud shows a more consistent decrease in yield point with increasing temperature as seen in Figure 2. At 30°C, the yield point is 30 lb/100ft², which decreases to 20 lb/100ft² at 40°C, and further drops to 16 lb/100ft² at 50°C. The lecithin-based mud demonstrates more consistent yield points across different temperatures. This consistency is crucial for effective hole cleaning, as it ensures predictable fluid behavior and stable cuttings suspension. Additionally, if the yield point of the mud is high, it poses an alert to the mud engineer that a larger pumping pressure needs to be applied to enable the mud to flow properly, which is critically required in the oil and gas industry for hole cleaning.

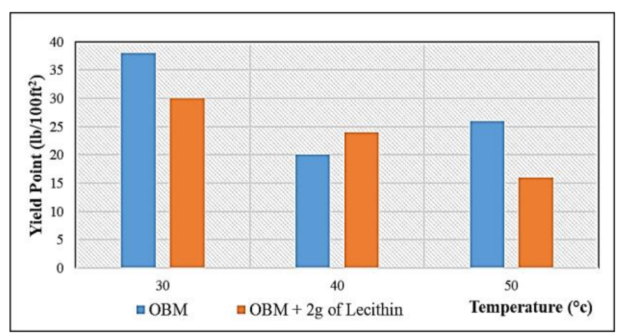

Figure 2. Yield Point of OBM with Lecithin at Varying Temperatures.

3.3. The Effect of Lecithin on Fluid Loss

Figure 3 shows the relationship between fluid loss over time and a substantial lecithin formulation. The pattern of fluid loss varies from 1 to 3 minutes. Figure 3 also shows the initial fluid loss sample values. However, a lower value of fluid loss was recorded in the mud sample with a 2 g concentration of lecithin during a shorter period of time (about 1–3 minutes). Furthermore, with an increase in time, there is further reduction. The API specifies a filtrate loss volume of less than 4.0 ml and a filter cake thickness of less than 2.0 mm. Using a filter cake, it was observed that as the lecithin content increased, the cake's thickness declined from 2 mm to 1.3 mm. According to Adesina et al., [20], low fluid loss is an important characteristic of effective drilling fluids and is required for borehole integrity. Cuttings are less likely to retain oil, which makes cuttings disposal easy, affordable, and beneficial for wellbore stability. In drilling operations, a thinner cake is preferable as it lowers the possibility of pipe sticking hazards [21].

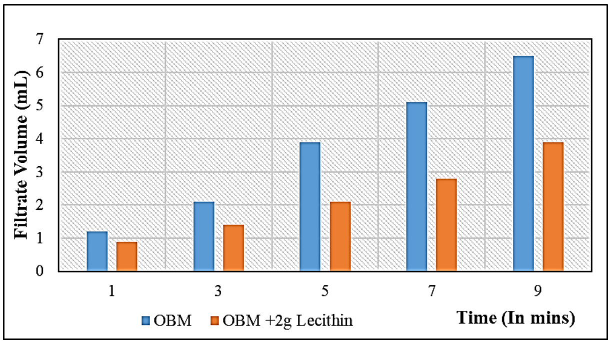

Figure 3. Filtration loss of Oil-based drilling mud samples.

3.4. Rheology

3.4.1. The Effect of Temperature on the Viscosity of the Oil Based Drilling Fluid

The comparative analysis of the effect of temperature variation at 30, 40, and 50 °C on the viscosities of different formulations A and B is shown in Figures 4 and 5, and the samples depict a change in viscosity with an increase in temperature. Viscosity, which is defined as the shear stress-to-shear rate ratio, is a measure of a fluid's internal resistance to flow. The viscosity of the lecithin-based drilling fluid was higher at 30 °C than at the other temperatures of 40 and 50 °C. The lecithin-based formulation (B) had a higher and more stable viscosity than the generic oil-based formulation (A), even at higher temperatures. This is expected because of the addition of lecithin and carboxymethyl hydroxyethyl cellulose (CMHEC) to the formulation. This unequivocally indicates that oil-based drilling fluids with higher lecithin content would outperform generic oil-based drilling fluids in high-temperature reservoir conditions with respect to mud stability, cooling effect, and improved ability to suspend and carry cuttings from formation to the surface.

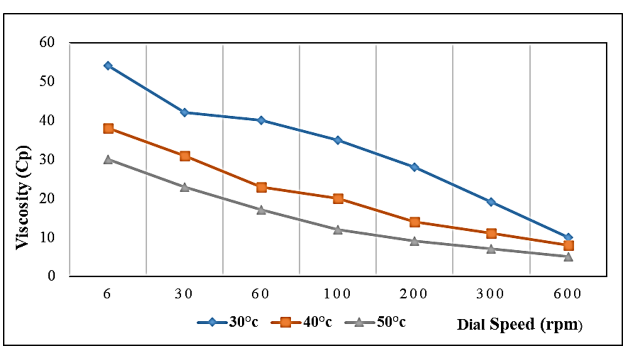

Figure 4. The Viscosity of Oil-Based Mud at Different Temperatures.

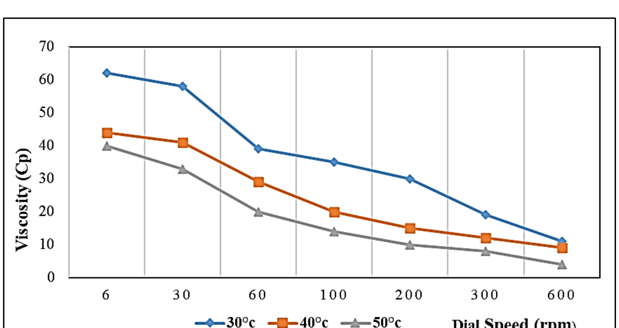

Figure 5. The viscosity of oil-based mud with increased Lecithin content.

4. Conclusion

The viscosity of oil-based drilling fluid was investigated in this study. The plastic viscosity, yield point, and gel strength of the drilling mud decreased with increasing lecithin content. This demonstrates the clear positive effect of lecithin as an emulsifier. Practically, gel strength refers to the mud's capacity to suspend cuttings while it is static. The knowledge of gel strength development over time is so important to detect any possible rheological problem in a mud system [10]. High-gel-strength oil-based drilling muds are unfavorable, because they need a lot of pumping pressure to break circulation after the mud has been static for a while. Additionally, increased gel strength during tripping operations may intensify the swabbing and surging effects. [9]. For optimum drilling, API recommends a gel strength between 3 and 20 lb/100 ft2 for 10 seconds and between 8 and 30 lb/100 ft2 for 10 minutes. In this study, the formulated sample was able to satisfy the API-recommended specifications. Several specific conclusions were drawn from the study.

1. The PV of the drilling mud sample with increased lecithin content ranged from 6-15cp which is ideal, because it enables the drilling fluid to carry cuttings to the wellbore and optimizes hole cleaning.
2. The increased concentration of lecithin content from 0g to 2g influenced the thickness of the filter cake, leading to a thin filter cake with a thickness range of 2mm – 1.3mm, resulting in an appropriate decrease in fluid loss.
3. Using highly viscous oil-based drilling fluids might result in ineffective cuttings transport, which clogs the wellbore and ultimately leads to non-productive time.

Recommendations

1. Future research might investigate the stability of lecithin-based muds at high temperatures, as well as their performance in the presence of nanoparticles.
2. Using local additives to improve the rheology of the lecithin-based drilling fluids.

Abbreviations

OBM – Oil based Mud
CMHEC – Carboxymethyl hydroxyethyl cellulose
API – American Petroleum Institute
θ600 – Dial reading at 600 rpm
θ300 – Dial reading at 600 rpm

Disclosure Statement

No potential conflict of interest was reported by the authors.

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