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(RESEARCH ARTICLE)

Enhancement of rheological properties and cutting carrying capacity of water based drilling fluid using Al_2O_3 nanoparticles

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Abstract

Drilling mud is a necessary component of drilling operations. There have been notable attempts to enhance the filtration and rheological properties and increase the cutting carrying capacity of water-based mud (WBM) using nanoparticles (NPs). This study investigates how varying Al_2O_3 concentrations affect the rheological properties and cutting carrying capacity of drilling fluids. In this study, different drilling muds were produced using bentonite (2.8g) without nanoparticle, 50% bentonite (1.4g) and 50% Al_2O_3(1.4) and 0% bentonite(0g) and 100% Al_2O_3 (2.8g). Testing and comparisons were done on the formed mud samples' physiochemical properties, rheology, filtration properties, and cutting carry index (CCI). The Power Law Model was used to define the rheological behavior of the manufactured mud samples, and results showed that all the mud samples were pseudoplastic fluids and remain a preference for drilling fluids because their flow behavior index (n) was less than 1. It was observed that the addition of Al_2O_3 is directly proportional to the plastic viscosity, apparent viscosity and yield point and inversely proportional to the gel strength of the drilling fluid. The study also shows that the addition of Al_2O_3 nanoparticle influences the cutting carrying index CCI as the calculated cutting carrying index gives a high cutting carrying index CCI which means that the hole cleaning potential of the drilling mud is good. The study shows that Al_2O_3 nanoparticles are feasible for use in drilling fluid formulation.

Keywords: Drilling fluid; Rheology; Nanoparticle; Shear stress; Power law model

1. Introduction

Drilling fluid's main function is to move drill cuttings from the bottom hole to the surface for disposal. To describe how well the hole is being cleaned, terms like cutting transport efficiency and hole cleaning efficiency are frequently used interchangeably. The drilling fluid rheological characteristics, drilling fluid density, cutting size, cutting shape, cutting density, hole size, pipe rotation, flow rate to mention a few each affects the cutting transport efficiency, penetration rate, etc. A range of negative occurrences, including mechanical sticking, high equivalent circulation density (ECD), slow rate of penetration (ROP), increased torque, and drag, might come from improper hole cleaning and result in lost productivity time (NPT). Therefore, during drilling and well planning, additional measures for hole cleaning are made.

According to Meng *et al.* [1], drilling fluid, also known as the "drilling industry blood," is essential for several functions such as, lubricating and cooling of the drill bit, cuttings removal, impeding formation damage, regulating formation pressure, plugging permeable formations, stabilizing and supporting the wellbore, and supplying buoyancy [2]. With regards to drilling fluids, there are two basic types namely Water-Based Mud (WBM) and Oil-Based Mud (OBM). The

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first drilling fluid (OBM) is more cost-effective and ecologically benign, whereas the second is the ideal drilling fluid for water-sensitive, intricate, and high-temperature formations [3]. In recent times, due to the need to produce from unconventional reserves like shale, the drilling industry needs enhanced drilling technology for deep-water reservoirs, shale gas, and oil [4]. Thus, developing a fit for purpose drilling fluids is pertinent because drilling fluids have a higher surface area to volume ratio than larger particles while nanoparticles (NPs) are stronger, have superior electrical and thermal characteristics, and are more chemically reactive. Researchers are motivated to use nanofluids to solve drilling problems because of the suitable qualities of NPs. Any fluid having at least one component with a particle size of 1-100 nm is considered a nanofluid in the oil and gas sector [5]. Drilling fluid experts are still interested in discovering novel multifunctional compounds that might enhance WBDF's capabilities while reducing material usage. Numerous researches have been conducted on the use of NPs to enhance the filtration control and rheological characteristics of WBMs.

The impacts of Al_2O_3 nanoparticles on the rheological properties and cutting carrying capacity of water-based drilling mud are investigated in this work. The study's objective is to develop drilling mud made with aluminum oxide nanoparticles, describe it, and evaluate its cutting carrying ability.

2. Material and methods

2.1. Material

The experiment used the following equipment and materials. Potassium chloride, Borax, Poly anionic cellulose, Bentonite, Caustic soda, Xanthan gum, water-based mud, industrial graded nanoparticle 75nm Aluminum Oxide, plastic rubber, mixer, electric weighing scale, spatula pH strip, API filter press, Baroid mud equilibrium, Thermometer, Conical Flask, Retort Stand, Crucible, Measuring Cylinders, Marsh funnel, Speed Rheometer, PH paper (Al_2O_3).

2.2. Mud Preparation

A bentonite mud was produced with reference to API (American Petroleum Institute) requirements. 350ml of water, 2.8g of bentonite, 0.20 soda ash, and 0.20 caustic soda were mixed. The mixture was allowed to settle over a period of 24 hours at ambient temperature (see Table 1).

Table 1 Drilling mud additives

S/No	Additives	Conc.	Property
1	WBM	350 ml	Based fluid
2	Potassium Chloride	18.00 g	Inhibition control
3	Borax	2.00 g	Preservative
4	Xanthan gum	2.80 g	Viscosifier
5	Polyanionic cellulose	2.00 g	Filtration control
6	Barite	76.80 g	Weighting agent
7	Soda ash	0.20 g	Calcium ion remover
8	Caustic Soda	0.20 g	Alkalinity control
9	Bentonite	2.8 g	Viscosifier
10	Aluminium oxide	Varied	Filtration loss reducer/rheology modifier

2.3. Rheological Properties determination

The agitated sample was put in a thermo cup, and the surface of the mud was made to align with the rotor sleeve's scribed line. The viscometer was started by switching to the high-speed setting and fully depressing the gear change. For the 600-rpm reading, a stable indicator dial value was reached and recorded. The switch's speed and indication value were set to 300 revolutions per minute then recorded and subsequently set at 200rpm, 100rpm, 60rpm, 30rpm, 6rpm, respectively. The switch was regulated to gel and 10sec gel was recorded and later recorded at 10mins gel. The viscometer measures the shear rates of the drilling muds at six different dial readings of 600, 300, 200, 100, 6, and 3 revolutions per min (rpm). Dial readings were performed thrice for repeatability, and the average values were reported. AV, PV, μ_e, YP, and 10 secs and 10 mins gel strength (G_S) were determined from the Bingham plastic fluid model described by Equations (1) to (4):

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

$$\text{YP (cP)} = \theta_{600} - PV \quad \text{.......2}$$

$$\text{AV (cP)} = \frac{\theta_{600}}{2} \quad \text{.......3}$$

$$\mu_e = 300 \times \frac{\theta}{\omega} \quad \text{.......4}$$

Where,
θ_{300} = dial reading at 300 rpm
θ_{600} = dial reading at 600 rpm
PV = plastic viscosity,
AV = apparent viscosity, and
YP = yield point.

The drilling mud's capacity to suspend drilled cuttings is measured by the 10 second- and 10-minute gel strengths (G s). The fluid flow behavior was described using the power law model. Equations (7) and (8) were used to get the flow behavior index "n" and the fluid consistency index "K" from the relationship between shear-stress and shear-rate obtained from the viscometer dial reading at "600" and "300." (8). Prior to that, the dial readings obtained as well as rotor speed values were respectively converted to shear stress (τ) and shear rate values (γ) using the Equations (5) and (6):

$$\tau \left(\frac{ib}{100ft^2}\right) = 1.067 \times \theta \quad \text{.......5}$$

$$\gamma(1/s) = 1.704 \times \omega \quad \text{.......6}$$

$$n = 3.23 \times log \frac{\theta_{600}}{\theta_{300}} \quad \text{.......7}$$

$$K \left(\frac{ib}{100ft^2}\right) = \frac{\tau}{\gamma^n} = \frac{\theta_{600}}{1022^n} \quad \text{.......8}$$

Where;
θ (lb/100 ft^2) indicates the dial reading, and
1.067 is the geometry factor of the viscometer,
ω represents the viscometer (rotor) speed (rpm) and

2.4. Density (Weight) Procedure

The fluid's temperature was properly measured and noted. The freshly collected mud sample to be weighed was then added to the dry cup until it was completely full. The cup was covered with the lid to ensure that some mud would escape through the hole at the top. A finger was used to plug the hole in the lid before the whole outside of the cup and arm were coated in dirt. The balance should then be completely dried. The rider was then adjusted along the knife edge, and the balance until the cup and arm were balanced, as seen by the bubble, outside of the arm. The rider's edge facing the mud cup was measured for mud weight.

2.5. Filtration

The mud cell was removed from the filter press frame prior to doing this experiment by pushing the cell towards the operator while lightly twisting it. Before adding the filter paper, the cell lip was cleaned, and the big 0-ring was well placed. After tightening the screw, the bottom was changed. The dual needle valve was then switched off after the pressure valve's regulator was set to 100 psi and the graduated cylinder was positioned beneath the filtrate tube at 25 °C for 30 minutes and readings were obtained every 5 minutes. Afterwards, the upper part of the valve was gradually backed off while the dual needle was reseated, and the pressure applied. At a pressure of 100 psi and the typical dirt temperature, the filtrate volume in cubic centimeters (to 0.1 cubic centimeters) was recorded.

2.6. Power Law Constants (n and K) Calculation

Several varieties of drilling mud are categorized as non-Newtonian fluid, which is defined as the conduct of a fluid in between the Newtonian fluid model and the Bingham plastic model. The power law model depicted in Equations 9 and 10 describes how shear rate and shear stress are related:

$$\text{Shear Rate } (\gamma) = \text{Rotational Speed x } 1.703 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 9$$

$$\text{Shear stress } (\tau) = k\gamma^{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

Where:
$\tau = shear\ stress$
K= $constitency\ factor$
$\gamma = shear\ rate$
$n =$ flow behavior index

From any two values of shear rate and shear stress, n and K may be determined. The V-G meter is used to determine the value of shear rate on the rig. Every mud test typically yields readings of 600, 300, to 3, which can be used to calculate ‘n’ and ‘K’ known as power law constants and obtained using the expressions in Equations 11 and 12

$$n = 3.22 log \frac{(2PV+YP)}{(PV+YP)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

$$K = (511)^{1-n}(PV+YP) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

2.7. Determination of cutting carrying capacity

The ability to effectively clean a drilling hole remains a vital role of the drilling fluid is hole cleaning. The presence of a clean hole indicates an effective mud circulation system. The capacity of the drilling fluid to transport cuttings to the surface of the well is defined as the Cutting Carrying Index (CCI), as expressed in Equation 13. When the CCI is more than or equal to 1, the hole has been cleaned properly; nevertheless, when it is equal to or lower than 0.5, the hole has not been cleaned properly [6]. The following equation represents the CCI, an empirical connection based on actual data:

$$\mathbf{CCI} = \frac{(\mathbf{K} \times \mathbf{AV} \times \mathbf{MW})}{\mathbf{400{,}000}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{13}$$

Where;
AV is annular velocity in ft/min.
MW is mud weight in ppg.
K is a Power Law Constant.

The Power Law constant (K) can be determined from equation 12 stated above:

$$K = (511)^{1-n}(PV+YP) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

Where;
PV is plastic viscosity in centipoises.
YP is yield point in lb/100sqft
n is flow behavior index.

3. Results and discussion

3.1. Effect of Nanoparticle on drilling mud Rheological Properties

The stability of the borehole, the pace of penetration, and the behavior of the drilling fluids during circulation are all significantly influenced by the rheology of the mud. This section presents the findings from rheological tests of mud samples containing aluminum oxide (Al_2O_3) nanoparticles. The concentration of nanoparticles in the drilling fluid is directly proportional to the yield point and plastic viscosity. The particles in any colloidal stable dispersion system frequently engage in repulsive forces with one another, according to Tombacz *et al.* [7]. As coagulation is prevented due to the high electrostatic attraction between negatively charged particles, an increase in the viscosity and yield point of the drilling fluid system is observed. The strong electrostatic interaction between the negatively charged Al_2O_3 nanoparticles and the negatively charged bentonite particles are factors that contributes to the rise in yield point.

3.1.1. Plastic Viscosity

The inclusion of Al_2O_3 nanoparticle, as shown in figure 1, led to higher values for the plastic viscosity from the 33 ib/100ft^2 without addition of nanoparticle to 34 ib/100ft^2 at 100% Al_2O_3. The enhanced rheological qualities are attributable to the capacity of Al_2O_3 nanoparticle to be evenly distributed throughout the bentonite containing traditional WBM [8].

According to [9] better drilling cuttings lifting efficiency requires a relatively low plastic viscosity. In a similar report, Aftab *et al.* [8] noted that for good mud circulation devoid of excessive pressure loss due to friction, the plastic viscosity of drilling muds containing nanoparticles should be low at room temperature. This is because when mud encounters drill cuttings, its viscosities increase naturally. As such, the addition of nano-Al_2O_3 to the traditional WBM may not need the use of a high-density mud.

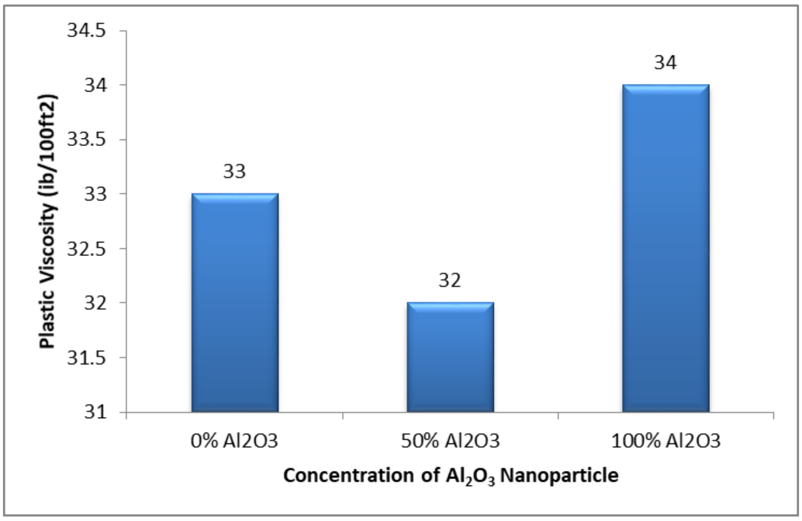

Figure 1 A function of varied Al_2O_3 nanoparticle concentration on plastic viscosity in water-based drilling mud

3.1.2. Yield Point

The yield point assesses mud's capacity to transport cuttings from the well bore. A drilling fluid with a greater yield point will be better able to transport cuttings than one with a lower yield point but same density.

The drilling fluid's yield point (YP) is a physical characteristic that indicates the initial force in pounds per square inch that must be applied to plastic or pseudoplastic, non-Newtonian fluids thus resulting in a dynamic state that proves the effectiveness of the drilling fluid in cleaning holes. As can be seen in figure 2, the yield point of the mud increased from 116 ib/100ft^2 without addition of nanoparticle to 131 ib/100ft^2 at 100% Al_2O_3.

The outcome indicates that the yield point of drilling mud was also greatly increased by the addition of the nanoparticle. This is also a result of aluminum oxide, Al_2O_3, nanoparticles having a bigger surface area and smaller size, which increases the electrostatic force of attraction between the mud particles. The altered viscosity of drilling mud that was achieved following the incorporation of aluminum oxide nanoparticle in the base mud would aid in the raising of drilling cutting from the bottom hole to the surface during drilling operations.

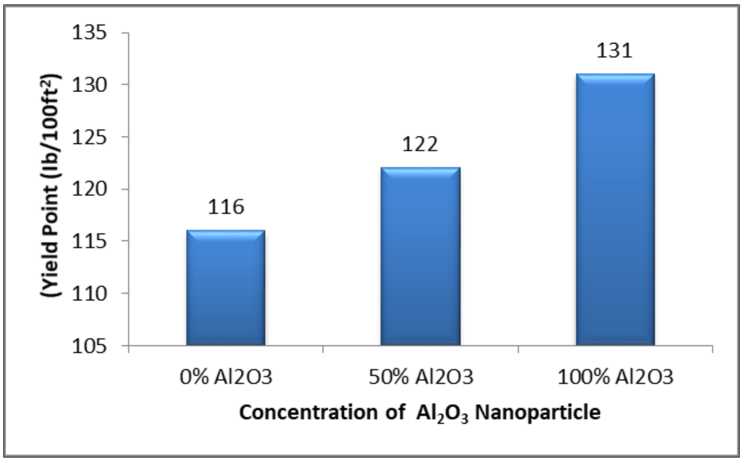

Figure 2 A variation of Al_2O_3 nanoparticle concentration on the yield point of drilling fluids

3.1.3. Apparent Viscosity

Apparent viscosity of a fluid is determined by the relationship between shear stress and shear rate. Elochukwu *et al.* [8] stated that for a drilling mud to effectively carry cuttings to the surface, its apparent viscosity must be able to demonstrate shear-thinning behavior with increasing shear rates. In shear-stress viscometer dial readings for the n-WBM experiments, the formed mud sample displayed pseudoplastic behavior. The drilling mud carrying capability is dependent on this shear-thinning property. Low apparent viscosity reduces the pumping rate provided beneath the bit at high shearing. Figure 3 shows that the apparent viscosity increased from 73cp without addition of nanoparticle to 82.5cp at 100% Al_2O_3.

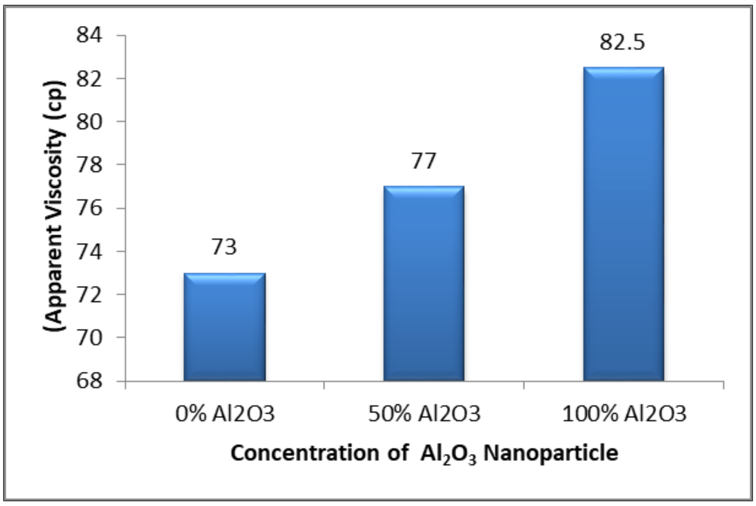

Figure 3 A function of varied Al_2O_3 nanoparticle concentration to the apparent viscosity

3.1.4. Gel Strength

The viscometer is often used to test the gel strength of drilling fluid at 3 RPM and time intervals of 10 secs and 10 min. It demonstrates the potency of the attractive forces in drilling mud under static condition [11]. The drilling fluids' gelation was gradually enhanced by the addition of various nanoparticle concentrations to the base mud, as seen by the gel 0s and gel 10m values of the various percentage concentrations of drilling fluids formulated using Al_2O_3 nanoparticles. To avoid drilling issues, a relatively low gel strength is required throughout the drilling process. This is in line with the reports of Mortada *et al.* [12], which demonstrates comparable gel strength findings employing nanoparticles as well as the reduction in the drilling mud's gel strength with the inclusion of nanoparticles. They explained how the strength of the gel is decreased by the addition of nanoparticles. Furthermore, Okie-Aghughu *et al.* [13] suggested that the gel should possess the adequate strength since solids would be well suspended in the hole and allowed to settle out on the surface. Additionally, high gel strengths should not be promoted because they might lead to a variety of drilling issues as shown in Figure 4 where the gel strength was reduced from 42 ib/100ft^2 at 10sec and 41 ib/100ft^2 10mins without addition of nanoparticle to 38 lb/100ft^2 at 10secs and 38 ib/100ft^2 at 10mins in 100% Al_2O_3.

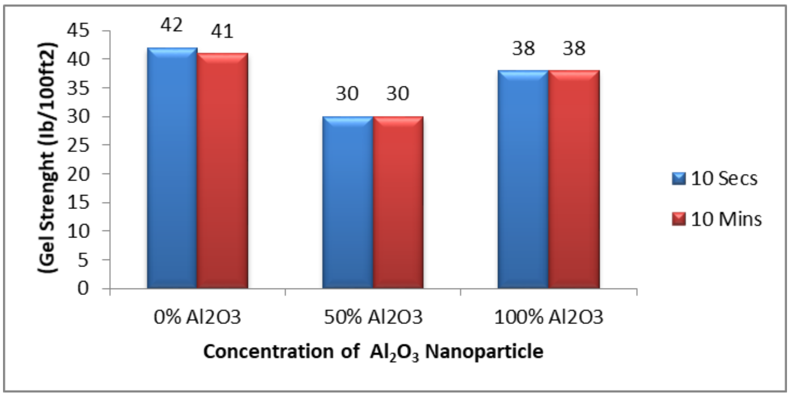

Figure 4 A function of varied concentration of Al_2O_3 nanoparticle on gel strength in WBM

3.2. Mud Density

Different percentage concentrations of the generated drilling mud were examined for density. The mud density of mud samples produced with varying amounts of bentonite and Al_2O_3 nanoparticles is shown in Figure 5. The reservoir conditions will determine the density of the water-based mud to be used, and the advantage of oil with high densities is that less barite will be used, lowering the cost of formulation. High density muds are preferred. According to Chikwe *et al.* [14], the denser the drilling mud is, the more difficult it is to drill. The more effectively it maintains column or hydrostatic pressure and suspends cuttings in the mud, the more effectively the bore hole may be cleaned. Additionally, for reservoirs faced with issues like the inflow of other fluids into the bore, denser drilling mud, such as nano water-based mud, is needed.

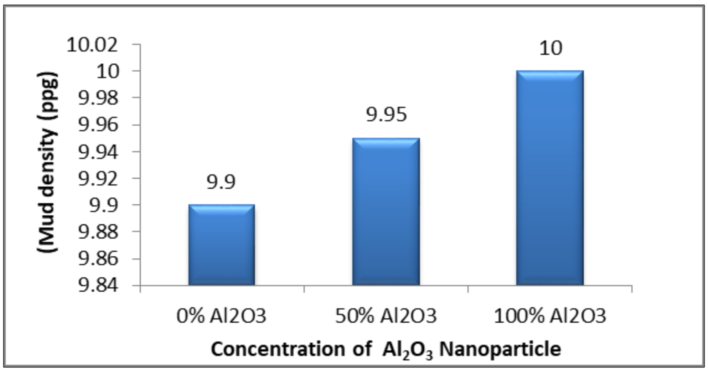

Figure 5 Mud Density of Al_2O_3 Mud Samples

3.3. Mud Filtrate Properties

3.3.1. Filtration Volume

The filtering abilities of freshwater-based samples with aluminum oxide nanoparticles are depicted in Figure 6. Spurt loss in static filtering is the haphazard quantity of filtrate produced by the propensity of smaller particles to pass through the surface of a porous media, such as filter paper or rock formation, before the deposition of filter cake. It displays how quickly the filter cake is dispersed throughout the filter medium. The higher the values, the slower the cake is laid. Yet, it conceals neither the caliber of the cake nor the total volume of filtrate.

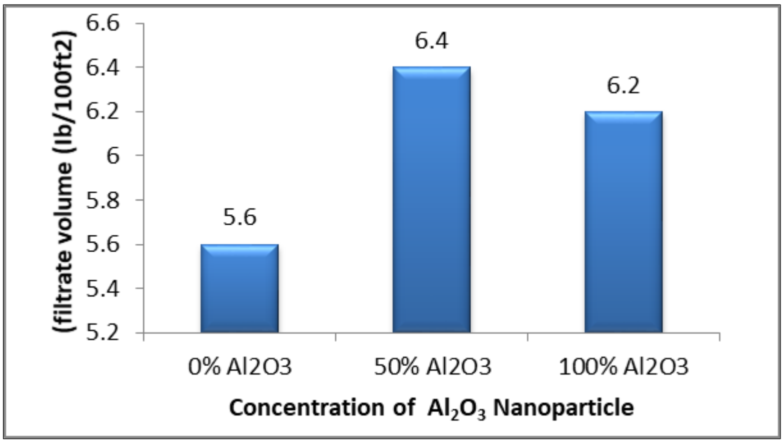

Figure 6 Filtration Volume of Al_2O_3 Mud Samples

According to Fadairo *et al.* [15], high filtration volumes in mud can cause a variety of issues, such as formation damage from filtrate and solids invasion, damaged zones that are too deep to be repaired by perforation or acidization, and more. wettability variations and variations in the relative permeability to oil or gas, Other issues include formation swelling caused by in-situ clays, formation plugging with fines or solids, invalid formation-fluid sampling tests, difficulties with formation evaluation brought on by excessive filtrate invasion and poor electrical property transmission through thick cakes, as well as potential mechanical issues with running and retrieving logging tools, and inaccurate properties measured by logging tools (measuring filtrate altered properties rather than reservoir fluid properties). which can go unnoticed because the filtrate flushes hydrocarbons out of the wellbore, making them harder to find. As a result, mud with lower filtrate quantities is preferred.

3.3.2. Filter Cake Thickness

The filter cake thickness of the mud samples containing aluminum oxide nanoparticles is shown in figure 7. As seen in the figure, prior to the addition of the Aluminum oxide Al_2O_3 nanoparticle, filter cake thickness of the water based mud was 4.57mm while at varied concentrations of the added Al_2O_3 (different percentage ratio of bentonite and nanoparticle), a slight reduction in the filter cake thickness was observed.

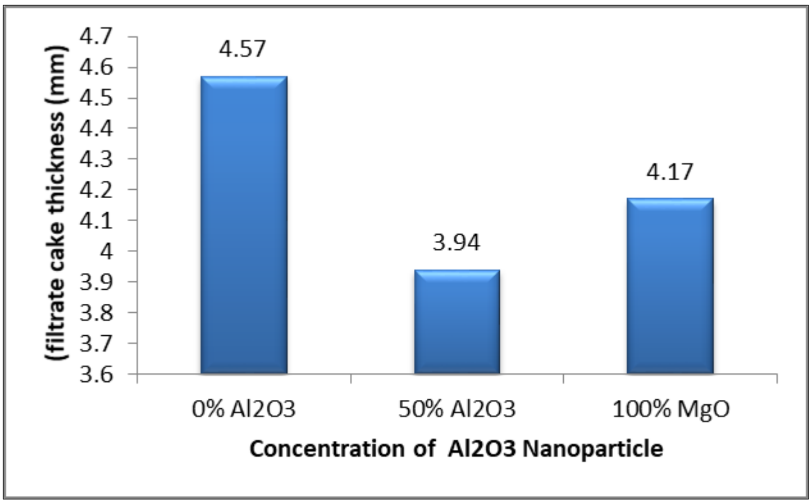

Figure 7 Filter Cake Thickness of Al_2O_3 Mud Samples

Despite being a key element in issues with differential sticking, pipe torque and drag, and narrow holes, cake thickness has received little attention in the drilling fluid literature. Cake thickness and filter loss are considered to be inversely related, therefore only filter loss has to be given. In truth, although cake thickness and filter loss are connected, the exact nature of the connection varies from mud to mud. Although the cake volume grows, the filter loss lowers as solids concentration rises. The swelling characteristics of the relevant clay minerals determine how much water is retained in the cakes of muds with various clay bases. For instance, because bentonite contains significant swelling capabilities, bentonitic cakes have a relatively high water to solids ratio and a low QwQc ratio. Due to the high solid concentration of Al_2O_3, less filter cake is produced. Note that the amount of water in the cakes is essentially unaffected by the concentration of particles in the suspension and is only somewhat smaller than that in the swollen clays. In fact, a fair indicator of the clay base's swelling abilities is the percentage of water in the cake.

It is critical to emphasize that too thick mud causes a wide range of issues. The drill string may differentially stick because to increased contact area, higher surges and swabbing caused by lower annular clearance, and tight areas in the hole that create excessive drag. Others include the principal cementing challenges brought on by insufficient filter cake displacement, the quick development of sticking forces brought on by greater filtration rates, and the increasing difficulty in running casing [15], because of this, mud made with aluminum oxide nanoparticles and a thinner mud cake performs better.

3.4. Shear Properties

Figure 8 depicts the relationship between shear stress and shear rate of drilling mud made with various Al_2O_3 nanoparticle concentrations.

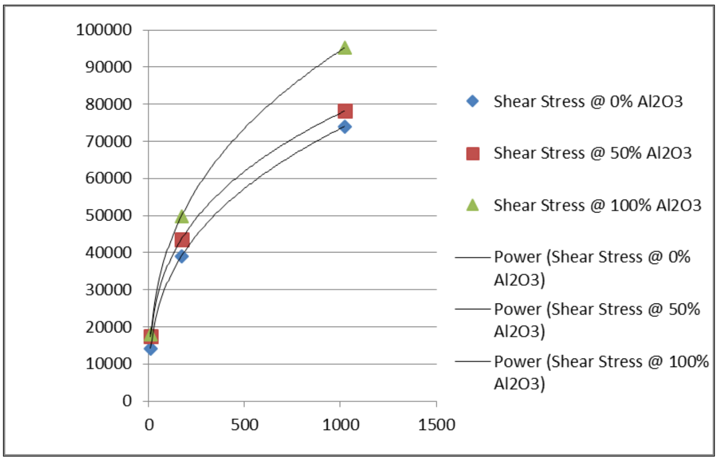

Figure 8 A plot of Shear Stress against Shear Rate for Aluminum Oxide nanoparticle drilling mud

The Power Law Model was used to calculate the shear rate and shear stress using equations 9 and 10. Here, the Flow Behavior Index and the Power Law Constant (K), also known as the Consistency Factor, are used to explain the flow behavior index (n). Equations 7 and 8 were used to compute them, which resulted in the following values: 0.358 (lbs.sn/100ft2), 0.3261 (lbs.sn/100ft2), and 0.362 (lbs.sn/100ft2), respectively, for the varied % weight concentration of the drilling mud created using Al_2O_3 nanoparticle. An effective flow curve can be shown in a conventional Power law model graphic. Due to the n value obtained, the Power law model plot displays a robust curve, demonstrating that the value is appropriate for the drilling mud containing Al_2O_3 nanoparticles. As can be observed in Fig. 8, the flow curve was solid. K describes the thickness or pumpability of the fluid. As n decreases as a fluid becomes more shear thin, K increases as a fluid becomes more viscous. This is demonstrated by the value of K discovered in this study for various concentrations of nanoparticle in water-based drilling mud. As observed in this study, the viscosity of the mud decreases when more Al_2O_3 nanoparticles are employed to create it, which causes the value of K to fall. When n is > 1, the fluid flow is dilatant; when n is equal to 1, it is a Newtonian fluid; and when n is less than 1, it is pseudoplastic. This indicates that when tension is applied, the fluid's viscosity reduces. The drilling fluid is pseudo plastic, which is advantageous for drilling operations since n of Al_2O_3 nanoparticle mud is 1.

3.5. Cutting Carrying Capacity Index of Nanoparticle Water Based Drilling Mud.

The Cutting Carrying Index is a measure of a drilling fluid's ability to carry drilled cuttings in the hole (CCI). A greater cutting carrying index produces better hole cleaning powers. The CCI suggests the following:

- A CCI that is ≤ 0.5, implies that the hole cleaning process is poor, and the hole problem may be detected.
- A CCI that is ≥ 1.0, indicates that the hole cleaning process was successful.

- A higher CCI indicates a better cutting carrying capacity

This was analyzed using equations 6, 7 and 8

Using a minimum annulus velocity of 150ft, which is the recommended value for use in drilling operations.

Table 1 Cutting carrying capacity of Al_2O_3 Nanoparticle Mud

Mud sample	**CCI**
0% Al_2O_3	22.9
50% Al_2O_3	30.4
100% Al_2O_3	25.9

This study is found to be consistent with study by Fadairo *et al*. [15] which they stated that higher CCI's simply means better hole cleaning capacities.

4. Conclusion

Al_2O_3 nanoparticles were utilized in this work to formulate water-based drilling mud at various mud concentrations in order to enhance the rheological characteristics of the mud. According to the results, adding nanoparticles to water-based drilling mud improves its rheological characteristics and raises its cutting carrying capacity index, increasing cutting carrying capacity.

The following findings may be made from the investigation; the rheological characteristics of the drilling fluid were found to be considerably impacted by the addition of nanoparticles and are influenced by the concentration of the nanoparticles injected. The study demonstrates that adding MgO and Al_2O_3 nanoparticles raises the yield point, apparent viscosity, and plastic viscosity. It also demonstrates that as the concentration of the nanoparticles rises, the gel strength of the drilling mud that created the Al_2O_3 nanoparticles falls. The study demonstrates that the drilling mud created utilizing the various nanoparticle concentrations has a high cutting carrying capacity index CCI, indicating that the carrying capacity of the drilling mud is good. The cuttings cutting carrying capacity index's encouraging findings suggest that employing nanoparticles in drilling operations is feasible.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that there is no competing interest in connection with this paper.

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