A Comparative Study of the Rheological Properties Under HPHT Conditions

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Abstract

Well drilling and the extraction of hydrocarbons from the wellbore depend significantly on drilling fluid. They have a variety of functions, including removing debris, regulating pressures to safeguard the well, ensuring the stability of the well, and reducing environmental effect. Water-based muds (WBMs) and Oil-based muds (OBMs), are the predominant choices of drilling muds and they encounter some limitations in maintaining optimal rheological properties under such extreme conditions, necessitating advanced formulations. WBMs struggle with stability, OBMs raise environmental concerns under High temperature-high pressure (HTHP) conditions in subsurface drilling. This project research is on comparative study of the rheological properties of formulated water-based mud (WBM) using nano particles and almond base oil under HTHP conditions. This study aims to investigate the rheological properties and performance of both nanoparticles incorporating water-based mud and almond oil-based mud, incorporating varying concentrations of silica oxide nanoparticles (0.1%, 1%, 5%, and 10%). The focus is on assessing the mud's density, gel strength, dial readings, plastic viscosity (PV), yield point (YP), apparent viscosity (AV), fluid loss, and mud cake thickness. Results demonstrate that the addition of silica oxide nanoparticles significantly enhances the mud's rheological properties, with optimal performance observed at a 5% concentration for both mud types. Cost-effectiveness, environmental impact, and ease of use were also evaluated, with silica nanoparticles in water-based mud having good rheological properties compared to normal water-based mud and almond oil-based muds offering superior environmental benefits, while diesel-based muds provided better cost efficiency and handling.

Introduction

Drilling fluids constitute for 15% to 18% of the overall cost of petroleum well drilling and they must typically meet these essential criteria: they must be: easy to use; cost-effective; and environmentally friendly (Khodja et al. 2010). Well drilling and the extraction of hydrocarbons from the wellbore depend significantly on drilling fluid (Vishnyakov et al. 2020). They have a variety of functions, including removing debris from the well, regulating formation pressures to safeguard the well, ensuring the stability of the well, supporting, lubricating, and cooling the drill string and drill bit and reducing environmental effect (Almotasim et al. 2023). The rheological characteristics of drilling muds, particularly in the context of severe conditions such as those encountered in High Temperature and High Pressure (HTHP) environments, play a pivotal role in determining the success of drilling operations. The viscosity and flow behavior of these muds under such extreme conditions are essential parameters that can significantly impact the efficiency and effectiveness of the drilling process. Among the various types of drilling fluids available, water-based muds (WBMs) and oil-based muds (OBMs) have traditionally been the primary options that drillers rely on (Agwu, 2021). These muds are specifically formulated to provide optimal performance in terms of cooling the drill bit, lubricating the drill string, and maintaining stability in the borehole. The choice between WBM and OBM often depends on the specific requirements of the drilling operation, such

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as the type of formation being drilled, the temperature and pressure conditions, and environmental regulations. In addition to these conventional options, ongoing research and development have led to the exploration of alternative drilling fluids, such as synthetic-based muds and various types of invert emulsion fluids, which offer improved performance in certain scenarios. The summary of other related work in this field is presented in Table 1, which provides a comprehensive overview of the various studies and findings that have contributed to the understanding and advancement of drilling mud technology, particularly concerning their rheological properties under extreme conditions.

Table 1—Review study.

Authors (year)	Materials Used	Base Fluid	Modified Properties	Summary of Result	Gaps Identified
Ananwe et. al. (2014)	Jatropha oil Groundnut oil	Oil	Viscosity	The OBM made with groundnut and jatropha oils were respectively 2.7 and 3 times more viscous than the mud based on diesel oils	Accounted for just jatropha oil
Chikwe et al. (2019)	Almond Oil Castor Oil Groundnut Oil	Oil	Rheological properties and environment friendly	Using almond oil is less toxic than diesel and has better cleaning hole capacity.	Did not account for different temperature ranges for the rheological properties.
Hassani et al. (2016)	SiO_2 ZnO Carbon nanotubes	Water	Rheological properties	Using 2.0wt% for all the nanoparticles showed twice the improvement in rheological properties with the most improvement from SiO_2	Need for comprehensive studies on the long-term effects and environmental impacts of nanoparticles

Methodology

The materials used in this research project include Bentonites, Barite, Nanoparticles (SiO_2 0.1wt%, 1wt%, 5 wt% and 10% wt): Nanoparticles particles are a particle with a diameter smaller than 100 nm. The components of silica dioxide nanoparticles are made of silicon and oxygen. In this project, four different concentrations were used (SiO_2 0.1 wt%, 1 wt%, 5 wt% and 10% wt). Deionized water, Carboxy Methyl Cellulose (CMC), Almond oil.

To create the formulation for a water-based mud, the subsequent procedure was meticulously carried out to ensure the desired properties and consistency were achieved.

1. 400ml of deionized water was accurately measured into a measuring cylinder.
2. The above quantity of water was emptied into the Hamilton beak mud mixer and fixed to the mixer.
3. The mixer is plugged into a power supply.
4. Bentonite of about (25g) was measured using an electric weighing balance and is poured into the Hamilton mixer then stirred for 5 minutes to ensure mixing is done evenly and absence of lumps.
5. 15g of barite was added to this mixture and stirred for 5 minutes.
6. 0.3g of the CMC was measured and on the electric chemical balance and poured inside the mud mixer which already contains the evenly mixed water
7. For water-based mud with nanoparticles incorporated in it, 4 different concentrations of silica oxide nanoparticles were used (0.1wt%, 1wt%,5 wt% and 10%wt).
8. It was stirred for 15 minutes to ensure evenly mixed and absence of lumps.

The specific methodology that was employed to derive the formulation for an oil-based mud involved several detailed steps.

1. 300ml of almond oil was accurately measured into a measuring cylinder.
2. The above quantity of oil was emptied into the Hamilton mud mixer and fixed to the mixer.

3. The mixer was then plugged into a power supply.
4. Bentonite of about (25g) was measured using an electric weighing balance and was poured into the Hamilton mixer then stirred for 5 minutes to ensure mixing was done evenly and absence of lumps.
5. 15g of barite was added to this mixture and stirred for 5 minutes.
6. 0.3g of the CMC was measured and on the electric chemical balance and poured inside the mud mixer which already contains the evenly mixed oil.
7. It was stirred for 15 minutes to ensure evenly mixed and absence of lumps.

Procedure for Measuring Mud Weight. The prepared mud mixture was introduced into the stationary mud cup and subsequently sealed with its lid. Any air bubbles and extraneous mud emerging from the aperture in the lid were meticulously removed. The stationary mud cup was then positioned within its holder. The sliding weight rider was adjusted until the balance achieved a stable state, with the level bubble centered. The mud density corresponding to each mud formulation was duly recorded.

Rotational Viscometer Measurement. The viscosity of a material and its yield point can be determined with the help of this apparatus, amongst other things. An inner bob and a spinning outer sleeve are two of the components that are included in this device. These components work together to shear and rotate the mud sample at a consistent rate. The test was carried out at a range of different speeds, such as 600, 300, 100, and so on. After placing the sample of mud in a cup (preferably, one designed to hold slurries), readings are obtained by rotating the cup containing the mud. After these components have been converted into a plastic viscosity, the point of yield is then attained.

Protocol for the Measurement of Rheological Characteristics. The mud specimen was introduced into the warm cup until it attained the designated mark on the cup's surface. Subsequently, the warm cup was positioned atop the viscometer's stand. The cup was elevated and maintained in place until the rotating sleeve was fully submerged, aligning with the recording device. Securement was achieved by engaging the locking mechanism, ensuring the cup was properly affixed. A mixing protocol was then initiated, involving a 10-second agitation period, followed by sequential adjustments of the handle to various rotational speeds. At the point where the dial reading balances out, values were obtained.

Plastic viscosity (PV) (cP) =600 RPM readings-300 RPM readings,..(1)

Yield point (YP) ($lb/100ft^2$)=300 RPM readings-plastic viscosity,..(2)

Apparent viscosity (AV) (cP) = $= \frac{600\text{RPM readings}}{2}$..(3)

It is important to note that the gel strength at 10 seconds, denoted in pounds per 100 square feet ($lb/100ft^2$), refers to the peak dial deflection occurring after a duration of 10 seconds. Conversely, the gel strength at 10 minutes, also measured in pounds per 100 square feet ($lb/100ft^2$), signifies the peak dial deflection observed after a period of 10 minutes.

Steps for the Measurement of pH. Activate the pH meter and proceed to rinse the electrode with distilled water, subsequently drying it with a clean tissue. Calibrate the pH meter employing deionized water (calibrated to a pH of 7.0). Procure a sample of the drilling fluid within a clean beaker. Thoroughly agitate the drilling fluid sample using a stirring rod or magnetic stirrer to guarantee homogeneity. Submerge the electrode into the drilling fluid sample, ensuring complete immersion without allowing contact with the container's base. Allow the pH meter to reach equilibrium and subsequently display the pH value. Document the pH value.

The electrode should be rinsed with distilled water subsequent to the measurement process. The procedure for evaluating high-temperature high-pressure (HTHP) fluid loss control involves utilizing a filtration assembly designed for HTHP filtration tests. The drilling fluid sample is prepared within the filtration cell, and thereafter, the requisite pressure is applied to the sample. The temperature is consistently maintained throughout the duration of the test. The filtrate that permeates through the filter medium is collected, and the volume of this filtrate is quantified over a predetermined time interval. Subsequently, the thickness of the filter cake is documented.

Results

This section presents the detailed outcomes of the experiments and analyses conducted to fulfill the objectives of the current study. The drilling segment delineates the results, which elucidate the influence on the rheological properties and characteristics of the mud subsequent to the addition of nanoparticles to water-based mud and the utilization of almond oil in the formulation of oil-based mud.

Silica Oxide Nanoparticles FTIR Analysis. **Figure 1** shows the results of a Fourier Transform Infrared (FTIR) spectroscopy analysis of silica oxide nanoparticles. FTIR spectroscopy is a technique used to obtain an infrared spectrum of absorption or emission of a sample. It provides information about the molecular composition and structure of the sample by measuring how different wavelengths of infrared light are absorbed by the sample.

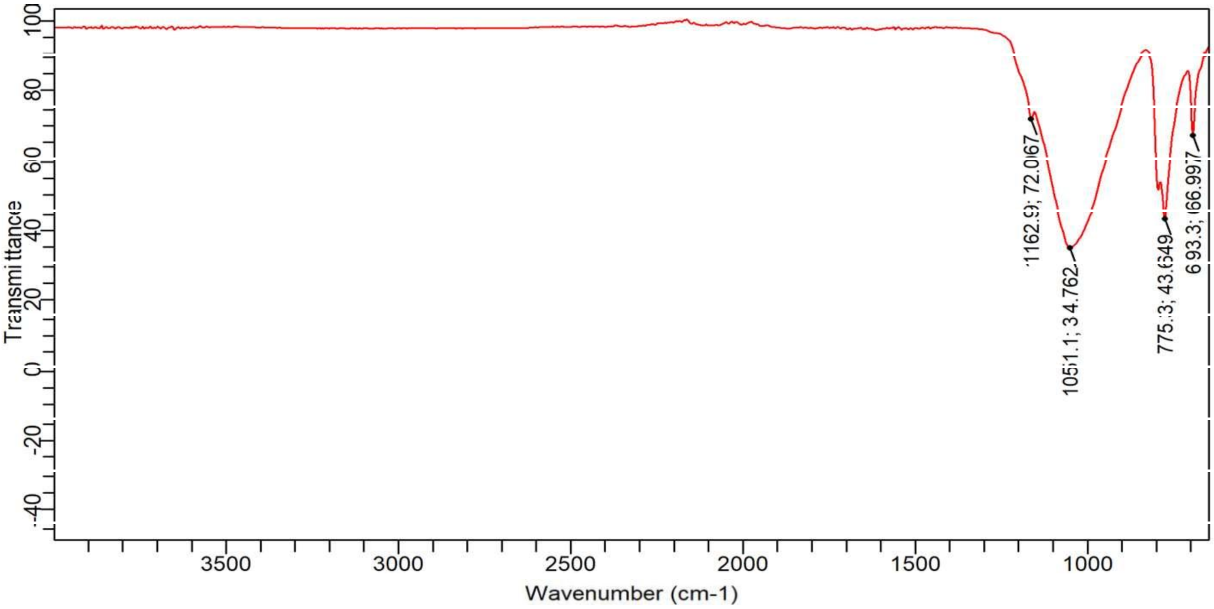

Figure 1—FTIR analysis.

Analysis of the FTIR Spectrum. The x-axis represents the wavenumber in cm^{-1}, which is the reciprocal of the wavelength and is directly proportional to the energy of the vibrations. The range typically extends from 4000 cm^{-1} to 400 cm^{-1}. The y-axis represents the transmittance (%), which indicates how much light passes through the sample. A lower transmittance at a specific wavenumber means higher absorption, corresponding to the presence of specific chemical bonds.

Four significant peaks are identified in the spectrum, each corresponding to specific vibrational modes of the silica oxide nanoparticles (**Table 2**):

Peak 1: This peak is likely associated with the bending vibrations of Si-O-Si bonds in the silica network having a wavenumber of 693.28484 cm^{-1} and intensity of 66.99708;

Peak 2: This peak is typically attributed to symmetric stretching vibrations of the Si-O-Si bonds having a wavenumber of 775.28627 cm^{-1} and intensity of 43.64883;

Peak 3: This peak corresponds to the asymmetric stretching vibrations of the Si-O-Si bonds, which is a characteristic peak for silica materials having a wavenumber of 1051.10927 cm^{-1} and intensity of 34.76249;

Peak 4: This peak is often associated with the asymmetric stretching vibrations of Si-O bonds, indicating the presence of silica having a wavenumber of 1162.92941 cm^{-1} and intensity of 72.06705.

Table 2—FTIR readings.

Peak Number	Wavenumber (cm^{-1})	Intensity
1	693.28484	66.99708
2	775.28627	43.64883
3	1051.10927	34.76249
4	1162.92941	72.06705

Water Based Mud Formulation. Five distinct formulations of water-based mud were carefully prepared and meticulously measured for their properties. Sample A serves as the foundational fluid mixture, comprising 25 grams of bentonite, 400 milliliters of deionized water, 10 grams of barite, and a precise amount of 0.3 grams of carboxymethyl cellulose (CMC). Following the creation of this baseline sample, Samples B through E were crafted by introducing varying concentrations of silicon dioxide (SiO_2) into the mixtures. Each subsequent sample was engineered to include a different amount of SiO_2, allowing for a comparative analysis of how this additive influences the properties of the water-based mud.

Sample A: 25g bentonite + 400 ml deionized water + 10g barite + 0.3 CMC,..(4)

Sample B: 25g bentonite + 400 ml deionized water + 10g barite + 0.3 CMC + 0.1wt% SiO2,.......................(5)

Sample C: 25g bentonite + 400 ml deionized water + 10g barite + 0.3 CMC + 1wt% SiO2,..........................(6)

Sample D: 25g bentonite + 400 ml deionized water + 10g barite + 0.3 CMC + 5wt% SiO2,..........................(7)

Sample E: 25g bentonite + 400 ml deionized water + 10g barite + 0.3 CMC + 10wt% SiO2,........................(8)

To thoroughly evaluate and compare the performance of all the different formulations of water-based mud, a series of comprehensive measurements were meticulously carried out. These measurements encompassed a variety of critical parameters, such as the determination of density, the assessment of pH levels, and the evaluation of gel strength, among other essential tests. Each of these measurements was crucial in understanding the unique characteristics and behaviors exhibited by the various mud formulations under investigation. The meticulous data collected from these tests were then systematically organized and presented in a clear and structured manner within **Tables 3** through **7**, providing a detailed comparative analysis of the results obtained from each formulation.

Upon conducting a thorough examination of the densities of all the samples under consideration, it has been observed that their values are remarkably similar, with a very tight clustering around the range of 8.65 to 8.8 ppg. This consistency is clear in the data presented in **Table 3**. Similarly, when analyzing the pH values of these samples, it becomes apparent that they also exhibit a high degree of similarity, with their values closely grouped around a range of 8.0 to 8.53 (**Table 4**).

Table 3—Density reading of the samples.

Sample A Base fluid, ppg	Sample B 0.1wt% SiO_2, ppg	Sample C 1wt%wt SiO_2, ppg	Sample D 5wt% SiO_2, ppg	Sample E 10wt% SiO_2, ppg
8.7	8.8	8.8	8.65	8.8

Table 4—pH readings of the samples for water-based mud.

Sample A Base fluid	Sample B 0.1wt% SiO_2	Sample C 1wt%wt SiO_2	Sample D 5wt% SiO_2	Sample E 10wt% SiO_2
8.35	8.0	8.49	8.53	8.39

Table 5—Gel strength on different fluid samples for water-based mud.

	Sample A Base fluid	Sample B 0.1wt% SiO_2	Sample C 1wt%wt SiO_2	Sample D 5wt% SiO_2	Sample E 10wt% SiO_2
Gel Strength (10 secs)	3	2	3	6	4
Gel Strength (10 mins)	12	9	12	17	15

Table 6 provides a detailed overview of the dial readings recorded for the five distinct mud samples, spanning a comprehensive spectrum from 6 rpm up to 600 rpm. It is evident that the presence of SiO_2 within these samples has a notable impact on the dial readings. Specifically, as the concentration of SiO_2 within the samples is incrementally increased from 1wt% to 10wt%, there is a corresponding and noticeable rise in the dial readings, indicating a direct correlation between higher SiO_2 content and increased dial readings. Conversely, when the concentration of SiO_2 is reduced to a minimal level of just 0.1wt%, the dial readings exhibit a decline, suggesting that lower concentrations of SiO_2 result in lower dial readings. This pattern underscores the significant influence that SiO_2 concentration has on the dial readings of mud samples under varying rotational speeds.

Table 6—Dial readings on different fluid samples for water-based mud.

Dial Readings	Sample A Base fluid	Sample B 0.1wt% SiO_2	Sample C 1wt%wt SiO_2	Sample D 5wt% SiO_2	Sample E 10wt% SiO_2
600rpm	22	17	23	23	28
300rpm	16	13	17	17	18
200rpm	12	11	13	13	14
100rpm	7	6	8	8	10
60rpm	5	4	5	5	6
30rpm	4	3	3	3	5
6rpm	1	1	1	1	2

As the concentration of silicon dioxide (SiO_2) within the base fluid is progressively elevated, it becomes increasingly apparent that there is a corresponding reduction in both the fluid loss and the thickness of the mud (**Table 7**). This phenomenon can be attributed to enhanced structural integrity and improved rheological properties that silicon dioxide imparts to the fluid. The addition of SiO_2 particles increases the viscosity and creates a more stable suspension, which in turn helps to reduce the escape of fluid from the mud system. Additionally, the presence of these particles contributes to the formation of a stronger filter cake on the wellbore walls, further minimizing fluid loss. The overall effect is a more controlled and efficient drilling operation, as the mud retains its desired consistency and thickness, ensuring better lubrication and cooling of the drill bit, as well as improved suspension of cuttings. This allows for more effective drilling and reduces the risk of wellbore instability, ultimately leading to cost savings and enhanced operational safety.

Table 7—Fluid loss and fluid thickness of the sample for water-based mud

	Sample A Base fluid	Sample B 0.1wt% SiO_2	Sample C 1wt%wt SiO_2	Sample D 5wt% SiO_2	Sample E 10wt% SiO_2
Fluid loss, ml	21	18	16	13	14
Mud thickness, mm	2.0	1.8	1.7	1.2	1.4

Oil Based Mud Formulations. In the realm of oil-based mud formulations, we have two distinct samples, designated as Sample F and Sample G. Sample F is meticulously crafted using a blend of components. It consists of 25 grams of bentonite, a versatile clay mineral known for its excellent rheological properties, which are crucial for mud formulations. This is then mixed with 300 milliliters of almond oil, chosen for its lubricating qualities and ability to reduce friction in drilling operations. To enhance the density and provide weight to the mud, 10 grams of barite are added; barite is a dense mineral commonly used in drilling fluids for its high specific gravity. Completing the formulation, 0.3 grams of carboxymethyl cellulose (CMC) are included; CMC acts as a viscosifier, helping to maintain the desired viscosity of the mud. This combination is carefully mixed to ensure homogeneity and optimal performance in oil-based mud applications. The specific formulation is represented as follows:

25g bentonite + 300 ml almond oil + 10g barite + 0.3 CMC..(9)

Sample G, on the other hand, shares some similarities with Sample F but differs in key aspects. It also comprises 25 grams of bentonite, providing the foundational rheological properties. However, instead of almond oil, this formulation uses 300 milliliters of diesel oil, selected for its superior ability to dissolve organic compounds and its cost-effectiveness. Like Sample F, it includes 10 grams of barite for increased density and 0.3 grams of CMC for viscosity control. The formulation is represented as follows:

25g bentonite + 300 ml diesel oil + 10g barite + 0.3 CMC..(10)

To evaluate the effectiveness of these formulations, the density of both Sample F and Sample G was measured. The density of Sample F was determined to be 9.1, indicating a relatively lightweight yet effective composition suitable for certain drilling conditions. In contrast, Sample G exhibited a slightly higher density of 9.3, suggesting a formulation that is better suited for scenarios requiring a denser mud to manage wellbore pressures more effectively. These measurements are crucial in determining the suitability of each formulation for specific drilling environments and objectives.

The pH values of Sample F and Sample G were measured to be 7.7 and 6.8, respectively, indicating that Sample F is slightly alkaline while Sample G is mildly acidic. **Table 8** provides a detailed examination of the dial readings for the two oil-based mud samples, encompassing a range from 6 rpm to 600 rpm. It is apparent that the oil component within both samples significantly influences the dial readings in comparison to the base mud sample (Sample A). Notably, Sample G, which contains diesel oil, exhibits a corresponding and significant increase in dial readings.

Table 8—Dial reading on the oil formulations.

Dial Readings	Sample A Base fluid	Sample F (with almond oil)	Sample G (with diesel oil)
600rpm	22	30	38
300rpm	16	23	26
200rpm	12	15	16
100rpm	7	12	14
60rpm	5	10	12
30rpm	4	8	9
6rpm	1	4	3

The gel strength measurements, taken at both 10 seconds and 10 minutes, for the two types of oil-based mud are detailed in **Table 9**. Upon examination of the data, it becomes evident that Sample F exhibits a significantly lower gel strength compared to Sample G at both time intervals. The fluid loss and mud thickness for the two oil-based mud are presented (**Table 10**). Specifically, Sample F, which incorporates Almond oil, exhibits a significantly higher level of fluid loss and a thicker mud thickness compared to Sample G.

Table 9—Gel strength of the mud formulations.

	Sample F: Almond oil	Sample G: Diesel oil
Gel Strength (10 secs)	3	4
Gel Strength (10 mins)	12	15

Table 10—Fluid loss and mud thickness of the mud formulation.

	Sample F: Almond oil	Sample G: Diesel oil
Fluid loss, ml	21	19
Mud thickness, mm	2.0	1.5

Comparison of Both Mud Formulation. **Table 14** provides a comprehensive review and summary of the rheological characteristics exhibited by each of the seven different mud samples under examination. This table meticulously details various essential parameters that are crucial for evaluating the performance and behavior of drilling fluids in various conditions. In particular, Samples C through G exhibit elevated plastic and apparent viscosity values compared to the base mud sample, indicative of a greater resistance to flow attributable to the presence of solid particles within the fluid. The yield point is also covered, representing the in the mud sample. Oil-based mud samples (designated as Sample F and Sample G) exhibit a greater yield point, suggesting that the presence of an oil component within the mud necessitates a higher minimum applied force to initiate flow. Furthermore, the gel strength at two distinct intervals—10 seconds and 10 minutes—is provided. This aspect is particularly important as it indicates the mud's ability to suspend drilled solids when circulation is stopped, such as during tripping operations. By examining these properties, one can gain valuable insights into the mud samples' overall performance and suitability for specific drilling applications.

Table 14— Rheology properties of the mud formulations.

Properties	Sample A Base fluid	Sample B 0.1wt% SiO2	Sample C 1wt%wt SiO2	Sample D 5wt% SiO2	Sample E 10wt% Sio2	Sample F Almond oil	Sample G Diesel oil
Plastic viscosity	6	4	6	10	7	7	12
Yield point	10	9	11	8	10	16	14
Apparent Viscosity	11	9.5	11.5	14	12	15	19
Gel strength (10 secs)	3	2	3	6	4	3	4
Gel strength (10 mins)	12	9	12	17	15	12	15

Discussion

The identified peaks and their wavenumbers are consistent with the characteristic vibrational modes of silica (SiO_2) bonds as seen in figure 1. The variations in peak intensities suggest differences in the concentration or environment of the chemical bonds in the sample. The presence of these peaks confirms the silica structure and provides insights into the specific bonding and arrangement of the SiO_2 network in the nanoparticles.

The analysis of the rheological properties of the samples, including the base fluid, SiO_2 nanoparticle suspensions in water- based mud, almond oil-based mud, and diesel oil- based mud, reveals significant insights into their potential applications and suitability for various industrial purposes. The data indicate that all samples exhibit shear-thinning behavior, where viscosity decreases with an increasing shear rate. This characteristic is advantageous for applications requiring ease of pumping and spreading at high shear rates while maintaining sufficient thickness at low shear rates. The addition of SiO_2 nanoparticles to the base fluid generally increases its viscosity, with the effect being more pronounced at higher concentrations. Specifically, at 5 wt% SiO_2, the sample exhibits the highest viscosity, which could be beneficial for applications needing thicker lubricants. However, beyond this concentration, the viscosity increases likely due to particle-particle interactions or aggregation, suggesting an optimal concentration threshold for enhancing viscosity without causing stability issues. From a cost perspective, the inclusion of SiO_2 nanoparticles must be carefully evaluated. While nanoparticles can improve the rheological properties of fluids, they also add to the overall cost of the formulation. The price of SiO_2 nanoparticles is relatively high, especially for high-purity or specially treated particles. Thus, the cost-benefit ratio must be assessed, particularly in comparison to more readily available and potentially cheaper alternatives like diesel oil. Almond oil, though exhibiting higher viscosity, is more expensive compared to using diesel oil or silica oxide incorporated water-based mud due to its sourcing and production process, which is typically more expensive than synthetic or mineral oils. Diesel oil, while providing high viscosity, is generally more affordable and widely available, making it a practical choice for heavy-duty applications where cost constraints are critical.

Environmental considerations play a crucial role in selecting suitable fluids for industrial applications. SiO_2 nanoparticles, while enhancing rheological properties, must be evaluated for their environmental impact during production, usage, and disposal. Nanoparticles can pose risks to ecosystems if not managed properly, necessitating the implementation of stringent environmental and safety protocols. Almond oil, being a natural and biodegradable product, offers a more environmentally friendly alternative, though its production must be sustainable to avoid negative ecological impacts. Diesel oil, despite its effectiveness and low cost, poses significant environmental concerns due to its petroleum-based nature and associated pollution risks. Therefore, its use should be carefully managed to minimize environmental damage, and alternatives should be considered where feasible.

The choice of fluid should balance rheological performance, cost-efficiency, and environmental impact. SiO_2 nanoparticles can enhance viscosity but come with higher costs and environmental considerations. Almond oil provides a natural and biodegradable option but at a higher price, while diesel oil, despite its cost-effectiveness, raises significant environmental concerns. The decision should align with the specific requirements of the application, budget constraints, and sustainability goals.

Conclusions

This study presents a comprehensive comparative analysis of the rheological properties of formulated water-based mud (WBM) enhanced with SiO_2 nanoparticles and oil-based mud (OBM) using almond oil under high-pressure high-temperature (HPHT) conditions. The primary objective was to investigate the effect of SiO_2 nanoparticles on the rheological behavior of WBM and compare it with OBM, specifically almond oil-based mud, to determine their suitability for HPHT drilling applications.

The rheological analysis revealed that both nanoparticle-enhanced WBMs and almond oil-based OBMs exhibit shear-thinning behavior, characterized by a decrease in viscosity with increasing shear rate. This property is crucial for effective mud circulation during drilling operations. The inclusion of SiO_2 nanoparticles in the WBM significantly altered its viscosity, with higher concentrations (up to 5 wt%) resulting in notable increases in viscosity. However, the increase in viscosity plateaued beyond this concentration, likely due to particle aggregation or saturation effects.

Almond oil-based OBM demonstrated higher viscosity across all shear rates compared to the base fluid and SiO_2-enhanced WBM. This suggests that almond oil could provide better hole cleaning and cuttings suspension, particularly in low shear rate conditions common in deep well drilling. Despite this, the cost and environmental considerations associated with almond oil and SiO_2 nanoparticles must be factored into their practical application.

In summary, the study concludes that while SiO_2 nanoparticles effectively enhance the viscosity of WBM, the optimal concentration must be carefully controlled to avoid stability issues. Almond oil based OBM, although exhibiting superior rheological properties, requires careful cost and environmental impact assessments.

Recommendations

Based on this study, the following recommendations are proposed:

1. It is recommended to use SiO_2 nanoparticles at an optimal concentration of around 5 wt% in WBM. This concentration maximizes viscosity enhancement without causing significant particle aggregation or stability issues.
2. Conduct a thorough cost-benefit analysis when considering the use of SiO_2 nanoparticles and almond oil for mud formulation. While nanoparticles improve rheological properties, their cost must be justified by the performance benefits they offer. Similarly, the use of almond oil should be evaluated for its overall cost implications, especially in large-scale drilling operations.
3. Implement stringent environmental impact assessments for the use of SiO_2 nanoparticles and almond oil in drilling fluids. Ensure that the production, usage, and disposal of these materials adhere to environmental

regulations and minimize ecological risks. Explore the development of biodegradable and environmentally friendly alternatives to conventional drilling fluids, aiming to reduce the ecological footprint of drilling operations.

4. For future research purposes, extend the research to evaluate the long-term stability and performance of SiO_2-enhanced WBMs and almond oil-based OBMs under varying HPHT conditions. Investigate the interaction mechanisms of nanoparticles at higher concentrations to optimize their dispersion and effectiveness. Explore the potential of other nanoparticles and natural oils to further enhance the rheological properties of drilling muds, aiming for improved performance and sustainability.
5. Conduct field analysis to validate the laboratory findings and assess the practical performance of SiO_2-enhanced WBMs and almond oil-based OBMs in real drilling scenarios. Field trials will provide critical data on the operational feasibility and economic viability of these formulations.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

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