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Impact of Barite Nanoparticles on Barite Sag in Water-Based Drilling Fluids

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Abstract

Barite sag remains a persistent challenge in water-based drilling fluids, particularly in high-pressure, high-temperature and deviated wellbores where density variations can compromise well control, hole cleaning, well stability and operational safety. Conventional weighting materials often fail to maintain suspension stability under such demanding conditions, highlighting the need for anti-sag solutions. This study presents a systematic evaluation of in-house synthesized barite nanoparticles (26.9–63.2 nm) manufactured using ball milling and incorporated into drilling fluids at concentrations of 0%, 3%, and 5% across densities of 9, 12, and 15 ppg. Using standardized API procedures, the fluids were assessed for rheology, filtration behavior, and sag tendency under both dynamic and static HPHT conditions to mimic realistic drilling environments. Results show that a 5% nanoparticle concentration significantly enhances drilling fluid performance, improving plastic viscosity (up to 50%), yield point (up to 51%), and gel strength (up to 80%), while also reducing fluid loss by 9–10% and mud cake thickness by up to 16%. Moreover, barite sag was substantially mitigated, with dynamic sag reductions of 10–50% and static sag reductions of up to 21% in inclined HPHT conditions. The novelty of this work lies in the comprehensive testing approach, from a practical perspective, covering the effect of an engineered barite nanoparticle to demonstrate a scalable and practical method to enhance sag resistance, suspension stability, and overall drilling efficiency.

Keywords: water-based drilling fluid; barite nanoparticles; rheological properties; fluid loss; mud cake thickness; dynamic sag; static sag; barite anti-sag

1. Introduction

The oil and gas drilling industry faces significant challenges in maintaining wellbore stability, especially in inclined wellbores, where keeping the wellbore stable is difficult. Therefore, companies typically aim to define suitable solutions before drilling as a proactive approach to mitigate potential problems [1,2]. One key challenge currently in focus is preventing barite sag, particularly in high-angle and deep wells. Barite, the primary weighting material in drilling fluids, tends to settle under these conditions, leading to density variations that can cause well-control issues, drill pipe sticking, and other drilling operational problems. Maintaining wellbore stability and preventing particle settling are critical factors for optimizing oil and gas recovery, as they directly influence flow resistance in reservoir fractures [3], fracture behavior in natural hydrogen reservoirs [4], and the rate of penetration in geothermal hot dry rock systems [5].

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This study aims to quantify the effectiveness of barite nanoparticles in preventing sag across a range of challenging drilling scenarios, providing valuable insights for the oil and gas industry, where sag-related issues can significantly impact operations.

The selection of weighting materials and polymers, such as XC-polymer, is fundamental to controlling filter cake quality and mitigating formation damage across various mud densities [6,7]. While traditional approaches were proposed and investigated to mitigate barite sag, such as increasing fluid viscosity or using specialized additives, such approaches often entail operational drawbacks, including increased pump pressure and potential formation damage. Barite nanoparticles represent a promising innovation in drilling fluid technology. Their ultra-fine particle size and high surface area-to-volume ratio suggest improvements in suspension stability and anti-sag properties. Early studies indicate that nanoparticle-enhanced drilling fluids may provide better particle suspension while maintaining desired rheological properties [8].

The aim of formulating drilling fluids and their use in a wellbore is to achieve various objectives, principally to regulate formation pressure [8]. To achieve the required density of drilling and completion fluids, barite ($BaSO_4$) is commonly used [8]. Several drilling fluids can be used for well drilling, but for conventional overbalanced operations, the fluid must have sufficient density to overbalance the formation pressure and maintain wellbore stability. The higher the formation pore pressure, the higher the drilling fluid density must be. Likewise, drilling fluids need to be able to suspend loose solids, such as drilled cuttings. Properly designed drilling fluid requires improving the fluid's thermal properties. Wellbore instability, lost circulation, pipe sticking, toxic gases, excessive torque, and drag are some challenges that nanoparticles in drilling fluids can help with [8]. Interaction between drilling fluids and formation fluids, which may cause reservoir damage such as reduced permeability in the near-wellbore area, is known as formation damage. Many fields and research studies have confirmed that improper drilling fluids or additives are among the leading causes of formation damage, resulting in reduced permeability near the wellbore. Circulation loss and formation damage are critical challenges. While oil-based muds (OBM) and specialized Reservoir Drilling Fluids (RDF) are often employed to mitigate these issues, they pose environmental and cost concerns. Consequently, enhancing water-based muds (WBM) with additives such as nanoparticles has emerged as a superior approach to minimize filtrate invasion and compete with the performance of OBMs [9].

Nanotechnology provides lightweight, strong, anti-corrosion materials necessary for the drilling fluid industry [10]. Drilling engineers control the rheology of drilling fluids by modifying the composition, type, or size distribution of nanoparticles to meet specific conditions [11]. Water-based mud with nanoparticles appears to be a promising technology. The benefits offered over traditional water-based mud systems make it an attractive solution.

Applications of nanoparticles, such as multi-walled carbon nanotubes (MWCNT) and nano-metal oxides, have been documented to enhance the efficacy of water-based drilling fluids [12]. Ismail et al. (2014) demonstrated that adding (MWCNT) and nano-metal oxides to water-based drilling fluids significantly enhances rheological properties and reduces fluid loss [12]. Barite nanoparticles improve the viscosity and suspension characteristics due to their large surface area. The result is that the mud becomes more stable and less subject to settling and fluid losses. Furthermore, nanoparticles could maintain the mud density and pressure [13]. Paydar et al. (2017) reported that nanoparticles improve drilling fluid performance, thereby enabling better drilling operations [14]. Hanson et al. (1990) found that drilling mud sag exacerbates in deviated wells stemming from dynamic density slumping, but its effects can be mitigated with proper treatment and techniques [15].

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Scott et al. (2004) emphasized that optimizing drilling mud properties and operational strategies, along with personnel training, can effectively manage barite sag, as illustrated by case studies from the Gulf of Mexico, West Africa, and Atlantic Canada, which highlight the need for standardized measurement techniques and effective mud management [16]. Wagle et al. (2015) found that adding calcium carbonate nanoparticles and rheological modifiers to organoclay-free inversion emulsion drilling fluids significantly reduced the sag factor and improved rheological properties under HPHT conditions [17]. Ponmani et al. (2019) found that laboratory-synthesized barite nanoparticles improved the anti-sag and rheological properties of water-based muds, reducing sagging, lowering plastic viscosity, increasing penetration rates, and decreasing filtrate loss during drilling [18]. Amighi and Shahbazi (2010) and Jefferson (1994) researched methods for predicting barite sag under both static and dynamic conditions [19,20]. Their field case studies revealed that the most severe barite sag typically occurs at angles between 60 and 75 degrees [19,20]. The risk of barite sag increases in wells angled between 30 and 75 degrees [15,17,18,21,22].

Nanotechnology in drilling fluids has evolved from basic property modification to the engineering of smart, stimuli-responsive systems. By leveraging surface-charge-mediated mechanisms for fines stabilization [23] and optimizing the synergistic effects of particle size and functionalization [24], these systems minimize formation damage. Furthermore, the advent of sustainable, salt-responsive nano-additives [25] highlights a shift toward robust fluids that maintain integrity under extreme conditions, necessitating rigorous electrokinetic characterization to ensure rheological stability.

This study focuses on quantifying the anti-sag benefits of barite nanoparticles while considering their effects on other critical drilling fluid properties. Although nanoparticle-enhanced drilling fluids have been investigated in previous studies, most available research has either focused on limited laboratory conditions, single-property evaluations, or the use of commercially available nanoparticles without systematic optimization. The present work uses in-house-synthesized barite nanoparticles prepared from normal barite, rather than commercially available nanoparticle composites. Moreover, the study characterized the prepared samples by measuring rheological properties, fluid losses, and mud cake thickness due to filtration at different nanoparticle concentrations across multiple mud densities under HPHT conditions to mimic the harsh environments at the bottom of wellbores. The study also assessed the sag tendency statically and dynamically under HPHT conditions. Thus, this approach allows for assessing sag resistance, rheological enhancement, and fluid-loss control under realistic operational scenarios, bridging the gap between lab results and real-world applications. The results highlight the scalability and cost-effectiveness of nanoparticle engineering in conventional water-based mud systems, offering a viable solution to mitigate wellbore instability and improve drilling fluid performance.

2. Materials

The primary material used was a commercial barite powder ($BaSO_4$) with a 4.2 specific gravity. The barite nanoparticles were manufactured in-house from normal barite using the ball milling machine (Retsch PM 200, Retsch-Allee 1-5, Haan, Germany) shown in Figure 1. The milling procedure was as follows: "60 g of standard barite were accurately measured for each milling cup, a total of 120 g of barite was milled for 24 h at a speed of 400 rpm, employing stainless steel balls" [26], with optimized parameters, including rotational speed, milling duration, ball-to-powder ratio, and ball size, systematically varied and refined through iterative experimentation to achieve the target nanoparticle size and morphology. After each milling cycle, particle size distribution and morphology were evaluated using scanning electron microscopy (SEM), and the process was repeated until consistent nanoscale particles were obtained. This optimization strategy yielded barite nanoparticles with sizes ranging from 26.9 to 63.2 nm, as shown in Figure 2. The quantitative particle size distribution (PSD), derived from the statistical analysis of 100 individual particles in the SEM micrographs, is presented in Figure 3. The analysis reveals a narrow distribution with a mean diameter of 39.08 ± 5.73 nm, which is suitable for incorporation into drilling fluid formulations.

Figure 1. Ball milling machine (Retsch PM 200).

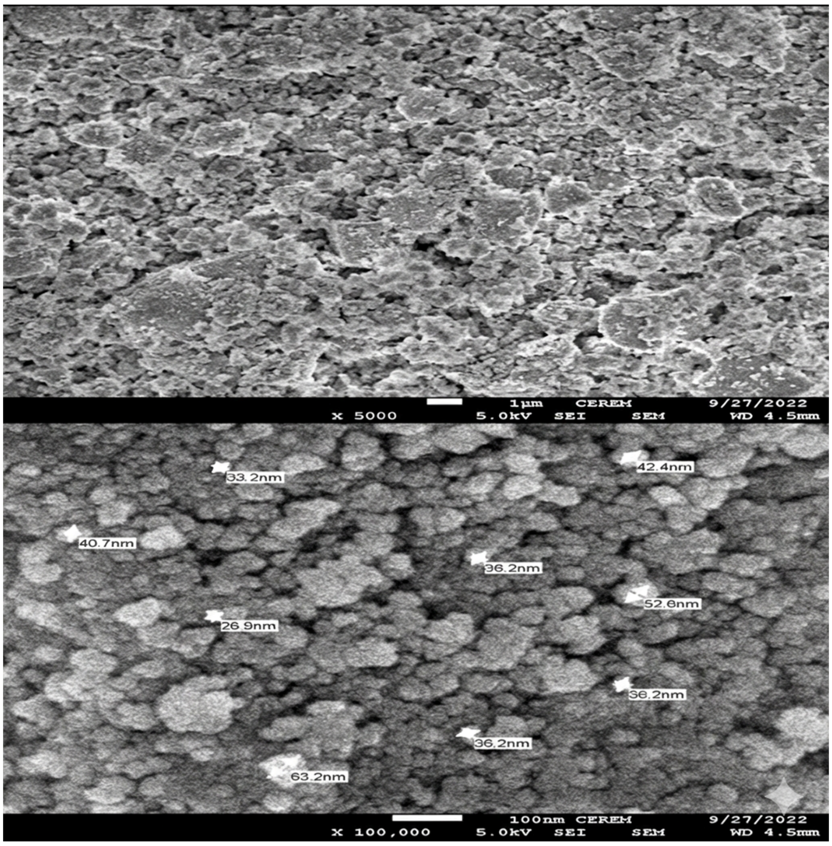

Figure 2. Scanning electron microscopy (SEM) micrographs of synthesized barite nanoparticles. This figure characterizes the barite morphology at two scales: general topography at 5000× magnification (**top**) and detailed individual particle measurements at 100,000× magnification (**bottom**). The high-magnification micrograph confirms the successful top-down synthesis of nanoparticles, with representative diameters measured between 26.9 nm and 63.2 nm. This reduction to the nanometric regime is essential for promoting an increase in the surface-area-to-volume ratio, which is the primary driver for the observed enhancement in suspension stability.

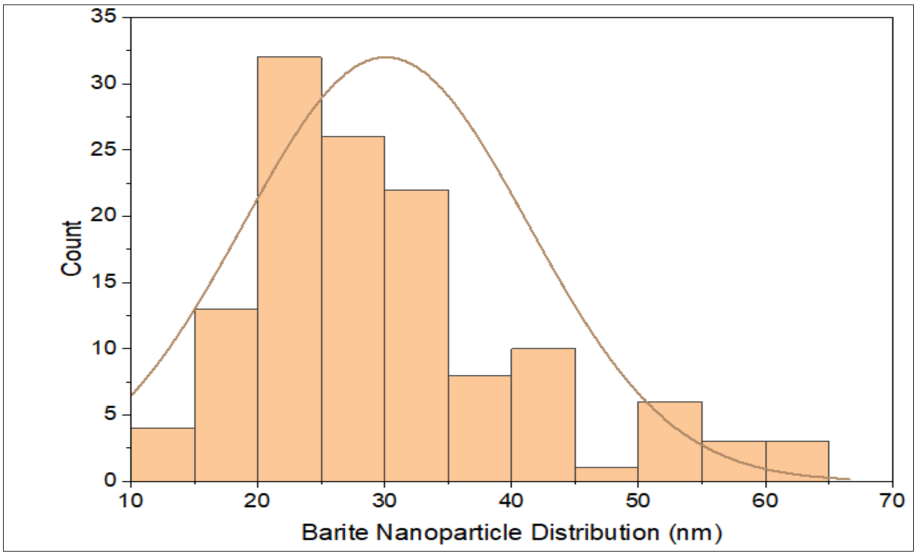

Figure 3. Particle size distribution (PSD) of synthesized barite nanoparticles. The histogram provides a statistical analysis of 100 particles measured from SEM micrographs, overlaid with a normal distribution curve. The analysis indicates a narrow distribution concentrated primarily between 20 nm and 40 nm, with a mean diameter of 39.08 ± 5.73 nm. This well-defined particle size profile confirms the consistency of the mechanical milling process and is optimized for the "pore-filling" mechanism, which contributes to the 9–10% reduction in fluid loss by decreasing filter cake permeability.

The drilling fluid formulation was prepared using distilled water as the base fluid, 4 g of bentonite, 0.004 g of caustic soda, 0.25 g of soda ash, and 1 g of xanthan gum. Multiple samples were prepared at varying densities and barite nanoparticle concentrations. Rheological testing was conducted using an Ofite Model 900 Viscometer, OFI Testing Equipment, Inc. (OFITE),11302 Steeplecrest Dr., Houston, TX, USA, to measure the drilling fluid properties and evaluate the effect of barite nanoparticles on rheological properties. API filter press testing was conducted to assess the stability and performance of barite nanoparticles under low-pressure, low-temperature (LPLT) conditions (100 psi pressure and ambient temperature). Anti-sag testing was conducted under static and dynamic conditions using an Ofite Model 900 Viscometer at 120 °F for dynamic conditions and 300 °F and 500 psi for static conditions. This allowed for a comprehensive evaluation of the impact of barite nanoparticles on drilling fluid properties and sag tendency. Tables 1 and 2 display the base mud composition and general description of barite nanoparticle addition for each mud sample density, respectively [26].

Table 1. Base mud composition.

Component	Function	Weight, g Per Lab. Unit (bbl = 350 g)	
Distilled Water	Liquid phase	340	
Bentonite	Viscosifier & filtration control	4	
Caustic Soda	pH adjustment	0.004	
Soda Ash	Hardness control	0.25	
Xanthan Gum	Thickening agent	1	
Barite	Weighting agent	Normal particles	As required
		Nanoparticles	As required

Table 2. Barite and barite nanoparticles addition for each mud sample at varying densities.

Formula	**Base Mud + Normal Barite + Nano Barite**								
Mud density, ppg		9			12			15	
Barite nanoparticles concentration, %	0	3	5	0	3	5	0	3	5
Normal barite, g	33	32.01	31.35	225	218.25	213.75	483	468.51	458.85
barite nanoparticles quantity, g	0	0.99	1.65	0	6.75	11.25	0	14.49	24.15
Total barite, g	33	33	33	225	225	225	483	483	483

3. Methodology

Commercial barite was used to produce barite nanoparticles in a ball mill. The normal barite was milled for 24 h at 400 rpm. The produced barite nanoparticles were used to prepare drilling fluid samples at varying concentrations. Standard API equipment was used to characterize the drilling fluid properties, including the mud balance, Ofite Model 900 Viscometer, API filter press, and Sag agent. This study employed a factorial design with two factors: barite nanoparticle concentration and mud density. The barite nanoparticles concentration factor had three levels: 0%, 3%, and 5% by weight of normal barite at each density. The mud density factor had three levels: 9, 12, and 15 ppg. Figure 4 presents a flowchart that provides a clear, concise overview of the experimental procedures.

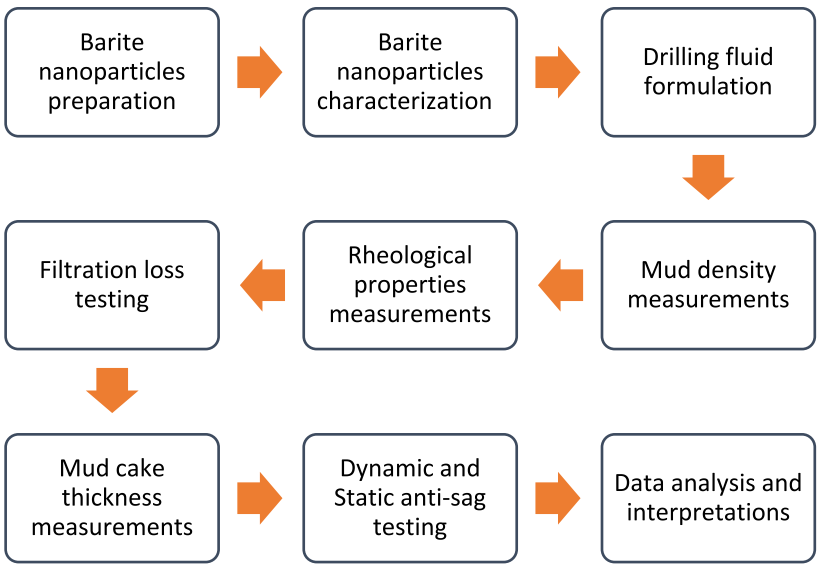

Figure 4. Experimental procedure flowchart.

Table 1 presents the properties and preparation details of the base drilling fluid formulated without barite. Table 2 lists the quantities of barite and barite nanoparticles added to the base fluid to achieve targeted mud densities of 9, 12, and 15 ppg. Nanoparticle concentrations of 0%, 3%, and 5% were selected based on commonly used concentrations in the literature. Multiple preparation trials were conducted to determine the total amount of conventional barite required for each density. The samples with 3% and 5% barite nanoparticle concentrations were prepared while maintaining the specified densities.

The selection of mud densities (9, 12, and 15 ppg) and nanoparticle concentrations (0, 3, and 5 wt%) was based on both existing literature and extensive preliminary laboratory investigations. It was observed that mud densities greater than 15 ppg and nanoparticle concentrations above 5 wt% did not provide further improvements in the fluid results. Specifically, at concentrations exceeding 5 wt%, the performance of sag resistance and filtration control typically reaches its maximum, while the plastic viscosity often increases to levels that could hinder injectivity. Therefore, these higher ranges were not included in this study to focus on the most efficient and economically viable performance window. A potential limitation of this design choice is that the saturation point of the nanoparticle-polymer interaction may vary under different chemical environments, though the current matrix is sufficient to validate the scalability of the proposed formulation.

To evaluate thermal stability and aging under real drilling conditions, dynamic sag tests were performed at 120 °F, and HPHT static sag tests were conducted at 300 °F and 500 psi. These tests simulate the aging process under both circulating and static states. According to this study's experimental results, barite nanoparticles in the 26.9–63.2 nm range maintain structural stability across these temperature ranges, preventing settlement. This approach ensures the results are representative of downhole conditions, as maintaining a sag factor near 0.53 at 300 °F demonstrates that the nanoparticle–polymer network does not degrade during the aging period.

To ensure the accuracy of the HPHT static sag results, the experimental system was maintained with high-precision control mechanisms. The temperature was regulated using an automated PID (proportional–integral–derivative) thermal controller with a tolerance of ±2 °F, while pressure was stabilized at 500 psi using a secondary pressure regulator with a maximum deviation of ±5 psi. To validate the reliability of the observed settlement factors, each experiment was repeated three times, and the average values were reported.

A standard bentonite-polymer water-based formulation was selected as the control medium to isolate the specific mechanistic contributions of the barite nanoparticles. Testing within a complex commercial fluid system containing multiple additives could introduce chemical interference, masking the fundamental interactions between the nanoparticles and the primary filter cake. This baseline formulation provides a clear reference for evaluating rheological and filtration improvements.

Rheological characterization and dynamic sag testing were conducted at 120 °F to adhere to standard API protocols for measuring flow properties under circulating temperatures. However, to validate the material's performance in high-temperature environments, static aging and sag tests were extended to 300 °F (HTHP conditions). This dual-temperature approach ensures the fluid is evaluated for both pumpability (120 °F) and thermal stability (300 °F).

4. Results and Discussion

After preparing each drilling fluid sample, the mud weight was measured for each sample. Then, the rheology tests were conducted using the Ofite Model 900 Viscometer, and an API filter press was used to evaluate the drilling fluid filtration. The sag test apparatus was used to assess the anti-sag properties of drilling fluids. Samples were subjected to static and dynamic conditions to measure barite settling rates over time. The efficacy of barite nanoparticles in reducing barite sagging was assessed by comparing results from samples containing barite nanoparticles to those without. The process was repeated for all prepared drilling fluid samples. Table 3 shows the complete results at 120 °F.

4.1. Plastic Viscosity

The results in Table 3 and Figure 5 show that the plastic viscosity of the water-based drilling fluid at 9, 12, and 15 ppg improved by 21%, 26%, and 50%, respectively, at 5% barite nanoparticle concentration andological behavior 120 °F. Moreover, the rheological behavior of the nanoparticle-inoculated drilling fluid mimics that of the pristine base fluid [27]. As shown in Figure 5, the plastic viscosity of the water-based drilling fluid with barite nanoparticles is higher than that of samples without nanoparticles. Thus, the suspension of normal barite is lower than that of samples including barite nanoparticles. Moreover, the impact of adding barite nanoparticles to the drilling fluid is more pronounced at higher mud densities. This behavior indicates that barite sag (barite settling) exacerbates at higher mud densities in the sample without nanoparticles, and that the inclusion of barite nanoparticles reduces barite sag tendency, especially at high densities.

Table 3. Drilling fluid properties for different mud samples at varying densities at 120 °F.

Mud Sample	Density, ppg	Drilling Fluid Experimental Results					
		PV, cp	YP, lb/100 ft^2	Gel 10 s, lb/100 ft^2	Gel 10 m, lb/100 ft^2	FL, mL	FC, 1/32 in
Base Mud Sample	9	6.3	12.3	3.6	4.4	11.7	0.198
3% Nano Barite		7.2	12.5	3.7	4.8	10.6	0.198
5% Nano Barite		7.6	12.8	4	5.4	10.6	0.167
Base Mud Sample	12	10.6	32.3	11.1	17.3	12.9	1.03
3% Nano Barite		12.2	36.2	13.5	18.6	11.7	0.984
5% Nano Barite		13.4	38.5	14.2	19.4	11.6	0.976
Base Mud Sample	15	15.6	85.3	55.6	61.3	18.45	2.80
3% Nano Barite		20.9	125.4	84.7	82.9	17.6	2.66
5% Nano Barite		23.4	129.3	100.2	87.5	16.65	2.63

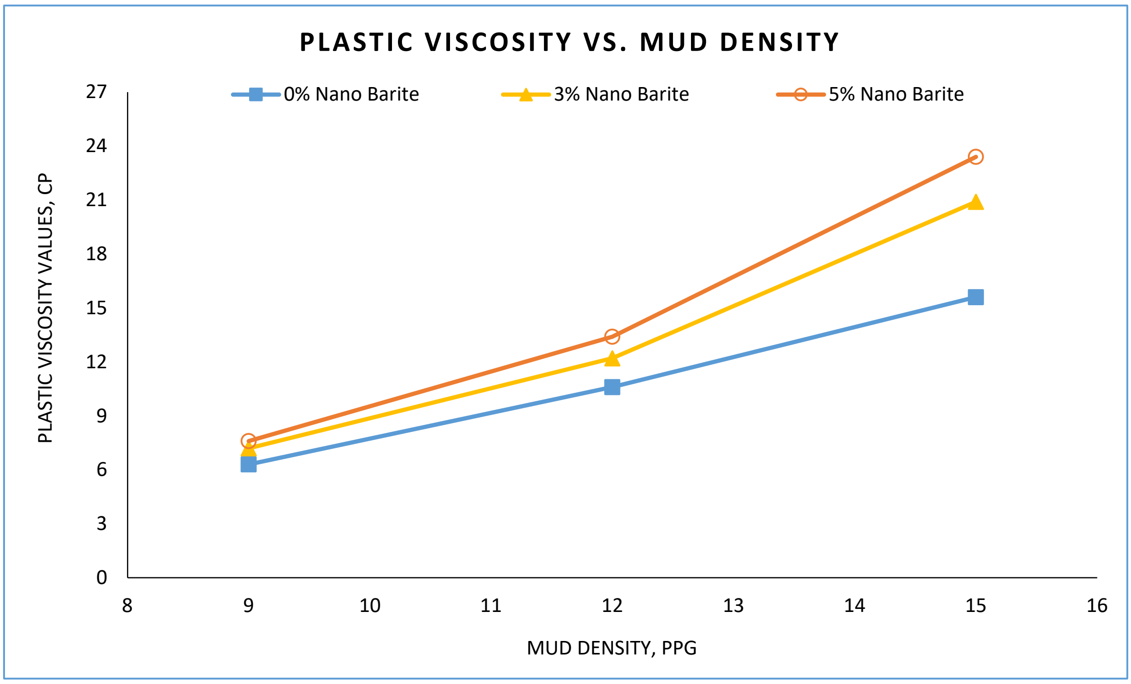

Figure 5. Barite nanoparticle concentration's influence on plastic viscosity at 120 °F.

The enhancement of nanoparticle interactions with the base fluid in the mud is driven by the nanoparticles' high surface area-to-volume ratio. This characteristic enables better interactions with drilling fluid components, resulting in improved viscosity. The incorporation of nanoparticles into water-based drilling fluids enhances plastic viscosity through direct or indirect chemical interactions between nanoparticles and base fluid. It is anticipated that nanoparticles and conventional polymers may be linked or bonded together, either directly or via specific intermediate chemical linkages, to combine the advantageous properties of each component, thereby improving drilling fluid performance [28].

Increasing the drilling fluid weight from 12 to 15 ppg resulted in a larger amount of nanoparticles, 11.25 to 24.15 g, respectively (see Table 3). This indicates that increasing the nanoparticle concentration enhances their interactions with the base fluid in the mud. This is depicted in Figure 5, highlighting the significant impact of nanoparticles at a higher mud density of 15 ppg compared with that at 9 ppg.

4.2. Yield Point

A high yield point highlights the dynamic suspension properties of barite nanoparticles compared to conventional barite, aiding cuttings suspension and enhancing wellbore cleaning during operations. Figure 6 shows that the yield point at 9, 12, and 15 ppg improved by 4%, 19%, and 51%, respectively, at a 5% barite nanoparticle concentration and 120 °F temperature. This reveals that the average yield point at 5% barite nanoparticles exceeds that at lower nanoparticle concentrations. As the concentration of barite nanoparticles increases, the yield point rises, with variable rates depending on the quantity of barite nanoparticles. This signifies that increasing the amount of barite nanoparticles in conjunction with a rise in mud density enhances the YP values of the drilling fluid. Consequently, the barite nanoparticles inclusion promotes cuttings suspension and wellbore cleansing as the drilling depth increases.

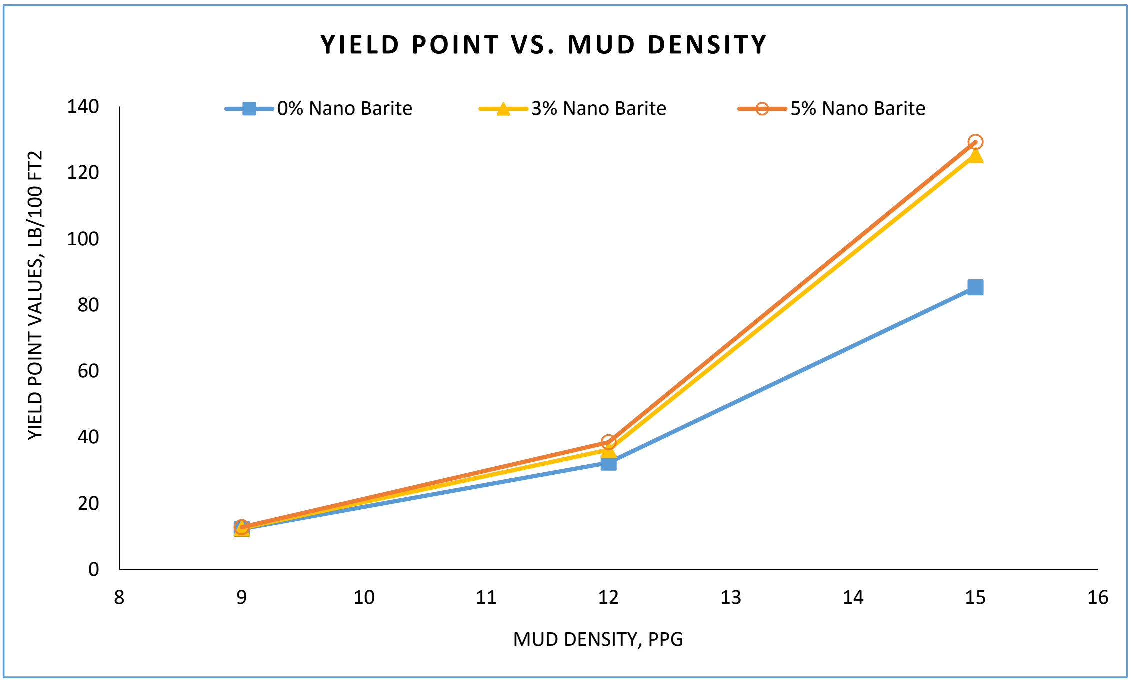

Figure 6. Barite nanoparticle concentration's influence on yield point at 120 °F.

4.3. Gel Strength

As summarized in Table 4 and illustrated in Figures 7 and 8, the results indicate a progressive increase in gel strength at both 10 s and 10 min with increasing barite nanoparticle concentration. The gel strength at 9, 12, and 15 ppg improved by 11%, 28%, and 80%, respectively, at 10 s gel strength, and by 22%, 12%, and 42% at 10 min gel strength, at 5% barite nanoparticle concentration and 120 °F. The phenomenon arises from electrostatic interactions that enable barite nanoparticles to bond to the base fluid, resulting in a robust structure and thereby enhancing gelation [12]. Furthermore, both Figures 7 and 8 show that the gel strength of 9, 12, and 15 ppg with 5% barite nanoparticles is superior to that of other samples at high mud densities. These observations indicate improved performance of the drilling fluid with barite nanoparticles.

Table 4. Percentage improvement in gel strength with 5% barite nanoparticles (120 °F).

Mud Density (ppg)	Gel Strength Increase at 10 s (%)	Gel Strength Increase at 10 min (%)	Relative Change from 10 s to 10 min (%)
9	11	22	+100
12	28	12	−57
15	80	42	− 47.5

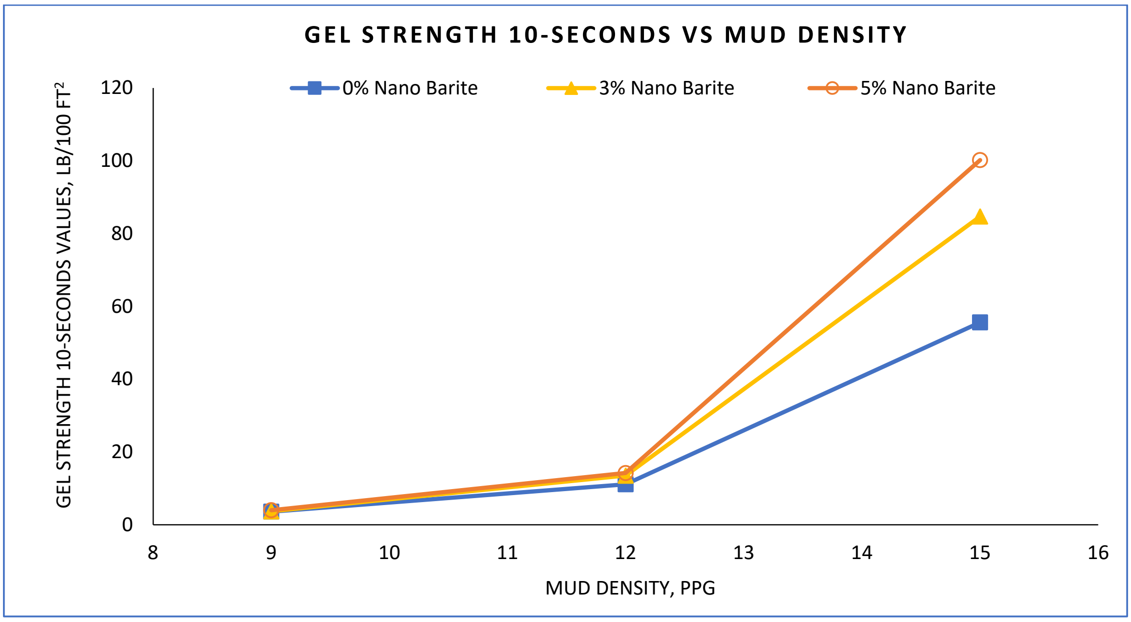

Figure 7. Barite nanoparticle concentration's influence on (10 s) gel strength at 120 °F.

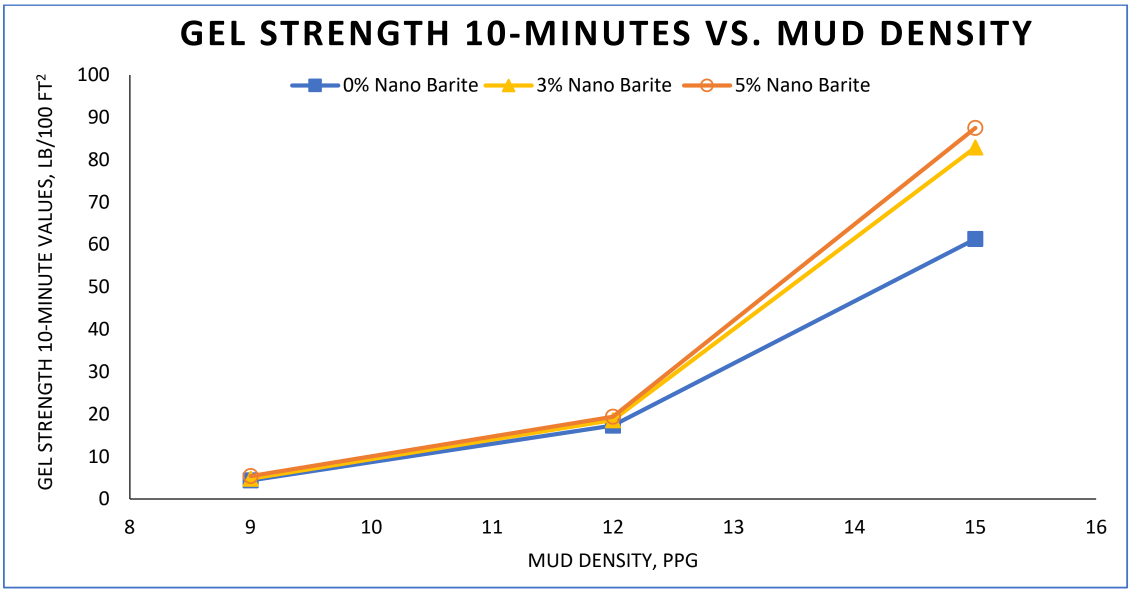

Figure 8. Barite nanoparticle concentration's influence on (10 min) gel strength at 120 °F.

4.4. Filtration Loss and Mud Cake Thickness

Figure 9 shows that a 5% barite nanoparticle concentration reduces fluid loss by 9%, 10%, and 10% for 9, 12, and 15 ppg, respectively. Additionally, Figure 10 shows that the filter cake thickness decreased by 16%, 5%, and 6% for 9, 12, and 15 ppg, respectively, at 5% barite nanoparticle concentration and 120 °F. The addition of barite nanoparticles resulted in a minimal effect on fluid losses and filter cake thickness because the bentonite is the main agent influencing both parameters. However, it is important to note that a thinner mud cake reduces the likelihood of pipe sticking during drilling operations.

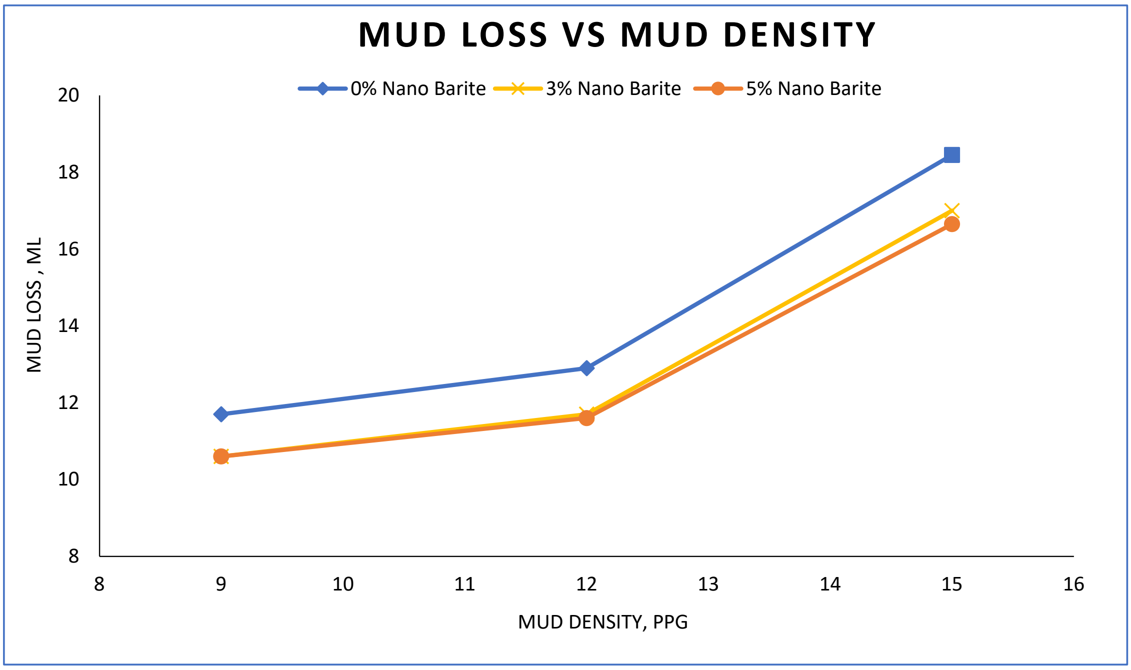

Figure 9. Barite nanoparticle concentration's influence on filtration loss at 30 minutes at 120 °F.

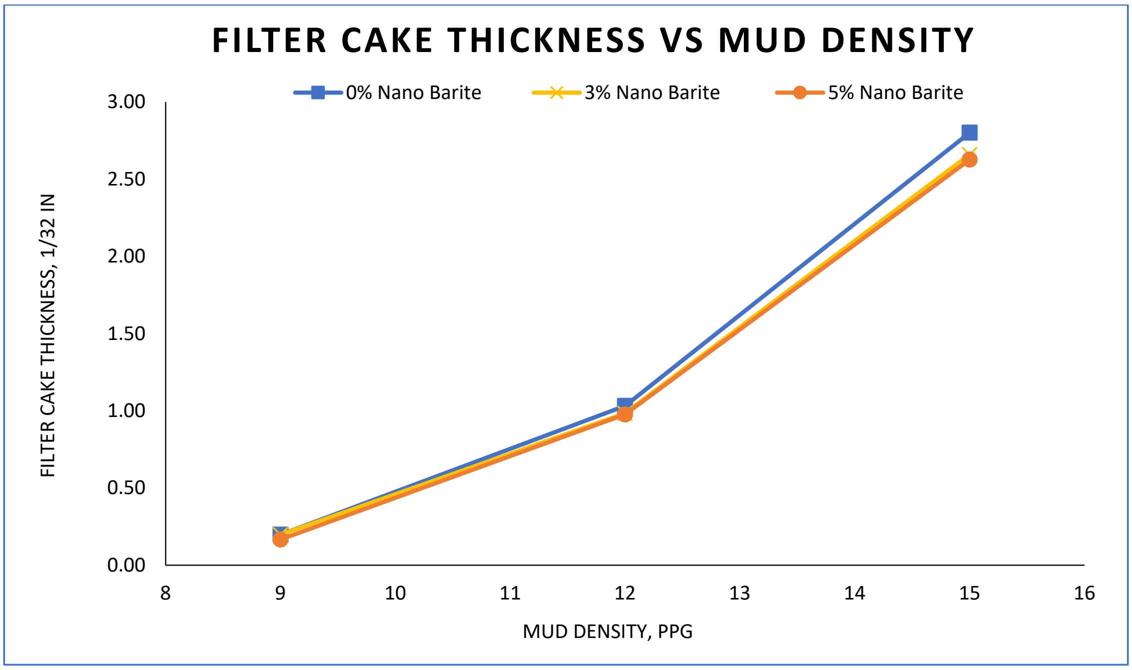

Figure 10. Barite nanoparticle concentration's influence on mud cake thickness at 120 °F.

To optimize drilling fluid performance, it is crucial to consider the relationship between the size of nanoparticles and the pore size of the drilled formation. The results of drilling mud rheology and fluid loss highlight the importance of ensuring that pore sizes of the drilled layers do not exceed the nanoparticle size, as smaller nanoparticles can lead to higher fluid loss.

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The 9–10% fluid loss reduction and decreased cake thickness align with literature reports for inorganic nano-additives (typically 5–15%), where nanoparticles function as secondary bridging agents within the primary bentonite matrix [25]. While 'active' nanoparticles like silica may show higher reductions, barite nanoparticles prioritize density stability with the additional benefits of microstructural refinement. The concentration range (0–5 wt%) was selected to capture the transition toward the performance plateau [25]. According to literature and many lab experiments, the 5 wt% nanoparticles concentration provides the optimum performance, and further increase in concentration beyond 5 wt% yields diminishing returns as the interstitial voids in the polymer-bentonite matrix become saturated [25]. This confirms that the three-point trend effectively reflects the optimized performance window.

The filter cake microstructure is governed by the mechanistic integration of barite nanoparticles ($d_{50} \approx 39$ nm) and the polymeric matrix. Acting as high-efficiency 'nano-fillers,' these particles optimize the packing density by occupying interstitial voids, transitioning the cake from a porous media to a cohesive nano-shield. The resulting structural refinement significantly eliminates localized high-permeability channels, thereby providing a robust defense against filtrate invasion and formation damage.

4.5. Effect of Barite Nanoparticles on Reducing Barite Sag Tendency

The study employed dynamic sag tests at 120 °F using the Viscometer Sag Shoe Test (VSST), shown in Figure 11. This apparatus was utilized to quantify the dynamic sag potential of the drilling fluid formulations at a controlled test temperature of 120 °F. Figure 12 shows the HPHT aging cells (left) and disassembled components, including the stainless-steel body and Teflon liner (right), used for the static sag tests. Static sag tests were conducted by aging the mud vertically at a reservoir temperature of 300 °F and a confining pressure of 500 psi for a 24 h duration [29–33]. Additionally, measurements for the static sag tests were taken at both vertical and 60-degree inclinations to understand sag behavior in various wellbore orientations. These tests were essential to validate the anti-sag efficiency of the 39.08 nm barite particles reported in our SEM analysis.

Figure 11. OFITE Viscometer Sag Shoe Test (VSST) assembly for dynamic sag evaluation. This apparatus was utilized to quantify the dynamic sag potential of the drilling fluid formulations at a controlled test temperature of 120 °F. The setup captures a specific volume of mud from the base of a viscometer cup under shear to measure density increases caused by particle settling. Key findings from this test demonstrate that the integration of barite nanoparticles significantly reduces the VSST sag weight, indicating superior suspension stability under dynamic flow conditions compared to conventional micro-barite systems.

Figure 12. High-pressure, high-temperature (HPHT) aging cells and oven setup for static sag measurement. The configuration shows the HPHT aging cells (**left**) and disassembled components, including the stainless-steel body and Teflon liner (**right**). Static sag tests were conducted by aging the mud vertically at a reservoir temperature of 300 °F and a confining pressure of 500 psi for a 24-hour duration. This setup enabled the calculation of the static sag factor by comparing the density of the top and bottom fluid fractions, confirming that nano-barite maintains a highly stable density profile even under extreme thermal stress.

The following two equations are used to calculate VSST and static sag factor (SF) [19–23].

$$VSST = 0.833 * (W_2 - W_1)$$

where $VSST$: Viscometer Sag Shoe Test, ppg.

W_1: weight of the mud-filled syringe taken from the sample at the beginning, g.

W_2; weight of the mud-filled syringe taken from the sample after 30 min, g.

A $VSST$ value of 1.0 ppg or lower indicates that a drilling fluid has a minimal tendency to sag [20,21].

$$SF = \rho_{bottom} / (\rho_{bottom} + \rho_{top})$$

where SF: static sag factor.

ρ_{bottom}: mud density from the lower part, ppg.

ρ_{top}: mud density from the upper part, ppg.

Static sag factor greater than 0.53 indicates the presence of sag [27–31].

4.5.1. Dynamic Sag Test

Figure 13 shows the dynamic sag test results for varying concentrations of barite nanoparticles at 120° F (48.8 °C) for three mud densities. The boundaries in Figure 13 show the safe and unsafe regions at 1.00 and 1.6, respectively. The dynamic sag decreases when barite nanoparticles are added to the drilling fluid. The reductions are 10%, 44%, and 50% for 9, 12, and 15 ppg, respectively, in a 5% barite nanoparticle concentration sample at 120 °F temperature. The results indicate that as mud density increases, dynamic sag values generally decrease for all samples containing barite nanoparticles, highlighting their effectiveness in reducing sagging. Notably, incorporating 3% and 5% barite nanoparticles lowers dynamic sag at various mud densities, especially at 15 ppg.

The observed reduction in dynamic sag (up to 50% for 15 ppg mud) suggests that barite nanoparticles fundamentally enhance the suspension kinetics under shear. Furthermore, the high surface-area-to-volume ratio of the nanoparticles enhances the interfacial coupling with the polymeric viscosifiers in the mud. This results in a more robust micro-gel network that effectively reduces barite sag by entrapping larger barite particles even under dynamic conditions.

Overall, the findings suggest that barite nanoparticles enhance the performance of WBM drilling fluids by decreasing barite sag, thereby improving mud stability and maintaining the rheological properties during drilling operations.

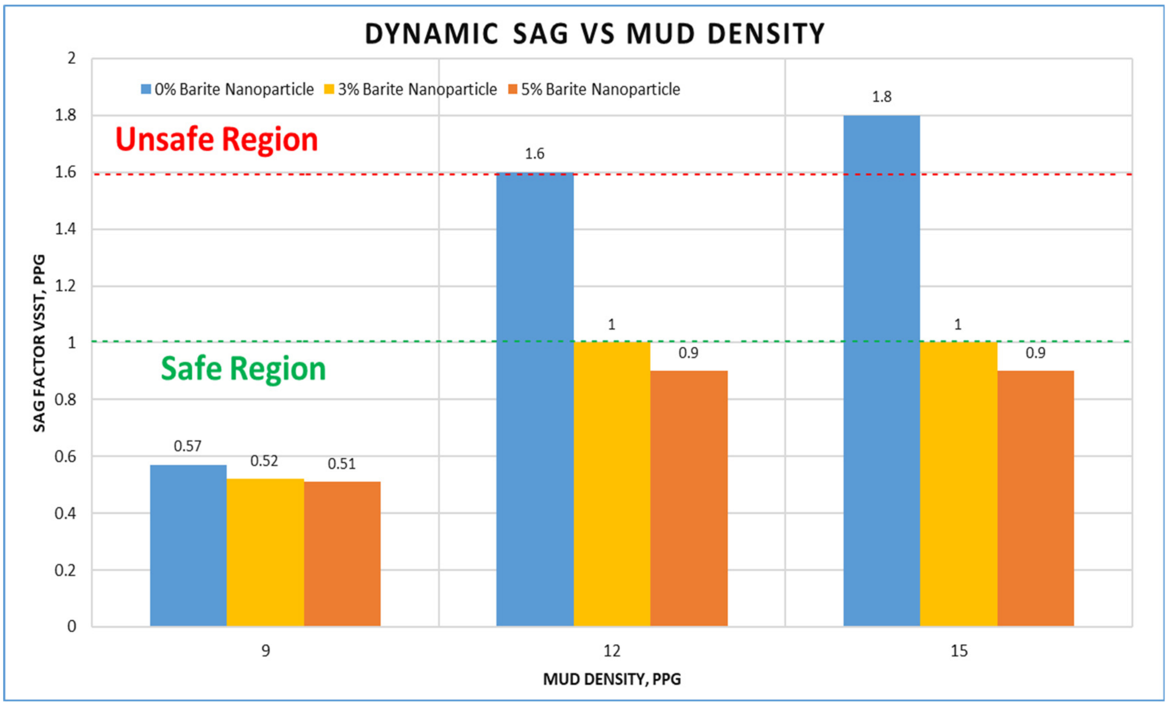

Figure 13. Barite nanoparticle concentration's influence on dynamic sag at 120 °F.

4.5.2. Static Sag Test

Figure 14 illustrates the vertical static sag results for varying barite nanoparticle concentrations at 300 °F. A critical red line is shown in Figure 14 at approximately 0.53, indicating the boundary between safe and unsafe conditions. Values above 0.53 represent potential sag issues. As shown, the vertical static sag decreased by 3%, 15%, and 19% for 9, 12, and 15 ppg, respectively, at a 5% barite nanoparticle concentration and 300 °F. The results confirm that adding barite nanoparticles significantly reduces vertical static sag; the optimal barite nanoparticle concentration for minimizing sag is 5%. At this level, sag values are notably lower than at 0% and 3% concentrations, indicating that 5% barite nanoparticles effectively enhance the overall performance of the drilling fluid by minimizing vertical static sag.

For 60-degree inclined orientation, Figure 15 illustrates static sag and mud density for different concentrations of barite nanoparticles at 300 °F. The addition of barite nanoparticles mitigated the static sag by 4%, 17%, and 21% for 9, 12, and 15 ppg, respectively, in the 5% barite nanoparticle concentration sample at 300 °F. The introduction of 3% and 5% barite nanoparticles significantly improved sag factors, keeping them around 0.53–0.54 across all densities, thereby stabilizing the drilling fluid. These findings suggest that 5% barite nanoparticle concentration effectively mitigates sag problems, especially in higher mud densities, leading to improved drilling performance and reduced operational issues.

In summary, the transition from unstable sag profiles to stabilized suspensions is a direct consequence of the integration between the nanoscale weighting agents and the fluid's chemical structure. The nanoparticles do not act solely as density contributors; they function as rheological modifiers that enhance the structural integrity of the fluid. The reduction in sag factors across dynamic, static-vertical, and static-inclined conditions confirms that a 5% concentration of barite nanoparticles provides the necessary electrokinetic and physical reinforcement to withstand challenging downhole environments. The reduction in barite sag is attributed to the Brownian motion of the nanoparticles (26.9–63.2 nm), which provides sufficient kinetic energy to counteract gravitational forces acting on larger barite particles [34]. Additionally, the inclusion of 5% nanoparticles facilitates network formation through electrostatic interactions with the base fluid, increasing the Low-Shear-Rate Viscosity (LSRV) [35]. This structural network prevents settling that effectively minimizes the sag factor even at high densities [36].

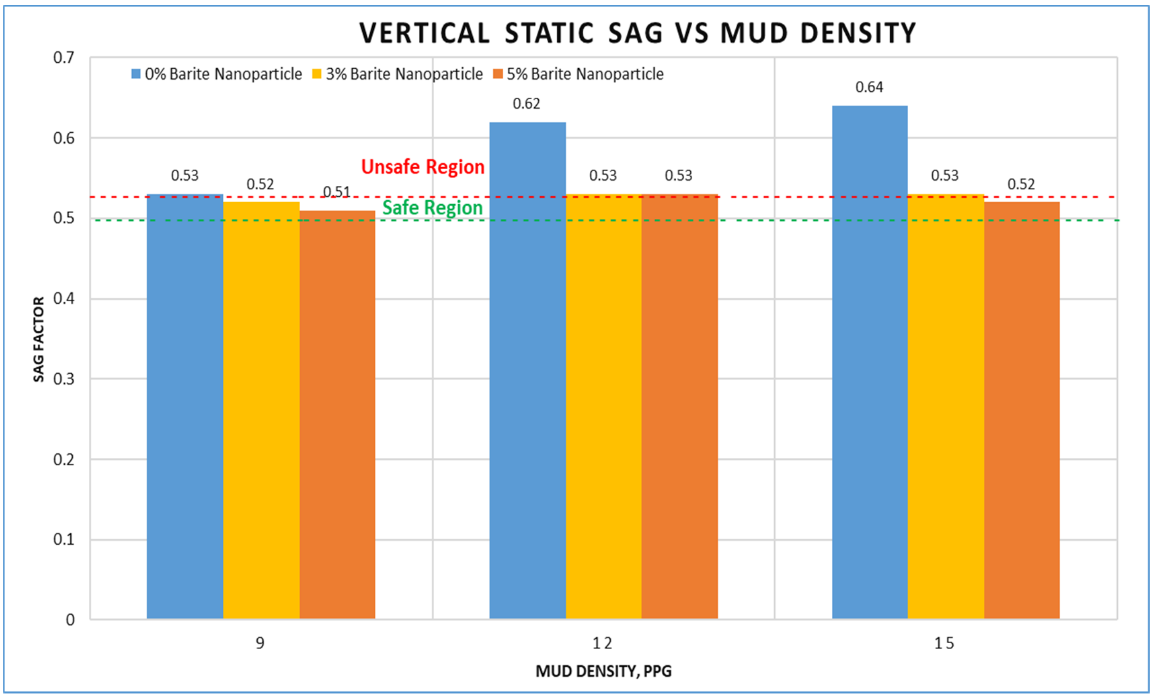

Figure 14. Barite nanoparticle concentration's influence on vertical static sag at 300 °F.

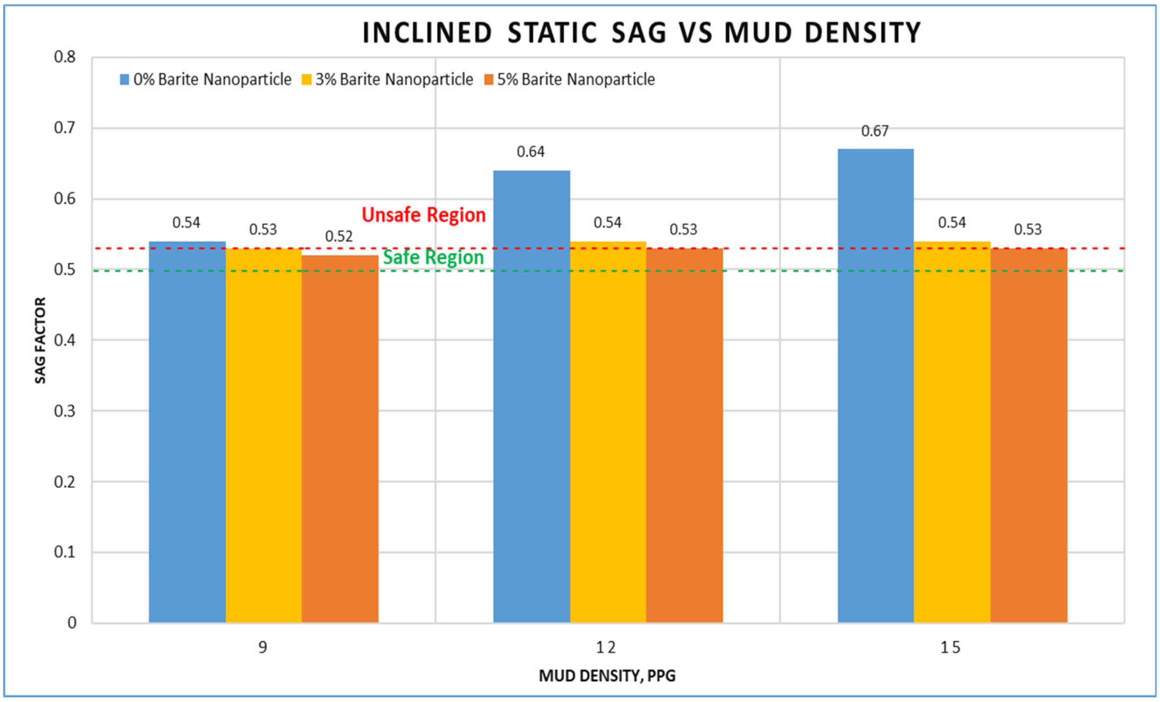

Figure 15. Barite nanoparticle concentration's influence on inclined static sag at 300 °F.

4.6. Zeta Potential and Colloidal Stability

The electrokinetic behavior of the barite nanoparticles, specifically the zeta potential, plays a critical role in the colloidal stability and rheological performance of the formulated water-based drilling fluid. Although in situ zeta potential measurements were not conducted in this study, the literature suggests that barite nanoparticles typically exhibit a negative surface charge in alkaline aqueous environments (pH > 9), often reporting values between −15 mV and −35 mV. This negative surface charge promotes electrostatic repulsion between the particles, effectively minimizing the risk of severe flocculation or "barite sag" under static conditions. The observed stability of the suspension in the rheological tests of this study further supports the hypothesis that the nanoparticles maintain sufficient electrokinetic repulsion to ensure a homogenous dispersion within the fluid matrix [23].

4.7. Wettability and Comparison with Micronized Barite

The wettability of the weighting agents significantly influences the formation of the filter cake and the overall filtration control. Barite is inherently hydrophilic, which facilitates its integration into water-based fluid systems without the need for surfactants. Compared to conventional micronized barite, the nanoparticles used in this study offer a substantially smaller size and a higher surface-area-to-volume ratio. This higher surface area enhances the interaction with fluid-loss additives, contributing to the development of a more compact and impermeable filter cake. Studies on micronized barite report that maintaining a strongly water-wet state is essential for reducing torque and drag while preventing the formation of thick and sticky filter cakes that lead to differential sticking [24,25,37].

5. Research Limitations and Future Work

While the current study provides a robust evaluation of nano-barite performance in high-pressure, high-temperature (HPHT) water-based drilling fluids, certain parameters remain outside the scope of this investigation and represent opportunities for future research:

- Fluid Formulations: This research focused on a specific water-based mud (WBM) chemistry. The interaction between barite nanoparticles and other weighting agents or varied salt concentrations (e.g., KCl, $CaCl_2$) requires further validation. Additionally, investigating the performance of nano-barite in oil-based muds (OBM) or synthetic-based systems remains a significant research gap.
- Long-term Thermal Stability: The aging cycles were conducted for a standard 24 h duration. Extending the thermal exposure to 48 or 72 h would provide deeper insights into the long-term chemical stability of the nanoparticle-polymer matrix under extreme reservoir conditions.
- Synergistic Effects: Future studies could explore the synergy between nano-barite and other nano-additives (e.g., nano-silica or carbon nanotubes) to develop multi-functional "smart" fluids capable of simultaneously managing rheology, filtration, and lubricity.

6. Conclusions

Based on the experimental work conducted in this study regarding the effects of barite nanoparticles on the anti-sag of water-based drilling fluids, the following conclusions can be drawn:

1. Suitability of Nanoparticle Size: The nanoparticle size range obtained in this study (26.9–63.2 nm) is proven suitable because it resists settling yet avoids the agglomeration observed with ultra-fine powders.
2. Enhancement of Rheological Properties: A 5% introduction of barite nanoparticles significantly improved the plastic viscosity, yield point, and gel strength of the drilling

fluids. These improvements are attributed to the electrostatic interactions that facilitated barite nanoparticles' bonding with the base fluid. This suggests that optimal nanoparticle levels effectively enhance the flow characteristics and hole-cleaning ability of the fluid.

3. Reduction in Fluid Loss: The inclusion of 5% barite nanoparticles led to a reduction in fluid losses by approximately 10% across different densities and a decrease in filter cake thickness of about 6% at 15 ppg. This reduction in thickness reduces the likelihood of pipe sticking during drilling operations.
4. Significant Reduction in Sag Tendency: The findings indicate that barite nanoparticles effectively mitigate both dynamic and static sag, especially at higher mud weights where sag problems are typically more severe. Dynamic sag was significantly reduced by 43.8% and 50% for 12 and 15 ppg, respectively. Similarly, static sag testing under HPHT conditions (500 psi, 300 °F) demonstrated substantial improvements, with a reduction of 21% at a 60-degree inclination for 15 ppg mud. These results clearly indicate that 5% barite nanoparticles stabilize the fluid in both vertical and deviated wellbores.
5. Overall Performance Improvement: The findings indicate that the incorporation of barite nanoparticles significantly enhances the rheological properties and performance of drilling fluids, especially at higher densities, while effectively mitigating sag tendencies, as shown in Table 5. This suggests that strategic formulation adjustments can lead to more efficient drilling operations in various conditions.

Table 5. Summary of the effect of barite nanoparticles addition.

Properties	Effect of Barite Nanoparticles
Plastic Viscosity	Increased
Yield Point	Increased
Gel Strength	Increased
Filtration	Decreased
Mud Cake Thickness	Decreased
Barite Sag	Decreased

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Nomenclature

API	American Petroleum Institute
FC	Filtration cake thickness
FL	Filtration loss
HPHT	High pressure, high temperature
LPLT	Low pressure, low temperature
MWCNT	Multi-walled carbon nanotube
nm	Nanometer
ppg	Pounds per gallon
PV	Plastic viscosity
SEM	Scanning electron microscope
SF	Static sag factor
VSST	Viscometer Sag Shoe Test
WBM	Water-based mud
YP	Yield point

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