Hindawi
Geofluids
Volume 2022, Article ID 5277126, 9 pages
https://doi.org/10.1155/2022/5277126

Research Article

Utilization of Vermiculite for Solving Hematite Sagging in Water-Based Drilling Fluids

Salem Basfar, Ashraf Ahmed, and Salaheldin Elkatatny

College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

Correspondence should be addressed to Salaheldin Elkatatny; elkatatny@kfupm.edu.sa

Received 16 February 2022; Revised 22 August 2022; Accepted 12 September 2022; Published 30 September 2022

Academic Editor: Zhiyuan Wang

The sagging phenomenon of solids, such as hematite, in drilling fluids is commonly experienced when drilling at elevated temperature conditions presenting operational and well control issues. Thus, we report herein the addition of vermiculite to water-based drilling fluid with the objective of improving fluid stability by hematite sagging mitigation. Different quantities of vermiculite clay (3–6 lb/bbl) were used and the sagging tendency was evaluated for the base and vermiculite-containing drilling fluids under static and dynamic conditions. From the sag measurements, the optimum vermiculite content was determined, and the influence on the key drilling fluid properties was studied by conducting the rheology, viscoelasticity, filtration, density, and alkalinity measurements. To simulate the practical elevated temperature, the tests were performed at temperature up to 250°F. The outcomes of this study revealed that the addition of vermiculite to the base drilling fluid significantly improved fluid stability. The content of 5 lb/bbl vermiculite was sufficient to mitigate the hematite sagging at elevated temperatures and drive the sag tendency factors to safe values. The ability of vermiculite to improve fluid stability was confirmed with the enhancement of rheological and viscoelastic properties, since the recommended vermiculite content resulted in a 24% reduction in plastic viscosity, 9% increment on yield point, and improved storage and loss modulus with better gelling structure. Also, the filtration properties were improved with 5 lb/bbl vermiculite, as the filtrated volume was reduced from 6.2 to 5 cm^3 and formulated a preferred filter cake with less weight and thickness. In addition, the small amount of vermiculite did not change the drilling fluid weight, and the pH was slightly dropped but within the practical alkalinity range.

1. Introduction

The drilling fluids play substantial roles in drilling operations by providing the hydrostatic pressure, carrying the drilled cuttings, well cleaning, string lubricating, conveying the hydraulic energy, and blocking the permeable formations; therefore, the design of suitable drilling fluid formulations is a key for successful drilling of oil and gas wells [1]. Water-based drilling fluids (WBDF) are commonly used with favorable technical and economic performance; nonetheless, their application in highly deep, deviated, and unconventional wells necessitates special considerations to comply with the elevated temperature and pressure conditions [2]. In such challenging conditions, several fluid stability-related issues can be occurred such as solids sagging, flocculation, and thermal degradation of polymeric additives [3–5]. Therefore, an optimization of WBDF with selectively qualified additives is required to overcome such critical challenges.

To obtain the fluid density required for maintaining the hydrostatic pressure, different solids known as weighting agents are used such as barite, hematite, ilmenite, calcite, magnetite, and Micromax [6–8]. Recently, hematite with a specific gravity of 4.9–5.3 is intensively applied as a weighting material presenting substantial enhancement in the rate of penetration (ROP), lower solids content, acid solubility, and low toxicity [7, 9, 10]. Nevertheless, at a temperature greater than or equal to 250°F, the solids content in the WBDF tends to precipitate and separate from fluid, especially with heavier drilling fluid density (i.e., ≥14 ppg) [11]. Several factors contribute to solids settlement including the drilling fluid properties, temperature, solid particle size, well inclination, and drilling parameters such as the pipe annular velocity [12–14]. This sagging phenomenon causes density variation and fluid instability which may result in pressure control issues in upper sections, elevated equivalent circulation density at the bottom, pipe sticking, and loss of circulation [15, 16].

Different solutions are proposed to mitigate the hematite sagging at both water- and oil-based drilling fluids and experimentally investigated. Some of these solutions used anti-sagging materials such as garamite, laponite, and perlite [11, 17, 18], while others proposed combining different weighting materials [19–22]. The research is continued to develop more feasible solutions for the hematite sagging issue.

Vermiculite is a hydrous phyllosilicate clay mineral with a specific gravity of 2.4–2.7 and a neutral pH of 7.0–7.5 [23–25]. This clay exfoliates, curls, and significantly expands when heated, which increases the water retaining capacity and makes it lightweight, compressible, incombustible, and highly absorbent as it can absorb 3–4 times its weight in water [23, 26]. The unique characteristics and commercial availability of vermiculite make its wide applicability in construction, agriculture, steel industry, and packaging [26–28]. Vermiculite was studied as a drilling fluid additive and the rheological and filtration effects on spud drilling fluid were addressed [29]. Recently, vermiculite was addressed as an anti-sag agent for mitigating the barite sagging tendency for WBDF and showed promising results with improved rheological and filtration performance [30].

According to our best knowledge, no former studies were performed to address the impact of vermiculite on the stability of hematite WBDF. Therefore, this work endeavors to assess the effects of incorporating vermiculite to hematite WBDF at elevated temperatures in terms of fluid stability improvement and sagging mitigation. Different quantities of vermiculite were considered to address the sagging tendency and determine its optimum amount. Also, the influence on the other drilling fluid properties (i.e., alkalinity, rheology, viscoelasticity, and filtration performance) was investigated via conducting routine drilling fluid tests.

The novelty of this study is represented by introducing and evaluating vermiculite as a new applicable anti-sagging solution for safe, efficient, and cost-effective drilling operations, since formulating a stable drilling fluid helps in minimizing the non-productive time and mitigating severe drilling operational and technical problems that are associated with the solids sagging and inconsistent properties issues.

2. Materials and Experiments

2.1. Materials. Hamilton Beach mixture was used to prepare the WBDF samples at ambient conditions. The applied formulation is described in Table 1 listing the practical components with the concentrations per one barrel and the order and function of each additive. Different amounts of the proposed vermiculite (0, 3, 4, 5, and 6 lb/bbl) were added as an anti-sag agent, and hematite was used to obtain the required density.

The proposed vermiculite clay was characterized to address the chemical composition, particle size distribution (PSD), and appearance. The elemental chemical composition was recognized using the M4 Tornado X-ray fluorescence (XRF). The results defined that the applied vermiculite contained 35% silicon, 20% magnesium, 14% aluminum, and 6% iron. The particle size distribution analyzer (PSD) indicated that 10% of the vermiculite sample has a particle size (D_{10}) of 2.14 μm, 90% has a particle size (D_{90}) of 124.9 μm, and the average particle size (D_{50}) is 23.18 μm. The scanning electron microscope (SEM) depicted the wide surface area and sub-rounded irregular shape of vermiculite particles that differs in size with a normal distribution (Figure 1).

Table 1: The WBDF formulation.

Component	Function	Quantity (lb/bbl)
Water	Base fluid	245
Defoamer	Antifoam	0.08
Sodium carbonate	Calcium ions controller	0.5
Potassium hydroxide	pH controller	0.5
Xanthan gum	Viscosifier	1.5
Bentonite	Viscosifier	4
Vermiculite	Anti-sagging	As required
Starch	Fluid loss controller	6
PAC-R	Fluid loss controller	1
Potassium chloride	Shale swelling controller	20
Calcium carbonate	Bridging	5
Hematite	Densifier	350

2.2. Experiments. It is important to measure the sag tendency for any proposed solution to evaluate its effectiveness which can be studied experimentally by observing the density variation using sag cell and viscometer [31, 32]. The sag tests were conducted under static and dynamic conditions and since the solids sagging was practically observed in both vertical and deviated wells [33], the static sag measurements were performed at vertical and 45°-inclination positions. In the static test, the fluid samples were aged in autoclave cells for 24 hours under 250°F and 300 psi, then the weights of 10 cm^3-fluid pulled from the top and bottom sections of the cell were measured. The static sag factors were quantified by determining the ratio of the top section weight to the sum of both upper and lower section weights. It is recommended to maintain the value of the sag factor below 0.53 [34].

The sag tendency under dynamic conditions was evaluated using a viscometer to apply 100 rpm rotation for 30 minutes at 120°F and placing the sag shoe at the cup's bottom (see Figure 2). The value of the viscometer sag shoe test (VSST) was defined by measuring the weights of 10 cm^3 fluid pulled from the sag shoe groove before and after rotation and using the below equation [35]:

$$\text{VSST} = 0.834 \times (W_2 - W_1), \tag{1}$$

where W_1 and W_2 are the fluid weights pulled before and after rotation, respectively. A value of 1.0 ppg or less of VSST implies a drilling fluid with a safe minimum sag tendency

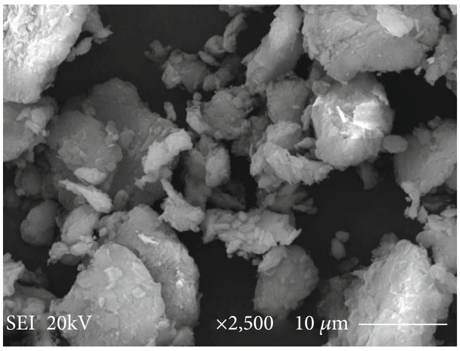

Figure 1: Vermiculite particles shape from SEM image.

Figure 2: Setup of dynamic sag test.

[35]. After evaluating the sagging performance with different amounts of vermiculite following the aforementioned sag tests, the optimal quantity was determined.

For a better understanding of the sagging tendency, the stability of colloidal dispersions for hematite and vermiculite was evaluated by measuring the Zeta potential of particles in a suspension state. In which, suspensions of 0.5 wt% of hematite with and without vermiculite were prepared using distilled water at a pH of 9.7. The samples were then placed in a multi-wrist shaker at ambient temperature for 24 hours to guarantee the charges' equilibrium. Then, the solutions were centrifuged to settle the large particles. After that, the magnitude of Zeta potential for these suspensions was evaluated using the Zeta potential analyzer with electrophoretic light scattering.

The evaluation of drilling fluid rheology and viscoelasticity can also give a good indication of sagging behavior [3, 34, 36, 37]. Accordingly, the viscoelastic performance and rheological properties involving plastic viscosity (PV), yield point (YP), and gel strengths were studied at 250°F and 300 psi, by adhering to the American Petroleum Institute (API) standard procedures, to address the impact of adding the determined vermiculite quantity compared to the base drilling fluid.

The time-dependent viscoelastic properties (storage modulus, G', and loss modulus, G'') and internal gel structure were evaluated to study the elastic and viscous behavior of the drilling fluids. The oscillatory amplitude and frequency sweep tests were conducted for this purpose using Anton Paar MCR-302 rheometer. The oscillation amplitude test was firstly applied by fixing the frequency with free amplitude increase with time. Then, the sweep frequency test was performed by fixing the shear strain value from the linear viscoelastic range (LVE) and letting frequency free. From plotting the G' and G'' versus shear strain on a logarithmic scale, the LVE was determined where the G' and G'' curves displayed plateau values and did not change with increasing the shear strain before breaking the inner structure of the fluid sample [38]. Also, the crossing point where G' is equivalent to G'' was determined to identify the flow point.

Since the filtration characteristics are highly affected by the solid particles' size and drilling fluid rheology [39–41], the filtration test was performed at 250°F and differential pressure of 300 psi to evaluate the behavior and analyze the composed filter cake characteristics for both base and vermiculite-containing drilling fluid. A 20-μm saturated porous ceramic disc, that has a diameter of 2.5 inches and thickness of 0.25 inches, was used as filtration media. The collected filtrated volume was monitored for 30 minutes. Then, the thickness and weight of the composed filter cake were determined.

Also, the drilling fluids' weight and pH value were measured at ambient conditions using mud balance and pH meter to address the effect of vermiculite addition.

The followed methodology for performing the afore-explained study experiments was summarized as a flowchart in Figure 3.

3. Results and Discussion

The prepared WBDF sample without vermiculite content is considered the base drilling fluid and its resulted key properties are listed in Table 2.

The effects of incorporating different concentrations of vermiculite (3, 4, 5, and 6 lb/bbl) on WBDF were thoroughly investigated and the obtained results were explained hereunder.

3.1. Sagging Tendency. The obtained sag factors of the base drilling fluid under static conditions at vertical and deviated positions, which were 0.58 and 0.59, confirmed the occurrence of solids sagging at elevated temperature (250°F) and drilling fluid weight of 16.7 ppg, besides the fact of the more accelerated sagging tendency in deviated wells than vertical ones [42]. The sag factor was successfully lowered when adding vermiculite, and as the added quantity was increased, the sag tendency was minimized, as depicted in Figure 4(a). Similarly, the base drilling fluid showed an elevated sag tendency under dynamic conditions with VSST of 2.3 ppg, where it was decreased with increasing the vermiculite content (Figure 4(b)). Since vermiculite clay has a wide surface

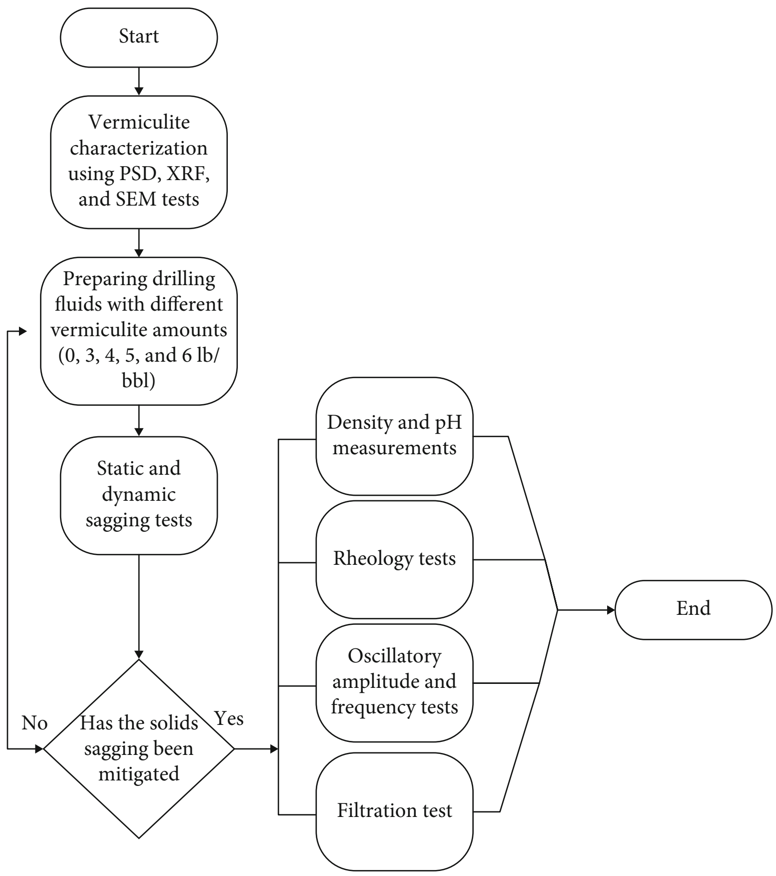

FIGURE 3: Experiments methodology.

TABLE 2: The resulted key properties of the base drilling fluid sample.

Property	Value	Unit
Density	16.7	ppg
pH value	11	—
Plastic viscosity	37	cP
Yield point	34	$lb/100\,ft^2$
10-sec/10-min gel strength	18/29	$lb/100\,ft^2$

area and is highly water-absorbent, it has a high surface colloidal activity. These characteristics might be attributed to this resulting enhancement in fluid stability that corresponded to the reduction of sagging tendency.

Based on the abovementioned results in Figure 4, adding 5 lb/bbl of vermiculite was sufficient to mitigate the solids sagging by reducing the sag tendency to the safe recommended values under both vertical and deviated static positions and dynamic conditions, where the values were 0.51, 0.52, and 0.85, respectively.

Zeta potential is a key technique for justifying the stability of the colloidal dispersion. The magnitude of Zeta potential measures the degree of electrostatic repulsion between similarly charged and adjacent particles in solution. The small Zeta potential means the attractive forces exceed the repulsion forces between the particles leading to aggregation, while the high Zeta potential (positive or negative) indicates better stability with higher aggregation resistance [43]. The zeta potential evaluation further demonstrated that adding vermiculite improves the suspension stability, as the magnitude was improved to -42.2 mV with vermiculite compared to -37.9 mV of blank hematite solution.

The influence of adding 5 lb/bbl of vermiculite on drilling fluid properties (i.e., rheology, viscoelasticity, filtration, density, and alkalinity) was thoroughly investigated.

3.2. Rheology Measurements. The rheology tests indicated that using 5 lb/bbl vermiculite reduced the PV favorably by 24%, from 37 to 28 cP and raised the YP by 9%, from 34 to 37 $lb/100\,ft^2$ (Figure 5(a)). The recommended PV value of WBDF should be as low as possible and below 25 cP [44, 45] with higher YP but not to exceed 50 $lb/100\,ft^2$ [46]; therefore, incorporating vermiculite resulted in much better performance with the PV and YP values approaching the recommended limits. The high colloidal dispersion of vermiculite, as indicated by zeta potential values, is mainly attributed to this improvement in rheological performance. Also, the improvement in these properties enhanced the YP/PV ratio from 0.92 to 1.32 with 44%, which improved the drilling fluid stability, wellbore hydraulics, and hole cleaning efficiency without causing flocculation [47, 48]. Moreover, the recommended vermiculite content resulted in a more robust gel structure as the 10-minute gel strength value was raised without exceeding the ceil of 35 $lb/100\,ft^2$, as

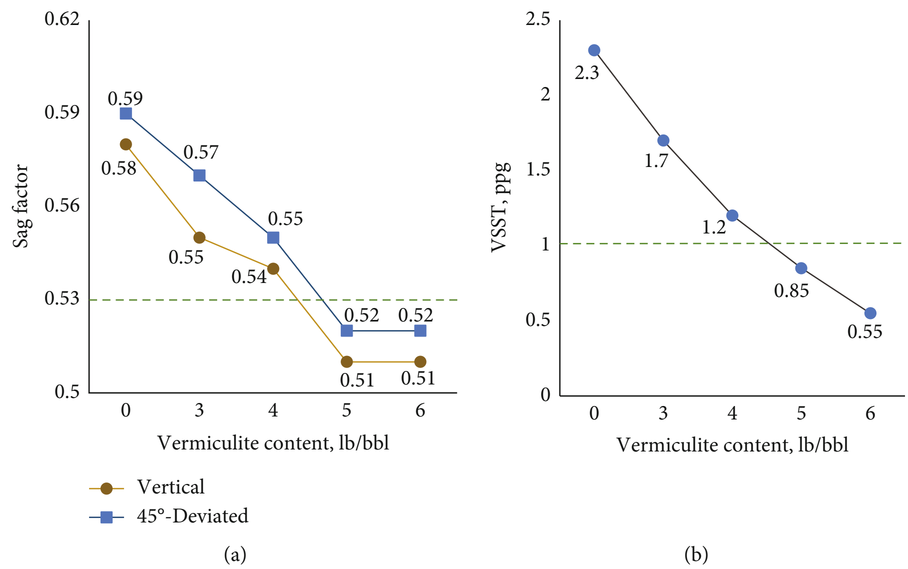

Figure 4: Effect of adding vermiculite on sag factor under (a) static conditions at 300 psi and 250°F and (b) dynamic conditions at 120°F.

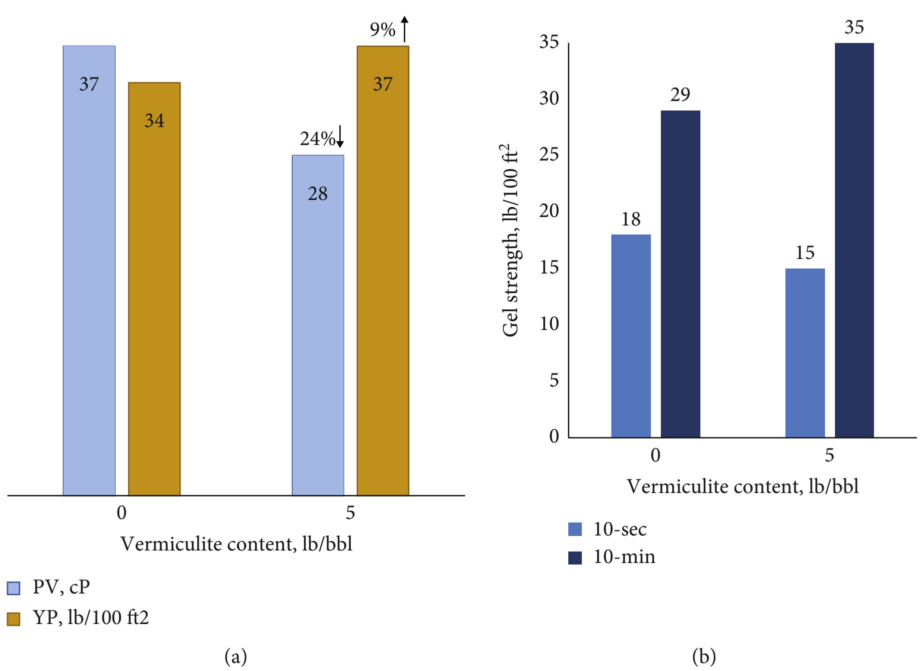

Figure 5: Effect of adding 5 lb/bbl vermiculite on (a) plastic viscosity and yield point and (b) gel strengths at 250°F.

illustrated in Figure 5(b), which means vermiculite helped in suspending the hematite particles and cuttings while no circulation.

The previously explained results of sagging tests were emphasized by the resulting improvement in yield point and gel strengths, which provided enough solids suspension capability at both dynamic and static conditions while maintaining the plastic viscosity as low as possible reduced both the pressure losses and velocity of solids settlement.

3.3. Viscoelasticity Behavior. It is necessary for drilling fluids to have a viscoelastic performance (viscous and elastic behavior) and the enhancement in its viscoelasticity can contribute to fluid stability improvement.

The acquired results from amplitude and frequency tests are shown in Figure 6. Adding 5 lb/bbl vermiculite extended the plateau values of G' and G'' with prolonged LVE, as shown in the amplitude test, which indicated more elasticity and solid-like conduct before breaking the inner gel structure. Also, the flow point (marked in the amplitude test figure) was postponed delaying the liquid-like behavior and confirming the better elasticity.

The frequency test confirmed the improvement in the stability of inner gel structure when adding 5 lb/bbl

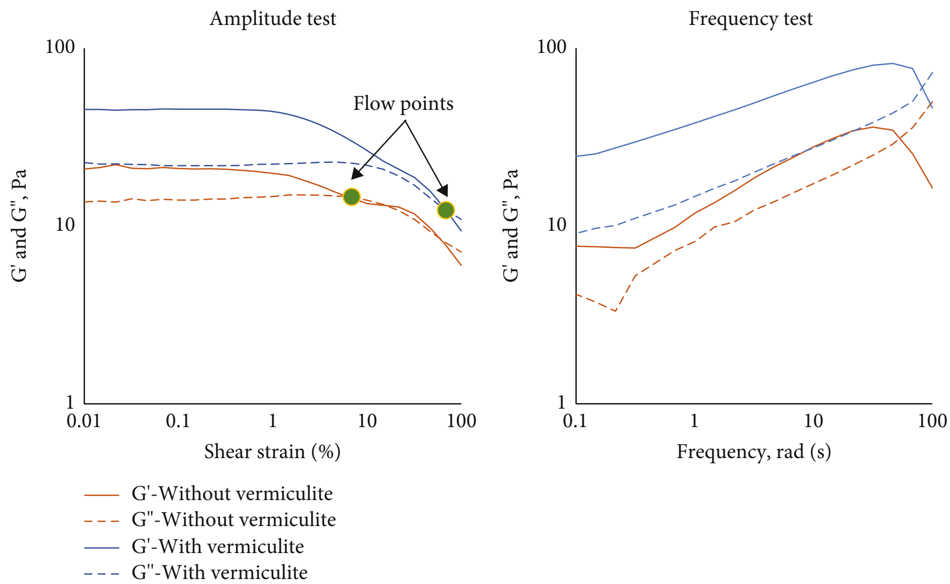

FIGURE 6: Results of oscillatory amplitude and frequency tests.

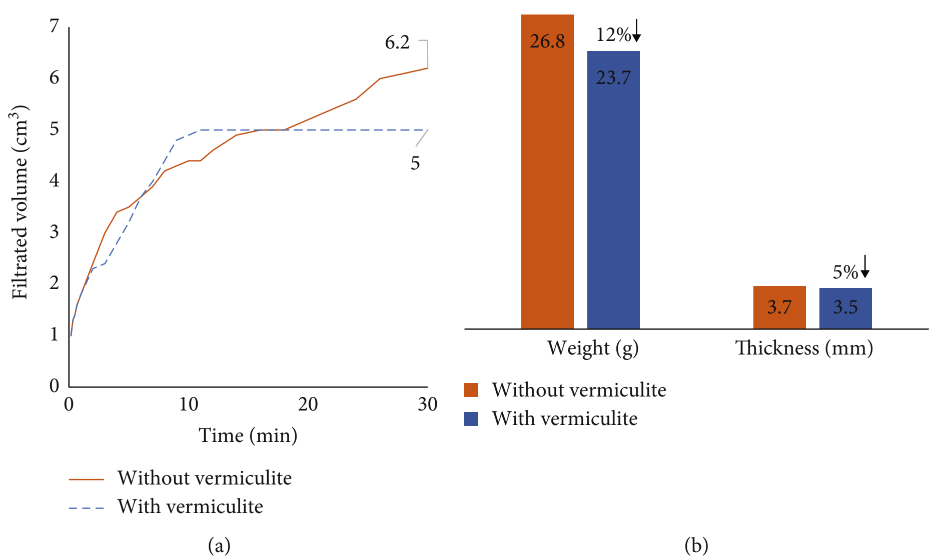

FIGURE 7: Effect of 5 lb/bbl vermiculite on (a) filtrated volume and (b) filter cake characteristics.

vermiculite as it resulted in higher storage and loss modulus. The fulfilled enhancement of viscoelastic properties indicated better suspension ability and fluid stability which supported the conclusions of sag and rheology tests.

3.4. Filtration Test. The high-temperature high-pressure filtration test showed a preferred filtration performance when adding 5 lb/bbl vermiculite compared to the base drilling fluid. The filtration volume was quickly stabilized and dropped by 19% from 6.2 to 5 cm^3 (Figure 7(a)), which indicated the fast plugging and contributed to reducing the solids invasion; hence reducing the formation damage. The characteristics of the composed filter cake (Figure 7(b)) showed a 12 and 5% reduction in weight and thickness that could help in minimizing the sticking potentiality and ease the removal process. The improved filtration performance with vermiculite is mainly caused by the characteristics of vermiculite particles and mud rheology enhancement.

3.5. Density and pH Measurements. The drilling fluid density did not change when adding 5 lb/bbl vermiculite because of its small quantity and low specific gravity of 2.4–2.7 g/cm^3. On the other hand, the pH was reduced from 11 to 9.7 with 5 lb/bbl vermiculite due to its low pH value (7.0–7.5) compared to the base drilling fluid. However, this resulted reduction was insignificant because the practical recommended pH range of drilling fluid is 9.0–11.0 and can be easily recovered by adding an alkalinity controller [34].

Comparing the attained results of this work with the previously provided solutions for the hematite sagging issue in the WBDF indicated the technical feasibility of the proposed vermiculite. In the literature, combined ilmenite/hematite and Micromax/hematite with ratios of 25/75 and 20/80%, respectively, were proposed for solving hematite settlement showing enhanced filtration characteristics and YP values, but with nonpreferred increment in PV values [20, 21]. Also, laponite was introduced as an anti-sag agent with similar behavior [11]. The increased PV value raises the equivalent circulating density (ECD), reduces the rate of penetration, increases friction, and requires additional pumping pressure [49]. This study showed that vermiculite was successfully added as an anti-sagging agent for effectively mitigating the hematite sag tendency for WBDF presenting enhanced drilling fluid stability and properties, as adding vermiculite increased the YP and significantly reduced the PV reflecting better hole cleaning and cutting suspension with improved filtration performance. Likewise, perlite, as an anti-sag agent provided competent mud performance [18].

In the end, further research is still required prior to field application trials to consider any change in drilling fluid formulation and to identify the corresponding optimum vermiculite content.

4. Conclusions

In this study, different amounts of vermiculite clay (3–6 lb/bbl) were examined to enhance the stability of hematite WBDF, and the influence on sagging tendency and drilling fluid properties were studied with the following outcomes:

(i) The high sagging tendency of hematite was mitigated when using 5 lb/bbl vermiculite as the sag factors under static and dynamic conditions were driven to the safe values

(ii) Adding 5 lb/bbl vermiculite resulted in better viscoelastic properties, lower PV by 24%, and higher YP by 9%, hence improved YP/PV ratio from 0.92 to 1.32. These improvements in rheology and viscoelasticity indicated better fluid stability

(iii) The recommended vermiculite content contributed to reducing the filtrated volume from 6.2 to 5 cm^3 and resulted in improved filter cake characteristics with less weight and thickness

(iv) The 5 lb/bbl vermiculite showed a trivial effect on drilling fluid density and alkalinity as the density did not change and the pH was slightly dropped to 9.7 but within the recommended alkalinity range

Data Availability

All the data are included in the main manuscript.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The authors would like to thank King Fahd University of Petroleum & Minerals (KFUPM) for employing its resources in conducting this work.

References

[1] H. Rabia, “Drilling fluids,” in *Well Engineering and Construction*, pp. 265–302, Entrac Consulting, London, 2002.

[2] A. Ahmed, A. Alsaihati, and S. Elkatatny, “An overview of the common water-based formulations used for drilling onshore gas wells in the Middle East,” *Arabian Journal for Science and Engineering*, vol. 46, no. 7, pp. 6867–6877, 2021.

[3] A. Saasen, D. Liu, and C. D. Marken, “Prediction of barite sag potential of drilling fluids From rheological measurements,” in *Proceedings of the SPE/IADC Drilling Conference*, Amsterdam, Netherlands, February 1995.

[4] M. Kruszewski and V. Wittig, “Review of failure modes in supercritical geothermal drilling projects,” *Geothermal Energy*, vol. 6, no. 1, p. 28, 2018.

[5] T. Reinsch, S. Regenspurg, E. Feldbusch et al., “Reverse cleanout in a geothermal well: analysis of a failed coiled-tubing operation,” *SPE Production & Operations*, vol. 30, no. 4, pp. 312–320, 2015.

[6] M. E. Hossain and A. A. Al-Majed, *Fundamentals of Sustainable Drilling Engineering*, Wiley-Scrivener, USA, 2015.

[7] A. Tehrani, A. Cliffe, M. H. Hodder et al., “Alternative drilling fluid weighting agents: a comprehensive study on ilmenite and hematite,” in *Proceedings of the IADC/SPE Drilling Conference and Exhibition*, pp. 4–6, Dallas, TX, USA, March 2014.

[8] W. Almutawa, A. Ahmed, S. Basfar, S. Elkatatny, S. Haidary, and P. Zitha, “Investigation of magnetite-based invert emulsion mud at high pressure high temperature,” *Arabian Journal of Geosciences*, vol. 14, no. 18, p. 14, 2021.

[9] J. Tovar, Z. Rodriguez, F. Quiroga et al., “An improved hematite for drilling fluids,” in *Proceedings of the SPE Latin America and Caribbean Petroleum Engineering Conference*, pp. 21–23, Caracas, April 1999.

[10] K. Rajendran, S. Sen, G. Suja, S. L. Senthil, and T. V. Kumar, “Evaluation of cytotoxicity of hematite nanoparticles in bacteria and human cell lines,” *Colloids and Surfaces B: Biointerfaces*, vol. 157, pp. 101–109, 2017.

[11] S. Basfar and S. Elkatatny, “Prevention of hematite settling using synthetic layered silicate while drilling high-pressure wells,” *Arabian Journal of Geosciences*, vol. 13, no. 12, p. 459, 2020.

[12] T. H. Omland, A. Saasen, C. Van Der Zwaag, and P. A. Amundsen, “The effect of weighting material sag on drilling operation efficiency,” in *Proceedings of the SPE Asia Pacific Oil & Gas Conference and Exhibition*, Jakarta, Indonesia, Oct. 2007.

[13] P. A. Bern, M. Zamora, K. S. Slater, and P. J. Hearn, “The influence of drilling variables on barite sag,” in *Proceedings of the SPE Annual Technical Conference and Exhibition*, Denver, Colorado, April 1996.

[14] T. H. Omland, A. Saasen, C. Van Der Zwaag, and P. A. T. Amundsen, “Using Taguchi and ANOVA methods to study the combined effects of drilling parameters on dynamic barite

sag," *Journal of Petroleum Science and Engineering*, vol. 121, pp. 126–133, 2014.

[15] P. D. Scott, M. Zamora, and C. Aldea, "Barite-sag management: challenges, strategies, opportunities," in *Proceedings of the IADC/SPE Drilling Conference*, Dallas, Texas, March 2004.

[16] D. Murray, M. W. Sanders, K. Houston, H. Hogg, and G. Wylie, "Case study - ECD management strategy solves lost circulation issues on complex salt Diapirs/Paleocene reservoir," in *Proceedings of the SPE Annual Technical Conference and Exhibition*, New Orleans, Louisiana, USA, September 2013.

[17] A. Ahmed, S. Basfar, S. Elkatatny, and R. Gajbhiye, "Enhancing hematite-based invert emulsion mud stability at high-pressure high-temperature wells," *ACS Omega*, vol. 5, no. 50, pp. 32689–32696, 2020.

[18] S. Basfar, J. al Jaberi, S. Elkatatny, and B. S. Bageri, "Prevention of hematite settling using perlite in water-based drilling fluid," *Journal of Petroleum Science and Engineering*, vol. 210, article 110030, 2022.

[19] A. Ahmed, S. Basfar, and S. Elkatatny, "Sagging prevention for hematite-based invert emulsion mud," *Journal of Energy Resources Technology*, vol. 144, no. 7, p. doi:10.1115/1.4052181, 2022.

[20] A. Ahmed, S. Basfar, T. I. Solling, and S. Elkatatny, "Prevention of hematite settling in water-based mud at high pressure and high temperature," *ACS Omega*, vol. 6, no. 36, pp. 23607–23613, 2021.

[21] S. Basfar, A. Ahmed, T. Solling, and S. Elkatatny, "Using manganese tetroxide for hematite settling prevention in water-based mud," *Arabian Journal for Science and Engineering*, vol. 47, no. 9, pp. 11579–11586, 2022.

[22] S. Basfar, A. Ahmed, and S. Elkatatny, "Ilmenite inclusion: a solution towards solid sagging for hematite-based invert emulsion mud," *Geofluids*, vol. 2022, Article ID 7438163, 9 pages, 2022.

[23] M. Sutcu, "Influence of expanded vermiculite on physical properties and thermal conductivity of clay bricks," *Ceramics International*, vol. 41, no. 2, pp. 2819–2827, 2015.

[24] H. Shirozu and S. W. Bailey, "Crystal structure of a two-layer mg-vermiculite," *American Mineralogist*, vol. 51, pp. 1124–1143, 1966.

[25] P. W. Harben, "Vermiculite," *The Industrial Minerals Handbook*, pp. 193–195, Industrial Minerals Information, Surrey, KT, ©2002, 1995.

[26] S. Hillier, E. M. M. Marwa, and C. M. Rice, "On the mechanism of exfoliation of 'vermiculite'," *Clay Minerals*, vol. 48, no. 4, pp. 563–582, 2013.

[27] B. Mukherjee, "The structure of vermiculite and some interstratifications," *Clay Minerals*, vol. 5, no. 29, pp. 194–202, 1963.

[28] W. A. Bassett, "The geology of vermiculite occurrences," *Clays and Clay Minerals*, vol. 10, no. 1, pp. 61–69, 1961.

[29] O. E. Kök, İ. Tanrıverdi, and Y. Erdoğan, "Usage of vermiculite as additive material in water-based drilling muds," *Natural and Engineering Sciences*, vol. 3, pp. 179–186, 2018.

[30] A. Ahmed, S. Basfar, S. Elkatatny, and B. Bageri, "Vermiculite for enhancement of barite stability in water-based mud at elevated temperature," *Powder Technology*, vol. 401, p. 117277, 2022.

[31] Z. AlAbdullatif, A. Al-Yami, V. Wagle, A. Bubshait, and A. Al-Safran, "Development of new kill fluids with minimum sagging problems for high pressure Jilh Formation in Saudi Arabia," in *Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference*, Abu Dhabi, UAE, November 2014.

[32] T. H. Omland, A. Saasen, and P. A. Amundsen, "Detection techniques determining weighting material sag in drilling fluid and relationship to rheology," *Annual Transactions of The Nordic Rheology Society*, vol. 15, p. 277, 2007.

[33] M. R. Amighi and K. Shahbazi, "Effective ways to avoid barite sag and technologies to predict sag in HPHT and deviated wells," in *Proceedings of the SPE Deep Gas Conference and Exhibition*, Manama, Bahrain, January 2010.

[34] J. Maxey, "Rheological analysis of static and dynamic sag in drilling fluids," *Annual Transactions-Nordic Rheology Society*, vol. 15, p. 181, 2007.

[35] C. Aldea, F. B. Growcock, L. J. Lee, J. E. Friedheim, and E. Van Oort, "Prevention of dynamic sag in deepwater invert emulsion fluids," in *Proceedings of the AADE National Drilling Conference*, Houston, Texas, March 2001.

[36] B. Bui, A. Saasen, J. Maxey et al., "Viscoelastic properties of oil-based drilling fluids," *Annual Transactions of The Nordic Rheology Society*, vol. 20, pp. 33–47, 2012.

[37] D. Power and M. Zamora, "Drilling fluid yield stress: measurement techniques for improved understanding of critical drilling fluid parameters," in *Proceedings of the AADE National Technical Conference and Exhibition*, Houston, Texas, USA, April 2003.

[38] T. Mezger, "Viscoelastic behavior," in *The Rheology Handbook*, pp. 108–121, Vincentz Network, Hannover, Germany, 2020.

[39] B. S. Bageri, A. R. Adebayo, J. Al Jaberi, and S. Patil, "Effect of perlite particles on the filtration properties of high-density barite weighted water-based drilling fluid," *Powder Technology*, vol. 360, pp. 1157–1166, 2020.

[40] R. F. O. Borges, B. F. Oechsler, B. R. Oliveira et al., "Reparameterization of static filtration model of aqueous-based drilling fluids for simultaneous estimation of compressible mudcake parameters," *Powder Technology*, vol. 386, pp. 120–135, 2021.

[41] H. Gudarzifar, S. Sabbaghi, A. Rezvani, and R. Saboori, "Experimental investigation of rheological & filtration properties and thermal conductivity of water-based drilling fluid enhanced," *Powder Technology*, vol. 368, pp. 323–341, 2020.

[42] P. Skalle, K. R. Backe, S. K. Lyomov, and J. Sveen, "Barite segregation in inclined boreholes," *Journal of Canadian Petroleum Technology*, vol. 38, no. 13, p. doi:10.2118/99-13-11, 1999.

[43] C. Jose Chirayil, J. Abraham, R. Kumar Mishra, S. C. George, and S. Thomas, "Instrumental techniques for the characterization of nanoparticles," in *Thermal and Rheological Measurement Techniques for Nanomaterials Characterization*, pp. 1–36, Elsevier, 2017.

[44] S. Perween, N. K. Thakur, M. Beg, S. Sharma, and A. Ranjan, "Enhancing the properties of water based drilling fluid using bismuth ferrite nanoparticles," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 561, pp. 165–177, 2019.

[45] A. R. Ismail, A. Aftab, Z. H. Ibupoto, and N. Zolkifile, "The novel approach for the enhancement of rheological properties of water- based drilling fluids by using multi-walled carbon nanotube, nanosilica and glass beads," *Journal of Petroleum Science and Engineering*, vol. 139, pp. 264–275, 2016.

[46] A. Katende, N. Boyou, I. Ismail et al., “Improving the performance of oil based mud and water based mud in a high temperature hole using nanosilica nanoparticles,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 577, pp. 645–673, 2019.

[47] G. V. Chilingarian, E. Alp, R. Caenn et al., “Drilling fluid evaluation using yield point-plastic viscosity correlation,” *Energy Sources*, vol. 8, no. 2-3, pp. 233–244, 1986.

[48] Z. Luo, L. Wang, J. Pei, P. Yu, and B. Xia, “A novel star-shaped copolymer as a rheology modifier in water-based drilling fluids,” *Journal of Petroleum Science and Engineering*, vol. 168, pp. 98–106, 2018.

[49] D. Carbajal, C. Burress, B. Shumway, and Y. Zhang, “Combining proven anti-sag technologies for HPHT North Sea applications: clay-free oil-based fluid and synthetic, sub-micron weight material,” in *Proceedings of the All Days*, Amsterdam, The Netherlands, March 2009.