Enhancement of Static and Dynamic Sag Performance of Water-Based Mud Using a Synthetic Clay

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ABSTRACT: Fluid homogeneity and stability are of high importance as they greatly affect the fluid performance in drilling operations. Solid settlement or solid sag is a severe issue that occurs in weighted drilling muds, especially at elevated temperatures, where the weight material tends to settle down causing well control problems. This study evaluates the effectiveness of a synthetic clay (laponite) to prevent the static and dynamic sag tendency of barite-weighted drilling fluid for elevated-temperature drilling applications. Several high-density mud samples were prepared by varying the concentration of the synthetic clay. The sag tendency of the fluid samples was evaluated in the lab using dynamic and static sag tests, and the optimal concentration was determined. The impact of synthetic clay on the density, pH, and rheological properties was also studied. Moreover, the filtration properties of the developed formulation were measured using high-pressure high-temperature filtration experiments. The synthetic clay was found to be effective in reducing the static and dynamic sag tendency of barite-weighted water-based drilling fluids. 0.75 lb/bbl of laponite was adequate to eliminate solid sag at a temperature up to 250 F. This amount of laponite slightly increased the plastic viscosity by 8%, while an increase of 42% and 43% were decreased by 15–20%. Additionally, the synthetic clay had an insignificant effect on the fluid density and pH.

1. INTRODUCTION

With the depletion of shallow oil and gas reservoirs, the urge to drill deep reservoirs has increased. The temperature of these deep formations may reach more than 300 F, adding more challenges to the drilling operations because the polymeric additives in the drilling fluid start to degrade at critical downhole conditions affecting the stability of the drilling fluids. The degradation of fluid stability at critical conditions leads to the separation of solid particles from the liquid phase of the drilling fluid in what is called solid sag or barite sag. This phenomenon takes place in vertical and inclined wells under dynamic and static conditions, causing variations in mud density along the well depth resulting in serious well control problems.

Several laboratory studies were conducted to analyze the sag tendency under static and dynamic conditions. Most of the methods depend on the density measurements to detect the solid particle distribution along the fluid column. This technique is performed using a different setup such as a sag cell, viscometer sag show test, and flow loops. Another method of barite sag detection relies on rheological and viscoelastic property measurements using different rheometers. These properties can be correlated with fluid stability to detect the solid sag phenomenon. Ultrasonic and nuclear magnetic resonance methods were also utilized to analyze the sag tendency of the drilling mud by detecting the density stratification using the sound velocity and the influence of the magnetic field, respectively. Ofei et al. also introduced another advancement in solid sag measurement using a cylindrical glass cell with the light scattering technique to characterize the homogeneity and settling speed of the solid particles in the drilling fluid.

Many techniques were introduced to enhance the thermal stability of the drilling mud and to mitigate the solid sag at high-temperature conditions, such as monitoring the rheological behavior of the mud and implementing good practices, adding rheology modifiers and/or antisagging agents to optimize the rheological properties, decreasing the particle size of the weighting material, and using combined weighting materials. All proposed formulations have some technical or economic limitations that require more research.
work to come up with an efficient and feasible solution to the barite sag phenomenon.

Optimizing the rheological properties of the drilling fluid by adding special additives is one of the successful techniques to improve the stability of the drilling fluids because rheological properties are one of the main factors that control barite sag. Several additives were proposed to maintain the rheological behavior of water-based fluids, such as viscosifiers, thinners, dispersants, and stability enhancers.20 Clays and polymers are added to increase the drilling fluid viscosity.30,31 However, these additives have some limitations. For instance, polymers degrade at high temperatures, affecting the drilling fluid viscosity, and flocculation of bentonite fluids was also observed at high temperatures.32

Laponite is a synthetic layered clay that has disk-shaped particles. The electrical double layers give laponite good dispersion and stability in water.1,33−35 The excellent properties of laponite make it a good candidate to improve the stability and rheological behavior of drilling fluids, particularly at elevated temperatures. Several studies were conducted to evaluate the thermal stability, rheology, and viscoelastic properties of laponite in water suspension. Huang et al.36 investigated the influence of laponite nanoparticles on the thermal stability of water-based mud using thermogravimetric analysis and viscosity measurements at different temperatures. They tested a synthesized polymer and a combination of laponite with the synthesized polymer. Adding laponite substantially increased the fluid viscosity at high temperatures and slowed the thermal degradation of the synthesized polymer. However, not much work on the chemical stability of laponite was conducted.35

Phuoc et al.32 studied the rheological behavior of a synthesized cation-exchanged laponite suspension in the presence of various metals. The cation-modified laponite was synthesized using a laser ablation technique. The aqueous suspension of the modified laponite showed a high viscosity and good shear thinning behavior. However, no mechanism was addressed, and because of the huge amount required for drilling applications, the use of the laser technique is economically impractical. Taghipour et al.37 studied the rheology of the drilling fluid with xanthan gum polymer and laponite using a flow loop setup and rheometers to tune a model drilling fluid and evaluate the impact of aging time on the drilling fluid rheology. Mourchid et al.37 investigated the viscoelastic and swelling properties of the laponite colloidal system to understand the gelation mechanism of laponite suspensions.

Huang et al.33 introduced another application for laponite nanoparticles to serve as a shale inhibitor. They found that laponite suspension is very effective in shale inhibition, with a different inhibition mechanism than other shale inhibitors. Liu et al.34 found that laponite suspension has the ability to plug the nanocracks in shale formations, preventing the water from penetrating deep inside the formation and thereby reducing shale swelling. Additionally, laponite mud formed a more compact filter cake compared to sodium-bentonite mud, making laponite a multifunctional additive for water-based muds.

Many of the previous studies focused on the thermal and chemical stabilities of laponite suspension by studying the rheological and viscoelastic properties at high-temperature conditions; however, no attention to the barite sag phenomenon was addressed. Therefore, this study evaluates the influence of laponite clay particles on the dynamic and static sag tendency in vertical and inclined wells at elevated temperatures. Moreover, the influence of laponite on the properties of drilling mud was investigated, such as density, pH, and rheological and filtration properties.

2. MATERIALS AND EXPERIMENTAL WORK

The drilling fluid was prepared in the laboratory by using water as a base fluid after treatment with sodium carbonate to maintain the calcium ion contamination. The pH of the drilling mud is maintained by adding potassium hydroxide. The viscosity of the mud is maintained by adding bentonite and xanthan gum polymer. Potassium chloride is added as a clay stabilizer, while polyacrylic cellulos (PAC-R) and starch are used as fluid loss control additives. Calcium carbonate is added as a bridging agent to help build the filter cake. The required fluid density is maintained by adding barite. A synthetic clay (laponite) is added to the drilling fluid in different concentrations as a stability enhancer.

2.1. Material Characterization. Barite and laponite were characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques to identify the mineral composition. Additionally, a particle size analyzer was used to measure the particle size distribution of both laponite and barite. The particle size distribution was measured because it has a great impact on the repulsion and attraction forces that influence the sagging phenomenon. Some studies, conducted on the impact of particle size on the solid particle settlement and cutting transport efficiency, confirmed the importance of particle shape and size in such phenomena.11,25,38

2.2. Fluid Preparation. A base fluid was prepared with a density of 14.8 ppg by mixing the essential drilling fluid additives using a variable-speed mud mixer. The mixing was done at ambient conditions, and the rotational speed was increased gradually from 10,000 to 17,000 rpm. First, sodium carbonate and potassium hydroxide were added to the base fluid (freshwater) to maintain the water hardness and pH, respectively. Then, bentonite and xanthan gum polymer were used to maintain the viscosity of the mud. Subsequently, the other drilling fluid additives were mixed with the mud formulation. Using the same procedure, two different mud samples were prepared using various concentrations (0.5 and 0.75 lb/bbl) of the synthetic clay. Laponite was added right after adding potassium hydroxide and mixed for 10 min. The used fluid formulation is described in Table 1.

2.3. Sag Tests. The effect of laponite on the drilling fluid stability was evaluated using static and dynamic sag tests. First, static sag test was performed at vertical and inclined conditions (45°) using static sag test apparatus.9 The test was run for 24 h at 250 F and 500 psi. The concept of sag test is to evaluate the

| Table 1. Used Mud Formulation (1.0 bbl of Mud) |
|----------------------------------------------|
| **additive** | **amount** |
| water | 0.7 bbl |
| sodium carbonate | 0.5 lb/bbl |
| potassium hydroxide | 0.5 lb/bbl |
| bentonite | 4 lb/bbl |
| xanthan gum polymer | 1.5 lb/bbl |
| potassium chloride | 20 lb/bbl |
| starch | 6 lb/bbl |
| PAC-R | 1 lb/bbl |
| calcium carbonate (25 micron) | 5 lb/bbl |
| barite | 350 lb/bbl |
| laponite | 0−0.75 lb/bbl |
homogeneity of the drilling mud by measuring the mud density at the top and bottom of the drilling fluid column after 24 h. The sag factor is introduced as an indicator of the fluid homogeneity along the drilling fluid column. The sag factor is calculated from the density of both top and bottom fluid samples using eq 1. For a stable and homogeneous fluid, sag factor should be ranging between 0.50 and 0.53, while particle settlement is anticipated when the sag factor is higher than 0.53.\(^\text{6,17}\)

\[
\text{sag factor} = \frac{\text{bottom density}}{\text{bottom density} + \text{top density}}
\]  

Second, the viscometer sag show test (VSST) was conducted to assess the dynamic sag tendency of the mud.\(^\text{8}\) The dynamic sag test is conducted at 120 F and atmospheric pressure. Two 10 mL samples are taken from the collection well, one at the beginning of the test and the other one after 30 min. Dynamic sag factor, VSST, is calculated by eq 2 using the weight of the fluid samples in grams, \(W_1\) and \(W_2\). The drilling fluid is considered stable when the VSST is equal to or less than 1, while a higher VSST value indicates an inhomogeneous and unstable drilling fluid.\(^\text{5}\) Table 2 summarizes the experimental conditions of the sag tests.

\[
\text{VSST} = 0.834(W_2 - W_1)
\]  

### Table 2. Experimental Conditions of the Sag Test

| parameter | dynamic sag | static sag |
|-----------|-------------|------------|
| temperature | 120 F | 250 F |
| pressure | atmospheric | 500 psi |
| time | 30 min | 24 h |
| inclination | 0 and 45° |

### 2.4. Rheology Measurement.

The impact of the synthetic clay on the mud rheology was investigated by measuring the rheological properties using a mud viscometer, model O~6~Fite 900. The measured properties are yield point (YP), plastic viscosity (PV), and gel strength. The PV and YPs were calculated using i and ii in the Appendix. Gel strength was measured after 10 s, 10 min, and 30 min using the direct reading at a rotational speed of 3 revolutions per minute (rpm). All measurements were conducted at 120 F and atmospheric pressure. Additionally, the fluid density and pH were measured at 80 F using a standardized mud balance and pH meter.

### 2.5. Filtration Experiments.

Filtration tests are conducted to study the influence of laponite on the filtration properties of the drilling mud. The tests were conducted at the same temperature of the static sag test, 250 F, with a differential pressure of 300 psi, and 10 μm ceramic filter discs were used as a filtration medium. The filtrate volume was collected over 30 min of filtration time, and the filter cake properties such as the filter cake weight and thickness were measured.

### 3. RESULTS AND DISCUSSION

#### 3.1. Material Characterization.

Barite and laponite samples were obtained from a local supplier. Barite was used in this study as a weighting agent, while laponite was used as an antisinging agent. Barite contained barium (75.1 wt %), sulfur (17.2 wt %), silicon (5.6 wt %), and very low concentrations of aluminum (2.1 wt %). Laponite clay mainly contained silicon (65.7 wt %), magnesium (31 wt %), and sodium (3.3 wt %)\(^\text{25}\) (Table 3. Figure 1 shows the XRD patterns of barite and laponite samples. The resulted XRD patterns matched the typical XRD patterns of barite and laponite available in the literature.\(^\text{39,40}\) The barite sample consists of 99.9 wt % barite with very small traces of impurities (0.1 wt %), while the laponite sample shows 100 wt % laponite. The particle size distribution of barite and laponite samples was obtained by a particle size analyzer. Barite powder revealed a normal distribution with a \(D_{50}\) of 2 μm, \(D_{10}\) of 17 μm, \(D_{90}\) of 30 μm, and \(D_{90}\) of 50 μm, while laponite showed smaller particle size with a \(D_{50}\) of 10 μm (Figure 2).

#### 3.2. Sag Tests.

Static sag tendency of the mud was measured at different concentrations of laponite under vertical and inclined conditions (Figure 3. The temperature was set at 250 F because, at this temperature, barite sag is likely to occur.\(^\text{26,29}\) The base fluid sample, without laponite, showed poor fluid stability at both inclination angles with a high sag factor (around 0.57). The sag factor exceeded the acceptable range, 0.50–0.53, according to the drilling practices, indicating a high tendency of barite sag.\(^\text{6,17}\) Laponite increased the drilling fluid stability by reducing the sag factor significantly. At 0.5 lb/bbl of laponite, the vertical and inclined sag factor decreased from 0.569 and 0.58 to 0.532 and 0.542, respectively, and these values are still above the acceptable value, while adding 0.75 lb/bbl brought the sag factor to the safe range with a sag factor of 0.502 and 0.51; therefore, less sag tendency is anticipated at that conditions. It was observed that the drilling fluid always performed better in vertical conditions than in inclined conditions because the inclination angle contributes significantly to the sagging phenomenon, and the critical range of inclination is between 30 and 60° as reported in previous studies.\(^\text{11,41}\) Similarly, the base fluid, without laponite, showed unfavorable sag tendency at dynamic conditions with a sag factor (VSST) of 2.3 (Figure 4. Adding 0.5 lb/bbl of laponite significantly improved the mud homogeneity and reduced the VSST to 1.54, which is still above the acceptable value (below 1).\(^\text{5,12}\) Increasing the concentration of laponite to 0.75 lb/bbl substantially reduced the VSST to...
0.17. This value is considered very low, and no solid settlement will be encountered with this concentration of laponite. The improvement in the dynamic and static sag tendency caused by adding laponite to the drilling mud can be attributed to the improvement in rheological properties that improved the suspension capability of the drilling fluid. Moreover, the

Figure 2. Particle size distribution of barite and laponite samples: (a) Histogram and (b) cumulative size distribution.

Figure 3. Effect of laponite concentration on the static sag tendency (250 F).

Figure 4. Effect of laponite concentration on the dynamic sag tendency (120 F).
electrostatic attractions and hydrogen bonding between xanthan gum polymer and laponite particles helped forming a strong bond that increases the thermal stability of the mud and slowed down the polymer degradation.13,34 This interaction also preserved the rheological properties of the mud, particularly the YP and gel strength, and mitigated the temperature effect. Laponite costs between 8 and 11 $/lb, and with the maximum concentration used (0.75 lb/bbl), adding laponite would increase the cost of the drilling fluid by 6–8.25 $/bbl. However, laponite is introduced as a solution to a common and serious problem with barite-weighted fluids that could cost a lot of money by increasing the nonproductive time and may cost lives in some severe cases when kicks occur. Therefore, solving this issue by adding little extra money to the drilling fluid cost would be technically and economically feasible.

3.3. Rheological Analysis. Figure 5 shows the influence of laponite concentration on the mud density and pH. Laponite had an unmeasurable influence on the fluid density because the added concentration was very low, and the density of the mud samples was 14.8 ppg. In contrast, a small increase (0.2) in the fluid pH was observed as the laponite concentration increased from 0 to 0.75 lb/bbl. This increase was because of the dissociation of hydroxide ions (OH\(^-\)) from the edges of laponite particles.35,44

The flow curve was constructed for the drilling mud samples using the measurements of the shear stress values at the corresponding shear rates (Figure 6). These measurements were obtained at 120 F using a drilling fluid viscometer. From the flow curves, the drilling fluid samples behave as non-Newtonian fluids. The rheology data was fitted using the common rheology models such as power law, Bingham plastic, Herschel–Bulkley, and Casson.31,45 These models are described in the Appendix.

Table 4 shows the rheology and fitting data for all mud samples, and the fitting curves are shown in the Appendix (Figures A1–A4). Casson model was the best model to represent the data with R-squared in the range of 0.996–0.999. As the concentration of laponite was increased, the consistency curve shifted upward, indicating higher values of the shear stress, while the slope of the curve remained almost constant; thus, no significant change in the PV will be noticed.36 Figure 7 shows the effect of laponite concentration on the PV and YP of the drilling fluid. The YP of the base mud increased from 33 lb/100 ft\(^2\) to 43 lb/100 ft\(^2\) and 48 lb/100 ft\(^2\) when the laponite concentration was increased to 0.5 and 0.75 lb/bbl, respectively. This increase in the YP indicates an enhancement in the mud capability to suspend solids, thereby improving the homogeneity of the drilling fluid throughout the drilling operation.13,46–48 Conversely, laponite had an insignificant influence on the PV, where the PV of all fluid samples was ranging between 33 and 38 cPa; consequently, no additional frictional pressure drop will result during fluid circulation.26 Furthermore, the increase in the YP without significantly increasing the PV helped maintain the YP to PV ratio (YP/PV) within a good range. YP/PV is an essential parameter in hole cleaning, and it can also be related to the fluid stability and sag performance (Figure 7).14,16

The base drilling fluid sample showed an initial gel strength of 19 lb/100 ft\(^2\) after 10 s, and then the gel strength increased to 47 lb/100 ft\(^2\) after 10 min before it decreased again to 45 lb/100 ft\(^2\) after 30 min of gel time. While the samples with 0.5 and 0.75 lb/bbl of laponite showed a continuous increase in the gel strength with time, the higher concentration of laponite yielded higher gel strength values (Figure 8). The increase in gel strength was induced by the electrostatic bonds between laponite particles and laponite and xanthan polymer particles, resulting in a stronger and quick gel structure.32,34 The gel structure helps suspend the weighting material and the drilled cuttings when the circulation is stopped.30,31,49 The high values of gel strength require more pumping pressure to start the flow; thus, if the pressure required to break the gel exceeds the maximum pump pressure, drilling fluid formulation should be optimized by...
diluting the mud or adding thiners to attain favorable rheology at such conditions.\textsuperscript{21}

3.4. Mechanisms of Enhancing Drilling Fluid Stability.

There are different methods in the literature used to mitigate the sag tendency of the drilling fluid such as reducing the particle size of the weight material,\textsuperscript{11,25} replacing the weighting agent with more stable alternatives or adding a combination of the weighting material,\textsuperscript{6,12,26--28} and optimizing the rheological properties of the drilling mud by introducing rheology modifiers or antisagging agents.\textsuperscript{8--10,22--24} The main mechanism for enhancing the drilling fluid stability in this study is the improvement of the rheological properties by adding the laponite additive. Rheological properties are the main properties responsible for suspending solid particles and drilled cuttings under dynamic and static conditions. Laponite is a synthetic nanosheet material that can easily hydrate and form a gel structure in aqueous solutions that can provide a good rheological performance.\textsuperscript{34} As confirmed by the rheological study, introducing laponite particles to the drilling fluid increased both the YP and gel strength by 43%, which in turn improved the suspension capability of the drilling fluid and significantly reduced the barite sag tendency. Additionally, laponite interaction with the xanthan polymer was another reason for maintaining the YP and gel strength and then eliminating the sag issue. There are two mechanisms by which laponite interacts with the polymer: electrostatic attraction and...
hydrogen bonding. These two mechanisms helped mitigate the temperature effect by improving the thermal resistance of the mud, slowing down the polymer degradation and preserving the rheological properties. This can also be achieved by adding bentonite clay to the drilling mud; however, these bonds are stronger with laponite due to the higher surface area of the laponite disc-shaped particles.33

### 3.5. Filtration Experiments.

The effect of laponite concentration on the filtration performance was studied using the high-pressure high-temperature (HPHT) filtration test.

![Filter cake at various concentrations of laponite.](image1)

**Table 4. Rheology and Fitting Data for the Mud Samples**

| Parameter          | laponite concentration |
|--------------------|------------------------|
|                    | 0 lb/bbl   | 0.5 lb/bbl | 0.75 lb/bbl |
| Dial readings      |            |            |             |
| \(\Theta_{100}\)   | 104.3      | 116.2      | 124.5       |
| \(\Theta_{200}\)   | 68.9       | 79.6       | 86.1        |
| \(\Theta_{300}\)   | 56.7       | 66.3       | 71.9        |
| \(\Theta_{400}\)   | 41.6       | 49.6       | 54.3        |
| \(\Theta_{500}\)   | 22         | 25.3       | 27.3        |
| \(\Theta_{600}\)   | 21         | 24.2       | 26.6        |
| R-squared           |            |            |             |
| Power law           | 0.9852     | 0.9524     | 0.9567      |
| Bingham plastic     | 0.9852     | 0.9734     | 0.9701      |
| Herschel–Bulkey     | 0.9938     | 0.9792     | 0.9966      |
| Casson              | 0.9962     | 0.9984     | 0.9986      |

**Figure A1.** Fitting data for power law model.

**Figure A2.** Fitting data for Bingham plastic model.

**Figure A3.** Fitting data for Herschel–Bulkey model.

**Figure A4.** Fitting data for Casson model.
4. SUMMARY AND CONCLUSIONS

An experimental study was performed to assess the effect of laponite clay on the static and dynamic sag tendency of water-based drilling fluid where barite is the weighting material. With the obtained results, the following is concluded:

1. The addition of laponite clay improved the fluid stability at elevated temperatures by reducing the static and dynamic sag. Only 0.75 lb/bbl of laponite was adequate to bring the sag factor to the safe zone; consequently, no solid settlement will be encountered at these conditions.

2. Adding 0.75 lb/bbl of the synthetic clay to the drilling fluid slightly increased the PV by 8% and significantly increased the YP by 42%, leading to an improvement in the ability of the drilling mud to suspend the solid particles which confirmed the sag test results. A high increase, 43–115%, in the gel strength values was observed; therefore, a thinner should be added with the synthetic clay to avoid the very high values of the gel strength.

3. Because the required concentration of synthetic clay was very low, no effect on the drilling fluid density was observed. Also, the synthetic clay slightly increased the pH of the drilling fluid because of the detachment of hydroxide ions from the edges of laponite particles. Moreover, laponite particles improved the filtration performance of the mud by reducing the total filtrate by 15% and the filter cake thickness by 20%, thus minimizing the formation damage induced by fluid invasion.

4. The proposed formulation can be used in drilling deep formations with minimal static and dynamic solid sag at elevated temperature up to 250 F. However, more research studies are required to optimize the concentration of laponite and other drilling fluid additives considering a wide range of concentrations, mud densities, barite types, other weighting materials, inclination angles, and drilling parameters to ensure optimum results in real field applications. Moreover, further studies should be performed to evaluate the effectiveness of laponite at higher temperatures to be used for HPHT drilling applications.

APPENDIX

\[ PV = \theta_{300} - \theta_{600} \]  

(i)

\[ YP = \theta_{300} - PV \]  

(ii)

Bingham plastic model

\[ \tau = \tau_0 + \mu(\gamma) \]  

(iii)

Casson model

\[ \sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu_p\gamma} \]  

(iv)

Herschel–Bulkley model

\[ \tau = \tau_0 + K\gamma^n \]  

(v)

Power law model (Figures A1–A4)

\[ \tau = Kn \]  

(vi)

NOMENCLATURE

PV and \( \mu_p \)  plastic viscosity, cPa

YP yield point, lb/100 ft²

K consistency

n flow index

\( \theta_{300} \)  dial reading at 600 rpm

\( \theta_{300} \)  dial reading at 300 rpm

\( \theta_{200} \)  dial reading at 200 rpm

\( \theta_{100} \)  dial reading at 100 rpm

\( \theta_{6} \)  dial reading at 6 rpm

\( \theta_{3} \)  dial reading at 3 rpm

\( \tau \)  shear stress

\( \tau_0 \)  yield stress

\( \mu \)  viscosity

\( \gamma \)  shear rate

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