Enhancing Hematite-Based Invert Emulsion Mud Stability at High-Pressure High-Temperature Wells

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ABSTRACT: Drilling fluids have a crucial continued role in drilling a successful well; however, most of the drilling technical and operational challenges are incorporated with the drilling mud stability and properties. The solid particles settling in drilling mud that deteriorates its stability is a common issue encountered in high-pressure high-temperature (HPHT) conditions. This issue, known as solids sagging, may eventually result in stuck pipes, wellbore instability, and loss of circulation. The objective of this work is to introduce garamite to enhance the stability of hematite-based invert emulsion mud under HPHT situations. The used garamite and hematite weighting material were analyzed using X-ray fluorescence, scanning electron microscopy, and particle size distribution to identify their compositions, morphologies, and particle sizes. The effects of adding different concentrations of garamite (0.5, 1.0, 1.25, and 1.5 g) to the field formula of hematite-based invert emulsion mud were investigated. The mud density, stability, sagging tendency, rheology, viscoelasticity, and filtration properties were studied to formulate a stabilized and distinguished-performance drilling mud. The obtained results indicated that garamite did not change the mud density while enhancing the emulsion stability by increasing the electrical stability proportionally with the added garamite quantity. The sagging experiments showed that adding 1.25 g of garamite is sufficient to prevent the sagging problem in both static and dynamic conditions as it was enough to enforce the sag parameters into the safe range of sag performance indicators. This 1.25 g of garamite improved the yield point by 152% from 19 to 48 lb./100 ft² with a slight increase in plastic viscosity from 14 cP for base mud to 18 cP and significant increase in the gelling strength and viscoelastic properties. Adding 1.25 g of garamite showed a slight enhancement in the filtration properties as the filtrate volume was reduced by 8% from 3.7 to 3.4 cm³ and the filter cake thickness has 16% reduction from 2.69 to 2.26 mm. As a result, a mud with distinguished performance, in terms of rheology, suspension, sag performance, and stability, was obtained. Hence, a basis for safely drilling the HPHT formations was delivered, which reduces the drilling cost by minimizing the nonproductive time.

1. INTRODUCTION

Drilling fluids are the main part of drilling oil and gas wells and have a crucial continued role in successful drilling operations. They contain solids and polymers to perform a variety of important functions at once. The weighting agents are the solid additives functioned to raise the drilling fluid density to maintain the fluid hydrostatic column and control the formation pressure.

The most popular weighting agent is barite since it is eco-friendly and has high specific gravity ([4.2−4.48 g/cm³]). However, barite has serious associated concerns such as the increment in the equivalent circulation density (ECD), removal issues especially in oil-based mud (OBM), and excessive torque. Besides, the increased demand, high global consumption, and reserve reduction led to the price hike and shortage of supply. Therefore, alternatives such as calcite, manganese tetraoxide, ilmenite, and hematite become desirable to be used as weighting agents with different ranges of densities.

The crystal-structure hematite (Fe₂O₃) with a specific gravity of 4.7 g/cm³ has been practically applied with some
benefits such as enhancing the rate of penetration, reducing the effect of weighting agents on rheological properties, and lowering the need of high solids content.19–22 The higher abrasiveness of hematite can be avoided by optimizing its particle size with less than 45 μm.18,23 However, in high-pressure high-temperature conditions, where higher density mud is required to suppress the formation pressure,24 the settling rate of solids is increased.18

The solid particles settling is a common issue encountered in high-pressure high-temperature (HPHT) conditions where downhole temperature is greater than 300 °F in both vertical and deviated wells and known as solids sag.25–27 This sagging issue is affected by the drilling fluid properties such as the low viscosity, fragile gel strength, low linear viscoelastic, solid particles characteristics, and drilling parameters, and it may eventually result in wellbore instability, stuck pipes, and loss of circulation due to the wide variation in mud properties.28–39 The sagging issue becomes more serious at an inclination angle above 30°, and the maximum sagging was observed to occur in the range of 45 to 60° wellbore inclination.28,40

To minimize/avoid the solids sagging issue, many solutions has been proposed and investigated in both oil- and water-based muds either by optimizing mud rheology using sag resistance materials and rheology modifiers,27,41–44 micronizing the weighting materials,15,24,45,46 or using a combination of different weighting materials.36,38,39,47–50 The use of micronized additives has shown successful applications in HPHT conditions, particularly in water-based mud, with satisfying performance in terms of rheology, lubricity, shale stabilization, and filtration properties.51–56

Garamite (organophilic phyllosilicate), besides its uses in coatings and cleaning, has been known and applied as a rheology modifier and suspension agent with nonaqueous drilling fluids. Its specific gravity [1.5–1.7 g/cm³], stability at high temperature, adhesiveness, and particle characteristics make its ability to reduce the solids sagging issue when used with barite.43

This work aims to study and analyze the effect of adding garamite to the hematite-based invert emulsion mud. The effects of this inclusion on sagging tendency, stability, rheological, viscoelastic, and filtration properties were studied to formulate a stabilized and distinguished-performance drilling mud.

2. MATERIALS

Five invert emulsion mud samples were prepared using a multimixer in ambient conditions. In these formulations, diesel and water were used as external and internal phases, respectively, with an 83:17 diesel-to-water ratio. Hematite was used as the weighting material. The key drilling fluid additives were described in Table 1 with their sequences, quantities, functions, and mixing times. Different concentrations of garamite [0, 0.5, 1.0, 1.25, and 1.5 g] were used to formulate the five mud recipes. The formulation without garamite is considered as a base mud.

Both hematite and garamite used in this study were characterized to understand the sagging behavior and their elemental compositions and morphologies by particle size distribution (PSD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM).

The PSD in Figure 1 shows that the average particle size (D₅₀) of hematite is 16.86 and that of garamite is 19.4 μm. The small used particle size helps in avoiding equipment erosion as hematite is highly abrasive at particle sizes greater than 45 μm.18,23

XRF figured out the elemental composition for hematite that contains mainly 95.84% iron, while the main components of garamite are 58.85% silicon, 24.85% magnesium, and small traces of chlorine, calcium, potassium, and iron, as shown in Figure 2.

The SEM images indicated that hematite has heterogeneous crystal-structure particles, which increases its abrasiveness and sagging tendency while garamite has slightly uniform particles with smooth edges, which makes it easy to be incorporated with less abrasiveness (Figure 3).

3. EXPERIMENTAL WORK

Figure 4 illustrates the methodology and experiments conducted in this work to formulate a stabilized and distinguished-performance drilling fluid.

3.1. Density and Electrical Stability Tests. After preparing the mud formulations (blank, 0.5, 1.0, 1.25, and 1.5 lb./bbl garamite), the densities and electrical stabilities were measured in ambient conditions using a mud balance and electrical stability tester, respectively.

3.2. Sagging Tests. The effect of garamite on sag tendency was investigated in both static and dynamic conditions to determine its optimal concentration for settling prevention. The static sagging test was conducted by subjecting the mud in an aging cell to 500 psi pressure and 350 °F temperature at vertical and 45° inclined positions for 24 h.18 Then, the

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Table 1. Drilling Fluid Formulation in Field Units (1 bbl of Mud)

| additive | unit | quantity | function | mixing time, min |
|----------|------|----------|----------|-----------------|
| diesel   | bbl  | 0.491    | continuous phase |                |
| Invermul | ppb  | 11       | primary emulsifier | 10              |
| lime     | ppb  | 6        | alkalinity control | 10              |
| Duratone | ppb  | 7        | fluid loss control | 10              |
| water    | bbl  | 0.143    | dispersed phase | 10              |
| CaCl₂    | ppb  | 32       | shale stabilization | 10              |
| Geltone II | ppb | 10       | viscosifier | 20              |
| EZ-Mul   | ppb  | 4        | secondary emulsifier | 10              |
| garamite | ppb  | 0/0.5/1.0/1.25/1.5 | antisagging material | 10 |
| CaCO₃    | ppb  | 30       | bridging material | 10              |
| hematite | ppb  | 300      | weighting material | 20              |
weights of 10 cm³ of the fluids from the upper and lower parts of the cell were measured to calculate the sag factor as follows:

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

(1)

The dynamic sag test was conducted at atmospheric pressure and 150 °F using a viscometer to yield 100 rpm rotation, and then the viscometer sag shoe test (VSST) value was quantified as follows:

\[ \text{VSST} = 0.834 \times (W_{\text{after}} - W_{\text{before}}) \]  

(2)

where \( W_{\text{before}} \) and \( W_{\text{after}} \) are the weights of 10 cm³ of the two fluid samples obtained from the cup bottom before and after 100 rpm rotation for 30 min, using the viscometer.

3.3. Rheology Tests. The rheological properties were obtained at 350 °F with an Anton-Paar rheometer. The plastic viscosity (PV), yield point (YP), and gelling strength after 10 s, 10 min, and 30 min were determined to investigate the influence of the recommended addition amount of garamite on the mud rheology compared with the base mud in the mentioned conditions.

3.4. Oscillatory Amplitude and Frequency Tests. The Anton-Paar rheometer was also used to perform the oscillatory amplitude and frequency tests at 150 °F to study the effects of adding the recommended amount of garamite on storage and loss moduli (\( G' \) and \( G'' \)). The amplitude test was performed at a fixed frequency of 10 rad/s and range of shear strains from 0.01 to 100%, and the region of linear viscoelastic and stability was determined therefrom. Meanwhile, the frequency test was conducted at fixed shear strain, from within the identified range of linear viscoelasticities, and several frequencies to obtain \( G' \) and \( G'' \).

3.5. HPHT Filtration Tests. Finally, the filtration performance was studied under static conditions for the recommended addition amount of garamite compared with the base hematite-blank mud formula. The filtration tests were conducted at 500 psi differential pressure and 350 °F using a 10 μm ceramic filtration disc as the filtration medium. The filtration volume was listed with respect to time for 30 min, and then the formed filter cake thickness was recognized.

4. RESULTS AND DISCUSSION

4.1. Density and Electrical Stability Tests. Adding garamite to the base hematite-weighted mud has no influence on the density, as it stays at 15.1 ppg, because the garamite powder density is 0.12 g/cm³ and its amount is very small compared to the used hematite amount. On the other hand, adding garamite enhances the emulsion stability of the mud since the electrical stability is increased proportionally with the added garamite quantity, reaching up to 670 V at 1.5 g of garamite compared to 415 V for the base hematite-blank mud. This is due to the lower garamite conductivity. Meanwhile, the practically acceptable value of electrical stability is 500 V.

4.2. Sagging Tests. The influence of garamite on sagging tendency was evaluated in both static and dynamic conditions.
The static sag factors in both vertical and inclined conditions for the base hematite-blank mud were 0.54 and 0.56, respectively, indicating a high sagging tendency and issue of solids settling. Practically, the recommended safe range of sag factors in vertical and inclined conditions is 0.50−0.53,25 which is achieved significantly by adding 1.25 g of garamite to be 0.506 and 0.509, respectively, while there is no additional evident improvement with 1.5 g of garamite, as shown in Figure 6.

The dynamic sag test showed the benefits of adding garamite as the VSST reduced from 1.3 ppg at the base hematite-blank mud to be within the safe recommended VSST value, which is less than 1.0 ppg,57 with an amount of 1.0 g and more of garamite, as depicted in Figure 7.

This encountered improvement on sagging performance is mainly due to the less abrasiveness and high dispersion of garamite besides its ability to produce formulations with high viscosity in the low shear range, which results in outstanding antisagging and antisyneresis properties.

From the sag performance tests, an amount of 1.25 g of garamite is sufficient and recommended to reduce the solids settling tendency to the acceptable range under the mentioned conditions.

4.3. Rheological and Viscoelastic Property Analyses.

The drilling fluid rheology was examined to study the effect of adding 1.25 g of garamite, recommended by the sagging tests, and compare with the base mud. Figure 8 confirms that adding 1.25 g of garamite produces higher shear stress and viscosity in the low shear range, which results in better sag, gelling, and suspension performance.

Figure 9a shows that at 350 °F, the plastic viscosity was slightly increased from 14 cP for base mud to 18 cP when adding 1.25 g of garamite. Meanwhile, the yield point increased
significantly from 19 to 48 lb./100 ft² for base mud and 1.25 g of garamite, respectively, because of the high garamite dispersion. Accordingly, the YP/PV ratio raised from 1.34 to 2.71 with a 102% increment that indicates much better stability performance, surge and swap pressures, equivalent circulating density, and hole cleaning and prevents the accumulation of cuttings while drilling highly deviated wells.\(^1\)\(^{-}\)\(^6\)\(^1\) Moreover, the high viscosity at a low shear rate of garamite enhances the suspension ability and gelling strength, as shown in Figure 9b where the gelling strengths at 10 s, 10 min, and 30 min were increased from 16, 14, and 13 lb./100 ft² for base mud to 25, 23, and 22 lb./100 ft² with 1.25 g of garamite, respectively, with an average 60% increment.

The oscillatory amplitude test (Figure 10a) showed that adding 1.25 g of garamite always increases both storage (\(G'_\)) and loss moduli (\(G''\)) and results in higher \(G'_\) than \(G''\) in the linear viscoelastic region that limited to 0.1% shear strain indicating a solid-like behavior and resistance to sagging. Moreover, the frequency sweep test described that the mud will be deformed viscoelastically without breakage on the internal structure, which exhibits elasticity behavior, as depicted in Figure 10b. The evaluation of these viscoelastic properties pointed out the enhancement on sag performance.
and mud stability after adding the recommended 1.25 g of garamite.

4.4. HPHT Filtration Tests. The filtration test results indicated that adding 1.25 g of garamite slightly enhanced the filtration properties. The filter cake thickness has 16% reduction from 2.69 to 2.26 mm, and the filtration volume after 30 min was reduced by 8% from 3.7 to 3.4 cm³, as depicted in Figures 11 and 12.

5. SUMMARY AND CONCLUSIONS
A worthy laboratory work was performed to investigate the effect of adding garamite on sagging tendency and key properties of hematite-based invert emulsion mud in HPHT conditions and to determine the optimum required concentration of garamite. Based on the obtained outcomes, the following can be concluded:

(a) Addition of garamite has no influence on the mud density, while the emulsion stability was enhanced proportionally with the amount of garamite because of its lower conductivity.

(b) Inclusion of garamite improved the drilling fluid stability by effectively minimizing the sag tendency in both static and dynamic conditions because of its key characteristics, such as low abrasiveness, high dispersion, and its ability to produce high viscosity at a low-shear rate.

(c) An amount of 1.25 g of garamite was sufficient since it was enough to enforce the sag factor and the VSST values to the safe range of sag performance.

(d) Adding this recommended amount of garamite enhanced the rheological properties as it significantly improved the suspension capability by increasing the yield point by 152%, confirming its uses as a rheology modifier and sagging resistant.

(e) The significant observed enhancement on the YP/PV ratio by 102% fulfills much better hole cleaning performance.

(f) 1.25 g of garamite increased the gel strength and viscoelastic properties indicating better suspension and sag performance.

(g) Adding 1.25 g of garamite reduced the filtration volume by 8% to 3.4 cm³, and the filter cake thickness has 16% reduction from 2.69 to 2.26 mm.

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Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The authors would like to thank King Fahd University of Petroleum and Minerals (KFUPM) for employing its resources in conducting this work. An acknowledgment is also due to BYK Company for providing the garamite material. In memory of Dr. Hisham Nasr-El-Din, my Ph.D. advisor who taught me how to write strong technical papers.

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