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Article

Evaluating the Effect of Claytone-EM on the Performance of Oil-Based Drilling Fluids

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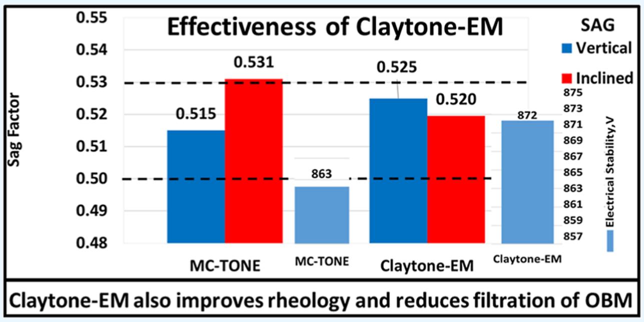
ABSTRACT: This study provides a detailed characterization and evaluation of Claytone-EM as a rheological additive to enhance the performance of oil-based drilling fluids (OBDFs) under high-pressure, high-temperature (HPHT) conditions. It also offers a comparative evaluation of the effectiveness of Claytone-EM with an existing organoclay, analyzing their mineral and chemical compositions, morphologies, and particle sizes. A series of experiments are performed to evaluate Claytone-EM's influence on crucial drilling mud properties, such as mud density, electrical stability, sagging tendency, rheology, viscoelastic properties, and filtration properties, to formulate a stable and high-performing OBDF. Results indicated that Claytone-EM had no significant impact on mud density but remarkably enhanced emulsion stability. Claytone-EM effectively mitigated sagging issues under both static and dynamic conditions, leading to improvements in the plastic viscosity (PV), yield point (YP), apparent viscosity (AV), and YP/PV ratio. The PV, YP, AV, and YP/PV ratios were improved by 11, 85, 28, and 66% increments, respectively, compared with those of the drilling fluid formulated with MC-TONE. The addition of Claytone-EM resulted in enhancing gel strength and improving the filtration properties of the drilling fluid. The filtration volume was reduced by 2% from 5.0 to 4.9 cm^3, and the filter cake thickness had a 13% reduction from 2.60 to 2.26 mm. These findings highlight Claytone-EM as a valuable additive for enhancing OBDF performance, particularly under challenging HPHT conditions. Its ability to provide emulsion stability, reduce static and dynamic sag, and control filtration holds the potential to enhance drilling operations, minimize downtime, and bolster wellbore stability. This study acknowledges certain limitations, including its temperature range, which could benefit from exploration at extreme temperatures. Additionally, the absence of flow experiments limits a comprehensive understanding of sag effects, and further research and field-scale evaluations are recommended to validate and optimize the application of Claytone-EM in OBDFs.



1. INTRODUCTION

Drilling fluids, also known as drilling muds, are critical components in drilling operations for oil and gas extraction. These fluids perform various functions that involve cooling and lubricating the drill bit, carrying the cuttings to the surface, controlling formation pressures, and maintaining wellbore stability.[1−6] Drilling fluids can be classified into three main types: water-based, oil-based, and synthetic-based, each with unique properties and applications.[7−9]

Oil-based drilling fluids (OBDFs) present various advantages in certain drilling applications when compared with water-based drilling fluids (WBDFs). OBDFs exhibit superior thermal stability in comparison to that of WBDFs, making them suitable for high-temperature drilling operations.[10] This stability ensures that OBDFs can sustain their rheological and filtration properties even under extreme temperature conditions, thereby ensuring efficient drilling and wellbore stability.[11,12] Moreover, OBDFs offer enhanced lubrication to the drill string, drill bit, and other downhole components compared to that of WBDFs.[13] This enhanced lubrication reduces friction, thereby resulting in reduced rates of equipment wear, decreased torque and drag, and ultimately, extended equipment lifespan and lowered costs.[14] Additionally, OBDFs exhibit lower reactivity with shale formations due to their reduced water content and wettability properties.[15] This reduced reactivity aids in the prevention of shale swelling, dispersion, or sloughing, which can give rise to wellbore instability and other drilling-related problems.[16]

The efficiency, safety, and success of drilling operations are heavily influenced by the properties of the drilling fluid.[17] These properties can be broadly classified into rheological properties, physical properties, and chemical properties.[8,13]

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Table 1. Summary of Recent Studies on the Application of OCs in OBDFs

objective	OC type	findings	reference
Studied the influence of the viscosity modifier and concentration on the rheological properties of OBDFs.	B34 and B128	The nature and concentration of the OC strongly influenced the viscous flow behavior of OBDFs.	42
Studied the effect of the OC concentration (1 and 3 wt %) and aqueous phase volume fraction on the rheology of organo-montmorillonite (OMMT) in invert-emulsion OBDFs.	Bentone 128	(1) At low concentrations of OC, the yield stress varied linearly; on the other hand, at high OC concentrations, the yield stress varied according to a power law model. (2) Increasing the OC concentration led to an increase in viscosity.	41
Studied the rheological properties and thermal stabilities of OBDFs using organo-palygorskite (OPAL) modified with cationic and nonionic surfactants.	Praepagen WB (cationic surfactant), Ultramina T50, and Ultramina TA20 (nonionic surfactants)	OPAL can be used as an additive to OBDFs due to its enhanced thermal stability and better rheological properties when compared with those of dispersions prepared with olefin at a high temperature (150 °C).	22
Investigated the effects of three different OCs, namely, organo-sepiolite (OSEP), organo-hectorite (OHEC), and OMMT, on the rheological properties of OBDFs at high temperatures.	Dioctadecyldimethylammonium chloride (DODMAC)	The study found that the OHEC particle-stabilized invert emulsion fluid provides better rheological properties than those of the other two OCs at high temperatures.	43
Investigated the effect of using modified Tunisian clay with different cationic surfactant concentrations on the rheological properties of OBDFs.	OC modified with a cationic surfactant.	(1) The rheological properties of the suspensions were influenced by the concentration of the surfactant used. As the surfactant concentration increased, the yield stress and consistency concentration increased. The best behavior was observed for the 3.0 CEC concentration. (2) The OC sample at 10 wt % showed the highest Herschel−Bulkley parameters, indicating that it could be used as a viscosity enhancer in OBDFs.	24
Studied the rheological behavior and microstructure of OBDFs using organo-bentonite (OBEN), specifically focusing on the effect of the surfactant type, amount of OBEN, temperature, and pressure.	Hexadecyltrimethylammonium (HDTMA-MMT) and PM199.	OBENs with a paraffin-type surfactant arrangement, like PM199, showed potential as control additives for OBDFs under high temperatures and pressures due to their ease of particle dispersion.	25
Studied the impact of the VG69 OC on the rheological properties of gasoil-based drilling fluids, specifically focusing on the yield stress, viscosity, viscoelasticity, thixotropic properties, and stability of the drilling fluids.	VG69	(1) The addition of the V69 OC increased yield stress, viscosity at an infinite shear rate, and viscoelastic and thixotropic properties of the gasoil-based drilling fluids. (2) The addition of 3g of V69 OC increases yield stress by 230%, enhances viscosity at an infinite shear rate by 3.4%, and improves mud stability by 70%.	23
Evaluated the effect of Claytone-EM on the performance of OBDFs and compared it with a pre-existing OC.	Claytone-EM	Claytone-EM enhances emulsion stability, prevents sagging, and improves the rheological and filtration properties of OBDFs under HPHT conditions.	this study

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Regular testing and analysis of these properties, along with appropriate adjustments to the composition or treatment of the fluid, are vital aspects of drilling fluid management. The selection and utilization of drilling fluid additives are determined by various factors, such as the type of formation being drilled, the drilling depth, and environmental regulations.[18] These additives are viscosifiers, fluid loss control agents, weighting agents, thinners, and lost circulation materials.[19] By properly selecting and using additives, it is possible to optimize drilling fluid performance and minimize the risk of formation damage and other problems during drilling operations.[20,21]

Organoclays (OCs) are used as additives to control the rheological properties and enhance the performance of drilling fluids, particularly in OBDFs and synthetic-based drilling fluids (SBDFs), due to their ability to adsorb and stabilize oil droplets and other nonpolar substances within the fluid.[22−25]

Clay minerals have favorable rheological properties and are used to increase the viscosity and stability of aqueous dispersions by forming a gel-like structure at low solid contents.[26] In recent years, the use of OCs, which result from the reaction of smectite clay and amine cation groups,[27,28] has received interest due to their notable physicochemical properties in oil media.[29−31] OCs are formed naturally by modifying clay materials with organic ammonium salts such as alkyl ammonium cations and are widely used in industrial applications as rheology modifiers, such as grease and cosmetics, as well as in the preparation of OBDFs.[32] Since OCs have been synthesized from naturally abundant clay minerals, they are relatively low-cost viscosifiers to manufacture. The modification process involves replacing the cationic particles on the surface of the clay with an organic compound, typically quaternary ammonium compounds.[32,33] The properties of the OC suspensions depend on the interactions between the organophilic ions and the solvent, the type of the exchanged ion, and the chemical characteristics of the solvent.[29,34,35] As a result, OCs possess unique properties that make them highly suitable for utilization in OBDFs.[28] One of the major advantages of OCs is their ability to increase viscosity and suspension properties while maintaining low shear rates, thereby preventing cuttings from settling within the wellbore and improving hole stability. Additionally, OCs offer benefits such as improved filtration control and rheological stability, which enhance overall efficiency during the drilling operation.[36−38] OCs are used as additives to control the rheological properties and enhance the performance of drilling fluids, particularly in OBDFs and SBDFs, due to their ability to adsorb and stabilize oil droplets and other nonpolar substances within the fluid.[24,37,39−42] The search for new OCs with favorable properties for use in OBDFs is an area of active research. Table 1 provides a comparative overview of the focus and findings of the current study with other relevant research on the application of OCs in OBDFs.

Claytone-EM is a high-efficiency rheological additive suitable for use in ODBFs and SBDFs to increase the carrying capacity and hole cleaning capabilities. It is a chemically modified smectite clay derived from bentonite that has been treated with a quaternary ammonium compound through ion exchange. The specific gravity of Claytone-EM is 1.6 g/cm^3, and it has a bulk density of 23 lb/ft^3. This product is supplied by the BYK company in the form of a free-flowing powder. This modification enhances the clay's affinity for nonpolar organic compounds and improves its rheological properties.

Claytone-EM is an organophilic phyllosilicate. Phyllosilicates, commonly known as sheet silicates, are a group of minerals that are characterized by their sheet-like structure, consisting of tetrahedral and octahedral layers.[44] Organophilic phyllosilicates are a subset of these minerals that have been modified to have an affinity for organic molecules. This modification is typically achieved through an ion exchange process where inorganic cations (such as Na^+, K^+, or Ca^{2+}) in the mineral structure are replaced with organic cations (such as quaternary ammonium ions).[45,46] The resulting organophilic phyllosilicates exhibit a range of chemical and physical properties, including hydrophobicity, swelling capacity, thermal stability, thixotropy, and high surface area.[5,11] In the oil and gas industry, organophilic phyllosilicates are used as additives in drilling muds. Their ability to swell in organic liquids helps seal the walls of boreholes, control the viscosity of drilling fluids, and facilitate the removal of drill cuttings from the well.[5,11]

From an environmental perspective, Claytone-EM offers benefits such as improved filtration control and rheological stability, which enhance the overall efficiency during drilling operations. It contributes to the reduction of fluid loss, aiding in the prevention of potential damage to the formation and ensuring the stability of the wellbore. Additionally, Claytone-EM is effective in stabilizing reactive clays and shales, which can mitigate wellbore instability issues, such as fluid loss and differential sticking. These properties align with environmentally friendly practices by minimizing their impact on the surrounding geological formations and ecosystems.

The cost-effectiveness of Claytone-EM as an additive for OBDFs is evident from its ability to positively influence critical drilling mud properties, such as emulsion stability, sagging prevention, rheology, gel strength (GS), and filtration properties. The application of Claytone-EM demonstrated notable enhancements in these characteristics. These improvements contribute to more efficient drilling operations, reduced downtime, and enhanced wellbore stability. Furthermore, the use of Claytone-EM as a rheological additive has the potential to minimize the need for additional treatments or additives, leading to cost savings in drilling operations.

The objectives of this study are to evaluate the impact of Claytone-EM on the rheological and filtration properties of OBDFs under high-pressure, high-temperature (HPHT) conditions. This study aims to compare the performance of Claytone-EM with that of an existing OC (MC-TONE) and assess its potential to enhance the suspension, gelling, and filtration capabilities of OBDFs. Mud properties, including mud density, electrical stability, sagging tendency, rheology, viscoelasticity, and filtration, were analyzed to develop a stable and high-performing formulation. Results show that the introduction of Claytone-EM enhances emulsion stability, prevents sagging under static and dynamic conditions, and improves plastic viscosity (PV), yield point (YP), apparent viscosity (AV), YP/PV ratio, GS, and filtration properties. Additionally, this study seeks to analyze the mineral and chemical compositions, morphologies, and particle sizes of the OCs to understand their impact on drilling fluid rheology and filtration performance. The ultimate goal is to optimize the performance of OBDFs and contribute to the efficiency, stability, and cost-effectiveness of drilling operations.

This study provides a detailed characterization and evaluation of Claytone-EM as a rheological additive to enhance the performance of OBDFs under HPHT conditions. It also offers a comparative evaluation of the effectiveness of

Claytone-EM with an existing OC, analyzing their mineral and chemical compositions, morphologies, and particle sizes. The impact of the introduction of Claytone-EM on various mud characteristics, including emulsion stability, sagging tendency, rheology, viscoelastic properties, and filtration properties, is evaluated through a series of experiments.

By effectively preventing sagging issues and improving the rheological properties of OBDFs, Claytone-EM can contribute to safer drilling operations with reduced risks of wellbore instability and drilling-related problems. Moreover, the enhanced performance of Claytone-EM in terms of stability, suspension, and flow properties can lead to more efficient drilling operations, reducing downtime, and improving overall productivity.

This study presents clear and quantifiable results, demonstrating the impact of Claytone-EM on mud density, emulsion stability, sagging issues, rheological properties, GS, and filtration properties. Furthermore, the use of Claytone-EM as a rheological additive can potentially reduce the need for additional additives or treatments, resulting in cost savings for drilling operations.

2. MATERIALS AND EXPERIMENTS

2.1. Materials. Two invert emulsion samples were prepared by using a practical field formulation at ambient conditions using a Hamilton Beach mixer. Table 2 highlights the mud formulation, describing the sequence, amounts, mixing duration, and functional roles of each component. The mixing was done under ambient conditions, and the rotational speed was 10,000 rpm. In these mud samples, the continuous phase was diesel, and the internal phase was water. Also, other functional additives were mixed to control the viscosity, alkalinity, fluid losses, shale swelling, and filter cake formulation. The additives used to prepare these mud recipes were obtained from a drilling fluid service provider, while the diesel was obtained from a local gas station.

Table 2. Mud Formulation Used in This Study

additive	quantity (ppb)	mixing time (mins)	function
diesel	154.46		continuous phase
primary emulsifier (carboxylic acid-terminated fatty polyamide)	8	10	emulsion stabilization
secondary emulsifier (carboxylic acid-terminated fatty polyamide)	6	5	enhance emulsion stability
lime	6	5	alkalinity control
$CaCl_2$ brine (25% weight)	65.53	15	dispersed phase/shale stabilization
organophilic clay	7	10	viscosifier
organophilic lignite	8	10	fluid loss control
barite	377	10	weighting material

2.2. Experimental Work. The following procedure was performed in order to evaluate the effect of using Claytone-EM on the drilling fluid properties:

1. Preparing the drilling fluid mixture at ambient temperature.
2. Measuring the density and electrical stability at ambient temperature.
3. Performing the static sag test at 275 °F and 500 psi differential pressure under vertical and inclined (45°) conditions.
4. Performing the dynamic sag test using the sag shoe and the rheometer at 150 °F and 100 rpm.
5. Performing the amplitude sweep test at 275 °F and 500 psi differential pressure to determine the linear elastic region of the fluid.
6. Performing the angular frequency test at 275 °F and 500 psi differential pressure to determine the storage modulus of the invert emulsion drilling fluid.
7. Performing the time sweep test at 275 °F and 500 psi differential pressure to determine the fluid's viscosity changes over time and assess its thixotropic behavior.
8. Measuring the rheological properties at 275 °F and 500 psi differential pressure.
9. Measuring the filtration properties at 275 °F and 500 psi differential pressure.

2.3. Material Characterization. The two OCs used in this study were characterized using particle size distribution (PSD), X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) to understand their mineral compositions, elemental compositions, and morphologies.

2.4. Density and Electrical Stability. The mud density and emulsion stability of the two samples prepared were measured using the mud balance and electrical stability tester at ambient conditions. The effect of the Claytone-EM OC on the stability of the mud is evaluated. The recommended value for the electrical stability is >400 V.[47]

2.5. Sagging Tests. *2.5.1. Static Sagging Tests.* The static sagging test is used to evaluate the tendency of a drilling fluid to settle or sag when subjected to minimal or no movement. This test provides insights into the stability and structural properties of the drilling fluid, particularly its ability to suspend solids and prevent settling over time.[48,49] The static test was carried out at vertical and 45° slanted positions by applying a pressure of 500 psi and a temperature of 275 °F on the drilling mud that was then aged in a cell for 24 h. Nitrogen gas was used to apply a pressure of 500 psi to prevent fluid vaporization. The weights of 10 cm^3 of the fluids from the upper and bottom parts of the aging cell were measured to calculate the sag factor using eq 1. The recommended sag factor is 0.50−0.53.[50]

$$SF = \frac{\rho_{bottom}}{\rho_{bottom} + \rho_{top}} \quad (1)$$

2.5.2. Dynamic Sagging Tests. Dynamic sagging tests are used to evaluate the rheological properties of drilling fluids under dynamic conditions, simulating the fluid's behavior while being circulated through the wellbore during drilling operations.[51] The viscometer was used to provide a rotation of 100 rpm for 30 min at atmospheric pressure and 150 °F to determine the dynamic sagging magnitude. The dynamic sagging value was determined by calculating the viscometer sag shoe test (VSST) value using eq 2. The recommended VSST value is 0−1.[52]

$$VSST = 0.833 \times (W_2 - W_1) \quad (2)$$

where W_1 is the weight of 10 cm^3 at time zero and W_2 is the weight of 10 cm^3 after 30 min.

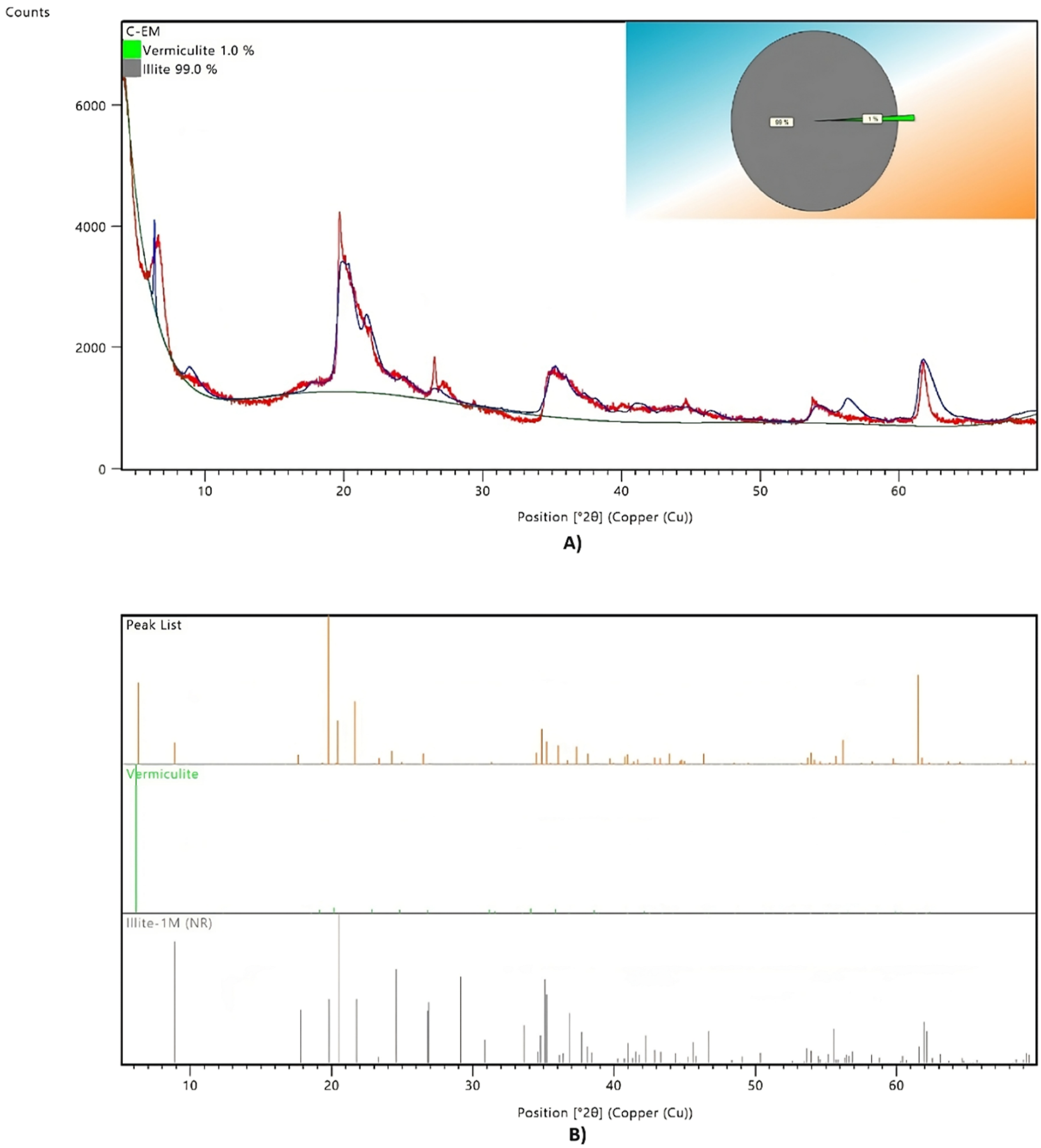

Figure 1. (A) XRD pattern and (B) plot of the identified phases of Claytone-EM.

2.6. Amplitude, Frequency, and Time Sweep Tests.

2.6.1. Amplitude Sweep Tests. An amplitude sweep test involves subjecting the drilling fluid to a range of shear amplitudes while maintaining a constant frequency. An Anton Paar rheometer was used to conduct oscillatory amplitude, frequency, and time sweep tests. The resulting data help determine the fluid's viscoelastic behavior (storage modulus G' and loss modulus G''). This test can provide insights into the fluid's ability to suspend solids and resist sagging or settling under different stress levels. This test evaluates the linear viscoelastic region (LVE) of the drilling fluid by varying the applied shear strain while maintaining a constant frequency. The LVE is the range in which the fluid exhibits a linear relationship between the applied stress and the resulting strain. Oscillatory amplitude tests were conducted to study the effect of using the Claytone-EM OC on the storage modulus G' and loss modulus G''. The amplitude sweep test was carried out at a fixed frequency equal to 10 rad/s, while the shear stress was varied.

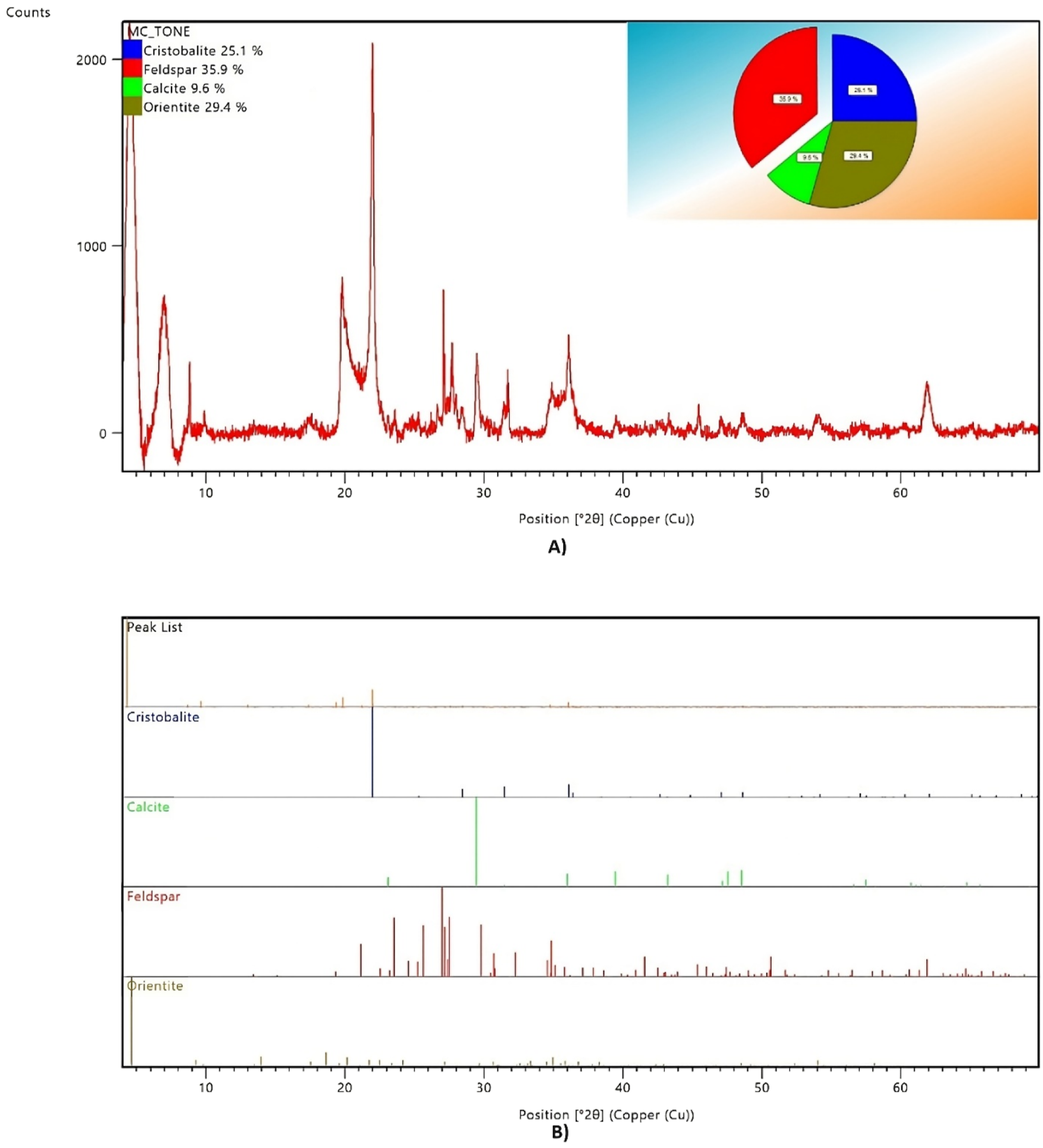

Figure 2. (A) XRD pattern and (B) plot of the identified phases of MC-TONE.

2.6.2. Frequency Sweep Tests. In a frequency sweep test, the drilling fluid is subjected to a range of shear frequencies while maintaining a constant shear stress or shear rate. This test measures the fluid's response to different shear frequencies and provides information about its viscoelastic behavior at varying rates of deformation. The data obtained from this test help characterize the fluid's dynamic behavior, such as its ability to maintain suspension and prevent sagging or settling under different drilling conditions. For the frequency sweep test, the angular frequency was varied, while the strain value was kept constant.

2.6.3. Time Sweep Tests. A time sweep test involves subjecting the drilling fluid to a constant shear stress or strain for a specific time. The test measures the fluid's viscosity changes over time and assesses its thixotropic property, which is the ability of the fluid to recover its viscosity after being subjected to shear. This test helps evaluate the fluid's stability, GS, and ability to suspend solids during drilling operations. The rheometer will record the fluid's viscoelastic properties,

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Table 3. XRF Analysis Results for the OCs Used in This Study

sample ID/chemical composition (%)	Mg	Al	Si	Fe	Cl	K	Ca
Claytone-EM	11.61	34.51	52.64	1.24			
MC-TONE		14.67	53.67	11.09	11.84	1.65	7.08

such as storage modulus G' and G'', at regular time intervals during the test for 60 min.

2.6.4. Rheology Tests. Rheology tests are performed to measure the flow and deformation behavior of drilling fluids. The rheological properties of OBDFs are crucial for their performance. The rheological properties were measured at 500 psi differential pressure and 275 °F by using a rheometer. The PV, YP, and AV were measured using a Grace viscometer (model M3600) to evaluate the effect of the Claytone-EM OC on the drilling fluid rheology and compare it with that of the base drilling fluid. GS was estimated directly from the dial reading at 3 rpm after different time periods (i.e., 10 s, 10 min, and 30 min). The following formulas were implemented to estimate the PV, YP, and AV

$$PV = \varnothing_{600} - \varnothing_{300} \quad (3)$$

$$YP = \varnothing_{300} - PV \quad (4)$$

$$AV = \frac{\varnothing_{600}}{2} \quad (5)$$

2.7. Filtration Tests. Filtration tests are performed to evaluate the fluid's ability to control fluid loss and the formation of a filter cake on the wellbore wall. HPHT filtration tests are conducted under elevated temperature and pressure conditions to simulate harsh downhole environments. The filtration tests were conducted at 500 psi differential pressure and 275 °F using an Ofite HPHT fluid loss tester and filter paper as the filtration medium. Digital Vernier calipers measured the filter cake thickness. The filtrate volume was measured as a function of time for 30 min, and the thickness and weight of the filter cake were recorded.

3. RESULTS AND DISCUSSION

3.1. Material Characterization. Figure 1 shows the XRD pattern and the plot of the identified phases of Claytone-EM. The results show that illite-IM (NR) with 99% predominates in the Claytone-EM mineral composition with 1% vermiculite. Figure 2 shows the XRD pattern and plot of the identified phases of MC-TONE. MC-TONE is composed of 35.9% feldspar, 29.4% orientite, 25.1% cristobalite, and 9.6% calcite. XRF results showed that Claytone-EM has 52.64% silicon, 34.51% aluminum, 11.61% magnesium, and 1.24% iron, while the components of MC-TONE are 53.67% silicon, 14.67% aluminum, 11.84% chlorine, 11.09% iron, 7.08% calcium, and 1.65% potassium, as shown in Table 3.

The PSD indicated that the average particle size (D_{50}) of Claytone-EM is 17.95 μm compared to 40.01 μm for the base OC MC-TONE, as shown in Figure 3. The smaller PSD of Claytone-EM improves dispersion and the overall stability of the drilling fluid system.

SEM images of Claytone-EM and MC-TONE are shown in Figure 4. SEM images of Claytone-EM unveil the presence of plate-like particles possessing a stacked structure. These particles appear as thin, flat plates with irregular edges. Additionally, it is common to observe a collection of small, irregularly shaped particles with a relatively smooth surface texture. The particles appear to be loosely packed together, forming a porous structure with many small voids and channels. This porous structure is due to the irregular shape of the particles and the way they pack together. Furthermore, the particles emerge as distinct platelets or stacks that are connected by several interactional mechanisms such as ion–dipole interaction, hydrogen bonds, acid–base reactions, charge transfer, electrostatic interaction, and van der Waals forces.[32,53,54] Moreover, the homogeneity and small size distribution apparent in SEM images imply that Claytone-EM is suitably dispersed within nonpolar fluids such as OBDFs. In comparison to Claytone-EM, MC-TONE shows heightened irregularity and more defined particle edges, thereby escalating its tendency to sag.

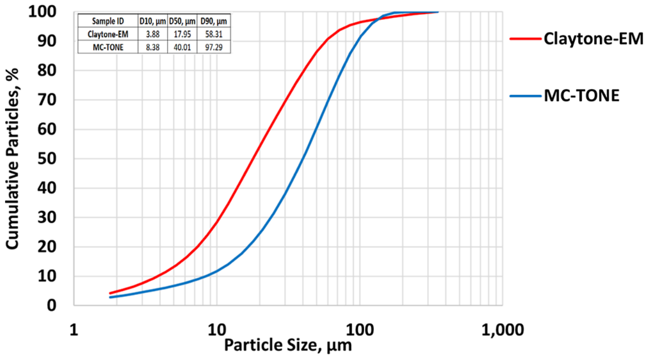

Figure 3. PSD for Claytone-EM and MC-TONE.

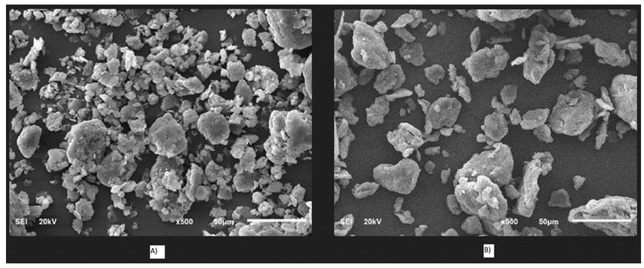

Figure 4. SEM images of (A) Claytone-EM and (B) MC-TONE.

3.2. Density and Electrical Stability. The results showed that using Claytone-EM does not affect the mud density as it stays at 15.0 ppg. Figure 5 shows that Claytone-EM slightly

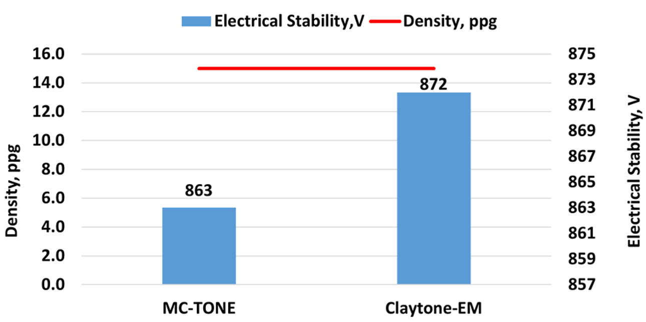

Figure 5. Effect of Claytone-EM on mud density and electrical stability.

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enhanced the electrical stability of the invert emulsion with a 1% increment to 872 V compared to 863 V for the mud prepared using the base OC. This can be attributed to the particle size of Claytone-EM, which is relatively small and possesses a high surface area.[55] Claytone-EM has been chemically modified with organic compounds that create a hydrophobic layer on the surface of the clay particles. This layer acts as an insulator, reducing the electrical conductivity of the drilling fluid. By inhibiting clay hydration, Claytone-EM helps maintain the electrical stability of the drilling fluid.[1,56] In addition, Claytone-EM can reduce the affinity of water droplets for the solid surfaces present in the fluid system. This reduction in water wetting can help minimize the contact between water and conductive solids, thereby reducing the potential for electrical conductivity and stability issues.[57−59] Also, Claytone-EM can form a stable network within the drilling fluid. This helps maintain the suspension and dispersion of solid particles, preventing their settling and aggregation. This will contribute to electrical stability by minimizing the formation of conductive pathways in the fluid.[14,48] Moreover, Claytone-EM helps prevent coalescence and the destabilization of water droplets, thereby maintaining the stability of the emulsion. This stabilization effect indirectly contributes to the electrical stability of the drilling fluid by reducing the potential for phase separation and minimizing changes in electrical properties.[60−62]

3.3. Sagging Tests. *3.3.1. Static Sagging Tests.* Figure 6 shows the vertical and inclined conditions' sag factors for the base OC fluid and Claytone-EM OC fluid. Results show that Claytone-EM increased the vertical static sag factor to 0.525 compared to 0.515 in the base fluid, but this increase is still within the acceptable range. Furthermore, the inclined sag factor decreased greatly from 0.531 in the base fluid case, which is higher than the recommended safe range of 0.50−0.53,[50] to 0.520. Claytone-EM is effective in preventing static sag due to its ability to serve as a rheology modifier and its impact on the suspension stability of the fluid system. It possesses thixotropic properties, allowing for reversible changes in viscosity under shear stress. The organophilic nature of Claytone-EM allows it to interact with the oil phase, forming a barrier that inhibits the settling of solids. This reduction in the settling rate helps maintain the suspension of solids during static conditions, thereby minimizing sagging in the drilling fluid. When the drilling fluid is in circulation, the shear forces reduce its viscosity, enabling easy flow and pumping. However, during static periods, the removal of shear forces causes the fluid to regain its higher viscosity, thus preventing the settling of particles.[50] This effect can be particularly beneficial in applications where prolonged static conditions are encountered, such as during well shut-ins or long periods of inactivity. Additionally, Claytone-EM contributes to the yield stress of the fluid system, which determines the minimum stress required to initiate the flow. A higher yield stress enhances the fluid system's ability to withstand the gravitational force acting on the suspended particles, thereby preventing static sag and maintaining a stable suspension. Moreover, the interaction between Claytone-EM particles and the other components in the fluid system can affect the overall suspension stability. These particles can create a network structure within the fluid, providing support and stability to the suspended particles and preventing their settling or separation. Furthermore, Claytone-EM can adsorb onto the surfaces of suspended particles, leading to changes in their surface properties and improving the overall stability of the suspension. The adsorption of these particles can hinder aggregation and settling, thus contributing to the prevention of static sag.

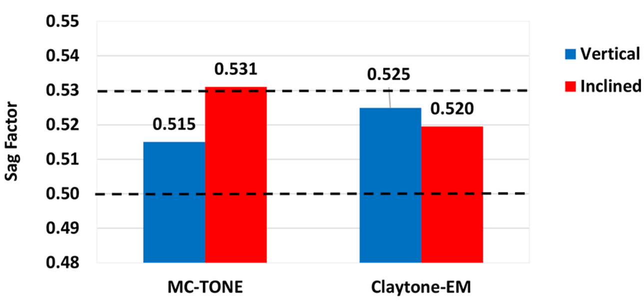

Figure 6. Sag factors under static conditions.

3.3.1.1. Dynamic Sagging Tests. Figure 7 shows the VSST sag factors for both OCs. The results show a reduction in the VSST value from 0.869 to 0.667 ppg. Claytone-EM can help improve the suspension properties of the drilling fluid by effectively dispersing and suspending solid particles such as weighting agents and cuttings. This prevents the settling or sagging of solids under high shear or dynamic conditions. Incorporating Claytone-EM into the drilling fluid helps enhance the suspension and stability of solid particles under dynamic conditions. The organophilic nature of Claytone-EM allows it to interact with the oil phase, forming a three-dimensional network that resists settling and maintains the particles in a suspension. The OC interacts with the solid particles and forms a network that impedes their settling. This effect is particularly significant under dynamic conditions where fluid movement tends to promote particle settling. By reducing the settling rate and sedimentation, Claytone-EM contributes to improved stability and reduced sagging in the drilling fluid during dynamic operations. Also, Claytone-EM can contribute to the yield stress of the fluid system, which is the minimum stress required to initiate flow. A higher yield stress helps the fluid system resist the component of gravitational force acting during dynamic motion more effectively, preventing dynamic sag and maintaining a stable suspension. In addition, Claytone-EM can enhance the stability of the oil−water emulsion, ensuring that the fluid remains homogeneous even under high shear conditions. This stability helps prevent the sagging and settling of the oil and water phases. In dynamic applications, Claytone-EM can increase the viscosity and GS of the drilling fluid, providing better resistance to sagging. The clay particles form a three-dimensional network structure that helps maintain the fluid's integrity and prevents sagging. Moreover, adsorption can help

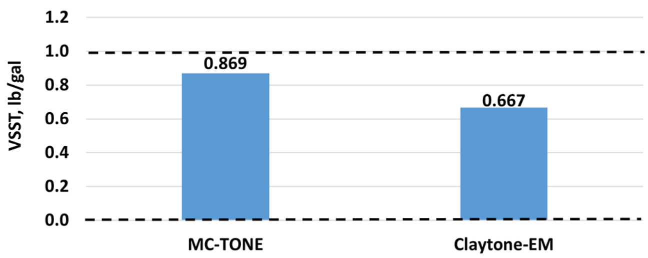

Figure 7. Sag factors under dynamic conditions.

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prevent the aggregation and settling of particles in dynamic applications, contributing to the prevention of dynamic sag. Furthermore, it allows the fluid to flow and level out easily during application and then rapidly increase in viscosity when subjected to dynamic forces, preventing the sagging or settling of particles due to its positive effect on the thixotropic behavior of the fluid. Furthermore, Claytone-EM exhibits shear-thinning behavior, meaning that the fluid's viscosity decreases under shear stress. This property allows the drilling fluid to flow easily during circulation, reducing the likelihood of sagging and improving the overall fluid performance. Lastly, Claytone-EM helps prevent the formation of gels or flocculation in OBDFs. Gels and flocculated particles can contribute to sagging and hinder fluid flow. Claytone-EM acts as a stabilizer, preventing the interaction between solid particles and other components of the fluid that leads to gelation or flocculation. This stabilizing effect helps maintain the fluid's integrity and reduces sagging tendencies during dynamic conditions.

3.4. Amplitude, Frequency, and Time Sweep Tests.

3.4.1. Amplitude Sweep Tests. The oscillatory amplitude test showed that Claytone-EM results in a small increase for both G' and G'' in the LVE region that is limited to 0.1% shear strain compared to the base OC fluid, as shown in Figure 8.

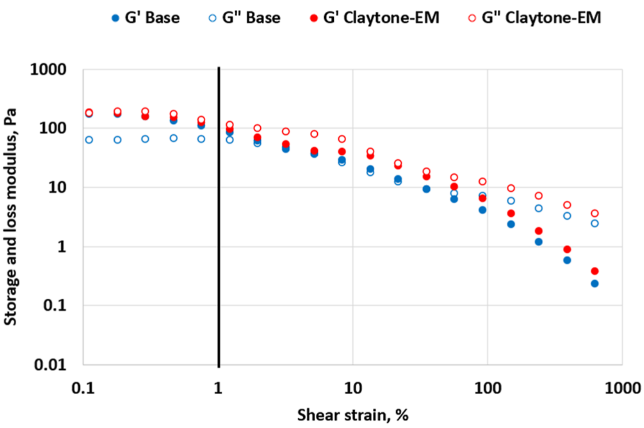

Figure 8. Amplitude oscillatory test results.

This results in better elasticity, sag resistance, and a solid-like behavior. Adding Claytone-EM can enhance the yield stress of the drilling fluid, making it more resistant to flow under high shear conditions. This effect is beneficial in preventing fluid loss and maintaining wellbore stability. Also, Claytone-EM can increase the elastic or solid-like behavior of a formulation, which is reflected in a higher G' value. This can be beneficial in applications where good sag resistance, thixotropic behavior, or suspension properties are desired. Furthermore, the presence of Claytone-EM can also affect the viscous or liquid-like behavior of a formulation, as shown by changes in the G'' value. An increased G'' value can lead to better leveling or flow control in specific applications. Moreover, the addition of Claytone-EM can enhance the overall viscoelastic properties of a formulation. This can lead to improved performance in terms of flow control, stability, and resistance to deformation. In addition, incorporating Claytone-EM into a formulation can result in increased complex viscosity, indicating higher resistance to flow under oscillatory shear. This can be beneficial for applications that require shear-thinning behavior or improved sag resistance. Furthermore, Claytone-EM can promote thixotropy in OBDFs, allowing them to regain viscosity after experiencing shear. This property is crucial for the effective suspension of cuttings during drilling operations. Lastly, Claytone-EM can modulate the viscosity of OBDFs during the amplitude sweep test. As the shear amplitude increases, the viscosity of the fluid may change. Claytone-EM can help maintain a consistent viscosity across a range of shear amplitudes, thereby stabilizing the fluid's rheological properties during the test.

3.4.2. Frequency Sweep Tests. The results of the oscillatory frequency sweep tests are shown in Figure 9. When Claytone-EM is added to a drilling fluid, it has been shown to enhance both G' and G'', indicating improved elasticity and viscous behavior. This means that at varying frequencies, the fluid will maintain its desirable flow properties without experiencing sagging or settling. This effect is particularly important in mitigating wellbore instability issues, such as fluid loss and differential sticking. Furthermore, Claytone-EM improves suspension properties within drilling fluids by preventing solids from settling out and causing issues such as blockages or pump wear. Also, Claytone-EM increases the material's storage modulus and improves its mechanical strength, which could be beneficial for applications that require high stiffness or resistance to deformation. Moreover, Claytone-EM also increases the material's viscosity and reduces its flowability, which could be beneficial for applications that require high thixotropy or sag resistance. The addition of Claytone-EM can improve the stability of a formulation by increasing its yield stress and resistance to deformation. In a frequency sweep test, this can be observed as an increase in G' at low frequencies, indicating enhanced elastic or solid-like behavior. In addition, Claytone-EM can impart shear-thinning behavior to OBDFs during the frequency sweep test. Shear thinning refers to the reduction in viscosity as the shear rate or frequency increases. Claytone-EM helps reduce the fluid's viscosity at higher shear rates or frequencies, facilitating easier flow and improved pumpability. This shear-thinning behavior allows the fluid to maintain good suspension properties for solid particles while ensuring efficient circulation and transportation. Moreover, Claytone-EM can enhance the stability of OBDFs during the frequency sweep test. It helps maintain the fluid's rheological properties, such as viscosity and elasticity, over a range of frequencies. This stability ensures consistent fluid behavior and performance in response to varying shear rates or frequencies encountered during drilling operations. Claytone-EM's ability to resist frequency changes contributes to the overall stability and reliability of the drilling fluid system. Lastly, the addition

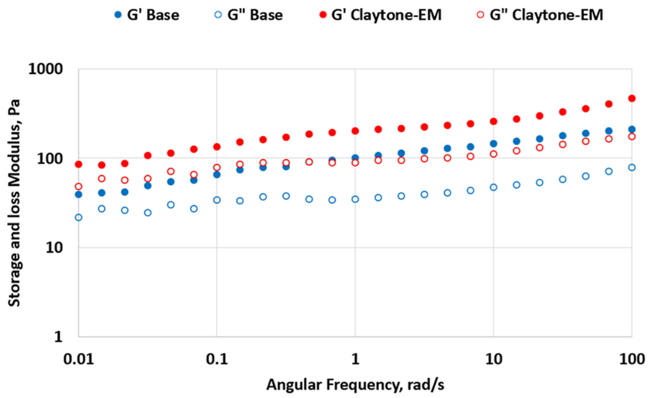

Figure 9. Frequency oscillatory test results.

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of Claytone-EM can influence the frequency dependency of the drilling fluid's rheological properties. Different frequencies can affect the fluid's response, including viscosity, elasticity, and phase angle, which measure the relationship between the applied stress and strain. Claytone-EM can modify the fluid's frequency-dependent behavior, allowing it to exhibit more stable viscoelastic properties across a range of frequencies during the frequency sweep test.

3.4.3. Time Sweep Tests. The results of the time sweep tests are shown in Figure 10. Claytone-EM increases the G' of the material, indicating improved solid-like behavior and resistance to deformation. The change in G'' over time may provide insights into the material's viscosity and liquid-like behavior. Furthermore, the addition of Claytone-EM also affects the G'' of the material. Moreover, Claytone-EM enhances the thixotropic behavior of a formulation, allowing it to thin under shear stress and recover its initial viscosity once the stress is removed. This property can be observed through the recovery of G' and G'' after a change in applied stress, demonstrating the material's ability to regain its structure over time. Claytone-EM can influence the behavior of the drilling fluid during a time sweep test. It can contribute to the formation of a stable gel structure, improving suspension properties and maintaining fluid stability over time. In addition, Claytone-EM can contribute to the long-term stability of OBDFs by preventing the settling and sagging of solids. This effect ensures consistent fluid performance over extended periods. Also, Claytone-EM can contribute to the stability of viscosity and elasticity in OBDFs during the time sweep test. The OC forms a network within the fluid, which helps maintain the rheological properties over time. This stability is particularly important in drilling operations as it ensures consistent fluid behavior and performance throughout the duration of the operation. Furthermore, Claytone-EM can help reduce the changes in viscosity and elasticity of OBDFs over time. The addition of Claytone-EM improves the resistance of the fluid to shear and deformation, resulting in minimal variations in rheological properties. This reduction in viscosity and elasticity changes allows for better control of the fluid's behavior and performance during drilling operations. Lastly, Claytone-EM can impart shear-thinning behavior to OBDFs during the time sweep test. Shear thinning refers to the reduction in viscosity as the shear rate increases. Claytone-EM helps reduce the fluid's viscosity at higher shear rates, allowing for easier flow and improved pumpability. This shear-thinning behavior aids in the circulation and transportation of the fluid while maintaining good suspension properties for solid particles.

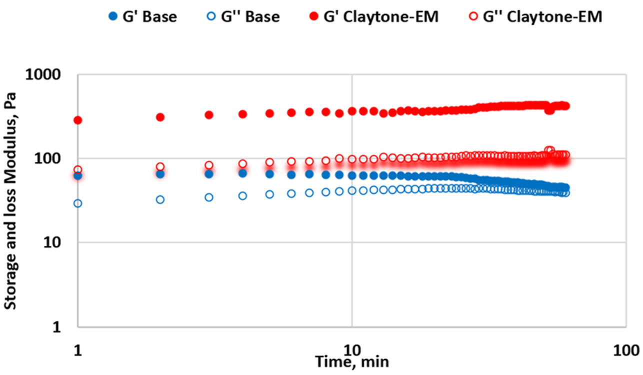

Figure 10. Time oscillatory test results.

3.4.4. Rheology Tests. The effect of Claytone-EM on drilling fluid rheology was assessed and compared with that of the base mud. Figure 11 confirms that Claytone-EM shows higher shear stress and viscosity in the low shear range. This results in better suspension performance, gelling, and sag. The effect of Claytone-EM on the mud rheology is shown in Figure 12 at 275 °F. The PV was increased by an 11% increment from 22.45 cP for the base mud to 24.96 cP with the Claytone-EM OC. Claytone-EM can enhance the PV of the drilling fluid by forming a network structure within the fluid. This network aids in the improvement of the fluid's flow resistance, which can be advantageous for the suspension and transportation of drill cuttings as well as the maintenance of appropriate hole cleaning. Drilling fluids typically demonstrate non-Newtonian behavior and exhibit shear-thinning characteristics, wherein their viscosity reduces as the shear rate increases.[6] Claytone-EM imparts shear-thinning behavior to the drilling fluid. Shear thinning implies that the viscosity of the fluid decreases under shear stress, such as when it flows through the drill bit. This attribute enables easier pumping of the fluid during drilling operations while maintaining the desired suspension and carrying capacity. Furthermore, the YP increased significantly by an 85% increment from 25.06 lb/100 to 46.43 lb/100 ft^2 due to the high dispersion of Claytone-EM. Claytone-EM forms a network structure within the fluid, which enhances

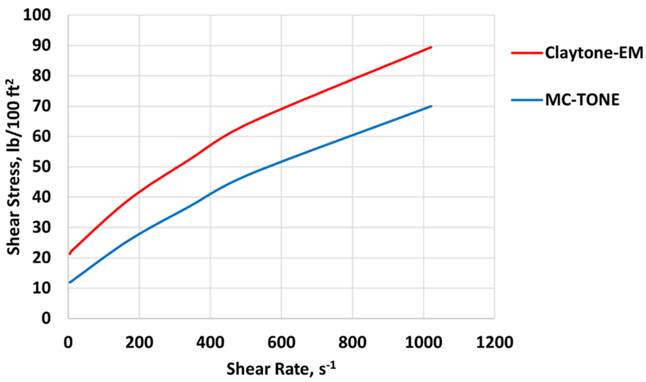

Figure 11. Effect of Claytone-EM on the stress−strain relationship at 275 °F.

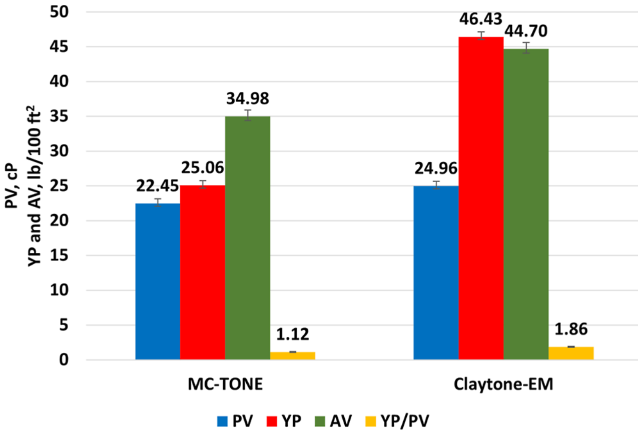

Figure 12. Effect of Claytone-EM on mud rheology at 275 °F.

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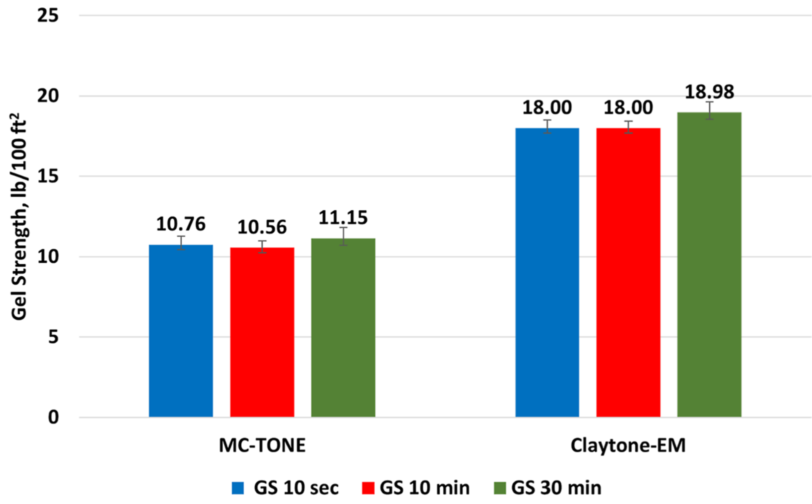

Figure 13. Effect of Claytone-EM on the GS at 275 °F.

interparticle interactions and cohesion. This increased interparticle bonding and structure contribute to a higher YP value, indicating greater resistance to flow at low shear stresses. This elevation in YP enhances the fluid's ability to suspend and transport drill cuttings, which is crucial for the proper maintenance of hole cleaning and the prevention of sag or settlement of cuttings during drilling operations. Additionally, a higher YP value can contribute to the preservation of borehole stability by providing improved support to the borehole walls. The introduction of Claytone-EM can enhance the drilling fluid's capacity to counteract deformation and flow under low-stress conditions, thereby averting the collapse or sloughing of the borehole walls during drilling operations. Furthermore, the YP plays a role in the development of an effective filter cake on the borehole walls. A drilling fluid with a higher YP value can create a more stable and uniform filter cake that aids in minimizing fluid loss and stabilizing the borehole. Moreover, Claytone-EM can augment the thixotropic behavior of a drilling fluid, allowing it to thin under shear stress and rapidly restore its initial viscosity once the stress is relieved. This property contributes to the fluid's capacity to uphold its YP and carrying capacity during drilling operations while simultaneously guaranteeing that it flows effortlessly through the system when necessary. The AV increased by a 28% increment from 34.98 lb/100 to 44.70 lb/100 ft^2. Claytone-EM can increase the viscosity of the drilling fluid by forming a network-like structure that hinders the flow of the fluid. The interparticle interactions and the formation of a clay particle network contribute to the increased AV. This can be beneficial in certain drilling operations where higher viscosity is desired for better hole cleaning and cutting suspension. Also, Claytone-EM can exhibit thixotropic behavior, which means that the viscosity of the fluid decreases under shear stress and recovers when the stress is removed. This property allows the fluid to flow more easily during pumping and circulation while maintaining its viscosity when static. Moreover, Claytone-EM can also cause the drilling fluid to exhibit shear-thinning behavior, where the viscosity decreases as the shear rate increases. At higher shear rates, the fluid's viscosity decreases, allowing for easier flow and improved pumpability. This shear-thinning effect can help maintain good circulation of the drilling fluid while still providing sufficient AV under high shear conditions. The YP/PV ratio increased by 66% from 1.12 to 1.86. A higher YP/PV ratio indicates better suspension and carrying capacity for drill cuttings, which is crucial for maintaining hole cleaning and preventing sag or settling of cuttings during drilling operations.[2,3] Figure 13 shows that the high viscosity at a low shear rate of Claytone-EM enhanced the suspension ability and gelling strengths. The gelling strengths at 10 s, 10 min, and 30 min were increased from 10.76, 10.56, and 11.15 lb/100 ft^2 for the base fluid to 18.00, 18.00, and 16.63 lb/100 ft^2, respectively. Claytone-EM forms a network structure within the fluid, resulting in enhanced interparticle interactions and the formation of a gel-like structure. This increased interparticle bonding and gel formation contribute to higher GS, indicating a greater resistance to flow under static conditions. Claytone-EM contributes to the development of the GS in drilling fluids. The gel structure formed by Claytone-EM can exhibit thixotropic behavior, meaning that it can recover its strength after being sheared or agitated. Adequate GS is crucial for preventing fluid loss into permeable formations, maintaining wellbore stability, and preventing sagging or slumping of the drilling fluid.

3.4.5. Filtration Tests. The filtration test results show that Claytone-EM enhanced the filtration properties. Figure 14 shows a 2% reduction in the filtration volume from 5.0 to 4.9 cm^3. Figure 15 shows a significant decrease of 13% from 2.60 to 2.26 mm in the filter cake thickness. The addition of Claytone-EM resulted in a decrease in fluid loss by enhancing

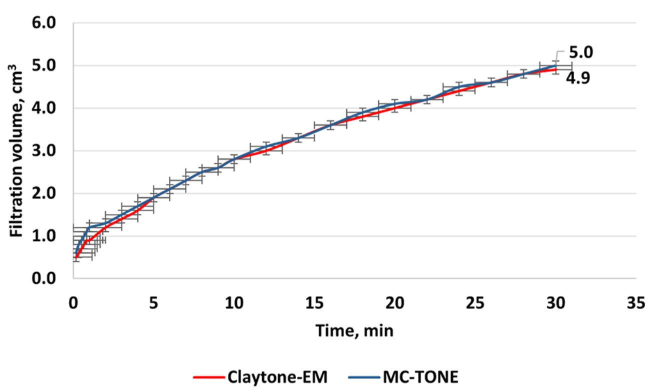

Figure 14. Effect of Claytone-EM on the filtration volume at 275 °F.

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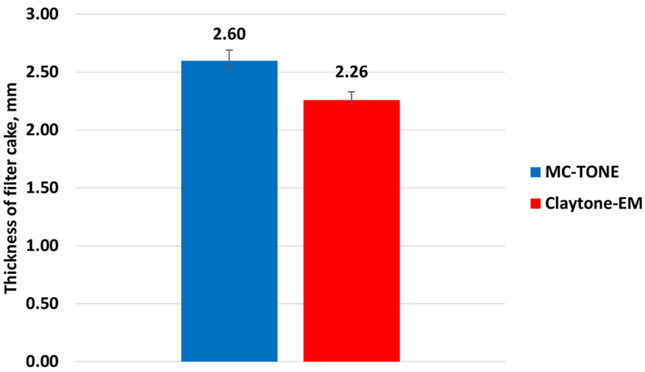

Figure 15. Effect of Claytone-EM on the filter cake thickness at 275 °F.

its AV and GS. These particular rheological characteristics possess the potential to produce a more efficient filter cake, consequently aiding in the prevention of fluid loss to the formation during drilling operations. Claytone-EM has a significant impact on the fluid's rheological properties and the formation of a filter cake. It can contribute to the formation of a more effective filter cake, which reduces fluid loss and minimizes the invasion of formation fluids. The reduction of fluid loss is of significant importance to ensure the stability of the wellbore and minimize any potential damage to the formation. One of the primary functions of drilling fluid is to establish a protective layer, commonly referred to as a "cake", along the walls of the wellbore, effectively hindering the loss of fluid into the formation. Moreover, Claytone-EM particles can create a compact layer on the filter medium, restricting the passage of the drilling fluid and preventing fluid loss. This contributes to maintaining the wellbore stability and minimizing formation damage.

3.4.6. Attributes of Claytone-EM. After conducting a comprehensive study on the use of Claytone-EM as a rheological additive in OBDFs under HPHT conditions, the advantages and disadvantages of Claytone-EM are summarized in Table 4.

This study concludes that Claytone-EM is a promising additive for improving the performance of OBDFs under HPHT conditions, providing better rheological characteristics, emulsion stability, and suspension properties. The use of Claytone-EM as a new rheological additive addresses drilling challenges and meets specific performance criteria for formulating drilling fluids. The limitations of this study include the temperature range in which it was carried out, which can be further studied at extreme temperatures. Also, the sag effects are not fully captured without flow experiments. Furthermore, cutting transport is not studied in this work. Further research and field-scale evaluations are recommended to validate and optimize the application of Claytone-EM in OBDFs.

4. DISCUSSION

The experimental results reveal a notable enhancement in the rheological properties of OBDFs when Claytone-EM is employed instead of MC-TONE, particularly in HPHT drilling environments. Claytone-EM demonstrates superior performance by enhancing electrical stability, minimizing static and dynamic sag, and improving filtration control through the creation of a more efficient filter cake. This improvement can be linked to the mineral and chemical composition disparities

Table 4. Advantages and Disadvantages of Claytone-EM

advantages	disadvantages
(1) Rheological Control.	(1) Limited Compatibility with Water-Based Systems[11]
Provides excellent rheological control and modification capabilities in various systems, including drilling fluids, paints, coatings, adhesives, and sealants. It can improve the viscosity, suspension, sag resistance, and overall stability of these systems.	Claytone-EM is primarily formulated for oil-based systems and may not be compatible with or exhibit the same level of effectiveness in water-based systems. Its performance in water-based formulations may be limited, and alternative additives may be required for such applications.
(2) Suspension and Antisettling Properties.	(2) Concentration Sensitivity.
Claytone-EM enhances the suspension and antisettling properties of fluids by effectively dispersing and suspending solid particles. It helps prevent settling and sagging, which is particularly beneficial in applications where solid particles need to be maintained in suspension over extended periods.	The performance of Claytone-EM can be sensitive to its concentration within a formulation. Finding the optimal dosage is essential to achieve the desired rheological properties and stability. Incorrect dosage levels may result in inadequate performance or undesirable effects.
(3) Compatibility with Oil-Based Systems.	(3) Dependency on Shearing and Mixing.
Claytone-EM is specifically designed for use in oil-based systems, making it an excellent additive for OBDFs, lubricants, and other oil-based formulations. It exhibits good compatibility with various oil-based materials, ensuring efficient performance in these systems.	Claytone-EM requires sufficient shear and mixing energy for proper dispersion and activation. Inadequate mixing may result in poor dispersion, reduced effectiveness, or inconsistent performance.
(4) Temperature Stability.	
Claytone-EM demonstrates good thermal stability, allowing it to maintain its rheological properties and performance across a wide range of temperatures. This stability is crucial in applications where the fluid or system is subjected to high-temperature conditions.	
(5) Enhanced Stability.	
Claytone-EM improves the stability of formulations by preventing settling, sagging, and phase separation. They form a three-dimensional network that helps suspend and stabilize solid particles, ensuring consistent performance over time.	

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between Claytone-EM and MC-TONE, as evidenced by the XRD and XRF results.

The action mechanism of Claytone-EM differs from that of MC-TONE due to their distinct chemical compositions and properties. Claytone-EM, a chemically modified smectite clay derived from bentonite, is organophilic, meaning that it has been altered to have an affinity for organic molecules. This modification is achieved through an ion exchange process, where inorganic cations in the mineral structure are replaced with organic cations. The resulting enhancement in Claytone-EM's affinity for nonpolar organic compounds improves its rheological properties. It forms a network structure within the fluid, leading to augmented interparticle interactions and the creation of a gel-like structure. This strengthened interparticle bonding and gel formation contribute to higher GS, improved emulsion stability, and enhanced rheological and filtration properties of OBDFs.

On the other hand, MC-TONE does not possess the same organophilic properties as Claytone-EM. It exhibits increased irregularity and more defined particle edges, potentially escalating its tendency to sag. Unlike Claytone-EM, MC-TONE may not contribute to the same level of gel formation and interparticle bonding, leading to reduced stability and performance in OBDFs.

5. CONCLUSIONS

This comprehensive laboratory study has conclusively demonstrated Claytone-EM's capability to effectively address challenges encountered in HPHT drilling operations. The findings reveal that the inclusion of Claytone-EM significantly (1) improves the electrical stability of inverted emulsions, (2) diminishes static and dynamic sags through thixotropic behavior, and (3) improves filtration control by creating a more efficient filter cake. Consequently, it also improves the rheological properties of the mud; these improvements lead to the stability of the wellbore, improving the overall performance of OBDFs.

Claytone-EM's introduction has exhibited promising outcomes in enhancing the rheological characteristics of OBDFs. These improvements hold substantial implications for both wellbore stability and the safeguarding of the formation during drilling operations. This study underscores the potential of Claytone-EM as a valuable additive, contributing to the overall performance and stability of OBDFs under challenging HPHT conditions.

The results obtained pave the way for further exploration of Claytone-EM's broader applications and the development of advanced drilling fluid formulations aimed at boosting the operational efficiency and wellbore stability in demanding conditions. Future research and field applications can provide insight into the practical implementation of Claytone-EM in drilling operations. Additionally, its potential in addressing other challenges within the petroleum industry warrants further investigation. This study serves as a foundation for ongoing efforts to harness the full potential of Claytone-EM in optimizing drilling processes.

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Notes

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