RESEARCH ARTICLE

Mitigating Barite Sag and Enhancing HPHT Performance of Oil-Based Drilling Fluids Using Micronized Saudi Calcium Carbonate

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Abstract

Barite sag and filtration control remain important challenges in oil-based drilling fluids used under high-pressure, high-temperature (HPHT) conditions. This study evaluates micronized calcium carbonate (Mic-Cal), prepared from limestone collected from the Aruma Formation in Saudi Arabia, as an additive for improving the stability and performance of an invert-emulsion oil-based drilling fluid. The Mic-Cal was characterized using particle-size distribution, X-ray fluorescence, X-ray diffraction, and scanning electron microscopy. Formulations containing 10, 20, and 30 lb/bbl Mic-Cal were evaluated after hot rolling at 350 °F (177 °C) for 16 h through static sag, density, and electrical stability tests, and the 20 and 30 lb/bbl formulations were further evaluated through HPHT filtration, rheology, and gel-strength tests. The material was predominantly micron-sized, with D50 and D90 values of 2.80 and 10.63 μm, respectively. At 20 lb/bbl, Mic-Cal reduced the static sag factor from 0.55 and 0.58 for the base fluid under vertical and 45° inclined conditions, respectively, to 0.52 under both conditions. The same dosage increased mud density from 14.0 to 14.3 ppg, while electrical stability remained above 400 V after thermal aging, indicating acceptable emulsion stability and solids oil-wetting. Compared with the base fluid, the 20 lb/bbl formulation increased apparent viscosity and yield point by approximately 20% and 56%, respectively, and reduced HPHT filtrate volume and filter-cake thickness by 11% and 33%. Increasing the Mic-Cal concentration to 30 lb/bbl did not provide further improvement in filtration or rheological performance. Under the tested conditions, 20 lb/bbl Mic-Cal provided the most favorable balance between sag mitigation, rheology, and filtration control.

Keywords: micronized calcium carbonate, oil-based drilling fluid, HPHT filtration, rheology, sag testing.

Nomenclature

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Symbol/Abbreviation	Definition
AHR	After hot rolling
API	American Petroleum Institute
AV	Apparent viscosity (cP)
BHR	Before hot rolling
D10/D50/D90	Percentile particle sizes (μm)
ES	Electrical stability (V)
GS	Gel strength (lb/100 ft^2)
HPHT	High-pressure, high-temperature
Mic-Cal	Micronized calcite
NPs	Nanoparticles
OBMs	Oil-based muds
OWR	Oil/water ratio
ppg	Pounds per gallon
PSD	Particle-size distribution
PV	Plastic viscosity (cP)
SEM	Scanning electron microscopy
SF	Sag factor
VSST	Viscometer sag shoe test
WBMs	Water-based muds
XRD	X-ray diffraction
XRF	X-ray fluorescence
YP	Yield point (lb/100 ft^2)
θ_{600}, θ_{300}	Dial readings at 600/300 rpm

1 Introduction

Rising energy demand has pushed the oil industry toward unconventional, shale-type resources, which bring low permeability, nanoscale pore throats, and wellbore instability caused by water-rock interaction [1]. The drilling fluid is a key design choice in such wells. It circulates through the drill string and annulus to maintain hydrostatic pressure, protect the formation, limit damage, clean the hole, lubricate the bit, and carry cuttings to surface while keeping the wellbore stable [2].

As wells become deeper and more difficult, particularly in deep water and in high-pressure, high-temperature (HPHT) reservoirs, the drilling-fluid formulation has to be optimized more carefully. Of the available fluid types, oil-based muds (OBMs) are usually the first choice for these conditions. In harsh environments they generally outperform water-based muds (WBMs), and in many wells that encounter extreme subsurface conditions they are difficult to replace [3]. The advantages of OBMs are well documented: they are stable, strongly inhibitive toward reactive shale, provide good lubrication, and tolerate high temperature, so they keep working at the pressures and temperatures found in deep wells [3]. Their hole-cleaning performance has also been compared experimentally with that of WBMs [4]. These properties improve drilling efficiency and safety and make it possible to reach reserves that would otherwise be hard to access. OBMs are more expensive, especially when mineral oils or specialty base fluids are used, so the fluid has to be matched carefully to the requirements of each well [5]. The mud can, however, be treated and reused, which offsets much of this cost over the life of a project. OBMs are normally formulated as water-in-oil emulsions, known as invert-emulsion drilling fluids [6]. The stability of this emulsion governs fluid performance and helps prevent common operational problems such as barite sag, stuck pipe, and lost circulation [7]. A well-stabilized invert emulsion therefore keeps the drilling process running smoothly and reduces non-productive time and the associated cost.

Over the past decade, interest in micro- and nanotechnology has grown steadily in the oil and gas industry. Drilling muds that contain fine solid particles are one of the more promising applications, because they address several drilling problems at once [8]. Even small amounts of such particles can reduce friction between the drill pipe and the borehole, improve filtration control, help cuttings transport, strengthen the borehole wall when drilling unstable formations, alter rock wettability, and limit corrosion [9]. Nano- and microparticles have been shown to improve the flow and filtration properties of WBMs and to preserve these properties after high-temperature aging [8]. They also help stabilize shale formations and improve borehole stability by plugging pore throats and reducing water invasion into the shale [10]. Over time, many types of nanoparticles (NPs) have been tested in nano-reinforced drilling fluids, often called nano-drilling muds, and rheological studies indicate that NPs have clear potential for new fluid designs. Because they are effective at low loadings, NPs can reduce the amount of other chemicals and solids required and thus lower drilling-fluid cost. Their high surface-area-to-volume ratio makes them effective at sealing narrow pore throats in the wellbore wall with less fluid invasion [9]. Nanoparticles can also raise the thermal conductivity of the fluid; heat-transfer gains of more than 20% over conventional mud have been reported [11]. At the same time, fine particles and polymers can migrate into porous formations and cause damage, so the particle-size distribution of the fluid has to be selected carefully.

Calcite (calcium carbonate) occurs naturally as limestone and has a specific gravity of 2.7-2.8 [2]. It is commonly used to raise mud weight to about 12 ppg. Calcite is often preferred over barite because it is acid-soluble, so its filter cake can be removed with hydrochloric acid [12]. In recent years its acid solubility has come to be valued more than its density, and calcite is now widely used as a bridging material

in drill-in, completion, and workover fluids. Calcium carbonate from other sources, such as eggshells, has also been evaluated as a weighting agent in drilling fluid [13]. The use of calcite microparticles in drilling fluids is a more recent development. Fine calcite particles are widely available, inexpensive, and safe to handle, which makes them attractive additives. Nanoparticle-based fluids have shown promise for improving drilling performance [14], and $CaCO_3$ nanoparticles in particular have been used as filtration-loss control agents in water-based drilling fluids [15]. $CaCO_3$ nanoparticles have also been used in nano-drilling fluids to seal the shale matrix and reduce fluid permeation into it, and the sealing particles can later be removed by acid [16]. Shokry et al. [17] showed that micronized calcite improves the rheology of water-based mud and reduces sag. To the authors' knowledge, however, the rheological and viscoelastic behavior of such fluids, and the settling of weighting agents in oil-based drilling fluids containing them, have not been resolved; these issues can compromise fluid stability and drilling performance. The concentration of calcite microparticles in oil-based mud therefore still needs to be optimized.

This study evaluates micronized Saudi calcium carbonate (Mic-Cal), prepared from a limestone outcrop of the Aruma Formation, as an additive for invert-emulsion oil-based drilling fluids. It examines whether the particle-size characteristics of Mic-Cal can improve static sag resistance, rheological performance, and HPHT filtration control. Mic-Cal was characterized by particle-size distribution analysis, scanning electron microscopy, X-ray diffraction, and X-ray fluorescence, and the effects of 10, 20, and 30 lb/bbl Mic-Cal on the oil-based drilling fluid were then evaluated.

2 Materials and Methods

2.1 Material Preparation

The limestone used to prepare Mic-Cal was collected from an exposed section of the Upper Cretaceous Aruma Formation in central Saudi Arabia. The Aruma Formation comprises carbonate- and shale-dominated successions and is generally subdivided into the Khanasir, Hajajah, and Lina members. The sample was taken from a limestone-bearing interval. Previous stratigraphic studies describe the formation as a Campanian-Maastrichtian succession deposited during a marine transgressive phase, with facies ranging from shallow-marine lagoonal to more open-marine settings [18]. Because carbonate mineralogy, impurities, and texture may vary between outcrops and stratigraphic intervals, the present findings apply specifically to Mic-Cal prepared from the sampled Aruma limestone. The limestone was crushed, ground, and sieved to obtain a predominantly micron-sized powder, which was used as a performance additive for OBMs.

2.2 Micronized Calcite (Mic-Cal) Characterization

The prepared Mic-Cal was characterized to determine its particle-size distribution (PSD), elemental composition, mineralogical phases, and particle morphology. The PSD of Mic-Cal and barite was measured with a HELOS particle-size analyzer. The chemical composition, crystalline phases, and morphology of Mic-Cal were evaluated by X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM), respectively.

2.3 Drilling Fluid Preparation

An invert-emulsion mud with an oil/water ratio (OWR) of 80/20 was prepared in a three-speed mud mixer at room conditions, with diesel as the continuous phase and $CaCl_2$ brine as the dispersed phase. The formulation in Table 1 served as the base for evaluating the effect of Mic-Cal at 10, 20, and 30 lb/bbl (28.5, 57.1, and 85.6 kg/m^3) on sag, filtration, and rheological properties. Additives were added in sequence: the primary and secondary emulsifiers first, followed by lime to provide alkalinity. Duratone was used as the fluid-loss control agent, and Geltone was added as the viscosifier. All additives were supplied by a drilling-fluid service provider in the Middle East and were mixed in the quantities and order specified in Table 1.

2.4 Performance Evaluation

The base fluid was first characterized by a series of standard laboratory tests following API RP 13B-2 [19]. Mud weight and the baseline (before hot rolling, BHR) rheology were measured first. The sample was then hot rolled at 350 °F (177 °C) for 16 h to simulate well conditions and to condition the fluid before the sag test. After hot rolling (AHR), the electrical stability, rheological properties, and high-pressure, high-temperature filtration parameters of the fluid were measured. The same sequence was then applied to the formulations containing Mic-Cal, so that the effect of Mic-Cal concentration on sag, density, emulsion stability, rheological behavior, and HPHT filtration could be compared directly with the base fluid. This comparison was used to

Table 1. Drilling fluid composition, expressed in pounds per barrel (lb/bbl), equivalent to grams per 350 cm^3.

Component	Quantity	Unit	Mixing time (min)	Function
Diesel	0.56	bbl	-	Continuous phase
Invermul	9	lb/bbl	5	Primary emulsifier
EZ-MUL	4	lb/bbl	5	Secondary emulsifier
Lime	6	lb/bbl	5	Alkalinity control
Duratone	7	lb/bbl	5	Fluid-loss control
Water	0.11	bbl	10	Dispersed phase
$CaCl_2$	24	lb/bbl	-	Brine salt (activity control)
Geltone	7	lb/bbl	10	Viscosifier
Calcium carbonate	10	lb/bbl	5	Weighting agent
Barite	300	lb/bbl	10	Weighting agent
Mic-Cal	0, 10, 20, 30	lb/bbl	10	Bridging material

identify how the base fluid and the micronized calcite particles interact and which changes in fluid properties could be attributed to the additive. All drilling-fluid measurements were performed in triplicate, and the reported values are the mean of three independent measurements.

2.4.1 Static Sag Analysis

Static sag testing shows whether a fluid can keep barite particles in suspension over time, and it is therefore a basic measure of fluid stability. It matters whenever circulation stops for extended periods, for example during a temporary suspension of drilling, during well-control operations, or when the drill string remains stationary in the wellbore. In these situations, the ability of the fluid to resist sag directly affects operational safety and efficiency. Static sag results help predict how a fluid will behave during idle periods and guide the design of fluids that behave consistently under varying operating conditions. Barite sag also depends on well inclination and pipe rotation under dynamic conditions [20]. The sag factor quantifies the density segregation that develops in a fluid column left at rest: a lower value means that the weighting material remains more uniformly distributed [17]. The sag factor (SF) was calculated with Eq. (1) after the fluid was held at 350 °F (177 °C) and 300 psi (2.07 MPa) for 24 h:

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

where MW_{bottom} and MW_{top} are the fluid densities at the bottom and top of the aging cell, respectively. An SF of 0.50 indicates no sag, values between 0.50 and 0.53 are generally considered acceptable [21], and values above 0.53 indicate a noticeable and undesirable tendency for static sag [22].

In this study, vertical and 45° inclined static sag tests were selected as an initial assessment of micronized Saudi calcite as a sag mitigator under static conditions, which is relevant to vertical and inclined well sections. The tests were run at 300 psi (2.07 MPa) and 350 °F (177 °C) for 24 h to observe the ability of the mud to keep barite suspended in a static HPHT environment. Static tests do not capture the effect of low-rate flow, pipe rotation, or annular eccentricity on sag; dynamic tests, such as the viscometer sag shoe test (VSST), are therefore planned in future work to evaluate sag under flowing conditions.

2.4.2 Density and Electrical Stability

Density and electrical stability are basic control parameters that influence OBM performance during drilling. The density of OBM is adjusted so that sufficient hydrostatic pressure acts on the wellbore, preventing the influx of formation fluids and maintaining wellbore stability. A correctly adjusted mud density is essential for controlling wellbore pressure, avoiding kicks, and drilling safely and efficiently [2]. Electrical stability (ES) reflects emulsion strength and the degree of oil-wetting of the solids. High ES values indicate a stable emulsion and oil-wet solids, which limit water invasion, improve lubricity, and help prevent barite sag and emulsion breakdown. ES was measured under ambient conditions. In this test, a sinusoidal alternating voltage applied across a pair of electrodes immersed in the OBM is increased gradually until the emulsion breaks down and current flows; the breakdown voltage is reported as ES [23].

2.4.3 Filtration Properties Evaluation

Filtration behavior under HPHT conditions is an important indicator of how a drilling or completion fluid will perform in a deep wellbore. HPHT filtration tests were conducted with an HPHT API filter press, which reproduces the elevated pressures

and temperatures encountered downhole and allows assessment of the thermal stability and filtration performance of a fluid and its additives. Samples were tested at 350 °F (177 °C) and a differential pressure of 500 psi (3.45 MPa). A standard filter paper with a mean pore diameter of 2-5 μm was used, and filtrate was collected over the standard API duration of 30 min. Filtrate volume was recorded at intervals and multiplied by two because the filtration area of the HPHT cell is half the standard API area, as specified in the API procedure. Filter-cake thickness was measured with digital vernier calipers. Filter-cake permeability was calculated with Darcy's law applied to the cake:

$$K_{fc} = \frac{1000\, q\, \mu_f\, Th_{fc}}{A_{fc}\, \Delta p_{fc}} \tag{2}$$

where K_{fc} is the filter-cake permeability (mD); q is the filtrate flow rate (cm^3/s), calculated as $\Delta V/\Delta t$ over the final measurement interval; μ_f is the filtrate viscosity (cP); Th_{fc} is the filter-cake thickness (cm); A_{fc} is the filtration area (cm^2); and Δp_{fc} is the pressure differential across the filter cake (atm).

2.4.4 *Rheological Performance Evaluation*

Rheological properties control cuttings transport and are linked to filtration loss and lubricity in HPHT fluids [24]; they also affect wellbore stability and the extent of formation damage. They were measured with a Grace M3600 viscometer. Plastic viscosity (PV), yield point (YP), and apparent viscosity (AV) were calculated with the Bingham plastic model from the dial readings at 600 and 300 rpm (θ_{600} and θ_{300}):

$$PV = \theta_{600} - \theta_{300} \tag{3}$$

$$YP = \theta_{300} - PV \tag{4}$$

$$AV = \theta_{600}/2 \tag{5}$$

where PV and AV are in cP and YP is in $lb/100\ ft^2$ ($1\ lb/100\ ft^2 \approx 0.479$ Pa). These parameters are widely used to assess drilling-fluid rheology and suspension capacity in the field. More complex models, such as Herschel-Bulkley, describe non-Newtonian flow in greater detail, but Bingham parameters were used here to allow direct comparison of the formulations according to standard practice.

Gel strength (GS) is another key parameter, describing the ability of a fluid to suspend drill cuttings and mud solids when circulation stops. It reflects interparticle electrochemical attraction within the fluid under no-flow conditions, which keeps cuttings suspended until circulation resumes and helps maintain wellbore stability. In this study, GS was measured after 10 s, 10 min, and 30 min of rest to follow how the gel structure, and thus the capacity of the fluid to hold cuttings and solids, develops during periods of inactivity. An appropriate gel strength is a compromise: it must be high enough to suspend cuttings but not so high that it produces excessive pressure when circulation is resumed.

3 Results and Discussion

3.1 Material Characterization

3.1.1 *Particle Size Distribution (PSD)*

The PSD of barite (the weighting material in the formulation) and Mic-Cal (the additive under study), measured with the HELOS analyzer, is shown in Figure 1. The two materials differ markedly in particle size, and this difference underlies their different roles in the formulation. Mic-Cal is considerably finer than barite. Its median particle size (D50) is 2.80 μm, compared with 16.64 μm for barite, and its D10 and D90 are 0.68 and 10.63 μm, compared with 2.04 and 48.40 μm for barite. Mic-Cal is therefore much finer overall, although its relative span, (D90−D10)/D50, is somewhat wider (3.55 versus 2.79 for barite). This fine size has direct implications for the behavior of Mic-Cal as an additive. Fine particles disperse more readily within the mud structure and can bridge more effectively. By occupying the voids between larger barite particles and other solids, Mic-Cal can produce a more stable and homogeneous solids packing, which in turn may modify the rheological properties of the fluid. The same fine particles can also contribute to a more compact, lower-permeability filter cake on the wellbore wall, reducing fluid loss and improving wellbore stability. Whether these expected benefits are realized in the OBM is examined in the following sections.

3.1.2 *X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) Analysis*

XRF determines elemental composition: the sample is irradiated with high-energy X-rays, the excited atoms emit fluorescence that is characteristic of each element, and the emitted radiation is detected and analyzed to identify the elements present. The XRF results for Mic-Cal (Figure 2) show that calcium is the dominant element, accounting for 97 wt% on an oxygen-free basis, with minor amounts of Fe (1.4 wt%), Al (0.7 wt%), Si (0.4 wt%), and S (0.2 wt%). The small Fe, Al, and Si contents are typical of minor clay or detrital impurities in natural limestone. Because these

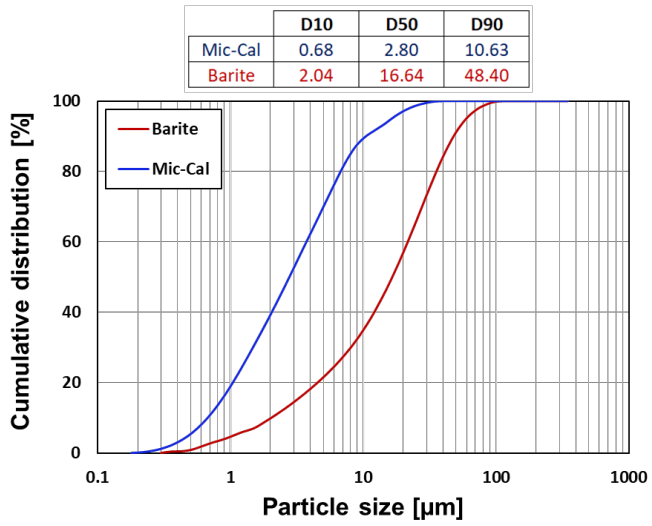


Figure 1. Particle size distribution of micronized calcite (Mic-Cal) and barite.

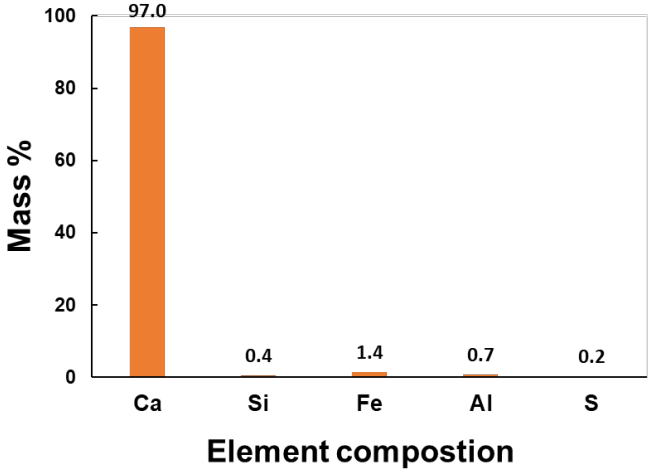


Figure 2. XRF analysis of micronized calcite (Mic-Cal) powder. The reported elemental mass percentages are given on an oxygen-free basis.

impurities are present only at low levels, they are not expected to affect the behavior of Mic-Cal in the mud significantly, although they should be monitored if limestone from other intervals is used.

The mineralogy of the crushed limestone was analyzed by XRD with a PANalytical Empyrean diffractometer operated at 45 kV and 40 mA using Cu Kα radiation. The pattern (Figure 3) shows the characteristic reflections of calcite, confirming calcite as the dominant crystalline phase. The sharp, well-defined reflections indicate that micronization did not degrade crystallinity. Only a few weak, unindexed reflections are present (e.g., near 26.6° 2θ, possibly trace quartz, consistent with the minor Si detected by XRF), so any secondary crystalline phases are present only in minor amounts.

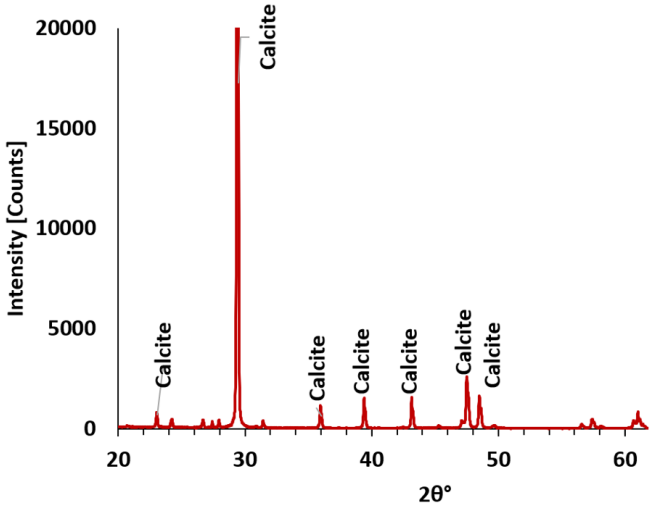


Figure 3. XRD pattern of micronized calcite (Mic-Cal).

3.1.3 Scanning Electron Microscopy (SEM)

SEM images of Mic-Cal at three magnifications are shown in Figure 4. At the lowest magnification (a), the surface appears relatively uniform with some textural variation, indicating a tightly packed and broadly homogeneous material. At higher magnification (b), the particles are closely packed and partly agglomerated, and the fine crystalline structure of calcite becomes clear; the surface roughness probably reflects the mechanical processing. At the highest magnification (c), the rhombohedral crystals typical of calcite are visible, with rough surfaces, distinct edges, and facets. The particles are fairly uniform in shape and mostly range from 1 to 10 µm. Overall, Mic-Cal consists of densely packed rhombohedral calcite particles whose surface roughness depends on mechanical processing. The agglomeration seen at the microscale is typical of such fine powders. The particle sizes observed in the micrographs are consistent with the laser-diffraction results (D50 = 2.80 µm, D90 = 10.63 µm), which supports the PSD data reported above.

3.2 Static Sag Analysis

Figure 5 shows the vertical and inclined static sag results for fluids containing different Mic-Cal concentrations after 24 h under static conditions. The purpose of the test was to assess how Mic-Cal affects sag, which determines whether the fluid remains stable and uniform when circulation stops.

The base fluid without Mic-Cal had a sag factor above the generally accepted upper limit (SF $>$ 0.53) in both orientations, indicating a clear tendency for solid

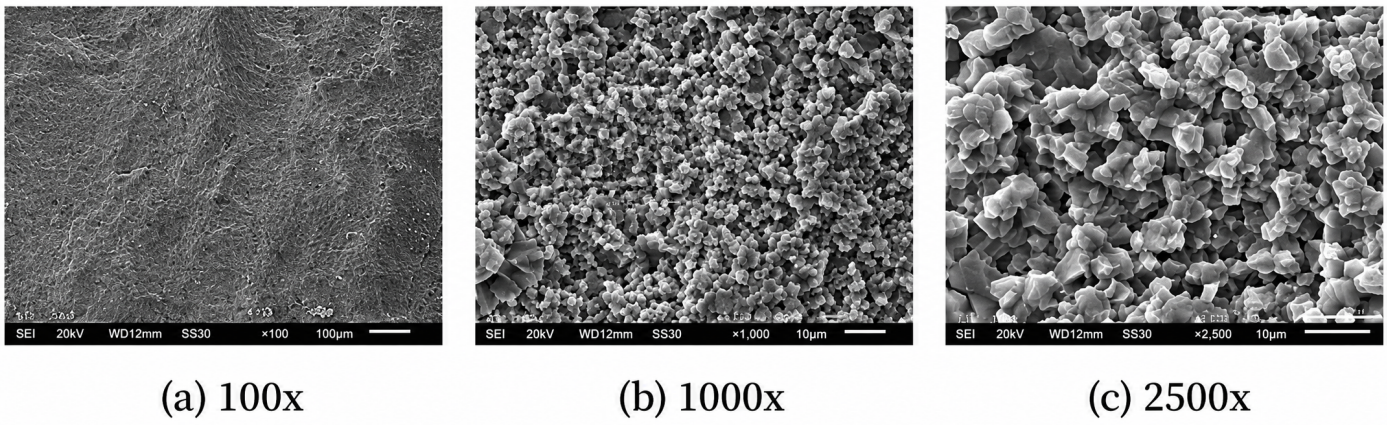


Figure 4. SEM micrographs of micronized calcite (Mic-Cal) at (a) 100×, (b) 1000×, and (c) 2500× magnification. Scale bars are shown in each micrograph.

particles to settle at rest. The inclined value (0.58) was higher than the vertical value (0.55), consistent with the faster settling that is usually observed in deviated sections, where particles need to travel only a short distance before reaching the low side of the cell [20]. Such settling causes uneven density distribution and can lead to wellbore instability and well-control problems. Adding 10 lb/bbl Mic-Cal lowered the sag factor, but the values (0.54 vertical and 0.55 inclined) remained above the acceptable range, so this concentration was insufficient. Because the 10 lb/bbl formulation did not reach the target range, it was not included in the subsequent HPHT filtration and rheological tests; its density, electrical-stability, and static-sag results are nevertheless reported in Table 2 to document the screening stage. At 20 and 30 lb/bbl, the sag factor dropped into the accepted range, and the difference between the vertical and inclined values almost disappeared (0.52/0.52 and 0.51/0.52, respectively). These concentrations therefore improve suspension stability effectively. Mic-Cal particles, being much smaller than barite, provide more surface area and contact points; they fill the gaps between barite particles and reinforce the particle network, forming a denser solids matrix that resists settling. A similar micro-bridging effect has been reported for fine weighting materials in other drilling fluids [22]. The additional improvement from 20 to 30 lb/bbl was marginal (0.01 in the vertical test and none in the inclined test), which suggests that the particle network is already well developed at 20 lb/bbl. Whether these higher concentrations also preserve the other properties needed for drilling, particularly rheology, emulsion stability, and filtration, is examined below.

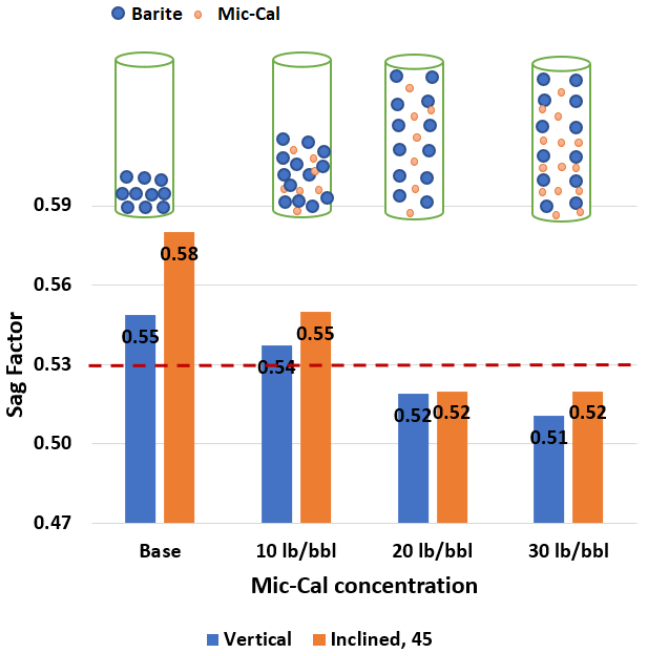


Figure 5. Static sag-factor results under vertical and 45° inclined conditions after 24 h at 350 °F (177 °C) and 300 psi (2.07 MPa). The dashed red line at a sag factor of 0.53 indicates the upper limit of the generally accepted static-sag range; values closer to 0.50 indicate more uniform solids distribution.

Proposed Mechanism of Mic-Cal in the OBM System

The suspension stability provided by Mic-Cal in OBM is attributed to its fine particle size, its interaction with the emulsifiers, and its compatibility with the other components of the formulation. The fine size increases surface area and allows Mic-Cal to fill the gaps between larger weighting particles such as barite, creating a network within the OBM matrix that reduces settling, particularly under static conditions. In OBM, solids must be oil-wet to be compatible with the

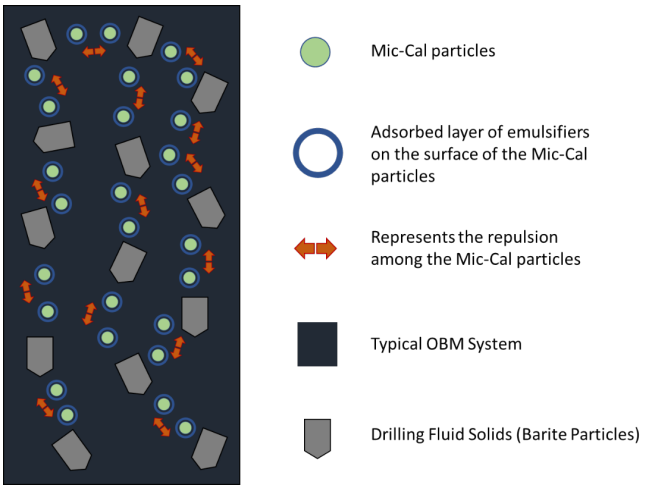


Figure 6. Schematic of the suspension mechanism of Mic-Cal in OBM. Mic-Cal particles (green circles) are stabilized by emulsifiers (blue rings) in the diesel phase (dark background) and dispersed with barite particles (gray shapes). Emulsifiers form a steric barrier (red arrows) around Mic-Cal, preventing aggregation and supporting uniform dispersion.

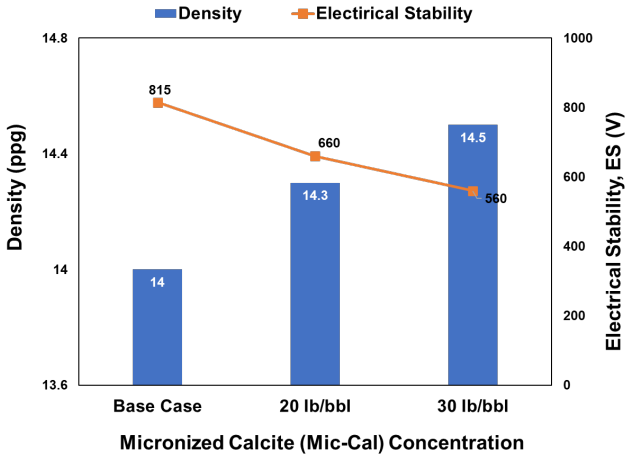


Figure 7. Density and electrical stability of the tested drilling formulations with and without Mic-Cal at different concentrations.

continuous phase. The emulsifiers in the formulation, Invermul (9 lb/bbl, primary) and EZ-MUL (4 lb/bbl, secondary), may adsorb onto Mic-Cal particles and form a steric barrier that prevents aggregation and keeps the particles dispersed in the diesel phase (0.56 bbl). In addition, Geltone (7 lb/bbl) may interact with Mic-Cal to increase yield point and gel strength. The resulting structure traps particles and reduces the tendency of heavier particles such as barite to settle, which is especially important under HPHT conditions. The increased viscosity and gel strength provide a supporting structure that helps maintain suspension stability, which is especially important at elevated temperature, where the viscosity of the base oil decreases. It should be noted that this mechanism is inferred from the macroscopic measurements reported here; direct evidence of emulsifier adsorption on Mic-Cal, for example from contact-angle or adsorption measurements, was not obtained in this study. Figure 6 illustrates the proposed mechanism schematically.

3.3 Density and Electrical Stability

Figure 7 shows the effect of adding 20 and 30 lb/bbl Mic-Cal on mud density and ES, and Table 2 summarizes density, ES, and sag factor for all concentrations. The base fluid had a density of 14.0 ppg (1.68 g/cm^3) and an ES of 815 V. With 20 lb/bbl Mic-Cal, density rose to 14.3 ppg (1.71 g/cm^3) and ES fell to 660 V. At 30 lb/bbl, density reached 14.5 ppg (1.74 g/cm^3) and ES dropped further to 560 V. All ES values nevertheless remained well above the commonly accepted minimum of 400 V for oil-based muds, indicating that emulsion stability stayed within an acceptable range [25]. This threshold is widely used in the field as a practical check of emulsion integrity, including for fluids intended for HPHT service. The density increase (0.3 ppg at 20 lb/bbl and 0.5 ppg at 30 lb/bbl) is in the direction expected from adding solids with a specific gravity of about 2.7. A simple mass balance predicts a smaller increase (about 0.2 ppg at 20 lb/bbl and 0.3 ppg at 30 lb/bbl), so part of the measured increase may reflect measurement uncertainty. The ES decreased by about 19% and 31%, respectively. The decrease in ES with Mic-Cal addition can be explained by several factors. First, ES depends on emulsion stability and on the oil-wetting of the solids [26], so added calcite surfaces that are not fully oil-wet can lower it. Second, inorganic solid particles are known to influence the formation and stability of water-oil emulsions [27], and a higher solids content increases contact between solids and dispersed water droplets, which may promote droplet coalescence and further reduce emulsion stability. Third, studies of crude-oil emulsions show that surface-active species adsorb onto inorganic solid surfaces [28]; by analogy, emulsifier molecules may adsorb on the calcite surfaces, leaving less emulsifier available to stabilize the droplets and lowering ES. Thus, while Mic-Cal raises mud density, which helps control wellbore pressure and prevent well-control events such as kicks or blowouts, the corresponding drop in ES indicates some loss of emulsion stability and oil-wetting that could affect the ability of the fluid to suspend solids and maintain wellbore stability. Increasing the Mic-Cal concentration beyond 30 lb/bbl

is therefore not recommended, and ES should be monitored during operations even though it remains within acceptable limits.

Table 2. Density, electrical stability, and static sag factor of the tested Mic-Cal formulations after thermal aging.

Mic-Cal (lb/bbl)	Density (ppg)	ES (V)	SF vertical	SF 45° inclined
0	14.0	815	0.55	0.58
10	14.1	720	0.54	0.55
20	14.3	660	0.52	0.52
30	14.5	560	0.51	0.52

3.4 Filtration Properties

Figures 8-10 show how Mic-Cal concentration affects filtration and filter-cake thickness. Figure 8 plots filtrate volume against time for the base fluid and for the 20 and 30 lb/bbl formulations. Adding 20 lb/bbl Mic-Cal reduced fluid loss: after 30 min, the filtrate volume was 7.2 cm^3, about 11% lower than that of the base fluid (8.1 cm^3). The flatter filtrate curve indicates that 20 lb/bbl Mic-Cal helps form a more effective barrier against fluid loss. In contrast, 30 lb/bbl Mic-Cal increased the filtrate volume to 10.2 cm^3, about 26% above the base fluid, and the steeper curve indicates poorer filtration control. Filter-cake permeability was calculated from Eq. (2), with q taken from the slope of the filtrate curve over the final interval (26–30 min, Figure 8), Th_{fc} from Figure 9, A_{fc} = 45.8 cm^2 (the standard API area, consistent with the doubled filtrate volumes), Δp_{fc} = 34.0 atm (500 psi), and μ_f = 3.1 cP. The calculated permeability decreased by about 41%, from 3.56×10^{-3} to 2.11×10^{-3} mD, at 20 lb/bbl, but increased by about 11%, to 3.95×10^{-3} mD, at 30 lb/bbl. These results suggest that excess Mic-Cal reduces packing or bridging efficiency and produces a more permeable filter cake. A likely reason is that, at the higher solids loading and with the lower emulsion stability indicated by the ES data, part of the fine particles aggregate into clusters that no longer fill the pores between barite particles efficiently, leaving more open flow paths through the cake. This concentration-dependent response agrees with the principle that filtration performance depends on the overall PSD and packing efficiency of the filter cake, and on the dispersion state of the fine particles, rather than on solids concentration alone [29, 30].

Figure 9 shows the filter-cake thickness of each formulation. The base fluid and the 30 lb/bbl formulation produced the same thickness (6/32 in, 4.8 mm), so the higher concentration did not reduce

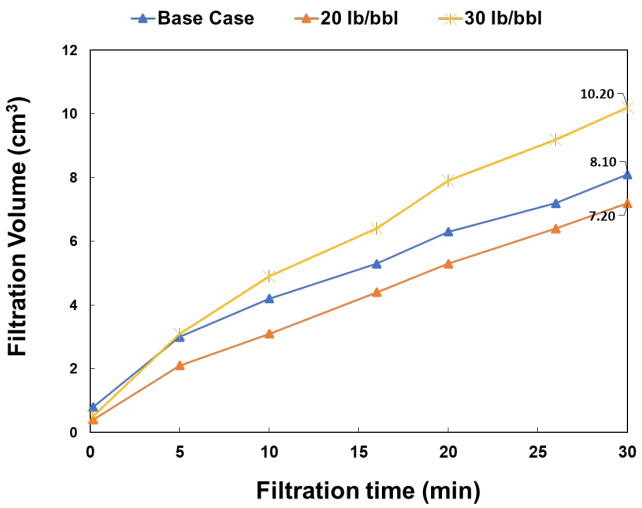


Figure 8. Filtrate volume versus time for the tested drilling formulations with and without Mic-Cal at different concentrations, measured at 350 °F (177 °C) and a differential pressure of 500 psi (3.45 MPa).

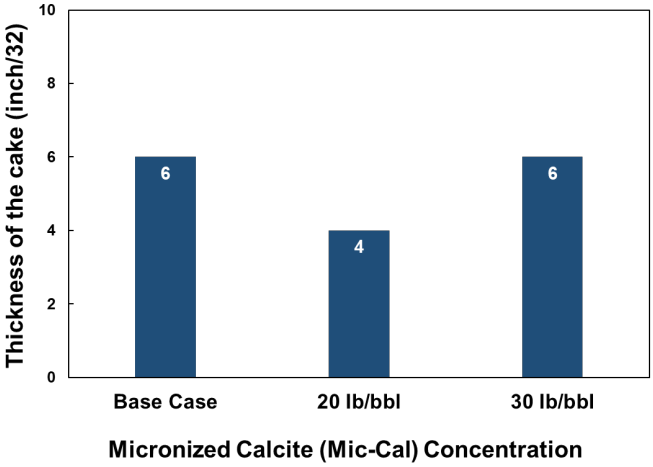


Figure 9. Filter-cake thickness of the tested drilling formulations with and without Mic-Cal at different concentrations, obtained with an HPHT filter press at 350 °F (177 °C) and a differential pressure of 500 psi (3.45 MPa).

cake thickness. The 20 lb/bbl formulation produced a thinner cake (4/32 in, 3.2 mm), about 33% thinner than that of the base fluid. Although the absolute difference is small (2/32 in; see also the photographs in Figure 10), a thinner filter cake reduces torque and drag, improves wellbore stability, and limits formation damage. These observations show that the Mic-Cal concentration has to be optimized. Mic-Cal is an effective bridging agent at 20 lb/bbl, where it reduces both filtrate volume and cake thickness while keeping the cake thin and of low permeability. At 30 lb/bbl, by contrast, it increases fluid loss and may weaken wellbore stability. Considering sag mitigation, filtration control, and

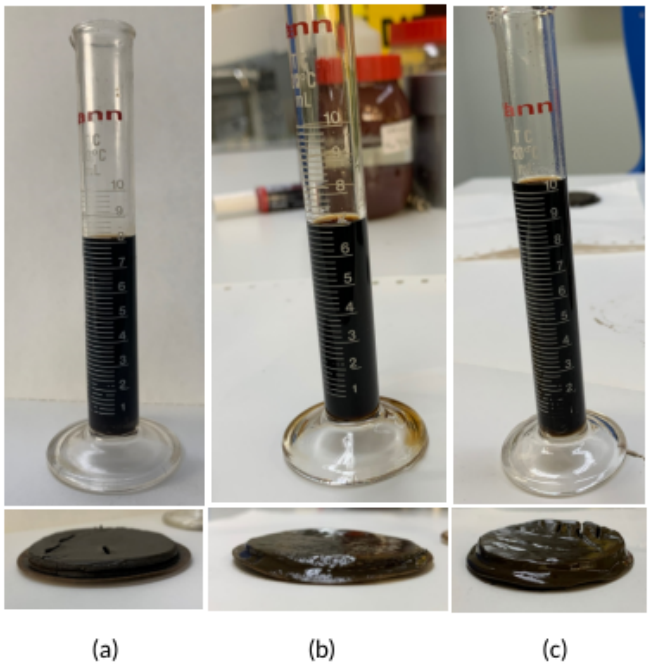


Figure 10. Photographs of the filtrate volumes and filter cakes obtained for the tested drilling-fluid formulations: (a) base fluid, (b) formulation containing 20 lb/bbl Mic-Cal, and (c) formulation containing 30 lb/bbl Mic-Cal.

post-aging rheology together, 20 lb/bbl gave the best overall performance among the formulations tested.

3.5 Rheological Performance Evaluation

This section describes the effect of Mic-Cal concentration on the rheology of the drilling fluid, measured before hot rolling (BHR) and after hot rolling (AHR) at 350 °F (177 °C) for 16 h to simulate elevated downhole temperature. In Figure 11, both the BHR and AHR flow curves show that 20 lb/bbl Mic-Cal gives higher shear stress at a given shear rate than the base fluid, indicating higher viscosity. A more viscous fluid is better able to carry cuttings to surface, which is essential for keeping the wellbore clean. All flow curves are concave toward the shear-rate axis and show a finite stress at low shear rate, i.e., the fluids are shear-thinning with a yield stress, which is the expected behavior of an organophilic-clay-viscosified invert emulsion. Before hot rolling, the 30 lb/bbl formulation showed higher shear stress than the 20 lb/bbl formulation across the tested shear-rate range. After hot rolling, however, the 30 lb/bbl curve was slightly lower than, or comparable to, the 20 lb/bbl curve, so increasing Mic-Cal beyond 20 lb/bbl did not improve post-aging rheology. This difference may be associated with particle aggregation at the higher solids concentration, which can alter the fluid microstructure and flow behavior [30]. The BHR and AHR curves also show an overall reduction in shear stress after hot rolling, consistent with thermal thinning. Even so, the 20 lb/bbl formulation retained a better post-aging rheological response than the base fluid.

Figure 12 supports these observations through AV, PV, and YP. Adding 20 lb/bbl Mic-Cal increased AV by approximately 20% relative to the base fluid, indicating better suspension capability. Increasing the concentration to 30 lb/bbl did not increase AV further, in agreement with the flow curves. PV followed the same pattern, rising at 20 lb/bbl and remaining unchanged at 30 lb/bbl. YP, which reflects the ability of the fluid to initiate flow and suspend cuttings at low shear, rose sharply by approximately 56% (from 9 to 14 lb/100 ft^2) at 20 lb/bbl, but at 30 lb/bbl it was only 22% above the base fluid, showing diminishing returns at the higher concentration. The YP/PV ratio, which is often used as an indicator of low-shear carrying capacity relative to frictional resistance, increased from about 0.39 for the base fluid to 0.54 at 20 lb/bbl and then fell to 0.42 at 30 lb/bbl. Mic-Cal therefore improves rheology, and hence cuttings transport and wellbore stability, up to an optimum of about 20 lb/bbl, beyond which the benefits level off or decline and fluid performance may become less effective. Figure 13 shows the gel strengths of the base fluid and the 20 and 30 lb/bbl formulations after 10 s, 10 min, and 30 min. Mic-Cal increased gel strength at all intervals, from 4 lb/100 ft^2 for the base fluid to 5, 6, and 7 lb/100 ft^2 (about 2.4, 2.9, and 3.4 Pa) at 10 s, 10 min, and 30 min, respectively, for both concentrations. Raising the concentration from 20 to 30 lb/bbl gave no further increase, so additional Mic-Cal beyond this level does not enhance suspension capacity. The base fluid showed flat gels (4 lb/100 ft^2 at all times), whereas both Mic-Cal formulations developed progressive but moderate gels. Such a gel profile is generally desirable, because it supports cuttings and weighting material during static periods without forming a rigid structure that is difficult to break. The improved gel strength is beneficial for maintaining wellbore stability and preventing cuttings settling when circulation stops, and the lack of further increase at higher concentration again points to an optimum near 20 lb/bbl. All measured gel strengths remain within the preferred ranges for oil-based muds, 4-10 lb/100 ft^2 for the 10-s gel and 4-15 lb/100 ft^2 for the 10-min gel [25], so the stronger gel structure should not complicate the resumption of circulation. Taken together, 20 lb/bbl

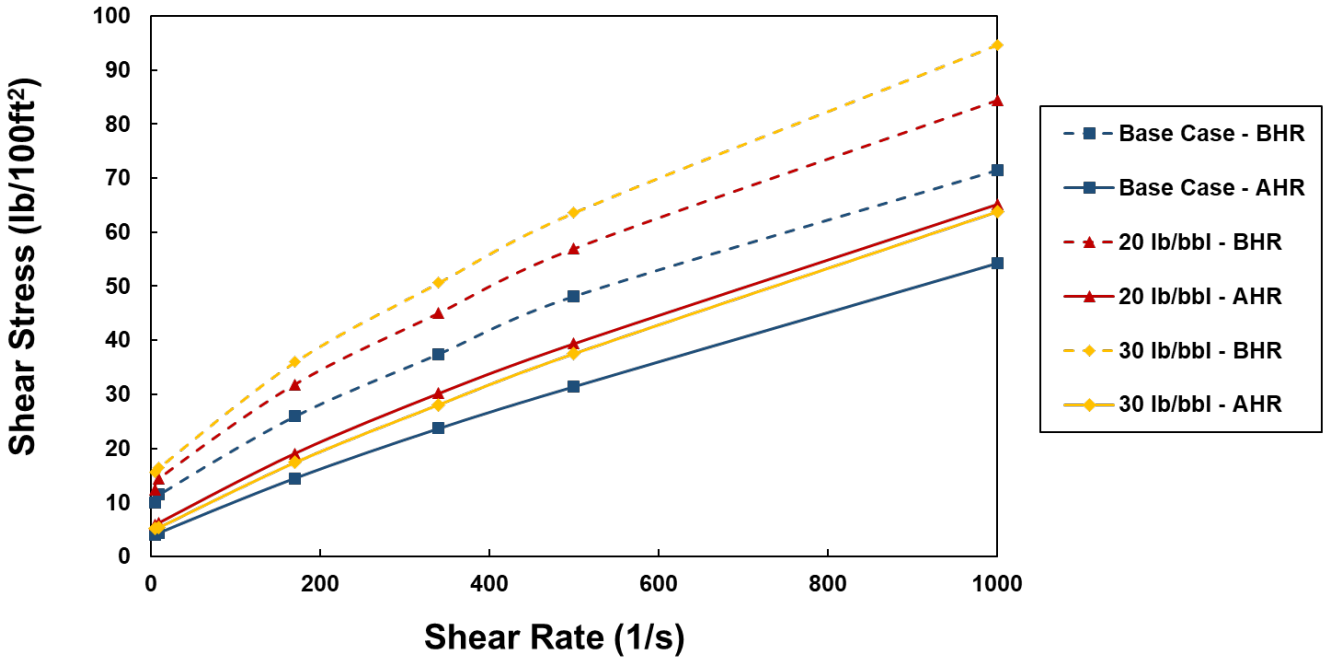


Figure 11. Shear stress versus shear rate for drilling-fluid samples with and without Mic-Cal at different concentrations, measured before hot rolling (BHR, dashed lines) and after hot rolling (AHR, solid lines) at 350 °F (177 °C) for 16 h. BHR curves provide the baseline rheology, whereas AHR curves reflect post-thermal conditioning.

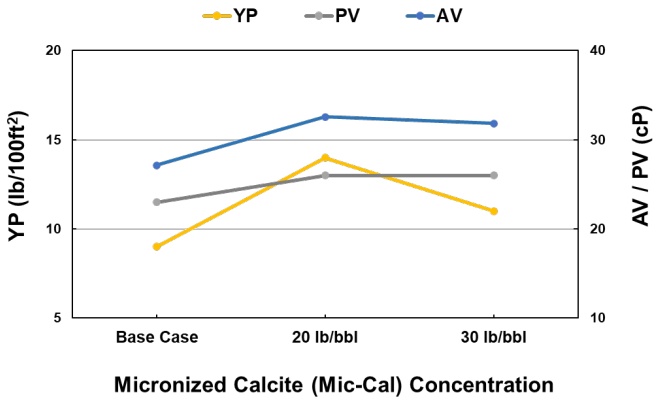


Figure 12. Apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) of the base fluid and Mic-Cal formulations after hot rolling at 350 °F (177 °C) for 16 h (AHR).

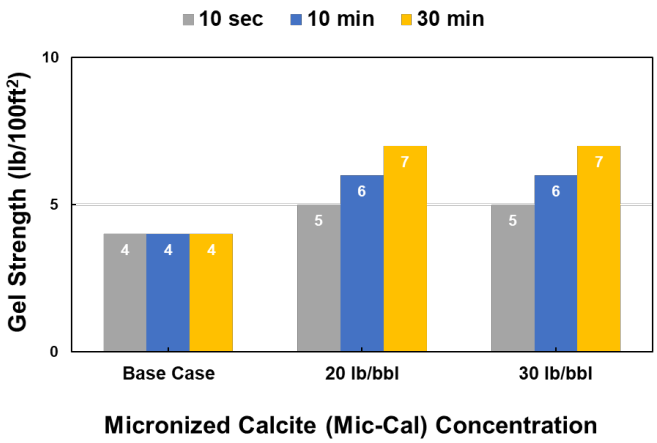


Figure 13. Gel strengths after hot rolling at 350 °F (177 °C) for 16 h (AHR) for the base fluid and formulations containing 20 and 30 lb/bbl Mic-Cal, measured after 10 s, 10 min, and 30 min of rest.

Mic-Cal improves the static carrying capacity of the fluid, and 30 lb/bbl brings no additional benefit.

4 Conclusion

This study evaluated micronized calcium carbonate (Mic-Cal) prepared from Aruma Formation limestone as an additive for an invert-emulsion oil-based drilling fluid. Under the tested laboratory conditions, the following conclusions were obtained:

- Mic-Cal was predominantly micron-sized, with D50 and D90 values of 2.80 and 10.63 μm, respectively.
- A concentration of 20 lb/bbl reduced the static sag factor to 0.52 under both vertical and 45° inclined conditions, compared with base-fluid values of 0.55 and 0.58, respectively.
- At 20 lb/bbl, Mic-Cal provided the most favorable overall performance, increasing apparent viscosity and yield point by approximately 20% and 56% and reducing HPHT filtrate volume and filter-cake thickness by 11% and 33%, respectively.

- Increasing the Mic-Cal concentration to 30 lb/bbl did not further improve post-aging rheological or filtration performance. Therefore, 20 lb/bbl was the best-performing dosage among the concentrations tested.

Data Availability Statement

Data will be made available on reasonable request from the corresponding author.

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Conflicts of Interest

The drilling-fluid additives were supplied free of charge by a drilling-fluid service provider in the Middle East; the supplier had no role in the study design, data collection, analysis, or interpretation of results, or in the decision to publish. The authors declare no other conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable. This study did not involve human participants or animals.

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