

Rheological investigation of effect of high temperature on geothermal drilling fluids additives and lost circulation materials

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ABSTRACT

High temperatures (HT) and the corrosive environment make the design of a geothermal drilling fluid a highly complex task. The presence of HT exacerbates the problems due to thermal degradation. Geothermal aquifers usually combine high-temperature and complex chemistry, making them highly corrosive. Although geothermal drilling fluids are exposed to thermal degradation, research of the effect on mud rheological properties in temperatures near or above 149°C (300°F) is limited.

In this study, a High Pressure-High Temperature (HPHT) rheology setup was used to measure drilling fluids' properties up to 204.4°C (400°F). Rheological behavior of viscosity, density, lost circulation, and alkalinity control additives were analyzed at HT. It was found experimentally that Bentonite alone is thermally stable at HT. In contrast, Caustic Soda showed a tendency to gelate at temperatures above 93.3°C (200°F), adversely affecting mud rheology. Alkalinity control materials to replace Caustic Soda were evaluated. Among them, Lime presented the best thermal stability at 204.4°C with a range of variation of 0.0024 Pa.s (2.4 cP) on apparent viscosity after three consecutive tests. Besides, it was tested 11 different lost circulation materials (LCM) for understanding their rheological behavior at HT. It was found that HT has less impact on fine granular materials rheological behavior with an average increase of 17.7% compared with the baseline. In contrast, flaky, fibrous, and coarse granular materials presented a more apparent impact in WBM rheology with a deviation of 166% compared with the baseline.

Abbreviations

Abbreviations

ECD	Equivalent Circulation Density
HT	High Temperature
HTHP	High Temperature High Pressure
LCM	Loss Circulation Material
NPT	Non-Productive Time
ROP	Rate of Penetration
PV	Plastic Viscosity
WS	Wellbore Strengthening
WBM	Water-Based Mud
YP	Yield Point

1. Introduction

The drilling fluid is a critical component of the well construction process. The essential functions of drilling mud are evacuating drilling

cuttings, avoiding the wellbore collapse, preventing the invasion of formation fluids into the wellbore, and cooling and lubricating the drill bit and drill string, among others. Special attention is given to its efficiency, as the drilling fluid is involved in every operation in the well construction process. In principle, the geothermal drilling fluids do the same functions as oil and gas drilling fluids; however, the geothermal temperatures can cause thermal degradation. This condition compromises some of their rheological properties.

One of the most adverse effects of high geothermal temperatures on the WBM fluids is the mud gelation. Mud gelation has been reported in different geothermal fields throughout the US (Cromling, 1973; Liles et al., 1976; Varnado and Stoller, 1978; Nuckols et al., 1981; Zilch et al., 1991; Tuttle and Listi, 2003; Tuttle, 2005; Finger and Blankenship, 2010). Alderman et al. (1988) suggested that the combined effect of clay dispersion and flocculation at geothermal temperatures causes an increase in yield stress and low shear viscosity. Tuttle and Listi (2003) suggested that gelation can also be caused by the solids drilled containing strongly for the free water in the fluid system. This contributes to mud dehydration and a severe rise in viscosity.

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Nomenclatures

°C	Celsius Degrees
CaCO ₃	Calcium Carbonate
°F	Fahrenheit Degrees
KOH	Potassium Hydroxide
NaOH	Caustic Soda
NH ₄ Cl	Ammonium chloride
ppb	Pounds Per Barrel
ppg	Pounds Per Gallon

The complexity of geothermal drilling makes it essential to use additives to control density, viscosity, alkalinity, filtration, and fluid loss. However, placing together additives to perform these functions does not ensure a successful application in geothermal operations. HT exposure to some mud additives has a noticeable impact on the rheology of drilling fluids. However, identifying individually which additives of the mud formulation are originating gelation has not been widely studied.

Mud gelation can cause various problems during drilling. A thick filter cake can lead to differential sticking, swab, and surge during tripping or gas retention in the mud. This unfavorable condition increases the frictional pressure losses during circulation, leading to an increase in the equivalent circulation density (ECD). This condition in narrow mud window operations could lead to induce mud losses. Drilling fluid gelation can also implicate the cementing jobs. Firstly, they appear to contaminate the cement. Secondly, drilling fluids gelled and thickened leaving a thick filter cake in the formation and the casing surfaces. This prevents correct cement bonding. Besides, thickened mud can cause cement channeling behind the casing, leading to large zones poorly or not cemented. Such zones can be filled with water that can vaporize at geothermal temperatures, creating voids that can lead to casing collapse (Varnado and Stoller, 1978).

The high temperature will also cause degradation of some WBM additives affecting their rheology and filtration control properties. Amani and Al-Jubouri (2012) corroborate experimentally that changes in the temperature significantly affect the rheological properties. The authors of the study suggest that the rheological behavior of drilling fluids tested under high temperature is the product of the mud components' thermal degradation. This degradation generates a molecular expansion that lowers the drilling fluid resistance to flow; thus, its plastic viscosity, yield point, and gel strength. These conditions compromise the drilling fluid cuttings carrying capacity, affecting the hole cleaning during the drilling operation.

This makes it worthwhile to evaluate the effects of specific components individually in the drilling fluid rheology when exposed to high temperatures. This may help identify some of the characteristics that made some additives more sensitive to high temperature exposure than others.

Besides, corrosive conditions are present in geothermal drilling. Geothermal aquifers usually combine high-temperature and complex chemistry, making them highly abrasive and corrosive (Finger and Blankenship, 2010). In geothermal fields in the US and Europe, it is not rare to find native brines with very high solid content (250,000 ppm). Furthermore, the presence of corrosive gasses such as H₂S and CO₂ makes this environment extremely challenging for the conventional alloys present in the drill pipe, bottom hole assembly (BHA), and drilling tools (Klapper and Stevens, 2013). It is frequent that in geothermal fields, reservoir fluids have pH values ranging from 5.7 to 7.6 (Liles et al., 1976).

The most impacting problem during drilling geothermal wells is the mud losses, mainly due to its high frequency and the high cost associated. The highly fractured rock environment found in geothermal drilling is one of the most common causes of massive mud loss events.

Fractures that measure from 1 to 3 thousand microns, or more, are complicated to seal and cure (Vivas et al., 2020). The lost circulation in geothermal drilling can represent 15% of the total drilling costs (Finger and Blankenship, 2010).

1.1. Drilling fluids in geothermal wells

In general, drilling fluid systems consist of base fluid (in WBM muds, the base is water), active and inert solids, and additives. These additives control the main drilling fluid properties; density, viscosity, chemical reactivity, and fluid loss control.

Drilling reports from various geothermal wells in many reservoirs revealed common drilling mud properties (Finger and Blankenship, 2010). These properties are summarized in Table 1:

1.1.1. Density

Mud density must be designed considering the pore pressure (formation pressure) and the fracture gradient expected. In geothermal applications, it is not rare that formation pressures are lower than O&G wells. WBMs of 1.08 to 1.20 g/cm³ (9 to 10 ppg) are typically used for geothermal drilling, though aerated muds are used to prevent mud losses (Liles et al., 1976). A geomechanical study is essential to understand the near-wellbore stresses, especially to avoid wellbore instability or formation fracture.

Density can be raised using weigh agents such as barite (the most common weighting agent) without unnecessarily modifying other drilling fluid properties. Density increased by drilling solid's content (e.g., cuttings or cavings) is undesirable. Adverse effects derived from the increase of drilling solids include reducing the penetration rate (ROP), filter cake thickening, and the wear of BHA/drill pipe tubular and mud pump parts by abrasion (Culver, 1998).

1.1.2. Viscosity

Viscosity, according to the needs, can be increased using viscosifiers or decreased using thinning agents. API quality bentonite is the predominant viscosifier for geothermal drilling. Required rheological properties can be controlled with bentonite in moderate concentrations (14.3-57 kg/m³), with good results in filter cake and viscosity (Tuttle, 2005). Nevertheless, not all bentonites are recommended for geothermal operations. Sepiolite and attapulgite can generate adverse effects such as wellbore instability, thicker filter cake, and inadequate plastic viscosity and yield point. Instead, the usage of high-quality bentonite clay is recommended (Tuttle and Listi, 2003).

The usage of polymers is also practical; however, polymers are highly affected when exposed to HT for a long time. Their primary application is for high viscosity pills for hole cleaning before wiper trips, electric logs, running casing/liners, or cementing jobs. Recent advances in proprietary HTHP polymers have successfully generated mud thinning and gel inhibition (Finger and Blankenship, 2010).

1.1.3. Alkalinity control

Selecting the appropriate fluid alkalinity is essential for the control of corrosion. Geothermal drilling fluids with high pH are necessary to regulate the effects of certain wellbore pollutants (CO₂ and H₂S). This is indispensable to mitigate corrosion and improve the solubility of certain

Table 1
Typical Geothermal Drilling Fluid Properties (After Finger & Blankenship 2010).

Property	Range
Density	1.03 – 1.15 g/cm ³
Funnel viscosity	35 – 55 sec
pH	9.5 – 11.5
Plastic viscosity	0.01 – 0.02 Pa.s
Yield point	35 – 125 kPa

drilling fluid additives (Finger and Blankenship, 2010). In fields as The Geysers, Imperial Valley, and Steamboat Springs, caustic soda (NaOH) has been used for alkalinity control (Liles et al., 1976). The incorporation of caustic soda in the system has been a conventional way of increasing alkalinity. However, caustic potash (KOH) has been increasing its popularity in geothermal applications due to its advantages in wellbore stability (Tuttle, 2005).

1.1.4. Filtration

This property represents how well the drilling fluid builds an impermeable coating on the wellbore wall to avoid leakage into the permeable rocks. As the hydrostatic pressure of the drilling fluid column must be higher than the pore pressure to prevent the influx of the formation fluids, the filter cake can prevent the drilling fluids could continually penetrate the permeable formations. It is essential that the mud quickly generates a filter cake capable of reducing fluid loss. Besides, the filter cake needs to be sufficiently thin and easy to remove to permit the production flow into the wellbore throughout the well's production stage (Caenn et al., 2016).

Various additives for filtration control apply to geothermal drilling operations. The most commonly used is lignite, thanks to its low cost and high accessibility. Lignite concentrations up to 34.2-57 kg/m³ are also needed for sufficient filtration control. However, thermal degradation can generate carbonate contamination in the mud, contributing to very high viscosity (Tuttle and Listi, 2003).

1.1.5. Drilling fluids formulation

As a minimum, a drilling fluid formulation designed to address geothermal conditions must include a thermal stable viscosifier, a filtrate control additive, a pH buffer, and LCM if mud losses are expected. In addition to the high-temperature constraints, the main limitations are the low-density requirement and the cost of the additives. Some high-tech HPHT additives are cost-prohibitive for geothermal applications. That could easily turn a technically properly designed well into an economic failure (Vivas et al., 2020).

Tuttle (2005) presented a summary of different additives recommended for geothermal applications based on field experience or promising lab tests (Table 2). To generate a basic formulation that meets the conditions mentioned above, the cited table's additives provide a good initial step. Most of the components can be easily found and they are relatively inexpensive.

1.2. Lost circulation materials

Lost circulation materials have been used for decades in the O&G and geothermal industry to seal and cure mud losses. Mostly, experimental studies on LCM are oriented to evaluate their capabilities in bridging and sealing fractures.

Few studies have evaluated the rheological behavior of lost

Table 2
Product Selection Criteria for Geothermal Drilling Fluid Systems (After Tuttle 2005).

Property/Characteristic	<177°C (<350°F)	177°C > (>350°F)
Rheology Control (Viscosity Increase)	API Bentonite, Synthetic Polymers	API Bentonite, Synthetic Co-Polymers
Rheology Control (Thinning)	Polyacrylates, Desco CF	New Co-Polymer Blends, Lignite, Desco CF
Filtrate/Water Loss Control	PACs, Starch Derivatives, Acrylamides	HT PAC Blends, Modified Acrylamides, Lignite
Alkalinity/pH Control	Caustic Soda, KOH, Lime	Caustic Soda, KOH, Lime
Inhibition/Lubricity	K+, Al+++--Based Additives, Gilsonite, TORKease	K+, Al+++--Based Additives, Gilsonite, TORKease
Lost Circulation	Cottonseed Hulls, Sawdust, Crosslink Plugs	Cottonseed Hulls, Sawdust, Crosslink Plugs

circulation materials. Iscan and Kok (2007) investigated the effects of walnut shells on WBM rheological properties. The authors found experimentally that an increase in walnut shells mass concentration beyond 114 kg/m³ makes the fluid unstable and susceptible to flocculate. Kulkarni et al. (2012) researched the rheological behavior and its potential influence on the plugging performance of carbon graphite. The authors suggest an influence in the drilling fluid normal stress with different LCM concentrations and its filtration performance.

It is generally accepted that high temperatures influence the rheological properties of drilling fluids containing LCMs. Conversely, the effect of the temperature on the LCMs performance is not fully understood (Alsaba et al., 2014). Alsaba et al. (2014) found experimentally that the sealing pressure is affected by temperature increase. For a blend of granular materials (graphite and calcium carbonate), the temperature increment from room temperature to 82.2°C reduces the sealing pressure by 8%. In the same research, a nutshell and graphite LCM with a mass concentration of 114 kg/m³ was tested in the same conditions, where the reduction in sealing pressure was above 30%.

2. Materials and methods

One of the objectives of this study consists of building a base WBM formulation with thermal stability. This base WBM will serve as the foundation for a mud recipe that addresses the geothermal challenges. The main challenges are related to the degradation of rheological properties and filtration and fluid loss prevention. A successful geothermal mud recipe must contain additives to control pH and fluid loss, maintaining rheological stability at HT conditions.

2.1. Materials and equipment

In Table 3, the materials tested to find a basic geothermal mud formulation are presented. These materials are among the most commonly used in geothermal applications. They also were selected due to their easy availability and their relatively low cost. Those conditions are relevant since geothermal drilling operations are very cost-sensitive.

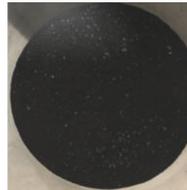
The materials presented are ready to use and required no preparation, except for the cedar fiber sieved in a 600µm mesh sieve shaker. This was done to have a more homogeneous size distribution of this material and obtain consistent results during experiments.

In Table 4, the lost circulation materials evaluated in this

Table 3
Materials selected for 1st stage of experiments.

Material	Concentration	Property	Acronym
Bentonite	57 kg/m ³ (20 ppb)	Rheology Control – Viscosity Increase	20B
Lignite	14.3 kg/m ³ (5 ppb)	Thinning - Dispersant	5LG
Caustic Soda	1.43 kg/m ³ (0.5 ppb)	Filtrate/Water loss Control	0.5CS
	2.85 kg/m ³ (1.0 ppb)		1.0CS
	4.28 kg/m ³ (1.5 ppb)		1.5CS
Potassium hydroxide	1.43 kg/m ³ (0.5 ppb)	Alkalinity/pH Control	0.5KOH
	2.85 kg/m ³ (1.0 ppb)		1.0KOH
	4.28 kg/m ³ (1.5 ppb)		1.5KOH
Lime	1.43 kg/m ³ (0.5 ppb)	Alkalinity/pH Control	0.5Lime
	2.85 kg/m ³ (1.0 ppb)		1.0Lime
	4.28 kg/m ³ (1.5 ppb)		1.5Lime
Cedar Fiber	14.3 kg/m ³ (5 ppb)	Lost Circulation	5CF

Table 4
Lost Circulation Materials selected for the experimental study.

Walnut Fine	Walnut Medium	Sawdust	Altavert	Graphite Blend	Bentonite Chips
					
Granular Non-deformable LCM Chemical inert Biodegradable SG: 1.25-1.30 Micronized Cellulose (MICRO-C)	Granular Non-deformable LCM Chemical inert Biodegradable SG: 1.25-1.30 Magma Fiber Fine	Flaky/Fibrous Deformable LCM Temporary temperature degradable SG: 0.4-0.6 Diatomaceous earth/amorphous silica powder (DEASP)	Fiber Deformable LCM Hole sweep additive Temporary temperature degradable Cotton Seed Hulls	Granular Non-deformable LCM Blend with different sizes Torque reducing material SG: 2.19-2.26 Calcium Carbonate	Granular Deformable LCM Non-toxic SG: 1.11-1.14 (dry) Cedar Fiber
					
Granular Deformable LCM Water-insoluble Cellulosic Material SG: 1.3	Fiber Deformable LCM Acid soluble Non-fermenting and non-corrosive SG: 2.6	Granular Non-deformable LCM Silica powder Squeeze pill design	Fiber Deformable LCM Biodegradable Temporary temperature degradable SG: 0.24	Granular Non-deformable LCM Acid soluble A blend of three sizes: 200, 80, and 30 CC SG: 2.75	Fiber Deformable LCM Water-insoluble Cellulosic Material SG: 0.6

experimental study are presented. These are some of the most often utilized LCM in geothermal applications. They were also chosen because of their ease of availability and inexpensive cost.

The HPHT rheometer has a frictionless bob shaft construction capable of instantly measuring small changes in shear stress by a non-mechanically rotational torque signal. The Fig. 1 presents the diagram of the components used to perform the HPHT rheology experiments.

2.2. Experiments Design.

In Fig. 2, the experiment workflow is presented. All samples were tested using the same protocol and measurement sequence. For consistency purposes, all samples were aged for 24 hours. The aging helps the additives to be hydrated. The testing temperature is 204.5°C, and the testing pressure is 2.76 MPa. In the first stage of experiments, the additives' thermal stability was analyzed at high temperatures. Once thermally stable additives were identified, a WBM base formula was generated. This base formulation was tested in an extended test to confirm its thermal stability. Finally, this formulation is used to perform a rheological screening of 11 different LCMs. The purpose is to identify

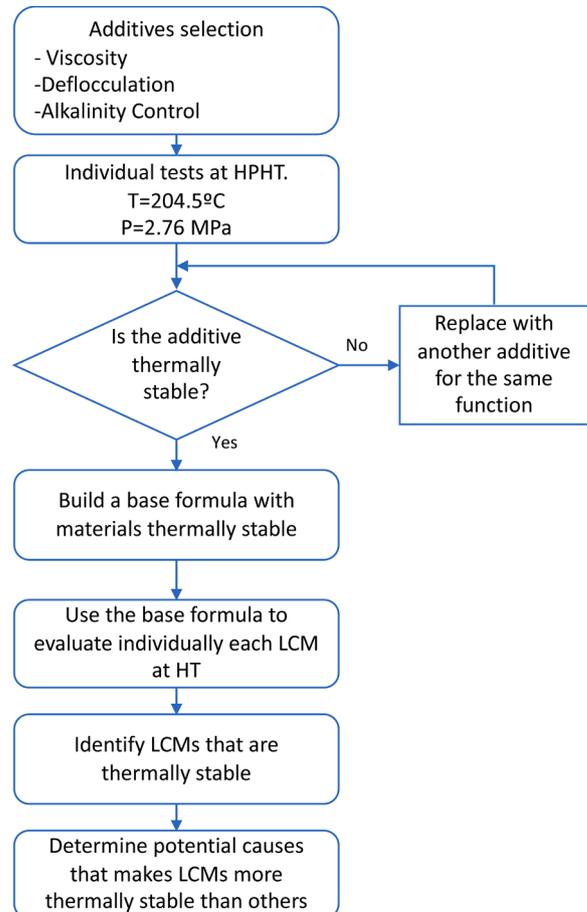


Fig. 2. Diagram of the experiment workflow.

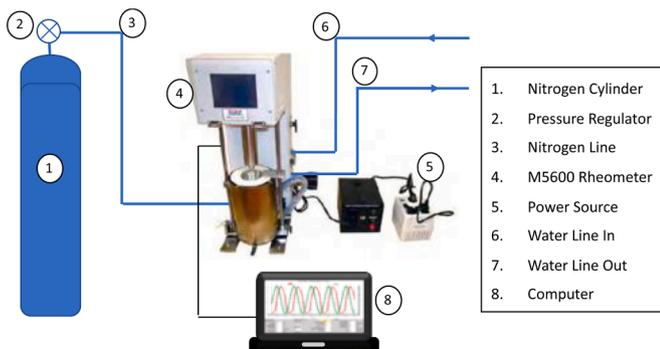


Fig. 1. Diagram of HPHT rheology test setup.

characteristics and components that make some materials more thermally stable than others, and therefore, more adequate to geothermal conditions.

3. Test results and analysis

To establish a base scenario, a WBM formulation was designed. Distilled water was mixed with bentonite (20B) as viscosifier, caustic soda (0.5CS) for alkalinity control, and cedar fiber (5CF) as LCM. The MW of the sample was 1.032 g/cm^3 (8.6 ppg). In Fig. 3, it is presented the apparent viscosity at a constant shear rate (170 s^{-1}) for the samples heated up from room temperature to 204.5°C . The viscosity of the sample was relatively stable up to 93.33°C . After 93.33°C , rheological behavior considerably changed, showing a viscosity increase until reaching 193.33°C . Then, the viscosity reading started showing a decrease. After the test was finished, the temperature was decreased to 29.5°C , and the pressure was ramped down to room pressure before removing the sample cup. Once the sample cup was removed, it was found that the mud sample had a portion that was gelled (Fig. 4), mainly located above the rheometer bob (red rectangle in Fig. 4). This could be an explanation of the behavior observed in Fig. 3. As the sample was heated above 93.33°C , the viscosity began to increase, and the mud sample began to thicken. As a result of the bob rotation, part of the sample was removed from the sample cup and accumulated at the top of the bob (Fig. 4). This reduction in the sample cup volume causes the torque on the bob to be decreased, and the viscosity measurement appears to decline.

Also, a low viscosity liquid portion with a high concentration of cedar fiber was settled at the sample cup bottom.

The experiments showed a separation of a gelled portion and a liquid portion of the samples. The cedar fiber accumulated on the sample cup bottom could be explained by the lack of suspension capability of the degraded mud.

In this experiment, some of the gelled fluid was accumulated outside the sample cup, causing a decrease in the sample cup volume. In this case, the torque on the bob decreases, and the viscosity measurement seems to fall. Therefore, the reduction in viscosity observed when the sample reached 193.4°C was probably an effect of mud gelation rather than a reduction in the sample viscosity.

To understand the potential cause of gelation, each component of the mud was tested individually. This permits to recognize their particular thermal stability and contribution to the gelation effect. The first test was performed with distilled water and 57 kg/m^3 of bentonite concentration. An extended test was performed to replicate the effect of three "circulations". In this test, the bentonite sample was exposed to 3 consecutive temperature ramp-ups. Initially, the fluid was ramped up from 29.5°C to 204.5°C at a constant shear rate (170 s^{-1}). Then, the sample was cooled down to room temperature and again ramped up to 204.5°C . This process was repeated three times to replicate the effect of temperatures ramp-up and cooling-down during drilling. This simulates

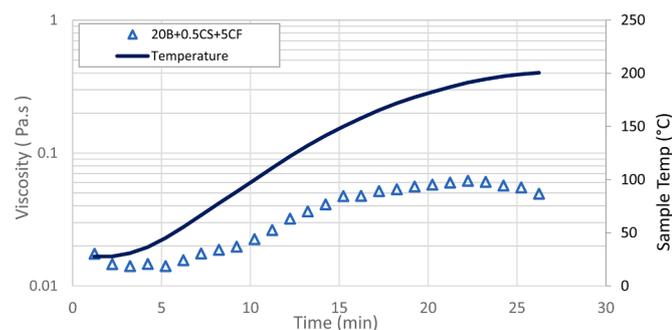


Fig. 3. Apparent viscosity of mud sample composed of Bentonite, Caustic Soda, and Cedar Fiber.



Fig. 4. A gelled portion of samples placed on top of the rheometer bob after 193.4°C test (left), and a portion of mud sample with a high concentration of burn Cedar Fiber in the bottom of the sample cup (right).

the thermal stress when the mud is circulated from the surface at ambient temperature, then pumped down where it is heated up until reaching the drill bit (maximum temperature), and then cooling down when the mud flows through the annular to surface and cooled in cooling towers. The test results showed that bentonite alone has a very high thermal stability (Fig. 5).

Once Bentonite thermal stability was verified, samples of bentonite (20B) combined individually with caustic soda (0.5CS), lignite (5LG), and cedar fiber (5CF) were prepared. The caustic soda concentration was selected due to its primary function as a pH buffer, rather than its effect on the mud rheology. Increasing the alkalinity to higher values than required could have adverse effects on drilling tools and casing.

In Fig. 6, there are presented the apparent viscosity at constant 170 s^{-1} of bentonite alone (20B), bentonite and cedar fiber (20B+5CF), bentonite and lignite (20B+5LG), and bentonite and caustic soda (20B+0.5CS). The results observed permit us to infer that caustic soda has poor thermal stability. At 65.6°C , the viscosity of the sample of bentonite and caustic soda was around 0.017 Pa.s , then when the temperature was increased to 176.7°C , the sample viscosity increased up to 0.08 Pa.s . This is more than 4 times the previous value. This shows how this sample is sensitive to the temperature increase. Additionally, the rheology test with caustic soda failed during readings at 204.5°C , where the rheometer rotor was staled out.

In Fig. 7, the rheometer bob pictures and the liquid portion recovered after each test are presented. Sample (a) is the bentonite alone (20B), sample (b) is bentonite with caustic soda (20B+0.5CS), sample (c) is bentonite with cedar fiber (20B+5CF), and sample (d) is bentonite with lignite (20B+5LG). The sample with caustic soda (sample b) shows a high amount of gelled portion, with less liquid phase recovered than the other samples. This confirms the rheometer readings. The sample of bentonite and cedar fiber (sample c) presented a reduction in viscosity from 0.056 to 0.025 Pa.s when ramped up from room temperature to 148.9°C . Then, the viscosity started to increase up to 0.068 Pa.s at 204.5°C . When the bentonite and cedar fiber sample was removed from the sample cup, it was found the sample viscosity increased. However, it was not found any evidence of mud gelation. The bentonite and lignite sample (sample d) presented similar behavior compared with the bentonite sample alone, suggesting they have an acceptable thermal resistance.

To verify if the caustic soda concentration has some gelation effect, samples of distilled water with bentonite and cedar fiber (20B+5CF) were prepared. Then, it was added caustic soda at different concentrations (0.5CS, 1.0CS, and 1.5CS). In Fig. 8 presents the apparent viscosity at a constant shear rate (170 s^{-1}) for the 3 samples, showing that caustic soda concentration has an apparent impact on mud samples rheology behavior. All 3 samples were relatively stable up to 93.3°C , rheological behavior considerably changed, showing a viscosity increase. The viscosity increase varies with the concentration of caustic soda. For operations requiring relatively high mud alkalinity, the caustic soda concentration increase will contribute to mud gelation.

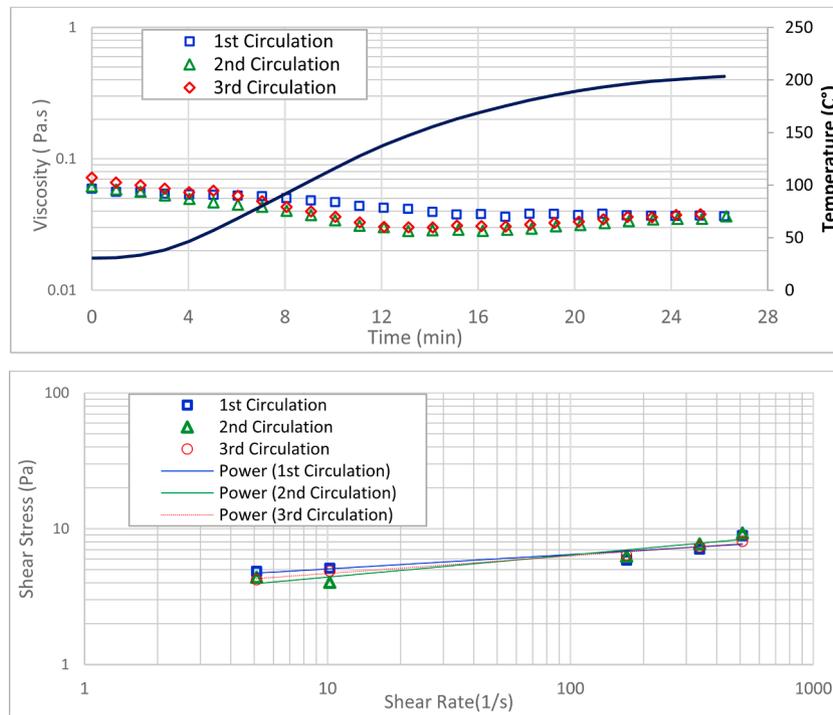


Fig. 5. Apparent viscosity vs. temperature and rheology of a sample of distilled water + Bentonite (20 ppb).

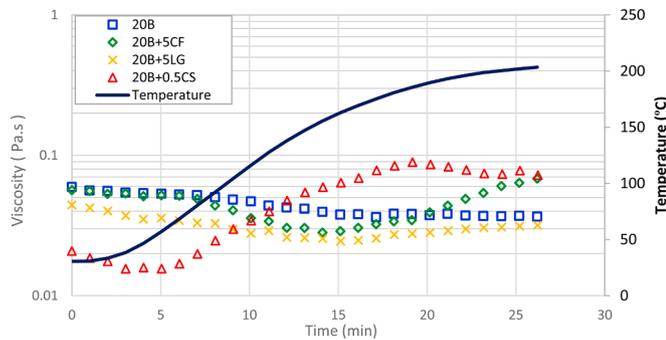


Fig. 6. Apparent viscosity vs. temperature and rheology of different samples.

Consequently, the need for an alternative pH buffer additive has been identified.

3.1. Replacing caustic soda (NaOH) as pH buffer

Potassium hydroxide (KOH), and lime (inorganic, calcium-based mineral), are alternatives for pH regulation in geothermal drilling (Tuttle, 2005). Due to their easy availability and relatively low cost, both were selected to be tested in the laboratory at geothermal conditions as potential caustic soda replacers for alkalinity control.

In the first experiment, it was prepared a sample of bentonite, lignite, and cedar fiber (base formulation) combined with KOH (1.43 kg/m³ - 0.5 ppb). A long test was performed with this formulation replicating the effect of 3 "circulations". The same sample was exposed to 3 consecutive temperature ramp-ups from 29.5°C to 204.5°C at a constant shear rate (170 s⁻¹), then cooled down to room temperature, and again ramped up to 204.5°C (Fig. 9).

The results showed that the formulation with KOH tends to increase the viscosity above 148.9°C. Also, at 204.5°C, results varied among circulations. In the first circulation, the sample viscosity was 0.0864 Pa.s. Then, in the second and the third circulation at the same temperature, the viscosity values were 0.1068 Pa.s and 0.0825 Pa.s, respectively.

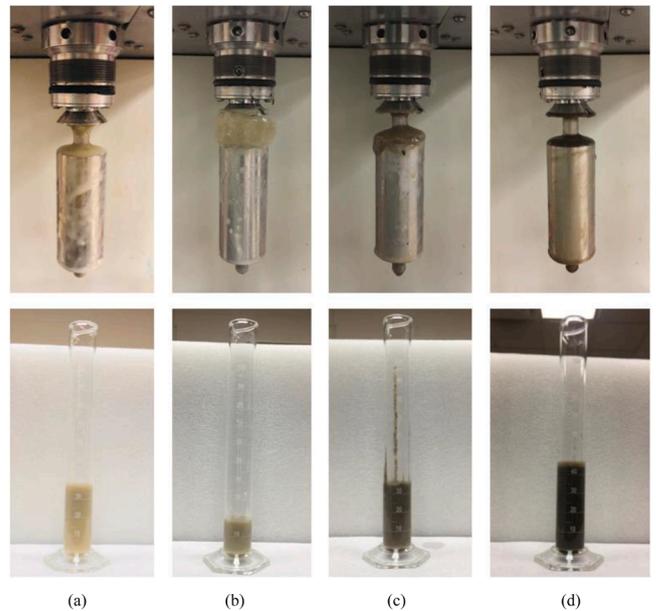


Fig. 7. Pictures of rheometer's bob and liquid portion of the samples of bentonite alone (a), bentonite + caustic soda (b), bentonite + cedar fiber (c), and bentonite + lignite (d).

Besides, during experiments, it was found that once the sample was aged and stirred, a thick and strong foam layer was formed at the mixing vessel surface. This kind of foam can generate undesired effects if not controlled with defoamer.

The second alkalinity control material tested was lime. It was prepared a sample of bentonite, lignite, and cedar fiber (base formulation) combined with lime (1.43 kg/m³ - 0.5 ppb). Also, an extended test was performed with this formulation replicating the effect of 3 "circulations". The same sample was exposed to 3 consecutive temperature ramp-ups from 29.5°C to 204.5°C at a constant shear rate (170 s⁻¹). Then, the

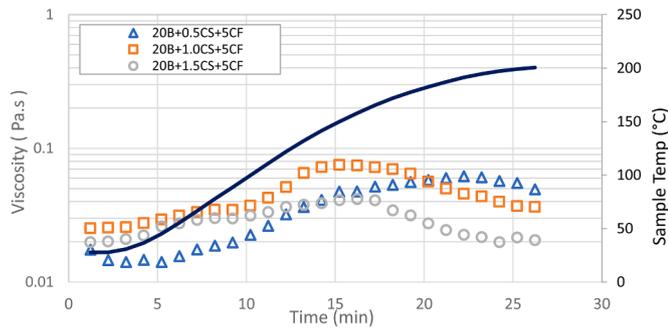


Fig. 8. Apparent viscosity of a mud sample measured at $170s^{-1}$ varying caustic soda concentration.

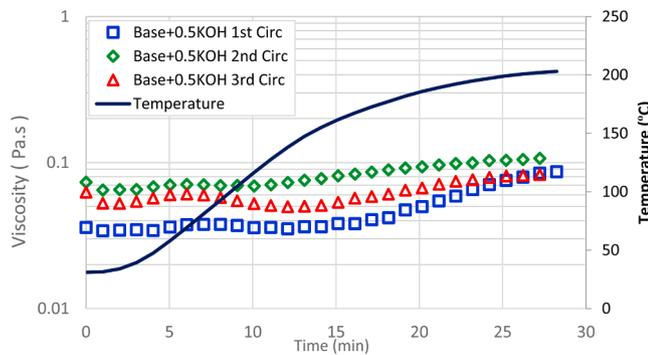


Fig. 9. Apparent viscosity vs Temperature of WBM formulation with bentonite (20B), KOH (0.5KOH), lignite (5LG) and cedar fiber (5CF).

sample was cooled down to room temperature and again ramped up to $204.5^{\circ}C$ (Fig. 10).

The results showed that the formulation with lime presents consistent values, especially after the first circulation. During the 3 circulations, once the sample reached the target temperature of $204.5^{\circ}C$, the sample becomes stable. Apparent viscosities around 0.06 Pa.s, with a range of 0.0024 Pa.s, were registered after the sample reaching $204.5^{\circ}C$ (Fig. 10). The results show that once the sample is initially heated up to HT, it can maintain stable properties. The stability remains despite the thermal stress caused by the heating up and cooling down during the circulation process. After each temperature ramp-up, the rheology readings were taken. Consistency Index (K) and Flow Behavior Index (n) were computed at $204.5^{\circ}C$ (Table 5). K and n values slightly decrease after each temperature ramp-up, but the decrease is not extensive. The results confirm that despite the thermal stress imposed on the sample, the rheological results remained consistent.

To evaluate the lime effectiveness as alkalinity control at HT, it was

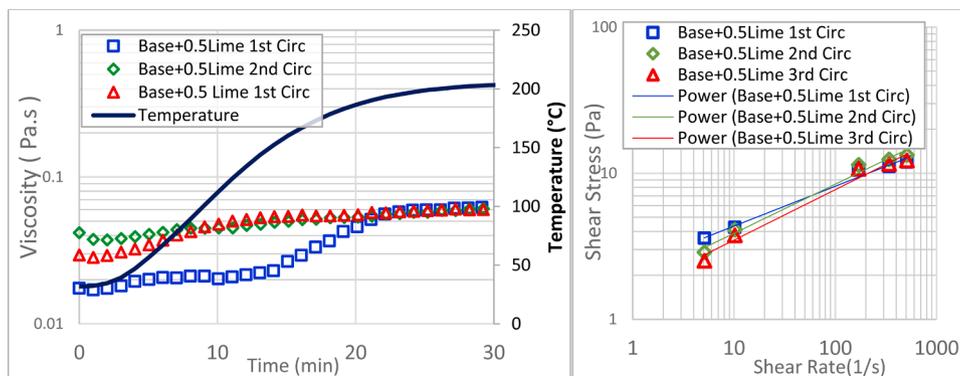


Fig. 10. Apparent viscosity vs temperature and rheology of WBM formulation with bentonite (20B), lime (0.5Lime), lignite (5LG) and cedar fiber (5CF).

Table 5

Consistency and Flow Behavior Indexes at $204.5^{\circ}C$ after consecutive temperature ramp-ups.

Sample	Consistency Index K	Flow Behavior Index n
Base+0.5 Lime 1st Temp Ramp-up	2.319	0.223
Base+0.5 Lime 2nd Temp Ramp-up	1.790	0.336
Base+0.5 Lime 3dr Temp Ramp-up	1.571	0.346

performed additional rheology tests. Samples of bentonite (20B), combined with lignite (5LG), and changing the lime concentration to 3 different concentrations (0.5Lime, 1.0 Lime, and 1.5Lime), were tested. For each test, the temperature was ramped up from $26.7^{\circ}C$ up to $204.5^{\circ}C$. Then, the temperature was maintained for 1 hour. This experiment evaluates the sample thermal stability exposed to the HT and if thermal stability remains during the time assessed. In Fig. 11, the test results are presented. During the period of time evaluated, there is no significant increase or decrease in the apparent viscosity, making this material suitable for the conditions tested.

Finally, to confirm the lime capability for alkalinity control, the pH was measured in the three samples tested. In Fig. 12, it is presented the pH test results. The lime concentration increase has an impact on increasing the sample pH. Adding $2.85\text{ kg}/m^3$ (1 ppb) of lime to the base sample+0.5 lime increased the pH by 1.75 units, and rheology variation was just 0.0016 Pa.s at $204.5^{\circ}C$. In this case, lime can adjust the alkalinity without a significant impact on the mud sample rheological behavior.

3.2. Establishing a base WBM for high temperatures

For establishing a base case scenario, a mud formulation with

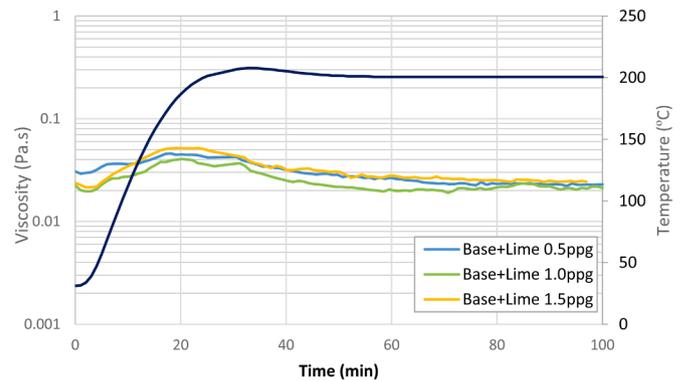


Fig. 11. Apparent viscosity at a constant shear rate ($170s^{-1}$) of a base mud with 0.5Lime, 1.0 Lime, and 1.5Lime.

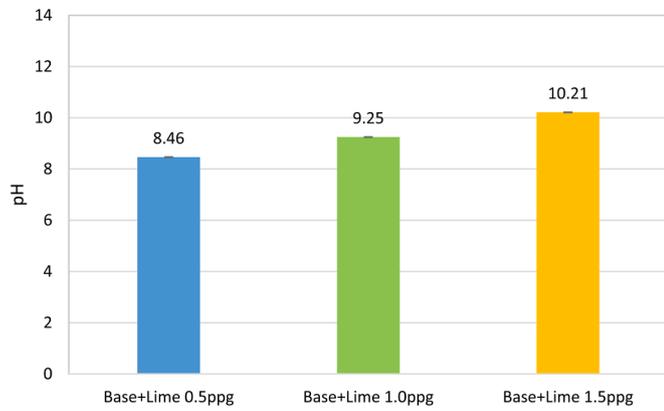


Fig. 12. pH measurements of a base mud with 0.5Lime, 1.0Lime and 1.5Lime.

bentonite, lignite, and lime (materials tested thermally stable) was prepared. To modify the density from 1.03 to 1.32 gr/cm³ (8.6 ppg to 11 ppg), barite was included. This sample, without LCMs, was tested at a constant shear rate (170s⁻¹). The objective of adding Barite is to evaluate the new formula to be density adjustable while thermally stable. The test comprises two stages; in the first stage, the temperature was ramped up from 32.2°C to 148.9°C. Then, in the second stage, the temperature was maintained constant at 148.9°C for 1 hour. The objective is to evaluate the mud thermal stability at high temperatures. Once the sample reached 148.9°C and maintained HT for 1 hour, the apparent viscosity did not present major fluctuations (±0.004 Pa.s to the average rheology at 148.9°C) (red line in Fig. 13 and Fig. 14). This confirmed the results obtained during the previous experiments, where all the base formulation components were tested as thermally stable.

The main advantage of this thermal stable formulation (Table 6) is that it permits identifying the effects of the temperature of the different LCM's and its impact on rheology. Any major variation of the sample rheology can be attributed to the LCM (or chemical interaction of the particular LCM with any of the mud components) tested in this experimental stage. The adjusted mud density prevents LCM sag during tests.

3.3. LCM HPHT rheology tests

After the establishment of a base scenario, 11 different LCM's; walnut fine, walnut medium, sawdust, Altavert, graphite blend, bentonite chips, micronized cellulose, magma fiber fine, diatomaceous earth/ amorphous silica powder (DEASP), cottonseed hulls, and calcium

carbonate blend, were tested individually, mixed with the base formulation (Table 7).

After analyzing the test results, a difference in the rheological behavior of coarsely granular, flaky, and fibrous materials was noticed. In Figs. 13,14, rheology tests of the mentioned materials are presented. The average percent difference between rheology readings of coarsely granular, flaky, and fibrous materials compared with the baseline is 166%. Fibrous materials, sawdust and magma fiber represent the highest variations to the baseline with 336% and 283%, respectively. Those materials also were tested prone to be gelled more than the rest of the materials. Walnuts also presented a high deviation in viscosity with a relevant observation. Walnut medium size LCM presented a variation of 219% to the baseline, and walnut fine presented a variation of 152%. If it is considered that both materials chemistry and physical properties are the same, the variation can be attributed to the size difference. Larger walnut size presented a greater deviation of rheology.

The LCM of this group that behaves similar to the baseline was the bentonite chips. Initially, as this LCM is made of bentonite, it seemed plausible that the material has a neutral effect. However, it was noticed that when this material was incorporated into the mud and mixed it, it started to agglomerate. The material was mechanically separated and incorporated with the mud into the rheometer sample cup for the HPHT rheology test. Once the test finished and the sample cup was disassembled, it was found that the bentonite chips again agglomerated and stuck together on the bottom of the sample cup. As the material was found separated from the liquid portion of the sample, it is difficult to identify if the effect of the LCM in the rheology was measured or not. The bentonite chips concentration in the rheology test was 42.8 kg/m³. Different attempts to mix the material at different conditions were tried without success. Mixing the material without aging or mixing with reduced concentrations of 28.53 and 14.27 kg/m³ was attempted. However, in all of them, the bentonite chips agglomerated and deformed.

A group of fine granular materials was tested at the same conditions; calcium carbonate blend, graphite blend, DEASP, and micronized cellulose. By contrast to coarsely granular, flaky, and fibrous materials, the fine granular materials behave similarly to the base case (Fig. 14). The average deviation of the materials tested to the baseline was 17.6%. The mentioned products do not show that they significantly alter the base fluid rheology. Besides, no evidence of mud gelation was observed. It is possible to infer that these materials are more thermally resistant at the tested temperatures than coarse, flaky, and fibrous materials.

To better understand the influence of LCM's particle size, a PSD (Particle Size Distribution) experiment was performed on fine granular

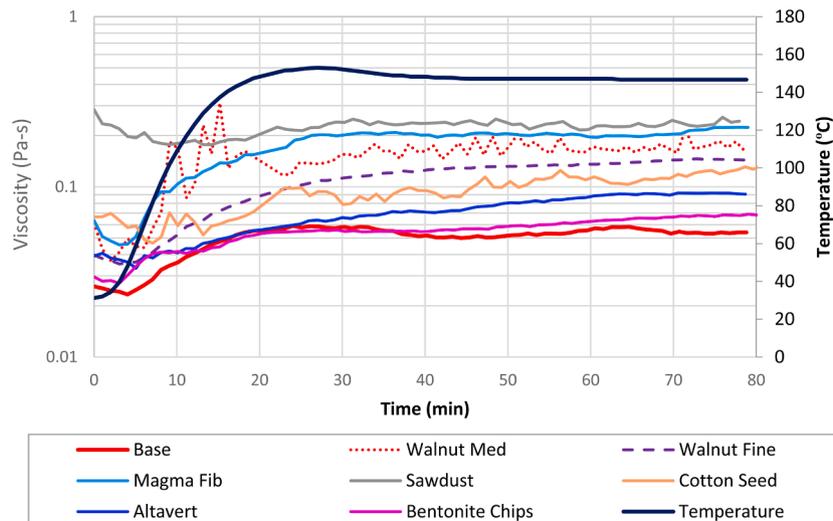


Fig. 13. Apparent viscosity of fibrous and coarse LCM's.

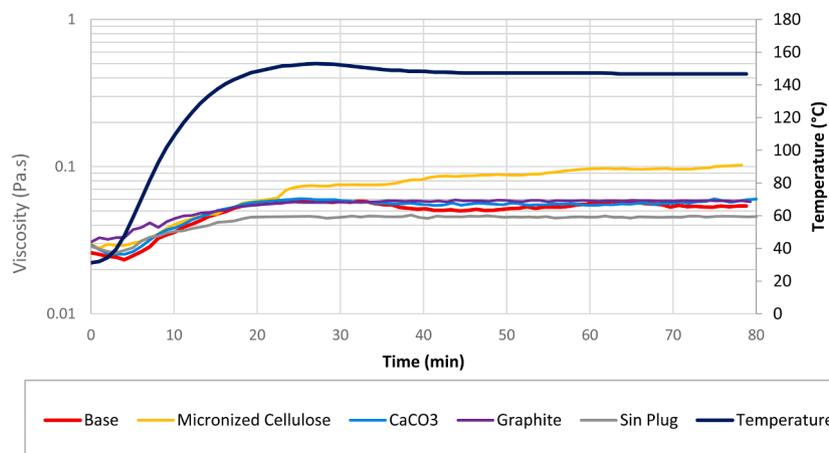


Fig. 14. Apparent viscosity of fine granular LCM's.

Table 6 Additives of base formulation.

Products	Concentration of product (kg/m ³)	Property/Characteristic
Bentonite	71.3	Viscosifier
Lime	2.85	Alkalinity/pH Control
Lignite	14.27	Filtrate
Barite	345.78	Densifier

Table 7 Materials and concentration of the base formulation.

Lost Circulation Material	Type	Concentration (kg/m ³)
Walnut Fine	Granular Coarse	42.8
Walnut Medium	Granular Coarse	42.8
Sawdust	Flaky, Fiber	22.82
Altavert	Fiber	1.43
Graphite Blend	Granular Fine	42.8
Bentonite Chips	Granular Coarse	42.8
Micronized Cellulose	Granular Fine	14.27
Magma Fiber Fine	Fiber	22.82
DEASP	Granular Fine	22.82
Cotton Seed Hulls	Fiber	34.24
Calcium Carbonate Blend	Granular Fine	57.06

materials. The PSD equipment measures particles from 0.375µm up to 2000µm. In Table 8, the test results on calcium carbonate blend, DEASP, micronized cellulose, and graphite blend are presented.

It is observed that the LCM with the smallest mean size, the DEASP, also presented the lowest average apparent viscosity at 148.9°C (0.0456 Pa.s). Calcium carbonate, with a mean size of 165.75µm, and micronized cellulose with a mean size of 505.66µm, presented average apparent viscosities at 148.9°C of 0.056 Pa.s and 0.091 Pa.s respectively. This

Table 8 Summary of PSD test on various LCM's.

Variable	CaCO3 Blend	DEASP	Micronized Cellulose	Graphite Blend
From (µm)	0.375198	0.375198	0.375198	0.375198
To (µm)	2000	2000	2000	2000
Volume	100	100	100	100
Mean (µm):	165.78	15.67	505.66	761.21
Median(µm):	88.24	11.21	406.97	717.12
Mean/Median ratio:	1.88	1.40	1.24	1.06
Mode (µm):	390.96	13.61	623.27	1908.87
S.D. (µm):	186.50	18.66	452.19	632.72
Variance (µm ²):	34782.60	348.30	204476.00	400336.00

shows the influence of size in rheological readings at HT. The mean size of graphite blend is the largest of the fine granular materials tested. However, the average apparent viscosity at 148.9°C is very close to the baseline (0.0585 Pa.s). This can be attributed to graphite lubricity. The effect lubricity of a graphite-based LCM was also documented by Alsaba et al. (2014).

4. Discussion and summary

Considering the geothermal drilling challenges, incorporating additives to control density, viscosity, alkalinity, filtration, and fluid loss are fundamental. However, the simple act of putting together additives to meet those functions does not guarantee a successful application in geothermal operations. Some additives thermal degradation has an apparent effect on the drilling fluids rheology and identifying which fluid components of the mud formulation are originating gelation has not been widely studied.

In this case, it is worthwhile to evaluate the effects of certain components individually in the drilling fluid rheology when exposed to high temperatures. This may help identify some of the characteristics that made some additives more sensitive to temperature changes than others.

In this experimental work, bentonite rheological behavior was evaluated at high temperatures, finding no mud gelation evidence. Two of the most common additives used in geothermal applications, caustic soda (alkalinity control) and lignite (filtration, deflocculation), were tested. It was identified when caustic soda is mixed with bentonite and exposed to temperatures above 93.3°C, mud gelation begins to occur.

Two materials were tested as potential replacements for caustic soda; potassium hydroxide and lime. In HPHT rheological experiments, lime showed better thermal stability than KOH and caustic soda.

Initially, it was tested the LCM effect with a bentonite and cedar fiber sample, showing that LCM also influences rheology at high temperatures. As diverse LCM additives have been used in geothermal drilling with diverse characteristics and properties, it was selected 11 different LCM materials to cover different alternatives.

After analyzing the HPHT rheological experiments results, there were identified characteristics that affects the rheological performance of LCM.

Shape: materials with irregular shapes, such as sawdust, magma fiber, or cottonseed hulls (see images in Table 4), seem to generate a viscosity increase when exposed to high temperatures. In contrast, rounded fine granular materials present a less seeming effect on the apparent viscosity.

Size: this characteristic seems to affect the apparent viscosity. When LCM of similar characteristics, such as walnut medium and walnut

fine were compared, walnut fine rheology was closer to the baseline rheology. In the LCMs evaluated, the materials with smaller particle size tend to behave more similarly to the base line.

Specific gravity: apparently, the specific gravity (s.g.), or the LCM's density, has no apparent influence on the rheological behavior. The walnuts tested provided a good example. Walnut fine and medium have the same specific gravity, but apparent viscosities were different. In contrast, calcium carbonate (s.g. 2.2) and graphite (s.g. 2.75) had very similar apparent viscosities trends and values, having different specific gravities.

Chemistry: this characteristic was not addressed directly and is not part of the scope of this experimental research. Although, some of the materials are claimed to be chemically inert (such as the walnuts, or cottonseed hulls), the temperature increase affected their apparent viscosity. There are chemical and physical interactions that can be analyzed in the future to complement the current findings.

In this experimental research, the materials that performed better were fine granular materials compared with coarse larger-sized granular materials and fibers. The probable reason is that smaller rounded and uniform particles have a larger surface area per unit of mass, meaning that the heat is distributed in a larger surface area at high temperatures, making these materials more thermally stable.

5. Conclusions

High temperatures affect the rheology of WBM. These drilling fluids formulations commonly use bentonite as a viscosifying agent and additives to improve rheology, filtrate control, and pH. To identify how thermal degradation is manifested, drilling fluid additives have to be tested individually at HT. The followings are the outcomes of this study:

- In literature, it is claimed that bentonitic fluids tend to gel at high temperature. In this research, it was found that bentonite itself has high thermal stability. In accordance, it is recommended to continue using bentonite as a viscosifier for geothermal drilling fluids due to its thermal stability, easy accessibility, and low cost.
- Caustic soda, the most common additive to control pH, presented poor thermal stability, evidencing a tendency to gel at temperatures above 93.3°C.
- After evaluating lime and KOH as potential substitutes of caustic soda, it was found it via experiments at geothermal conditions that lime is the alkalinity control material that presented the best performance in rheological stability at high temperatures.
- A basic formula compounded by water, bentonite, lime, and lignite was tested at high temperatures, showing adequate thermal stability. This basic formulation can be adjusted in density using barite, remaining thermally stable.
- It was found that shape and size directly affect the rheological behavior of LCM when exposed to high temperatures. In contrast, it was found that there is no direct relation between rheological behavior and LCM's specific gravity.
- The lost circulation materials that performed better in the HPHT rheology tests were rounded uniform fine granular materials. These materials showed less rheology impact in the base mud formulation than the impact caused by coarse larger-sized granular materials and fibers.

The conclusions presented were based on observations made during this research and applied to the different mud samples used in the analysis. It is important to remember that muds with different additives concentrations can have varying responses to high temperatures. However, the general behavior of mud is assumed to be roughly comparable.

Below there is presented detailed description of their diverse contributions to the published work.

CRedit authorship contribution statement

Cesar Vivas: Investigation, Writing – original draft, Conceptualization. **Saeed Salehi:** Supervision, Writing – review & editing, Resources, Methodology.

Declaration of Competing Interest

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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