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Wellbore Strengthening for Geothermal Applications: Experimental Study of Thermal Degradation of LCM to Address Wellbore Tensile Failure.

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ABSTRACT: Drilling mud losses are the most unpredictable and challenging problem in geothermal drilling operations. High temperatures and a corrosive environment make the design of a geothermal drilling fluid a very complex task. The presence of high temperature exacerbates the problems due to the thermal degradation of drilling fluid additives. Furthermore, thermal degradation implicates mud rheology affecting the Equivalent Circulating Density (ECD). This condition could potentially lead to wellbore tensile failure. Lost Circulation Materials (LCM) are used for wellbore strengthening in these environments. However, the study of LCM performance in High Pressure-High Temperature (HTHP) conditions is limited.

Thus, an extensive laboratory study was performed on lost circulation materials in Water-Based Mud (WBM) applications. Laboratory tests were performed using an HTHP rheometer to measure drilling fluids' properties up to 260°C. 11 different LCMs were tested in a controlled environment for understanding properties that made those components prone to fail at high temperatures. The results show that coarsely granular, flaky, and fibrous materials tend to degrade at high temperatures. This condition is manifested in a viscosity increase up to 4 times the baseline when tested at 149ºC. This condition leads to frictional losses increase leading to an undesirable ECD increment. An HPHT Permeability Plugging Tester (PPT) was used to measure the wellbore strengthening performance of LCMs. The results show that fine granular materials performed better in the high-temperature tests presenting the highest fracture sealing pressures. The results also show that particle size has repercussions in thermal stability and LCM effectiveness to increase wellbore tensile strength.

1. INTRODUCTION

The increase in energy demand worldwide has led to the rise in the need for new energy generation sources such as renewable energy. Geothermal power generation is one of the most important renewable energy resources. A geothermal power generation plant benefits from the thermal energy stored in the earth to generate clean power. Geothermal energy is renewable energy with the highest capacity factor. According to information from the US Energy Information Administration (EIA 2020), the geothermal energy capacity factor averages 72% in the last ten years (Fig. 1). It is not uncommon for geothermal plants to reach values well over 90% (Sanyal and Enedy 2011, Vivas et al. 2020). Because of its independence from seasonal factors, geothermal energy is one of the more efficient baseload power sources that can operate continuously to meet the minimum power demand 24/7.

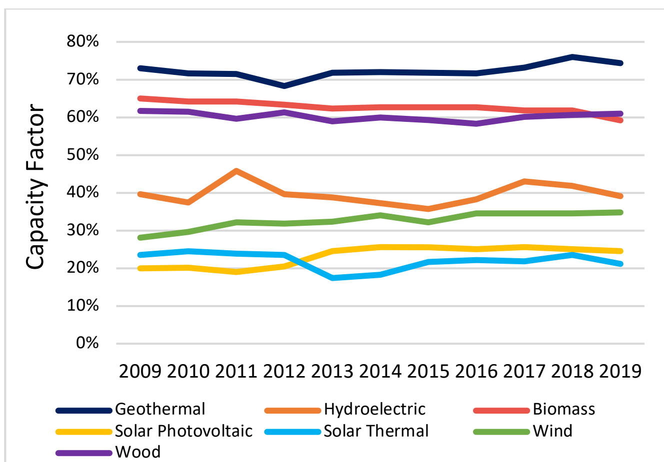

Fig. 1. Capacity Factors for Utility-Scale for Renewable Energy Sources 2009-2019 (Vivas et al. 2020).

Although its potential to provide constant energy, the widespread of geothermal production has been limited by various factors such as lack of access to thermal supplies, high capital costs, and operating risks during geothermal well drilling.

Mud losses are the most documented single issue in geothermal drilling. Marbun et al. (2013) described how operational problems associated with mud losses and stuck pipe events, causing the operating drilling times to be four times the amount of time initially planned in a field in Indonesia. Pálsson et al. (2014) described how non-controlled mud losses prevented the planned well depth from being reached in Iceland's Krafla field. In this operation, multiple sidetracks were attempted, but the loss of circulation did not allow reaching the planned target. Bolton et al. (2009) described how total losses caused a well control event in the Wairakei field, New Zealand. To stop the blowout, a relief well to intercept the uncontrolled well was drilled. These examples depict how operational problems have a high impact on the drilling time scheduled, and therefore, the well costs.

The problems associated with mud losses account for 20% of drilling costs (Finger and Blankenship, 2010). Besides, uncontrolled losses can generate major well integrity issues and potentially affect the future's well life cycle.

Lost circulation is caused by mud entering into porous or fractured rock, causing the reduction in the hydrostatic column (mud column). In this case, the mud is getting into the formation instead of returning to the surface (Hinkebein et al.,1983). Geothermal reservoirs are characterized to contain complex fracture networks (Rossi et al. 2020). This highly fractured rock environment is one of the most common causes of massive mud loss events.

For curing mud losses, the first approach is the addition of LCMs in the drilling fluid. Mostly, the LCM usage intends to cure existing losses. Although, techniques to use LCM as a preventive practice had been documented. Wellbore Strengthening is the concept representing the collection of techniques used to expand the mud window for drilling. The goal is to increase the fracture pressure by successfully plugging and sealing fractures while drilling to improve the formation fracture gradient deliberately (Salehi, 2012).

1.1. Stresses Around the Wellbore

The intact rock downhole is in a stress state, with the three principal stresses acting in the principal directions (overburden, maximum horizontal, and minimum horizontal stress). Once the wellbore is drilled, a portion of the stressed rock is removed. In this case, the mud pressure provides the support that prevents wellbore collapse (Fjær et al., 2008).

The stresses around the wellbore can be expressed as follows (Fjær et al., 2008):

$$\sigma_r = p_w \qquad (1)$$

$$\sigma_\theta = 2\sigma_h - p_w - 2\eta\left(p_{fo} - p_f(R_w)\right) \qquad (2)$$

$$\sigma_z = \sigma_v - 2\eta\left(p_{fo} - p_f(R_w)\right) \qquad (3)$$

p_w = mud pressure

σ_r = radial stress

σ_θ = hoop stress

σ_v = vertical stress

σ_h = minimum horizontal stress

p_{fo} = pore pressure

$p_f(R_w)$ = reservoir fluid pressure at the wellbore wall

In Eq. (2), it is observed that an increment in the mud pressure causes a decrease in the hoop stress. Fig. 2 offers a graphical representation of the Kirsch solution (Kirsch, 1898). This depicts how the reduction in the hoop stresses can lead to a tensile failure.

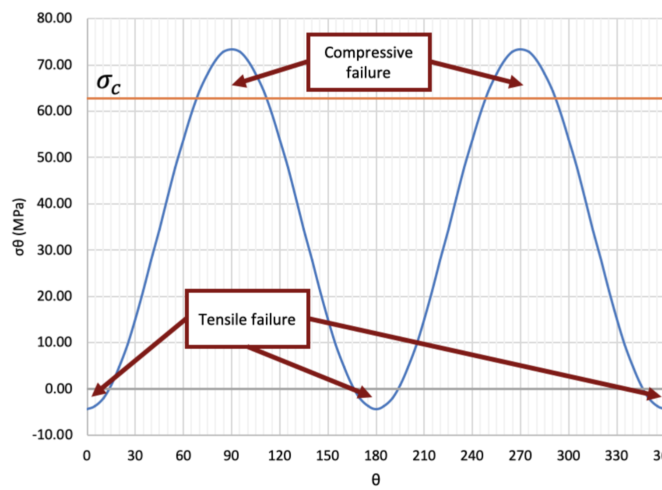

Fig. 2. Representation of tensile failure and compressive failure sections in a wellbore using the Kirsch Solution.

1.2. Wellbore Strengthening

In wellbore strengthening, the LCM intentionally increases the fracture gradient of a wellbore by adding LCM to bridge and seal fractures near-wellbore (Salehi and Nygaard 2011). Three physical models describe the wellbore strengthening concept and how they enhance the wellbore strength in drilling operations; stress cage model, FCS (Fracture Closure Stress) model, and FPR (Fracture Propagation Resistance) model (Magzoub et al. 2019).

The concept of stress cage was introduced by Alberty and McLean (2004), and it explains how mud additives help to seal fractures induced during drilling. The stress caging theory is to place solids at or close the mouth of a recently drilling-induced fracture that will serve to build a bridge. The bridge creates the support to hold particles that generates the seal, insulating the drilling fluid pressure from the rest of the fracture. If the seal is successful, the fluid pressure of the isolated portion of the fracture will be dissipated to the pore pressure. Then, the fracture, without the pressure that maintains it open, will close. This process increases the hoop stress around the wellbore beyond its original value.

In the FCS model, a fracture in the wellbore is generated and widened, expanded in length but not in width. LCM is forced to fill the fracture. LCM starts to accumulate inside the fracture, and as the carrier fluid is filtrating into the formation, it creates an "immobile mass" within the fracture. The immobile mass holds the fracture open and isolates the fracture end from the drilling fluid pressure. Fracture is getting more difficult to open due to increased fracture closing tension and the fracture end isolation (Dupriest, 2005).

In the FPR model, unlike FCS and stress cage models, the hoop stress is not increased (Magzoub et al., 2019). This wellbore strengthening approach relies on the continuous addition/maintenance of lost circulation materials. The latter's concentration is supported by the constant recovering and re-usage of solids, contributing to generating a fracture resistance propagation. The idea is that a mud cake causes an impermeable layer that prevents the drilling fluid pressure from expanding the fracture (Morita et al.1996). The mud cake contributes to filtration reduction either by generating a filter cake in wellbore walls or a deposition of particles (solids) within the rock and the cake (Rabbani and Salehi, 2017).

In this study, we conduct diverse experiments to evaluate the impact of different LCMs in the mud window. Rheology tests were performed to assess how the thermal degradation of LCM affects the mud window. Besides, Filtration tests were performed to evaluate how the LCM selection contributes to fracture pressure increase.

2. METHODOLOGY

The experimental study consisted of two main stages. The first stage of experiments consisted of measure the rheology of 11 different LCMs with base mud. The second stage of experiments consists of screening different LCM's to evaluate their capability of sealing fractures at HT. Besides, HT's effect in rheology tests when LCM's were incorporated into the geothermal base formula was analyzed. The main challenges are related to the thermal degradation of rheological and filtration properties.

Fig. 3 presents the schematic of the components used to perform the HPHT rheology experiments. The testing temperature was 149°C, and the testing pressure was 2.1 MPa.

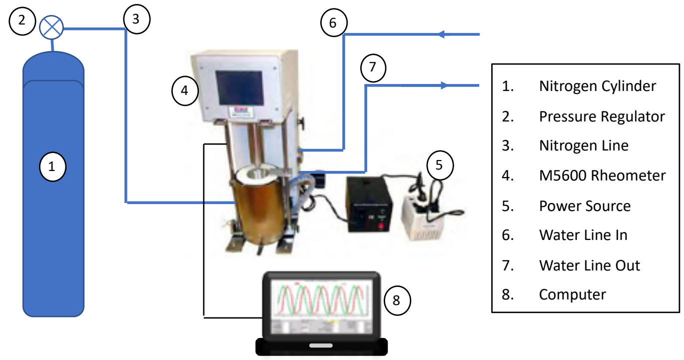

Fig. 3. Rheology experimental equipment setup.

For the rheological tests, the additives used in the base mud are described in Table 1.

Table 1. Additives of the Base Formulation

Products	Concentration of product ppb | (kg/m^3)	Property/ Characteristic
Bentonite	25 | (71.33)	Viscosifier
Lime	1 | (2.85)	Alkalinity/pH Control
Lignite	5 | (14.27)	Filtrate
Barite	121.2 | (345.8)	Weighting agent

The base formula was tested with eleven 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. The LCMs were tested individually with the concentration presented in Table 2.

Table 2. LCM concentration for rheology and filtration tests

Lost Circulation Material	Type	Concentration ppb | (kg/m^3)
Walnut Fine	Granular Coarse	15 | (42.8)
Walnut Medium	Granular Coarse	15 | (42.8)
Sawdust	Flaky, Fiber	8 | (22.8)
Altavert	Fiber	0.5 | (1.43)
Graphite Blend	Granular Fine	15 | (42.8)
Bentonite Chips	Granular Coarse	15 | (42.8)
Micronized Cellulose	Granular Fine	5 | (14.27)
Magma Fiber Fine	Fiber	8 | (22.8)
DEASP	Granular Fine	8 | (22.8)
Cotton Seed Hulls	Fiber	12 | (34.2)
Calcium Carbonate Blend	Granular Fine	20 | (57.1)

The filtration experiments were performed with an HPHT permeability plugging tester (PPT). This equipment is designed for performing filtration tests while avoiding LCM settling (Fig. 3). This is because the slotted disc (disc with a 1000 μm fracture width) and the collecting assembly are placed at the pressure cell top. For this study, the experiments were performed at 149°C using the LCMs in the concentrations specified in Table 2.

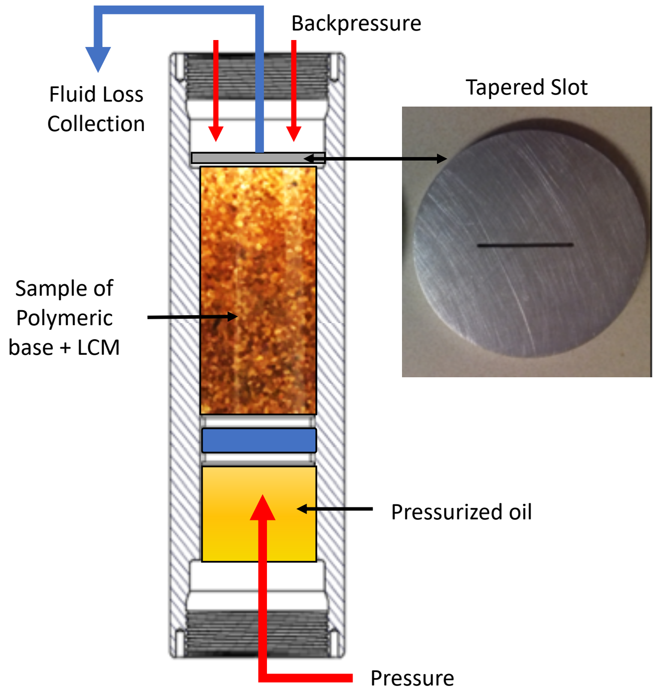

Fig. 3. Filtration experimental equipment description.

The novelty of the process is the usage of solids-free mud; in this case, distilled water with an HPHT polymer. The polymer is a commercial polymer that ¨activates¨ with temperature, providing enough rheology to keep the LCM in suspension. The advantage of using a free of solids mud for the test is that the LCMs directly generate the sealing action. This helps to provide an individual evaluation of each material sealing performance.

The mud was prepared with distilled water and 3% in weight of the HPHT polymer. The mud was then aged for 24 hours and heated up to 176.7°C at 3.45 MPa for activation. Once the mud is activated, it was mixed with the LCMs. The mud mixed with LCMs is aged for 24 hours before tested in the PPT apparatus. For this initial screening, the disc with 1000μm fracture was selected to evaluate each LCMs performance, and experiments were performed twice.

3. RESULTS AND DISCUSSION

This section presents the results of rheology tests, comparing how the thermal degradation of each LCM affects the base mud. Besides, it is explained what the implications are with an example. Then, the filtration results are presented, and the filtration and maximum sealing pressure are examined.

3.1. Rheology Tests

Most LCM materials are claimed as inert additives. Although, in this experimental research, it was found that the LCMs can affect the rheology of the drilling mud. To identify characteristics that affect the rheology, the LCMs were divided. Coarse granular, flaky, and fibrous materials were tested, and results are presented in Fig. 4. The values plotted in red represent the base mud formula without LCMs (baseline). In Fig. 4 it is possible to see how the addition of the different LCMs changes the shear stress, representing an alteration in the mud viscosity. Materials like sawdust and magma fiber present a variation of 336% and 283% compared with the baseline. Once the muds with the latter LCMs were removed from the sample cap, mud gelation was evidenced.

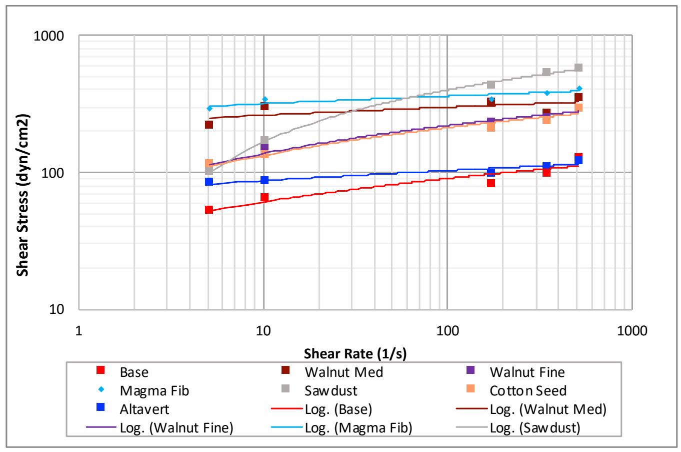

Fig. 4. Shear stress vs. shear rate of coarsely granular, flaky and fibrous materials.

In contrast, fine granular materials presented a similar rheological behavior compared with the baseline (Fig. 5). 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.

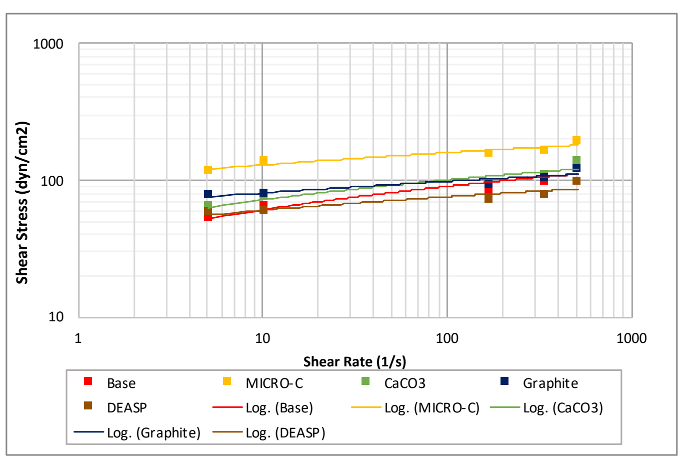

Fig. 5. Shear stress vs. shear rate of fine granular materials.

To evaluate this rheological behavior's implication in the stresses around the wellbore, the rheology results were applied in a well model. The information used came from the Well 58-32 from the Utah FORGE project. The well has a measured depth of 2298 m and a true vertical depth of 2295 m (vertical well). The well geometry was built using the information from the drilling reports (Fig. 6). The intention is to compute the equivalent circulating density (ECD). ECD represents the additional differential pressure caused by the frictional losses when the drilling fluid is circulated through the well annular. This extra pressure affects the Pw, affecting the stresses around the wellbore.

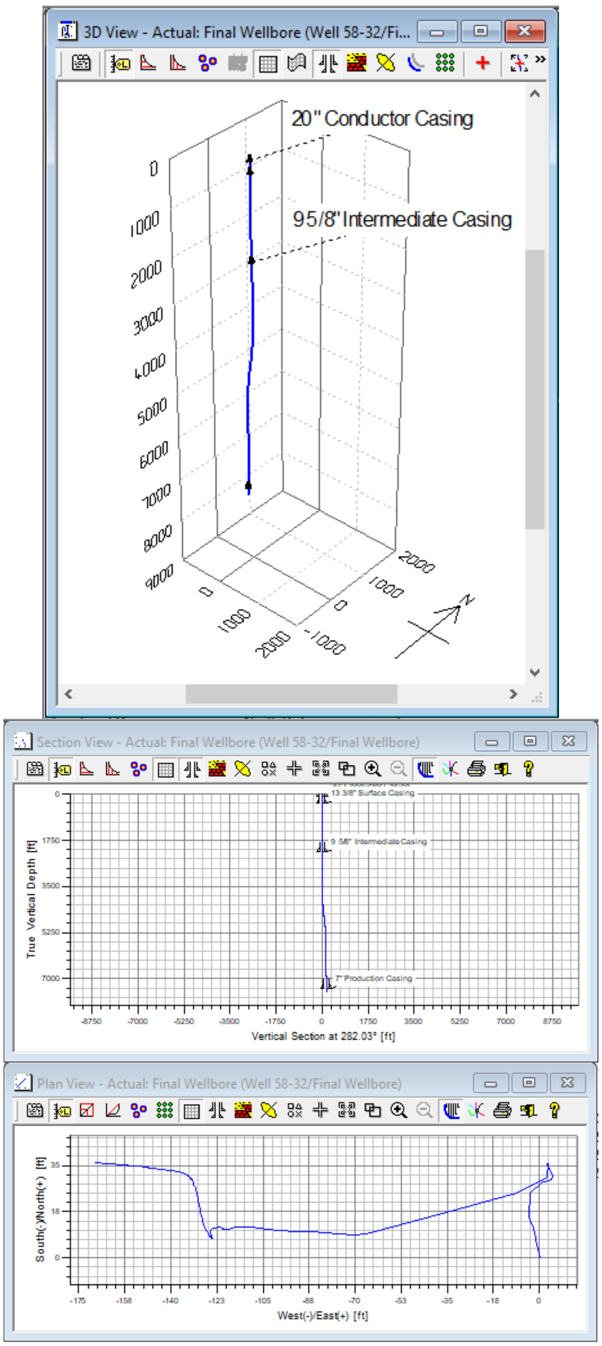

Fig. 6. Well path of Utah FORGE Well 58-32 uploaded in a commercial simulator, COMPASS™ Directional Path Planning Software.

ECD values were computed using the methodology and equations described in the API 13D recommended practices. Table 3 presents the resulting ECDs using the rheology calculated for every mud sample.

Table 3. ECD computed for the different mud+LCM samples.

LCM	ECD ppg	ECD sg	dP psi	dP Mpa
Base	0.37	0.0439	143.14	0.99
DEASP	0.30	0.0364	118.79	0.82
Graphite	0.38	0.0461	150.18	1.04
CaCO3	0.40	0.0482	157.32	1.08
Altavert	0.41	0.0491	160.11	1.10
Bentonite chips	0.43	0.0520	169.65	1.17
MicroC	0.66	0.0797	259.94	1.79
CottonSeedHulls	0.96	0.1150	375.03	2.59
Walnut Fine	1.07	0.1288	419.89	2.90
Magma	1.38	0.1652	538.60	3.71
Walnut med	1.44	0.1732	564.73	3.89
Sawdust	2.11	0.2535	826.67	5.70

Nadimi et al. (2018a) performed an experimental and modeling study of well 58-32 geomechanics. They found that the critical pressure to open the fractures is from 4.14 to 6.21 MPa above the pore pressure for fractured zones in the well. In other words, that range represents the mud window. The interval with the highest fracture concentration in the well 58-32 is the interval of 2225 m to 2295 m. In that interval, it is concentrated 50% of the well's fractures (Nadimi et al. 2018b). In Fig. 7 the incremental pressure computed with the different muds is presented. The critical pressure (orange line in the plot) is also shown. In this case, LCMs that cause an incremental pressure of 2 MPa or more can jeopardize the operation by reducing the operational mud window.

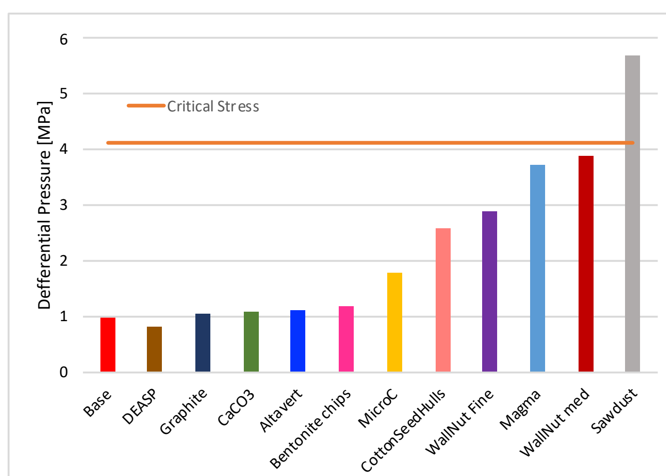

Fig. 7. Incremental pressure of the different mud samples at the 2295 m of depth.

LCMs like sawdust, magma fiber, and medium-size walnut are used in geothermal operations due to the easy access and low cost. This experimental study found that high temperatures trigger an undesirable viscosity increase in the latter materials. However, these materials can be used with an addition of a thinner or a deflocculant. The downside of this solution is that procedure increases the amount of solids with the potential formation damage. Besides, reduction thinning additives can cause a reduction in the carrying capacity of the LCM, with the consequential materials sag.

3.2. *Filtration Tests*

Filtration tests are key to analyze the physical mechanical behavior on drilling fluids in an environment that recreates the wellbore conditions (Salehi et al. 2016). For this experimental study PPT was used to conduct the experiments. In Fig. 8 the 30 minutes filtration results collected from the different LCM mud samples are presented. The materials that presented the best performance were the fine granular materials. Graphite, calcium carbonate, and micronized cellulose were effective in sealing the fracture. These materials can be appropriate for a wellbore strengthening strategy for the test conditions and fracture width tested.

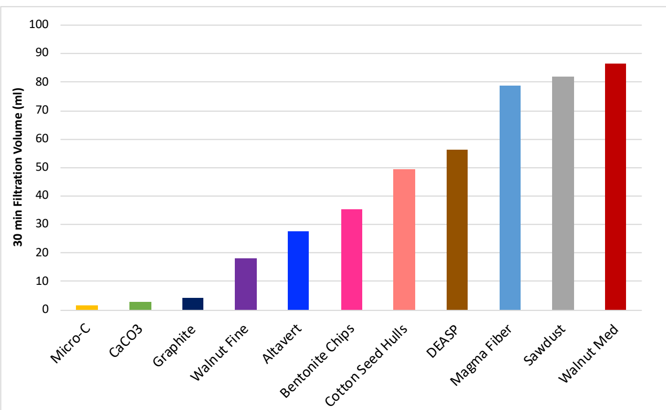

Fig. 8. Filtration results of the mud+LCM samples.

Once the filtration experiments were concluded, the maximum differential pressure that the sealed fracture can support was recorded. For doing this, the pressure of the mud cell was intentionally increased by 0.7 MPa (100 psi) intervals. The maximum pressure before the sealed fractured failed for every material is presented in Table 4.

Table 4. Maximum sealing pressure of the mud+LCM samples.

LCM	Max Sealing Press (MPa)	Max Sealing Press (psi)
Graphite	8.27	1200
CaCO3	6.21	900
Altavert	5.86	850
MicroC	4.83	700
Walnut Fine	4.14	600
Walnut Med	3.45	500
Magma Fiber	2.76	400
Bentonite Chips	2.07	300
Cotton Seed Hulls	2.07	300
DEASP	2.07	300
Sawdust	2.07	300

The maximum sealing pressure of a sealed fracture represents the robustness of the LCM to bridge and seal a fracture. Graphite, calcium carbonate, Altavert, and micronized cellulose presented sealing pressures close to or above 5 MPa. This additional differential pressure prevents the mud losses if Pw is increased.

3.3. *Discussion*

LCM selection is mainly based on availability and cost. Although, for high-temperature applications, there are implications that go beyond their capability to control mud losses. Different authors have documented the high ratio of unsuccess usage of LCM vs. attempts in geothermal operations. In this study, we present an LCM screening to understand the behavior of LCM at high temperatures. Besides, the implication in the wellbore tensile failure is given.

In this study, the concept of analyzing LCM from the rheological perspective is analyzed. In the conditions tested, 149°C at 2.76 MPa, LCM selection impacts the mud rheology. Fine granular materials presented a better performance, with a smaller impact in viscosity increase. Coarse granular, fiber and flaky materials have a considerable effect on the rheology, with an average increase in viscosity of 166% compared with the baseline. The viscosity increase directly affects the ECD, impacting the stresses around the wellbore. This consideration is sufficient to recommend a rheology screening in LCM for HPHT applications. Geothermal applications are especially critical due to the narrow window environment in highly fractured formations.

The specific causes of thermal degradation of LCM are not part of this experimental study. Although, results suggest that LCM's particle size and shape affect how materials behave at high temperatures.

Filtration and sealing pressure tests at HPHT permitted understanding the performance of LCMs for bridging and sealing a 1000 µm fracture. The LCM concentrations of the different tests (up to 20 ppb) were lower than the concentrations used for curing losses, where it is not rare to see concentrations of 80 ppb and above. The concentrations used in this study were intended for a wellbore strengthening strategy. In this case, the objective is the LCMs concentration is maintained during the drilling operation. In this case, the LCMs are used as wellbore strengthening materials.

Fine granular materials also presented a notably better performance under the testing conditions. The micronized cellulose showed the lowest filtration volume with a low material concentration in the mud (5 ppg). Here it is essential to highlight that the LCMs were tested in a mud without solids. The sealing action is performed only by the LCMs. Calcium carbonate (20 ppg) and graphite (15 ppg) also presented low filtration loss volumes.

The maximum sealing pressure tests permitted to quantify the potential incremental pressure that the sealed fractures can withstand. Graphite, calcium carbonate, Altavert, and micronized cellulose presented the highest maximum sealing pressure. The usage of these materials has the potential to reduce the likelihood of wellbore tensile failure.

4. CONCLUSION

This study investigates the implication of LCM usage in the stresses around the wellbore for geothermal applications. 11 different LCM were screened in rheology, filtration, and sealing pressure experiments. One of the most relevant outcomes of this study is the importance of rheological tests on LCMs. The rheology experiments revealed that coarse granular, fibrous, and flaky LCMs exposed to temperatures of 149°C and above, are prone to have an undesirable viscosity increase. The viscosity increase in some LCM samples is enough to induce wellbore tensile failure. So this is recommendable to perform LCM rheology screenings for geothermal applications.

From the filtration standpoint, fine granular materials presented a better performance on sealing fractures in this study's experimental conditions. Materials like micronized cellulose and graphite shown low cumulative filtration. The sealing pressure experiment represents how LCM helps to reduce wellbore tensile failure.

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