

Article

Evaluation of Lost Circulation Material Sealing for Geothermal Drilling

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Abstract: Lost circulation is a pervasive problem in geothermal wells that can create prohibitive costs during drilling. The main issue with treatment is that the mechanism of plug formation is poorly understood. Here we applied two experimental approaches to characterize the clogging effectiveness of different materials. Fracture flow tests with different geometries were conducted with various individual materials and mixtures at relevant conditions. A high-temperature flow loop system was also developed to inject single- and mixed-material plugs into a gravel pack with a non-uniform geometry to compare with the fracture tests. The fracture tests revealed that single materials tended to form no plug or an unstable plug, while mixtures of materials were uniformly better at sealing fractures. Gravel pack tests at high temperatures show most of the materials are intact but degraded. The fibrous materials can create partial or unstable plugs in the gravel pack, but mixed-material plugs are far more effective at clogging. Both test types suggest that (1) mixed materials are more effective at blocking fluid flow and (2) fibrous materials seal fracture openings better, while granular materials seal inside fractures or pore throats better. Further research is needed to study the long-term stability of different plug configurations.

Keywords: lost circulation; geothermal systems; fracture permeability; clogging tests



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1. Introduction

Lost circulation (LC) is a phenomenon encountered during drilling wherein a large amount of drilling fluid escapes the wellbore into the surrounding rock mass. The occurrence of LC can result in several complications, such as drilling mud loss, unbalanced borehole pressures, blind drilling, and wellbore collapse [1]. LC is a particularly difficult problem in geothermal drilling due to the hard rocks, low fracture gradients, high pressures/temperatures (HPHT), corrosive formation fluids, and geologic complexity [2]. The occurrence of LC during geothermal drilling is a major source of non-productive time that represents, on average, 10–20% of the total drilling costs [3,4]. Previous reviews of geothermal drilling have shown that the primary cost incurred during LC events came not through the costs of the treatment method but from the non-productive time spent attempting to treat the loss zone unsuccessfully [5]. Given this, during geothermal drilling, an important factor for reducing LC cost is to use the most effective treatment possible. High upfront costs are required for drilling geothermal wells; therefore, reducing such costs is critical to enabling global goals of increasing renewable energy production and meeting carbon reduction promises. Thus, it is necessary to develop an improved understanding of treating LC under conditions relevant to geothermal systems.

LC is typically treated with the use of “lost circulation materials” (LCMs) that are mixed into the drilling fluid either before encountering losses (e.g., preventative treatment)

or after losses have occurred (e.g., corrective treatment). These materials are highly variable in their properties and have many classifications, which have been developed to characterize them. In geothermal drilling, many materials have been utilized to treat LC, including but not limited to calcium carbonate, graphite, micronized rubber, diatomaceous earth, walnut shells, sawdust, micronized cellulose, rice husks, polymers, and various commercial blends. However, the LC treatment is often ineffective at mitigating moderate to severe fluid loss zones. If LCMs are unsuccessful in curing lost circulation, cement plugs may need to be set, resulting in drilling delays and increased costs. In geothermal wells, the geologic complexity creates unique loss situations, so previously successful approaches in oil and gas drilling in sedimentary rocks, compared to the fractured crystalline rocks common for geothermal systems, may not work [2]. Also, the higher temperatures can produce a more rapid breakdown of many LCMs. A typical approach during geothermal drilling is to use the least-costly LCM first, then use progressively more expensive materials until losses stop [6]. However, this approach has been shown to be ineffective without a proper understanding of how LCMs clog loss zones [7].

Various theories have been formulated to describe using LCMs to plug fluid losses and strengthen wellbores, including stress cage theory [8], fracture resistance theory [9], and fracture closure stress [10]. Laboratory research conducted has shown that, generally, the behavior of LCMs in a loss zone can be characterized in one of four ways: (1) transport of the LCM through the zone with no clogging; (2) formation of a filter plug that does not impede fluid flow; (3) an unstable plug that forms from LCMs and resists some flow but breaks down above a certain level of wellbore stress; and (4) the formation of a plug that holds up under pressure and prevents fluid loss [1,11,12]. A schematic of each of these scenarios is shown in Figure 1. Experimental and field research has shown that the most important factors in forming a successful LCM plug are particle size distribution and particle morphologies [13,14]. As a result, numerous rules have been developed, both in and out of industry, to determine the ideal selection of LCM particle sizes for loss zone sizes, such as the Abrams' rule (i.e., median particle size of LCMs equal to or greater than $1/3$ of the median pore size), the Vicker's method (i.e., $D_{90} = \text{largest pore throat}$, $D_{75} < 2/3$ of largest pore throat, $D_{50} \sim 1/3$ of the mean pore throat, $D_{25} \sim 1/7$ of the mean pore throat, $D_{10} > \text{smallest pore throat}$), the Haliburton method (i.e., D_{50} of particles equal to $1/2$ the estimated fracture width), and the Alsaba method (i.e., particle size distribution of $D_{50} \geq 3/10$ of the fracture width and $D_{90} \geq 6/5$) [15–19].

Though particle sizes and morphologies are widely acknowledged as critical to the formation of an LCM plug during drilling, they are not universally accepted or applicable to every situation. Moreover, these rules only address whether a plug forms, not whether it will be able to withstand the differential pressure across the bridge or be stable under the pressure fluctuations that occur during drilling operations. Others have suggested that LCM selection should be based on other properties of LCMs. The formation of the bridge may depend upon the most likely configuration of one or two LCMs at the initial bridging stage and the ability of those LCMs to withstand the pressure without yielding [11]. It has also been observed through a combination of mechanical and flow tests that the maximum sealing capacity of an LCM plug is a function of the particles' mechanical properties and size/shape; it is not based on the absolute dimensions of the LCM [11]. The strength and durability of a macroscopic plug in a loss zone can be thought of as a scaling up of the microscopic properties of the selected LCM [20,21].

Experimentally, the primary method for testing the clogging performance of an LCM–drilling fluid mixture has been to use fracture or slot tests, injecting the LCM-laden fluid through the fracture to evaluate its effectiveness [1,7,11,13,22]. This method is ideal under the assumption that LC primarily occurs through pre-existing or drilling-induced fractures. However, research has shown that the specifics of the fracture test setup can drastically affect LCM performance results, and so results depend highly on the chosen conditions [23]. An additional issue with using fracture or slot tests for LCM experiments is that loss zones in geothermal drilling can include fault/shear zones, porous formations, and

vugs or cavernous zones [1]. An idealized fracture system, even if able to simulate the range of pressure and temperature conditions downhole (ex. geothermal wells that encounter LC have temperatures varying from 120–360 °C in the US [6]), may not adequately simulate all types of loss zones. Furthermore, this method can neglect the effects of other components of LC treatment. For example, the selection of a drilling fluid is critical for treating LC, as it must be able to keep particles in suspension while permitting the drilling fluid–LCM mixture to enter a loss zone. Drill cuttings, for example, can often seal loss zones as they are transported in the well, but only if the fluid is able to prevent particle settling and avoid particle degradation [24]. One method for testing the drilling fluid transport of particles is the use of flow loop systems with various particles in suspension [25]. This method, however, has rarely been used to test the effectiveness of different LCMs [14]. Drilling fluid selection is also critical in how it interacts with the LCM—for example, it has been shown that common LCMs like magma fiber will dissolve when suspended in bentonite drilling fluids but not when interacting with other polymers like xanthan gum [26].

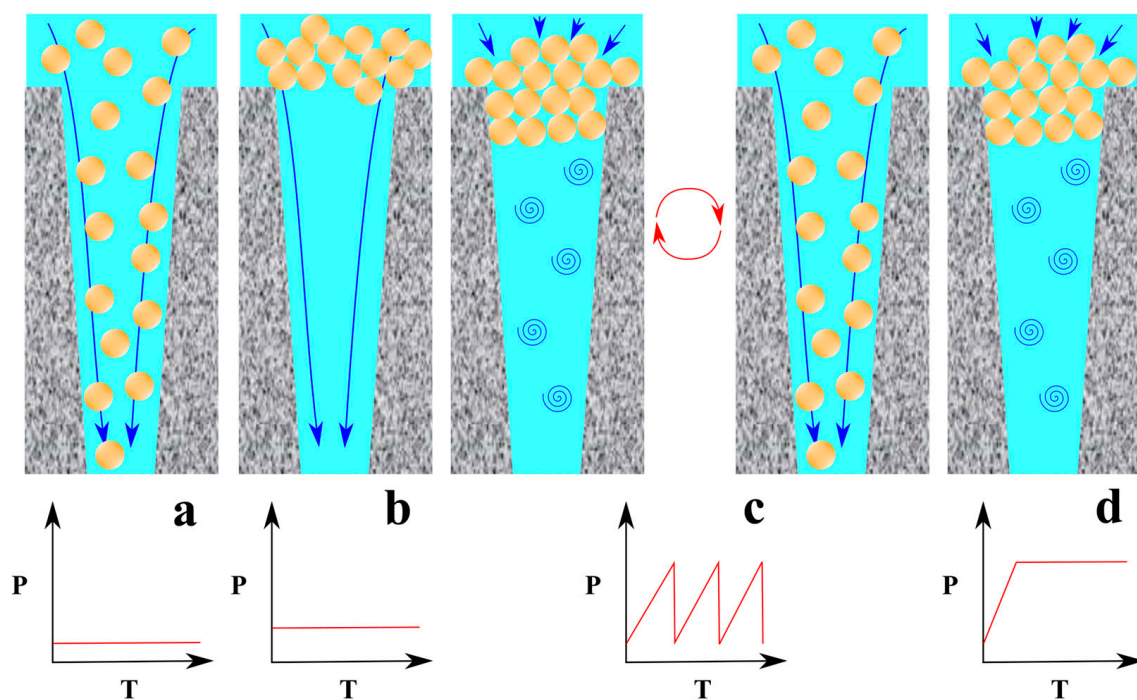


Figure 1. Schematic of clogging scenarios with LCMs and how the pressure (P) resisted by the plug changes with time (T) in each scenario. Schematics show (a) LCM transport with no clogging; (b) LCM bridging but continued fluid flow; (c) intermittent, unstable clogging where LCM cannot remain as a bridge under the pressure buildup; (d) LCM bridging and restricted fluid flow.

However, most LCM selection during drilling is primarily carried out through trial and error and past drilling experiences [5,27]. With regard to LC during geothermal drilling, the high downhole temperatures are likely to increase the degradation and breakdown of any organic LCM. Previous studies of LCMs have shown that many common LCMs employed in geothermal wells experience 10–50% mass loss above 100 °C, after heating for only 1 day [26,28]. The reliability of an LCM for treating LC during drilling needs to account for their degradability in geothermal conditions. Further work is needed to understand how various material properties, other than LCM size and morphology, control plug stability.

To this end, our work details research on the clogging effectiveness at high temperatures of several types of LCMs commonly used during geothermal drilling. Two types of tests were conducted to evaluate LCM effectiveness at the millimeter scale: (1) single-fracture clogging experiments on fracture models with a finite length and surface roughness,

using a standard HPHT filtration test system at ~ 90 °C; and (2) complex fracture zone clogging tests using a gravel pack within a custom-made HPHT flow loop system at 190–225 °C. The single-fracture tests showed that, generally, the LCM performance depended on the grain size distribution and the fracture aperture, while the flow loop tests showed that the performance of LCMs at high temperatures depended upon the LCM's ability to permeate the inner matrix of the gravel pack. Post-test analysis of the samples revealed the structure of both the clogged fractures and gravel packs. It was observed that in both fracture systems, the best LCM performance was achieved by mixing two different types of LCMs. For single-fracture systems, good clogging and LC prevention were achieved only by the formation of a strong filter cake at the entrance to the fracture. In contrast, for a complex fracture zone (gravel pack), the best performance was observed when either mixed granular particles or LCMs with a mixture of rigidities penetrated deep into the fractures.

2. Materials and Methods

2.1. LCMs Tested

There exists a wide variety of LCMs in existence with various properties that have been employed in treating LC that occurs in petroleum and geothermal wells [1]. These materials come with a variety of physical properties that affect their effectiveness as a plug. Generally, it is agreed that the most important material attributes are grain size distribution and particle morphology [13]. These properties affect the likelihood of a plug forming, as the morphology affects the likelihood of bridging an aperture, and particle size distribution affects the likelihood of adequately packing a loss zone to impede fluid loss (i.e., Figure 1). This is why most LCMs are classified by their morphology as granular, flaky, fibrous, or composites [14]. Other LCM physical properties can be important for plug formation as well. Mechanical strength and compaction have been shown to affect pressure resistance in plugging fractures [15]. Frictional resistance controls the ability of particles to adhere and form [21]. For geothermal wells, the thermal and chemical resilience of an LCM is critical to its ability to act as a long-term seal [26]. The desirability of each LCM property, however, will vary according to the conditions in each well [6].

The LCMs tested in this study were provided by Sinclair Well Products and North Star Energy Products. In this work, eight different LCMs are tested (as well as a mixture of several types), with each shown in Figure 2a. For WCA 200/300, WCA 200 (gellant) was mixed with WCA 300 (filling material) to form a slurry for clogging LC zones. A particle size analysis was conducted for the different LCMs (not for WCA 200, as the gellants are designed to dissolve when mixed in water). The particle size of the non-microcellulose LCM was determined through sieving, while the microcellulose types were characterized using SEM measurements (Figure 2b).

For most of the commercially available LCMs shown in Figure 2a, the particle sizes shown in Figure 2b were determined via a sieve analysis using ASTM E11 standard sieves. For the fine microcellulose LCM, laser diffraction was used to determine the particle size distribution in detail in the range of 10 nm to 3.5 mm (Malvern Panalytical Mastersizer 3000). The actual size distribution of the fine microcellulose had a D10, D50, and D90 of 11.7, 55.3, and 176.3 μm , respectively. During the measurement, the LCM sample was mixed with water, stirred by the sample preparation module, and flowed through a channel crossing a laser beam. The scattered light was measured, and then the particle size could be interpreted from the light intensity spectrum.

For simplicity, we adopted a classification based on the appearance of the different LCMs: granular, flaky, fibrous, or slurry. Various properties of the different materials are listed in Table 1. Abbreviations listed in the table will be used to refer to each LCM throughout this work.

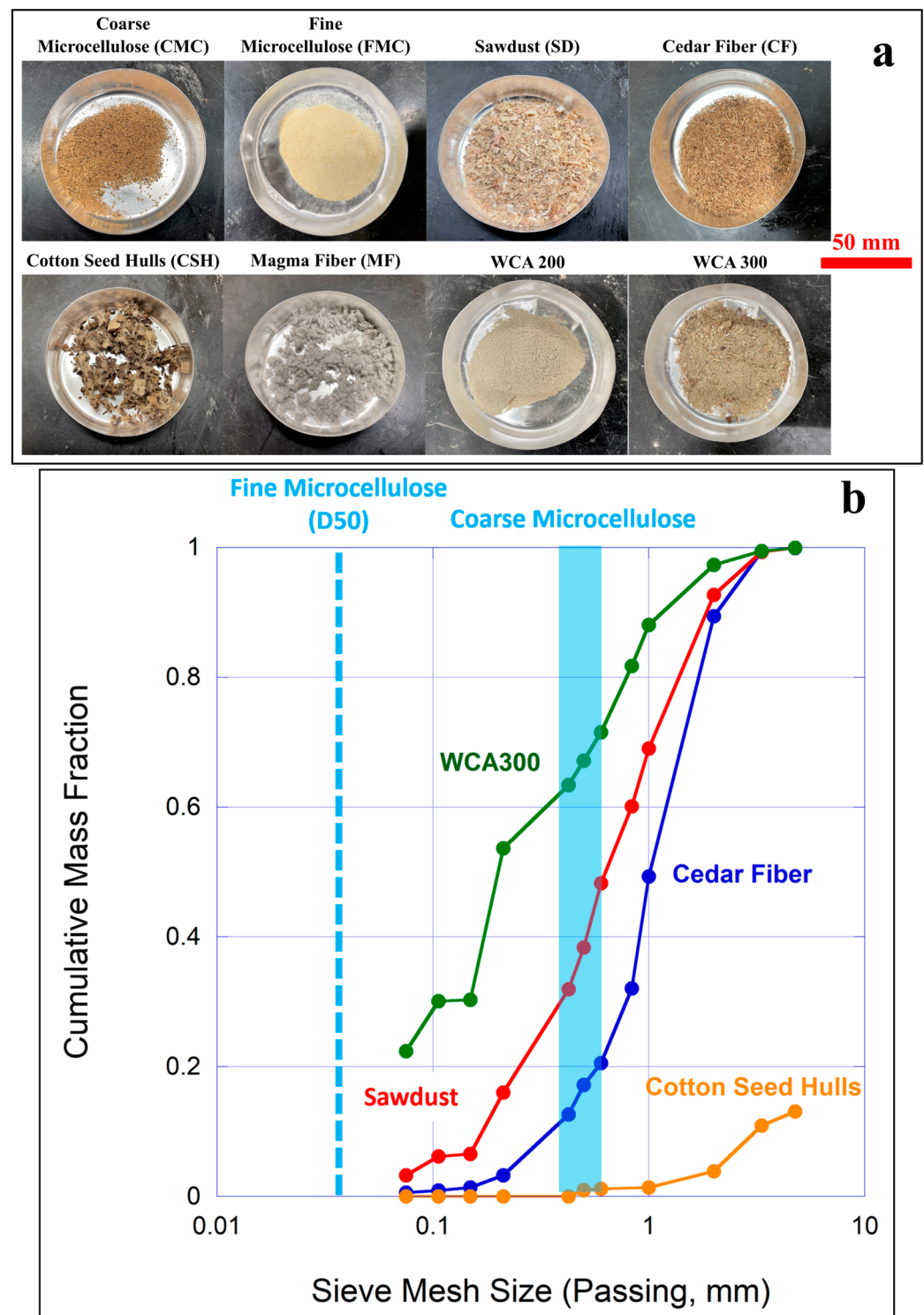


Figure 2. (a) Images of LCMs tested in this study. (b) particle size distribution obtained through sieving and SEM analysis. The particle size distribution for the cedar fiber samples is very narrow due to the elongate nature of the LCM. A large portion of the cotton seed hulls did not pass through the largest 10 mm sieve due to the clumping nature of the cotton seed hulls.

Table 1. Description and physical properties of various LCMs tested in this study.

LCM	Coarse Microcellulose	Fine Microcellulose	Sawdust	Cedar Fiber	Cotton Seed Hulls	Magma Fiber	WCA 200	WCA 300
Classification	Granular	Granular	Flaky/Fibrous	Fibrous	Fibrous	Fibrous	Slurry	Slurry
Specific Gravity (-)	1.3	1.3	0.91	0.24	0.6	2.60	1.20	0.33
Diameter (mm)	0.40–0.90	0.05–0.10	0.05–5.00	0.05–5.00	0.40–10.00	0.50–4.00	0.05–0.15	0.08–5.00
Swelling (%)	1–5	1–5	10–20	1–5	10–20	0	-	5–10
Description	Ground Walnut/Almond Shells	Ground Walnut/Almond Shells	Wood Dust	Ground Cedar Fiber	Cotton Seed Hulls	Spun Rock Wool	Polymer	Granular/Flaky/Fibrous
Abbreviation	CMC	FMC	SD	CF	CSH	MF	WCA 200	WCA 300
Provider	Sinclair Well Products	Sinclair Well Products	Sinclair Well Products	Sinclair Well Products	Sinclair Well Products	Sinclair Well Products	North Star Energy Products	North Star Energy Products

2.2. Single Fracture Tests

The primary method for testing the clogging effectiveness of lost circulation material is through the use of fracture or slot tests to evaluate LCM bridging in a drilling fluid passing through a fracture [11,23]. Our first test used a modified version of the API standard bridging materials tester. We used a commercial permeability plugging tester (41.37 MPa or 6000 psi model, Ofite, Houston, TX, USA) for the tests with some modifications (Figure 3a). First, for improved temperature control and safety, an independent temperature controller (Oakton 9500, Oakton Instruments, Gelderland, NL) was added to the power supply. In addition, for controlling the fluid pressure and the flow rate, a syringe pump (ISCO/Teledyne 500D) was used to inject the drive fluid (water) into the lower chamber of the tester. Lastly, to test the clogging of a fracture that is more realistic than commonly used slotted discs for this type of experiment, we developed an internal module that could house fracture(s) with a range of geometries (Figure 4).

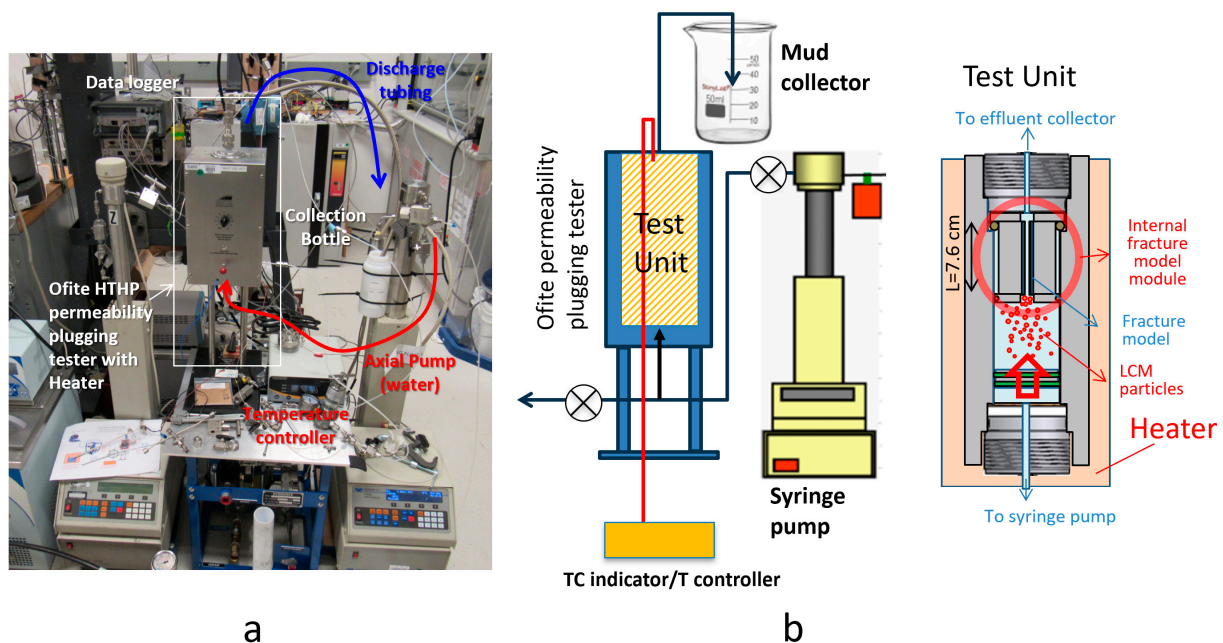


Figure 3. Laboratory system used for fracture clogging experiments. Commercial equipment was used, with improvements to the temperature and flow/pressure controls (a). A schematic of the test setup is also shown where the LCM particles are injected through the artificial fracture (b).

This module was designed so that a pair of thin plates (a $3.81\text{ cm} \times 7.62\text{ cm} \times \sim 3\text{ mm}$ model is shown in Figure 3) could be inserted to represent a nominally flat or rough and parallel fracture. The fracture aperture can be changed by using Viton spacers and stainless-steel shims on the back sides of the fracture plates. Tapered shims can be used to represent a fracture with varying (reducing) apertures. Additionally, instead of using a fracture model and shims, the cavity of the module can be filled with large solid particles such as gravel and glass beads to represent a fractured zone or a pack of large particles including drilling chips and calcite LCMs.

Although natural rock samples can be used for the fracture model, in this study, we used transparent soda-lime glass plates with a manufactured surface texture (i.e., commercially available shower-window glass sheet). This allowed us to visualize the distribution of the LCM that infiltrated the fracture during the post-experiment examination of the samples, as well as to conduct quantitative mapping of the fracture aperture distribution via a UV-light-induced fluorescence intensity mapping of the fluid injected into the fracture [29]. The use of the soda-lime glass is conservative in the sense that the surface of the soda-lime glass is smoother than natural rock surfaces, which might cause LCM particles to slip more, rather than catch on the roughness of a natural fracture.

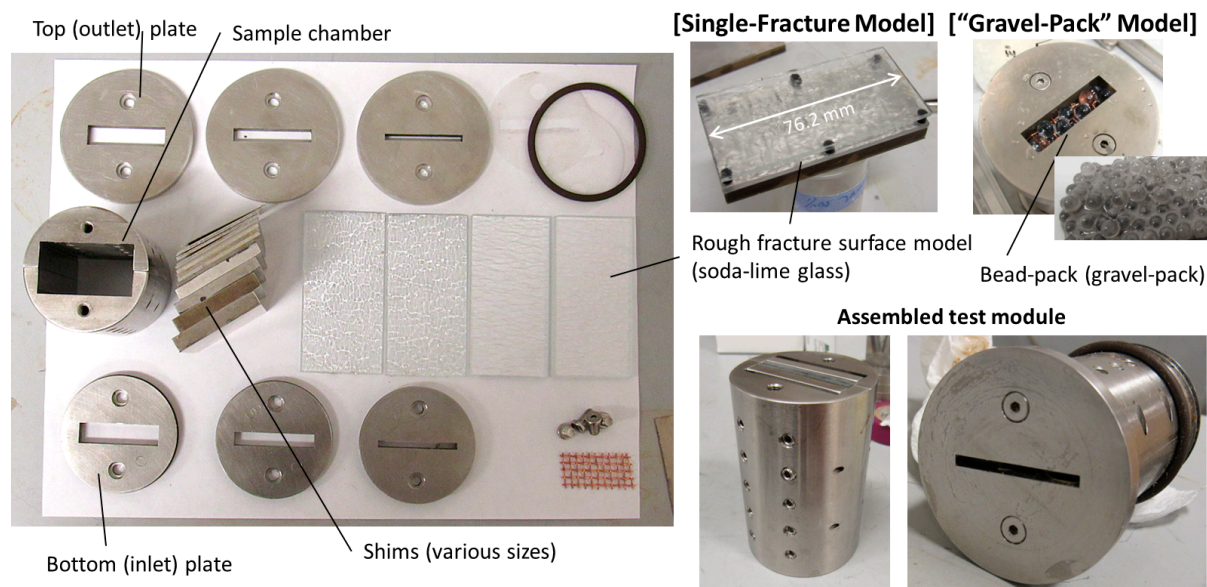


Figure 4. Internal fracture module made of stainless steel. A pair of plates with rough surfaces is used to represent a fracture with a finite depth, which is inserted in a rectangular cavity within the module. Alternately, the cavity can be filled with discrete particles (gravels, beads) to represent a rubble zone or a pack of coarse drill cuttings and LCMs. The length of the module shown here is ~9 cm.

The permeability (or conductivity) of a model fracture can be determined by testing the hydraulic conductivity of the fracture module independently using a standard hydraulic permeability test, such as a falling-head permeability test. In our experiment, glass plates with a range of separation distances were used in the fracture module to determine equivalent hydraulic apertures of the rough model fractures (Figure 4).

Before the tests, the drilling fluid was prepared by first making 20 wt% bentonite mud (CETCO MX-80, Mineral Technologies Inc., New York City, NY, USA) that exhibited a viscosity of 20–30 cP at room temperature [27,30]. The pure bentonite mud was then mixed with 5 wt% of selected types of LCMs in a mechanical mixer. The LCM mixed mud was then rested overnight before being used in the experiment. Note that the rather high bentonite content in the fluid had to be used so that both light and dense LCM particles did not segregate within the mud when introduced in the lower holding chamber, as shown in Figure 3b.

During the tests, the mixed mud was first introduced into the test system, and the system was heated up to 90 °C. This temperature was selected because the mud temperature during geothermal drilling can still be substantially lower than the reservoir temperature, especially when the fluid circulation rate is high due to significant fluid losses. Subsequently, a prepared fracture module containing a selected type (roughness, aperture, length) of the fracture model was inserted above the mud chamber, and then the test vessel was sealed. The filtration test was then conducted by pumping water into the lower chamber of the test vessel separated by a mobile piston plug, to drive the LCM containing mud through the fracture module. For all the tests, the injection was conducted with the upstream pressure increasing linearly from 10 psi (~0.06 MPa, initial pressure) to 500 psi (~3.45 MPa) in 2 min (when possible). The maximum flow rate was limited to 100 mL/min, which was observed when clogging did not happen, and the pressure did not build up.

The total volume of the mud that could be injected during a single test was limited to ~200 mL due to the size of the mud-holding chamber. If clogging was achieved before the mud ran out, the pressure was held at 500 psi and the further loss of fluid was monitored over 30 min; then, the pressure was reduced to ambient. After the experiment, the fracture samples containing an LCM filter cake were carefully extracted from the fracture module, and the distribution of the LCM within the fracture was observed and recorded.

2.3. Flow Loop Tests

The traditional methods for testing LCM clogging include the use of fracture or slot tests with LCM-laden drilling fluid passing through a single aperture. Our second test is a novel method, simulating lost circulation treatment in a porous and more hydrologically complex zone. To test the clogging ability of the LCM mixtures in a heterogeneous system, a high-temperature flow loop system was developed similar to what is employed for testing drilling fluid behavior [25]. A schematic of this system is shown in Figure 5.

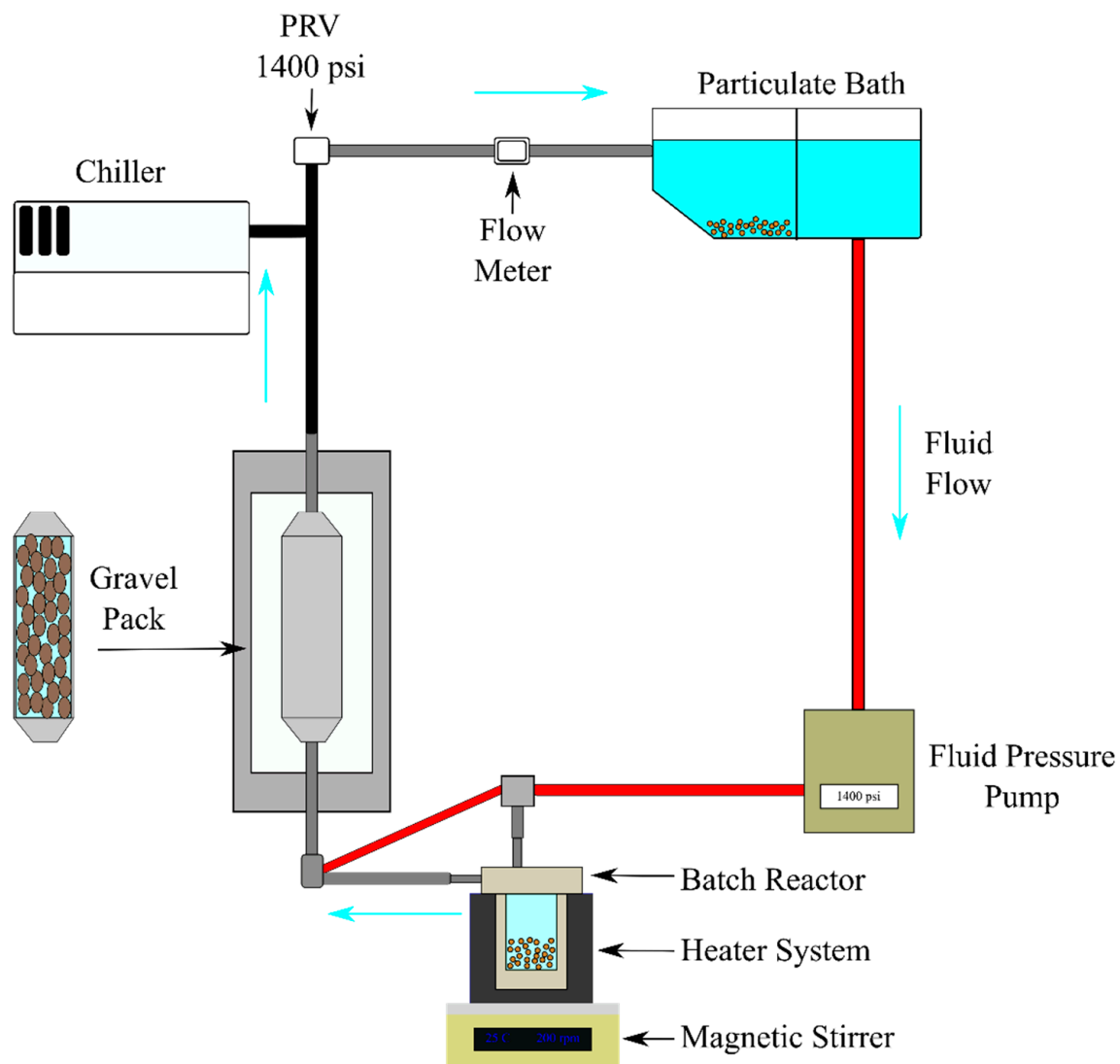


Figure 5. Schematic of flow loop system constructed. Blue arrows indicate the direction of fluid flow during testing.

The purpose of the system is to cycle water through a permeable analog system continuously while injecting different LCMs to test their different efficiency in clogging the system. The permeable system here is a gravel pack, shown in Figures 5 and 6e. A stainless-steel pressure vessel was constructed with a sealed internal volume of 1647 cm³. Steel end caps act as seals at both ends, with each cap possessing a ~2.5 mm hole to allow both water and LCMs to enter the gravel pack during testing. To construct the gravel pack, a silicate-rich subrounded gravel, with a sieved grain size distribution of 6.3–9.5 mm, was procured from Buildology in Albuquerque, NM, USA. XRD analysis of the gravel demonstrated a composition of 55% quartz, 28.5% albite, and 16.5% calcite.



Figure 6. Photos of flow loop system equipment showing: (a) the empty testing frame and batch reactor; (b) gravel pack cylinder in testing frame; (c) Hydrex pressure system for maintaining constant flow through; (d) flow meter and catchment tank for removing LCMs that pass through gravel pack; (e) untested gravel pack showing gravel and Teflon covering inside.

For testing, a Teflon sleeve was first placed around the rim of the gravel pack to allow for sample extraction and post-test analysis, and then the sifted gravel was added to the pressure vessel and compacted. Subsequently, the pressure vessel was sealed with end caps at both ends with high-temperature polyolefin O-rings and Teflon backup rings. Finally, the gravel pack sample was placed inside a loading frame with a heater capable of generating temperatures up to 220 °C (Figure 6b). At the top and bottom of the gravel pack, nipple seals with high-temperature O-rings were connected and sealed at each end cap to allow water flow through the system.

The main testing system has several components. The fluid pressure is provided by a Hydrex hydrostatic pressure system (Model 10-603REX, Hydrex, Cypress, TX, USA) that is able to continuously push fluid through the system. During testing, a basin of water is filled from which the Hydrex pulls water (Figure 6d). The system is designed so that the water flow from the Hydrex can be diverted into either an attached batch reactor or directly into the gravel pack system. The batch reactor (Figure 6a) is a heated 4838 Parr vessel, sealed with a Teflon O-ring. During testing, each LCM mixture is placed inside the batch reactor, so that heated LCM mixtures that are also thermally degraded under a designed temperature can be injected into the gravel pack. The batch reactor was seated atop an Ohaus Guardian 5000 (Ohaus, Parsippany, NJ, USA) stirring hot plate so the mixture in the reactor could be actively stirred to keep the LCM in suspension during testing. To measure the inlet pressure of the gravel pack, a pressure transducer was installed at the upstream end of the gravel pack. Once fluid and LCMs flowed through the gravel pack, the exiting LCM–fluid mix was chilled by water by a heat exchanger (ATS-Chill600V, Advanced Thermal Solutions, Norwood, MA, USA) in order to reduce

the fluid temperature to below 100 °C. The chilled mixture then reached the downstream pressure relief valve (PRV) set at 9.65 MPa (1400 psi). This valve was designed so that the mixture was allowed to exit into the catchment system only when the pressure upstream of the PRV exceeded the set pressure. Downstream of the PRV, the mixture passed through a flow meter (Picomag DMA-15, Endress+Hauser USA, Greenwood, IN, USA) that was used to read the flow rate in the system before the mixture entered the catchment system. Any particles that entered the catchment system would remain trapped via gravity separation, while the water would continue flowing through and be pulled back into the loop through the Hydrorex pump system.

The same procedure was used for each test, though in a few cases, modifications had to be made due to technical difficulties (e.g., electrical surge shutting down equipment, PRV clogged by LCMs creating pressure buildup). The tests were conducted by executing the following steps:

- (1) The sealed gravel pack was placed in the testing frame with connections at both the top and bottom to allow water to flow through.
- (2) The frame was lowered so that the outer vessel completely covered the sample.
- (3) The LCM mixtures were added to the batch reactor. Each LCM mixture was approximately 500 mL, with an LCM/water mass ratio of 1:4 for each mixture, which was stirred at 200 rpm overnight. To increase the viscosity and keep the LCM in suspension during testing, 1.5 g of xanthan gum was added as a viscosifying agent to the mixture (viscosity of LCM mixtures at temperature determined by [29]). Once prepared, the mixture and a magnetic stir bar were placed in the batch reactor and sealed, then the batch reactor was connected to the rest of the system.
- (4) Water was added to the catchment basin so the system could begin pumping water through.
- (5) The Hydrorex pump was then run to pump water through the system, though not through the batch reactor, to fill it with water and test for leaks before heating.
- (6) If no leaks occurred (e.g., pressure builds to 9.65 MPa upstream during the pressure cycles) then the system was shut off.
- (7) A heating blanket and shield were placed around the loading frame, and then the temperature was increased. Overnight, the temperature was increased and allowed to sit at 190–225 °C (varies slightly between tests).
- (8) The following morning, the system was opened to push water through the batch reactor and into the gravel pack. The Hydrorex pump then began pumping water through the flow loop. The LCMs were then pushed into the gravel pack, and their clogging could be evaluated.
- (9) The flow loop was allowed to run for ~8 h before being shut off each day, for 3 days of testing.
- (10) At the end of the third day, the flow loop heating was ended, and the system was allowed to cool to ambient temperatures overnight.
- (11) The next day, the setup was disassembled, and the gravel pack sample was removed from the loading frame.

2.4. Post-Test Analysis

After testing, the gravel pack was opened and dried at 60 °C to remove any remaining water. Once dried, a two-component epoxy (EpoxAcast 692 Deep Pour, Smooth-On Inc., Macungie, PA, USA) was mixed and poured into the gravel pack to preserve the sample with any trapped LCMs. After 3 days, the bottom end cap was removed, and a hydraulic press was used to push out the preserved sample from the sample holder. The epoxied gravel packs were each photographed and then cut parallel and perpendicular to the long axis of the cylinder so the captured LCM could be observed inside each gravel pack sample.

3. Results

3.1. Single Fracture Tests

3.1.1. Microcellulose Tests

The first clogging experiments were conducted for CMC (size 0.4–0.8 mm), FMC (D50~50 μm), and a 50:50 mixture of FMC and CMC. As shown in Figure 7, for a “narrow” fracture with a hydraulic aperture (equivalent to flat parallel plates) of 0.75 mm, both FCM and CMC failed to clog the fracture and reduce fluid loss, resulting in the depletion of the injected fluid. An examination of the sample showed that FMC simply flowed through the fracture. The CMC did form a filter cake at the fracture inlet, but the mud filtered through the pore space. In contrast, the mixed FMC + CMC formed a filter cake and stopped the fluid loss (Figure 7). The fluid loss history in Figure 7 indicates that near-complete clogging occurred at a pressure as low as 0.69 MPa (~100 psi). However, for a wider-aperture fracture ($h_H = 1.71$ mm), the mixed FMC + CMC could not stop the fluid loss, as no filter cake formed. Note that the D50 was less than 0.5 times the fracture aperture (Figure 2b).

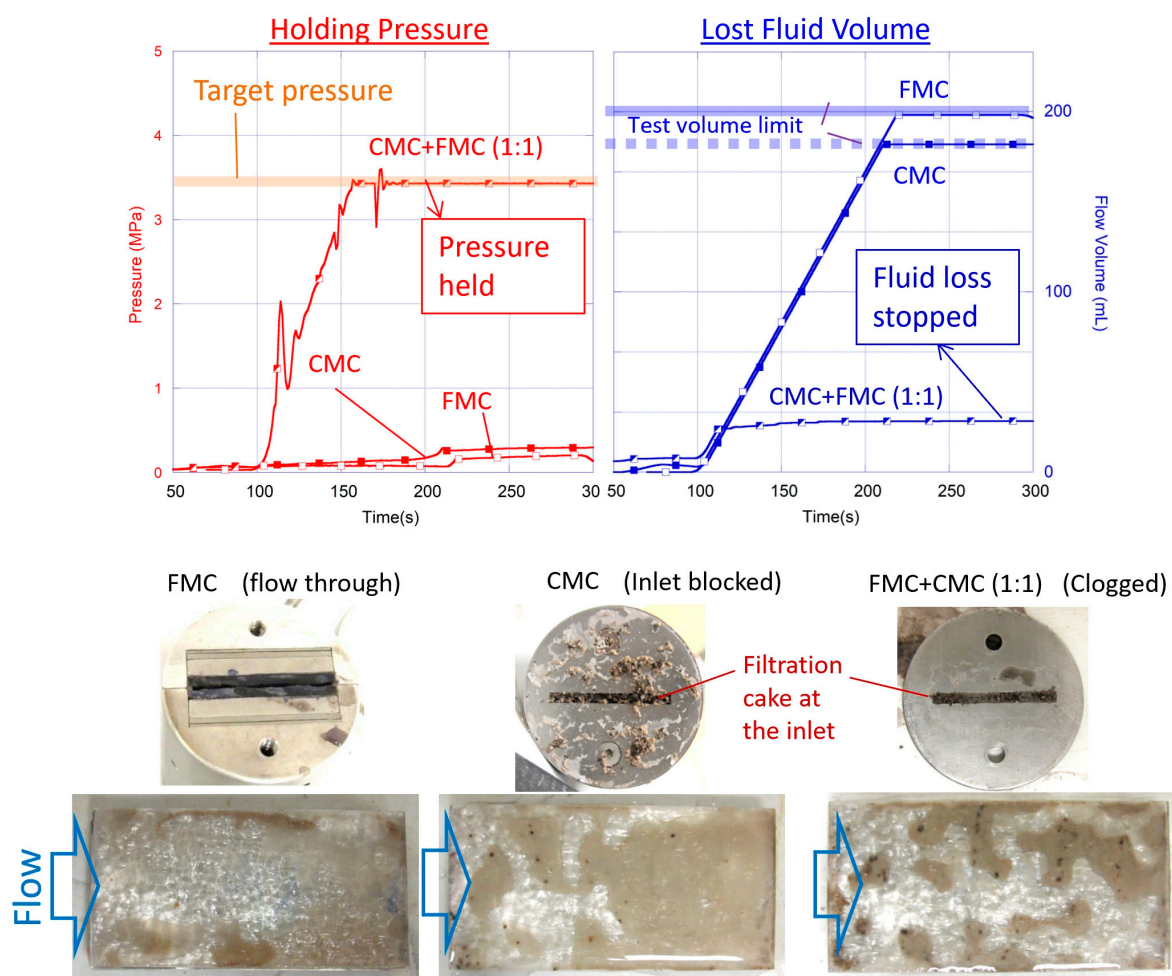


Figure 7. MC clogging tests (“narrow” fracture with $h_H = 0.75$ mm). FMC simply flowed through the fracture. CMC formed a filter cake blocking the entrance but did not stop the fluid loss. In contrast, the combined use of both FMC and CMC was highly effective in clogging the fracture with minimum fluid loss.

3.1.2. Single LCM tests

Next, different types of LCMs with wider grain-size distributions were tested on a wide-aperture fracture ($h_H = 1.71$ mm). In this case, both CSH and CF LCMs behaved similarly to the CMC on a narrow fracture, forming a filtration cake but not successfully

stopping the fluid loss (Figure 8). In contrast, SD and WCA 200-300 LCMs exhibited rapid oscillation of the injection pressure—indicative of an unstable filter cake forming, which can withstand some levels of differential fluid pressure and reduce fluid loss. For the duration of the fluid loading stage, stable clogging was not achieved in these cases. The images of the fractures after the experiment confirm that both filtration cake formation and the penetration of the LCM into the fracture occurred (Figure 8).

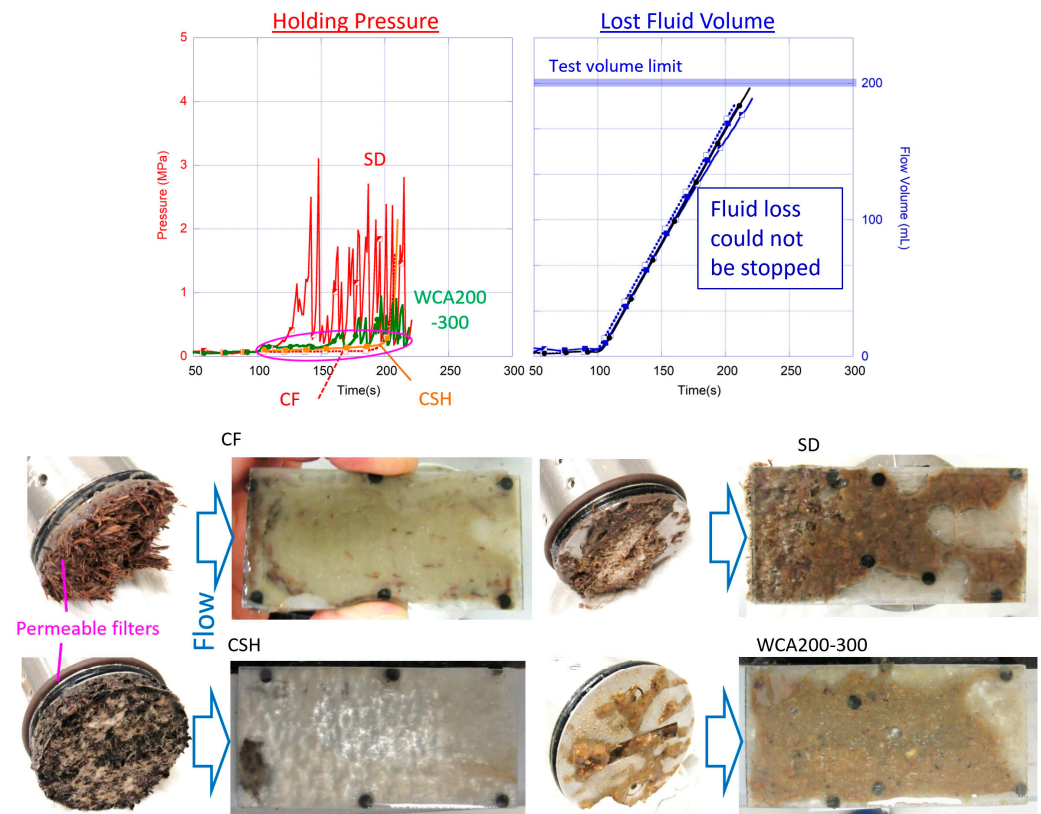


Figure 8. Single-type LCM tests (“wide” fracture with $h_H = 1.71$ mm). CF and CSH formed a thick filtration cake but could not stop the fluid loss. In contrast, SD and WCA 200-300 resulted in intermittent clogging, which was indicated by rapid pressure oscillations and the LCM penetrated into the fracture.

3.1.3. Mixed LCM tests

Mixing different types of LCMs helps broaden the particle size distribution, and also takes advantage of the unique roles played by different types of LCMs. Based upon the performance of the single-type LCM, we observed that both CSH and CF are effective in forming a filter cake over a wide-aperture fracture (i.e., effective “bridging”), while SD can clog the pore throats within the filter cake (i.e., effective “sealing”). Note that the WCA 200-300 is a blend of multiple types of LCMs with a range of particle sizes (Figure 2). Here, we used three mixtures—SD + CSH, SD + CF, and FMC + CF—on a wide-aperture fracture ($h_H = 1.71$ mm).

The first two samples (SD + CSH and SD + CF) both successfully stopped the fluid loss, with SD + CSH being more effective and resulting in faster clogging and less fluid loss (Figure 9). In contrast, although a filter cake did form, the combination of FMC + CF did not stop the loss, because the FMC leaked through the pore space between the packed CF. The photos in Figure 9 of the fractures after the experiment show that, unlike the filter cakes that failed to stop the fluid loss, the SD + CSH and SD + CF filter cakes in these experiments show the penetration of the filter cake into the fractures, possibly due to the increased differential pressure across the filter.

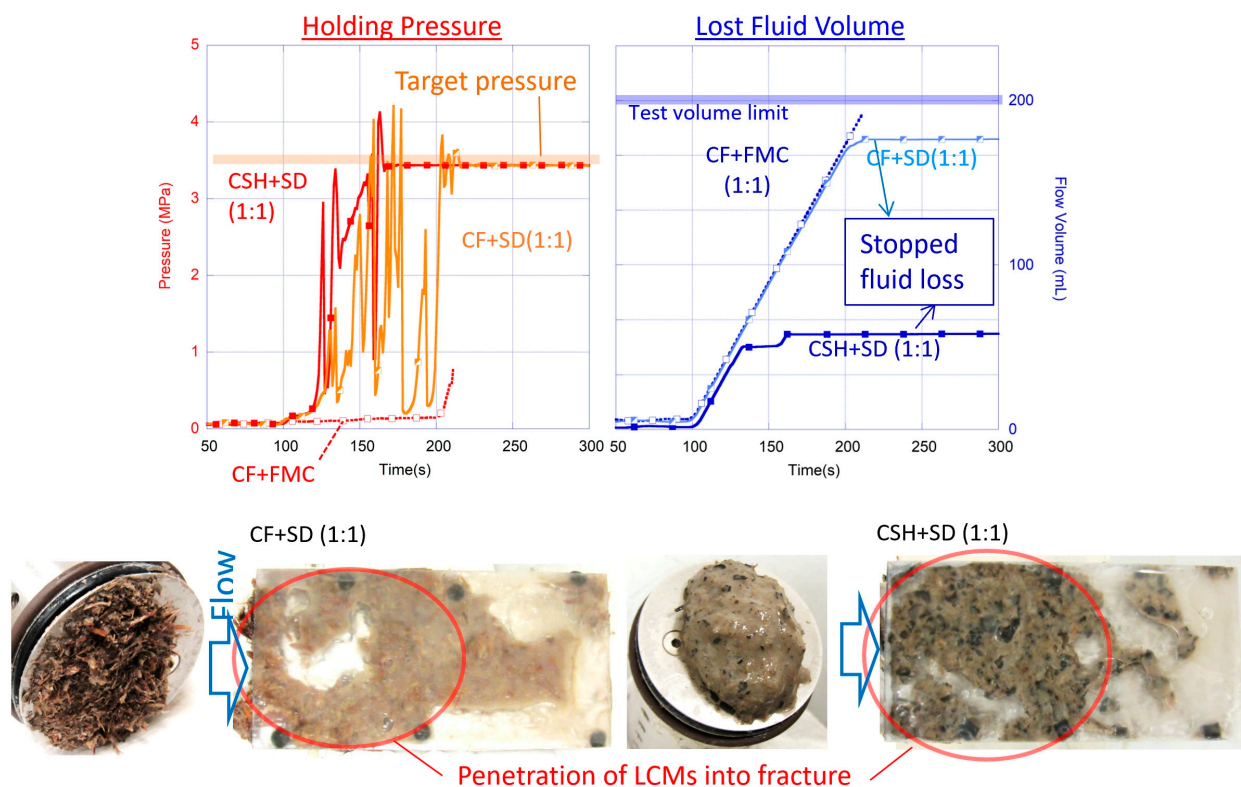


Figure 9. Pressure results for LCM mixtures with “wide” fracture with $h_H = 1.71$ mm. By combining SD + CF and SD + CSH, the fracture was clogged effectively, and the fluid loss was stopped.

3.2. Flow Loop Tests

3.2.1. Single LCM tests

As can be seen in Figure 10, once the water flow began, the gravel pack temperatures dropped from their high of 185–225 °C (Table 2) within 1–2 h and stabilized at a lower temperature around ~130–180 °C. Once flow was halted at the end of the day, the gravel pack temperatures returned to their pre-flow level. The upstream fluid pressure in Figure 10b reflects how the system pumps water through the gravel pack, increasing the pressure until it exceeds the downstream PRV, set at 9.65 MPa; then, fluid pressure drops until the PRV closes and the cycle begins again. If no clogging occurs in the gravel pack or system, as one would expect for the initial test with only water flowing through, the maximum upstream fluid pressure should be only slightly greater than 9.65 MPa (Table 2). If the LCMs become trapped in the gravel system and increase the pressure required to flow through the PRV, we would expect to see (1) a maximum upstream fluid pressure of more than 0.5 MPa of the set PRV and (2) a flow rate lower than the average values measured for water with no clogging.

Table 2. Every LCM test in the gravel pack and the parameters measured during each test.

LCM Tested	Days Tested	Max Fluid Temperature (°C)	Max Fluid Pressure (MPa)	LCM Trapped in Gravel
Water	1	185.0	9.9	No
SD	3	188.9	10.1	No
CSH	1	193.0	11.3	Yes
CF	3	201.1	10.6	No
MF	3	224.2	10.9	Yes
CMC + CMC	2	193.3	21.8	Yes
SD + CSH	3	212.2	11.2	Yes
FMC + CF	3	215.7	12.2	Yes

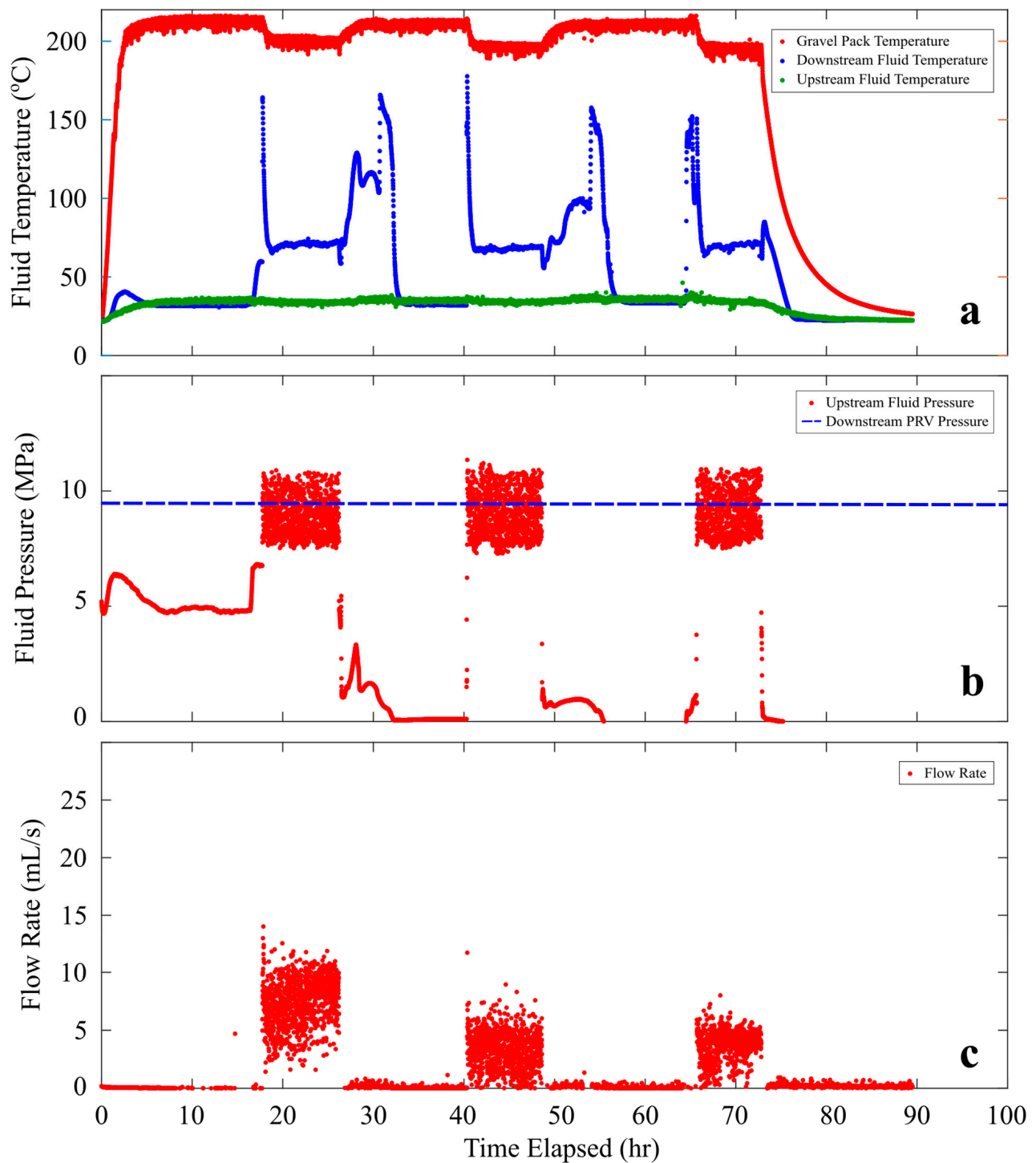


Figure 10. Example of flow loop experiment data for the test with MF as the LCM showing: (a) the fluid temperatures, (b) the fluid pressure; (c) the flow rate during the test. The dashed line in (b) indicates the set PRV pressure that controls the minimum pressure the system must build to in order for water to flow continue flowing through the system. Note that once the PRV activates and the pressure-regulated flow starts, rapid pressure oscillation occurs in the upstream pressure. Corresponding to the changes in the induced differential pressure, flow rate in the downstream also fluctuates. The temperatures in (a) indicate: the fluid temperature measured inside the testing frame and touching the gravel pack; the downstream fluid temperature measured along the exit tubing for the water that has flowed through the gravel pack; the upstream fluid temperature measured along the tubing ahead of the gravel pack in the flow system (see Figure 5).

We are primarily concerned with the difference between the downstream (PRV) pressure and the upstream fluid pressure (e.g., Figure 10b). The fluid pressure difference (when above 9.65 MPa) shows how each LCM creates additional flow resistance through the gravel pack samples. In Figure 11, we report the fluid pressure difference and the flow rate data for the water test (e.g., to show the unobstructed case) and the single-type LCM tests. The data reported are the average of every 3 min of measurements.

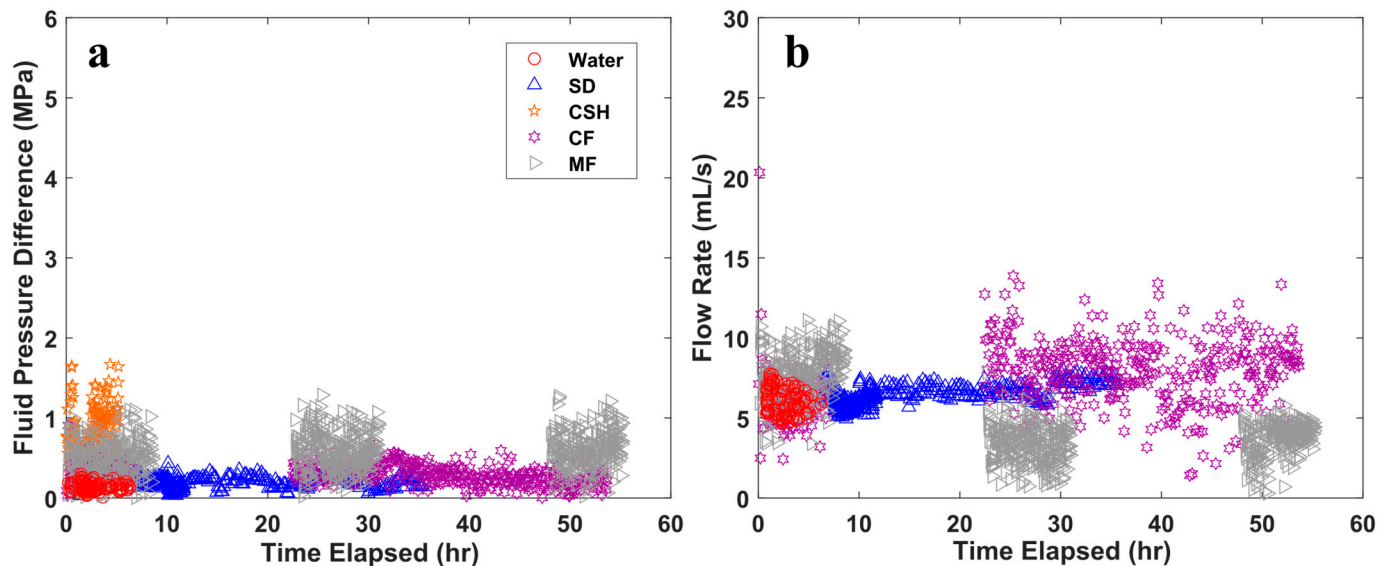


Figure 11. The differential pressure (a) and flow rate (b) measured during the water and single LCM tests. Differential pressure is the difference between the downstream PRV (set to 9.65 MPa) and the pressure upstream of the gravel pack. All measurements are mean values measured every 3 min during the testing phase.

Several observations can be made from Figure 11. The fluid pressure difference is low for the water-only test, as would be expected (red circles). The SD and CF tests also did not experience significant pressure buildup, indicating that clogging by the LCM was limited. In contrast, larger buildups of pore pressure were observed for the CSH and MF tests.

The baseline flow rate obtained from the water-only test was around ~6 mL/s (Figure 11b). Both the SD and CF tests exhibit similar flow measurements to the water test. The flow rates measured during the CSH test were 5–6 times the water test measurements, and the data are suspected to be in error; thus, we choose to disregard it here. The cause of this anomalous behavior is unknown. The magma fiber test showed the largest drop in flow rate as pumping continued (Figure 10c). After the first day of flow, the flow rates decreased to 3–4 mL/s on the second and third days, corresponding to the increase in average pressure measured on those days (Figure 11a).

When the flow-through tests were concluded, the gravel packs were removed from the system and residual water was drained. The first observation of the LCM clogging came when the top end cap of the vessels was removed to see if any LCMs were trapped in the system (Table 2). No LCMs were observed in the opened SD and CF test samples, corroborating the test data. A small amount of CSH was observed at the top of the gravel pack, but significant amounts were observed at the top of the MF-tested gravel pack (Figure 12). All the LCMs observed show some degree of thermal degradation from the high temperatures. In particular, the MF (Figure 6c) appears less as a fibrous material and more as a loose mesh or powder surrounding the entrance port for the gravel pack.

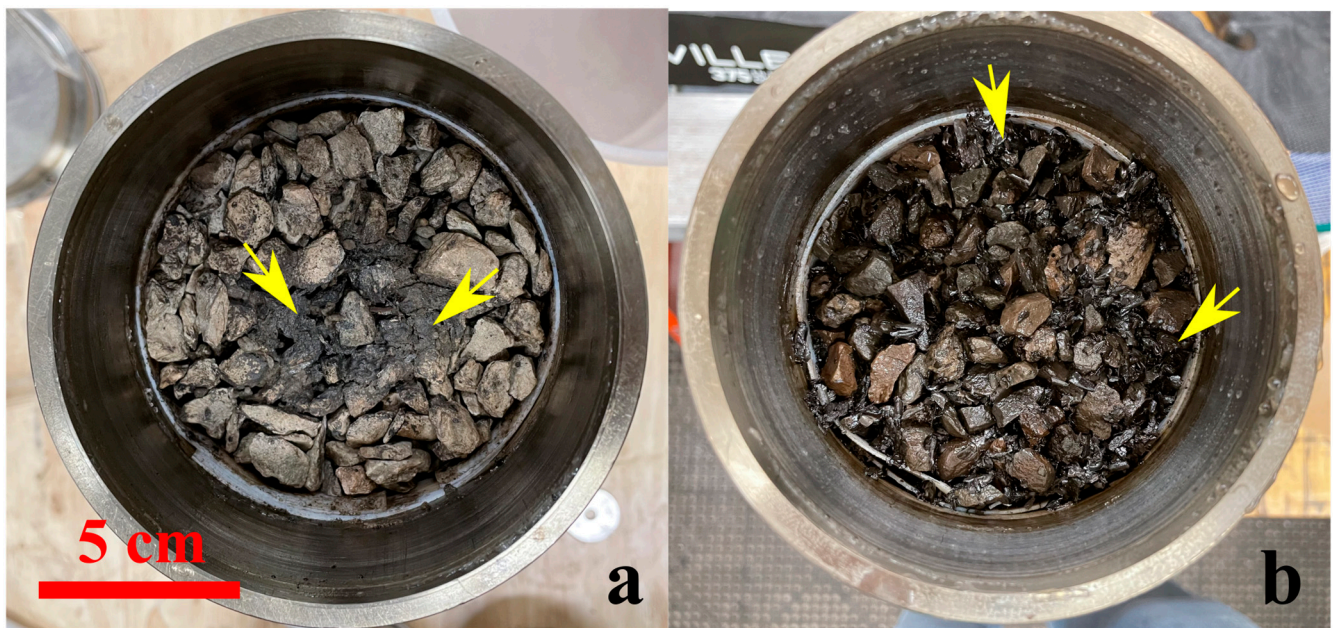


Figure 12. Inlet side of the gravel pack after testing was completed for MF test (a) and CSH test (b). Arrows indicate visibly preserved LCMs after water was emptied.

3.2.2. Mixed LCM tests

Given the increased clogging efficiency of mixtures in the fracture test, we tested three LCM mixtures with similar compositions: FMC + CMC, CMC + CF, and SD + CSH. The results for the pressure differences and flow rates observed are shown in Figure 13.

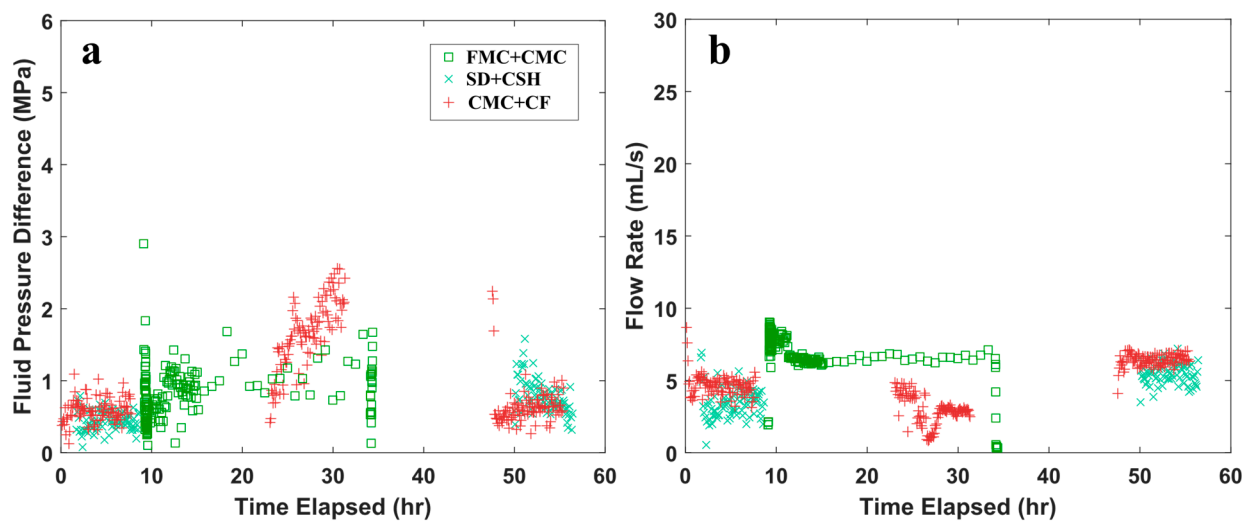


Figure 13. The differential pressure (a) and flow rate (b) measured during the mixed LCM tests. Differential pressure is the difference between the downstream PRV (set to 9.65 MPa) and the pressure upstream of the gravel pack. All measurements are mean values measured every 3 min during the testing phase. Note that the FMC + CMC test was terminated early due to a very large pressure buildup.

The pressure and flow rate data are remarkable in that they all exhibit increasing fluid pressure above the observed water values. The highest upstream pressure observed was in fact for the FMC + CMC test (Table 2) where it reached nearly 22 MPa. Though not as dramatic, the CMC + CF test also exhibited a large increase in pressure after the 1st day of testing with a corresponding large reduction in flow rate (Figure 13). Curiously though, the

pressure and flow rate data show that by the third day, the clogging seems to have stopped for the CMC + CF test. A small pressure buildup occurred for the SD + CSH test but there was no flow rate reduction, as was the case in the other tests.

The clogging potential of the mixtures was further demonstrated when the samples were opened up (Figure 14). Each sample had traces of LCMs trapped at the surface. It is interesting that CF is observed in the gravel pack when mixed with FMC but not during the single LCM test. By far the highest concentration of LCMs observed in the sample appears to be for the FMC + CMC sample, though it is primarily the CMC grains that appear to be trapped in the structure (Figure 14a).

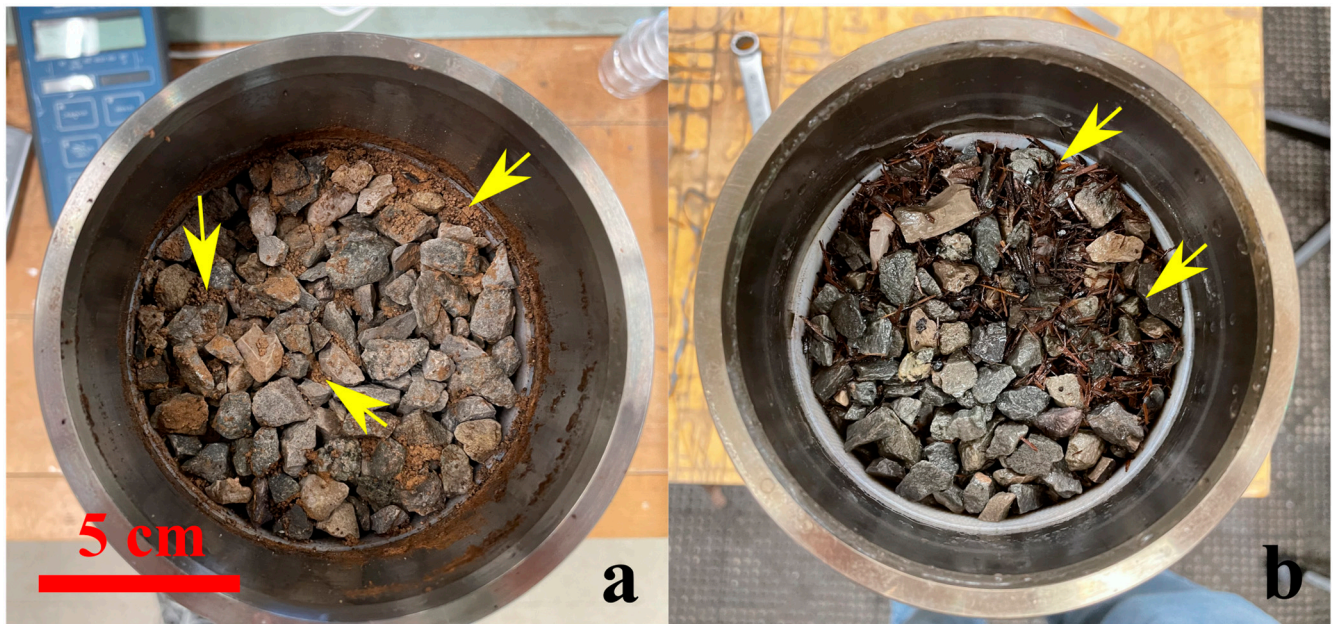


Figure 14. Inlet side of the gravel pack after testing was completed for FMC + CMC test (a) and CMC + CF test (b). Arrows indicate visibly preserved LCM after water was emptied.

3.3. Post-Test Sample Analysis

To examine the LCM accumulation within the gravel packs, the samples were dried for 24 h at 60 °C then epoxied at ambient conditions for ~72 h to preserve the structure and LCMs. Two epoxied samples were analyzed using a CT scan to find the internal porosity of each sample. The porosity of both was averaged to 45.5%—very close to the estimated porosity of 44.8% based on the gravel density and vessel internal volume. Once the epoxy was set, the gravel packs were removed from the vessel and cut into sections.

Examples of the epoxied and cut gravel pack samples are shown in Figure 15. Examining the internal structure of the gravel packs indicates differences from the observations at the entrance to the gravel pack (Figures 12 and 14). With one exception, significant LCM accumulation within the bulk of the gravel pack did not occur. The MF traces were restricted to the top 0.5 cm of the gravel pack, while the mixed materials in the SD + CSH and CMC + CF samples only appeared to penetrate ~1.5 cm of the gravel pack (Figure 15b,c). The only exception to this is the FMC + CMC test sample (Figure 15a). CMC is clear throughout the top of the sample (Figure 14a) and can be seen as far as 6.5 cm from the top of the sample (Figure 15a). There are no obvious FMC particles trapped in the matrix. It is possible that their small size (Figure 2b) leads to them being difficult to detect, or they are washed away when the water drains from the sample. It is notable that significant CMC was not observed inside the CMC + CF test sample, despite the pressure buildup, but it was noted in the FMC + CMC test.



Figure 15. LCM trapped in epoxied samples: (a) FMC + CMC trapped in matrix; (b) SD + CSH trapped at the entrance to the matrix; (c) CMC + CF trapped in the matrix entrance. Direction of flow through gravel pack in (a) is from left to right; entrance to gravel pack is shown in both (b,c). Red boxes indicate where trapped LCM can be seen in the epoxied samples.

Point count analysis of five of the cut surfaces in gravel packs was conducted to find the pore throat diameters and relate them to the performance of the different LCMs. A pore throat distribution was determined, with the average diameter of the pore throats being ~ 2.1 mm. However, the mode of the pore throat distribution is 0.44 mm. Based on these results, with the largest pore throats estimated at ~ 5 mm, we can compare these observations to the grain sizes determined in Table 1. The single LCM tests of CSH and MF showed some clogging at the top of the gravel pack, creating a small but stable pressure buildup in the system, but this was not the case for a filter cake within the gravel pack. Meanwhile, the single LCM tests with SD and CF tests showed no material trapped either at

the top of the matrix or in the internal structure. Meanwhile, the mixtures all showed some degree of clogging of the matrix. By far the best performance was the granular mixture of FMC + CMC (Table 2), with modest pressure buildups occurring during both the SD + CSH and CMC + CF tests.

If the mode of the gravel pack pore throats is 0.44 mm, then it makes sense that the CMC becomes clogged in the structure (Figure 15a). With a grain size distribution between 0.40 and 0.90 mm, the CMC is likely to get caught all across the structure. This may also be why the second greatest pressure buildup occurred in the CMC + CF test. However, the FMC is not seen in the matrix given its grain size distribution is 0.05–0.10 mm. It is feasible though that the smaller FMC acted as a “filling” particle between the single LCM bridges that formed inside the matrix, strengthening the pressure resistance of the plug. Conversely, the longer, fibrous “clumps” of CSH and MF are trapped at the entrance to the gravel pack due to the large diameter of the clumps (Table 2). If any fibers were to break from the clumps and enter the gravel pack, they are unlikely to form a plug as they lack the rigidity of individual strands to resist the fluid pressure [31,32]. CF only appears to create pressure when mixed with the CMC in the mixed test. None of the CF enters the matrix, but its large aspect ratio (Figure 2, Table 1) does make it ideal for bridging the entrance to the matrix. It is likely that the granular CMC, in this case, complements the CF by acting as the “filling” particle, resulting in a stronger LCM bridge. The lowest performance of mixtures occurs with the SD + CSH test. No SD is actually identified in the post-test analysis of the sample, though CSH was found at the gravel pack entrance. In theory, SD should be able to act as the “filling” particle to the bridge created by the fibrous CSH, especially given the SD has a large size distribution and an irregular morphology ideal for clogging [33]. The observation of the fluid exiting the system shows that SD continually passes through the gravel pack and out of the system. It seems that SD lacks sufficient rigidity to form a stable bridge and resist pressure, considering its low mechanical strength compared to the CMC, FMC, and CF.

4. Discussion

Previous studies have corroborated the importance of the LCM size distribution needed to control lost circulation in geothermal wells [11,26,34]. The results of the fracture tests and gravel pack tests similarly confirm this assessment, at least at the millimeter scale employed in our experiments. Moreover, the two test types allow us to simulate different loss zone types one might encounter during geothermal drilling. Often, losses occur in more-porous rocks above the geothermal reservoir and the less-permeable reservoir during drilling [6]. Here, the gravel pack tests provide a simulation of above-reservoir LC, while the fracture tests better simulate LC in the fractured reservoir rocks.

In the LCM clogging tests, a stable bridge is only formed in the 0.76 mm fracture tests with granular LCMs when a large size distribution exists between the CMC and FMC, but at larger fracture widths, no bridge will form. A large plugging effect is seen with the gravel pack tests as well, where the peak of the distribution is ~0.44 mm. The smaller FMC fills in the gaps around the initial one- or two-component bridge (Figure 15a). The tests with single LCMs are also similar (Figure 8) as the elongated or fibrous LCMs form a bridge across the fracture aperture but do not halt fluid flow, acting as bridges or permeable networks. Similar results are seen in the gravel pack tests where the fibrous LCMs appear to partially seal the entrance but do not fully clog the pore network. The mixtures of LCMs are universally more effective in both setups, but the differences are telling. Figure 9 shows that for the fracture tests, the combination of FMC + CF is not effective, while SD + CSH and SD + CF do form stable plugs. One possible reason for this is the small size (<0.1 mm) of the FMC, making it poorly paired to fill in the gaps between the CF bridging particles, whereas the SD is a much better filling material for both CF and CSH in the fracture tests (Figure 9). It is likely that the CMC + CF combination used is a much better complement, as seen in the gravel pack tests (Figure 13), as the CMCs are closer in size to the CF and can better act as filling particles to the initial CF bridge. Similarly, the poor effectiveness of the

WCA 200–300 for stably clogging the fracture is likely related to the grain size distribution as well (Figure 8). Although the WCA 300 component of this mixture contains a wide variety of granular, flaky, and fibrous particles (Table 2), the grain size distribution may not be well suited for every loss zone encountered in geothermal drilling, as the selected LCM should depend upon the rock formation and how effectively drill cuttings clog fractures during drilling [1]. While using a large grain size distribution may provide a better chance of sealing any LC zone, it means that a relatively small number of particles are likely to seal the permeable zone.

Future work will be needed to relate the effectiveness of different grain size distributions to different loss zone types. While our results validate the need for adequately tailoring LCM particle shape and size in forming a plug, this does not consider other factors in terms of how stable the seal will be and its ability to accommodate pressure. The mechanical strength and brittleness/ductility of an LCM are critical to determining the compressibility of a plug and how the grain size will change under pressure [15]. Photoelastic analysis of plug formation in the laboratory has shown that the plug can be thought of as a mesoscale chain of forces in a permeable zone, and the plug stability depends on how the packed LCMs can distribute the mechanical forces without sliding or deforming [21,34,35]. Our results are similar, in that the LCM mixtures with the best ability to reduce fluid losses in both test systems have the greatest ability to accommodate the corresponding pressure buildup. Previous research with each of these LCMs was able to show that the different LCMs tested here have different degrees of compressibility under pressure, and this difference in packing will affect the pressure resilience of any plug [26]. Some researchers separated the LCM types into three categories: (1) fracture mouth “plugging particles” that cross the opening to the loss zone; (2) “bridging particles” that are narrower than the entrance width of the loss zone but will form a bridge inside the fracture or pore throat; and (3) “filling particles,” which fill in gaps around the bridging particles and seal the narrowest apertures [34]. A schematic of how this arrangement would work in sealing a fracture around a borehole is shown in Figure 16. An ideal selection of these three particle types should be not only based on geometry but on their mechanical behavior [34]:

- (1) The plugging particles should have higher ductility and tensile strength.
- (2) The bridging particles should have higher frictional coefficients, irregular geometries, and high rigidity/compressive strength.
- (3) The filling particles should be highly compressible with higher viscoelastic behavior.

This approach can explain many discrepancies in our test behavior if one separates the LCMs into each type based on experimental data (Table 3). Depending on the aperture width, the ideal bridging particles are similar to CMC; plugging particles are elongated with a degree of elasticity like SD, CF, or the WCA 200–300 mixture; and the ideal filling particles are similar to FMC and are able to pack around the bridging particles and seal any gaps (i.e., Figure 7). A mixture of rigid and soft mechanical properties creates a more stable seal, especially in cases where negative pressures (i.e., borehole pressures decrease below the formation pore pressure) could occur, and the mesoscale structure requires a degree of elasticity to resist breaking [33].

Table 3. Description of each LCM’s sealing role based on compressibility and grain size. Assessment of particle mechanical properties is based on compaction tests of each LCM and LCM mixtures [25].

LCM	CMC	FMC	SD	CF	CSH	MF	WCA 200-300
Grain Size	0.40–0.90	0.05–0.10	0.05–5.00	0.05–5.00	0.40–10.00	0.50–4.00	0.05–5.00
Mechanical Description	Rigid	Rigid/Elastic	Elastic	Rigid	Elastic	Elastic	Rigid/Elastic
Ideal Type	Bridging	Filling	Plugging/Filling	Bridging/Plugging	Plugging	Plugging/Filling	Plugging/Filling

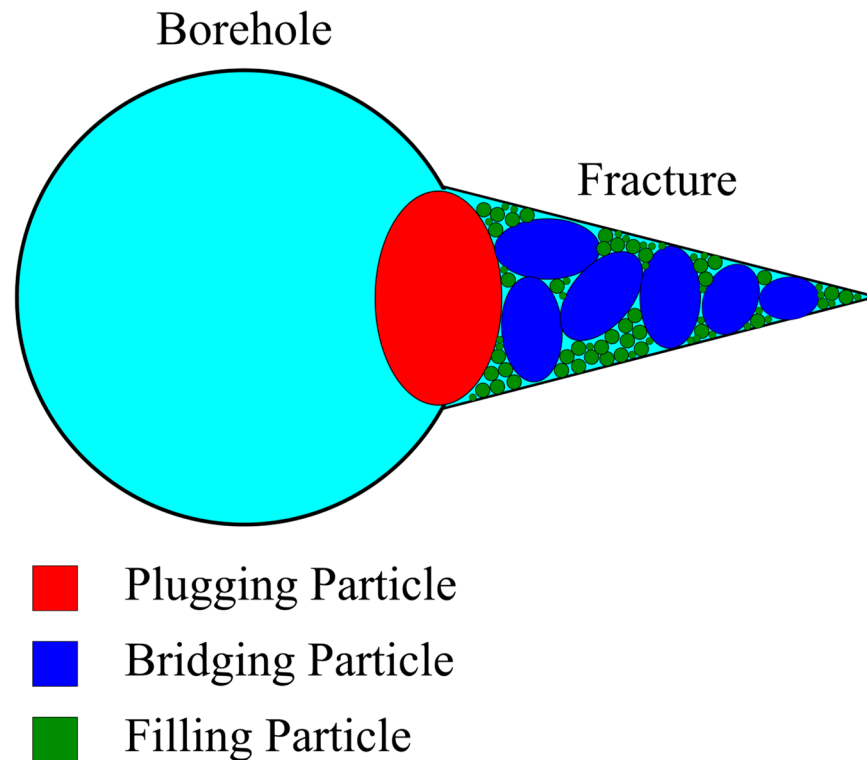


Figure 16. Schematic of how different types of LCM act in sealing a borehole fracture. Image adapted from [34].

Beyond the LCM particle morphologies and mechanical properties, other factors should be accounted for that can affect a stable plug. Both chemical and thermal resistance are an important factor in selecting an LCM plug [33]. For example, the high-temperature degradation of the LCM plugging material has been shown to reduce the pressure-bearing capacity of an LCM plug by nearly 50%. The high temperatures in a geothermal system are likely to thermally degrade any LCM used for treating fluid losses in a well [32]. Both temperature and chemical resistance are factors that should be considered, as they alter the morphology of many LCMs (ex., magma fiber tested here), reduce the friction coefficient of the particles (and thus their bridging capability), and enhance the ductility of formerly rigid LCMs. For example, the use of magma fiber, which appears to degrade easily under pressure and temperature or mixing with reactive chemicals, may not be recommended as the only LCM component for some treatment plans in geothermal wells [26]. However, drilling often requires that LCM plugs be temporary or easily removable—for example, by injecting a corrosive acid to flush the LCM—so utilizing LCMs with a certain dissolution/degradation rate may be preferable depending upon the circumstances [33]. This is especially true in geothermal systems where drillers wish to avoid injecting LCMs that could clog the target fracture zones for producing hot fluids [4]. Further work is needed to assess how higher temperatures and corrosive fluid conditions in geothermal systems are likely to alter the geometric and mechanical properties (e.g., particle morphology, compressibility, frictional resistance) needed to form a stable plug during drilling.

5. Conclusions

Two experimental approaches were used to characterize the clogging effectiveness at the millimeter scale of various LCMs with different morphological and mechanical properties for use in treating LC during geothermal drilling. Fracture tests and gravel pack tests were conducted with single LCMs and mixtures of LCMs at elevated pressures and temperatures, consistent with subsurface geothermal conditions, to evaluate the efficacy of different characteristics of clogging homogenous and heterogenous zones. Both test types showed that the effectiveness of both single and mixed LCMs depended firstly upon the

width of the fracture or pore throats that were being clogged, and secondly, on the grain size distribution used in this study. Calibrating the grain size distribution to achieve the right balance of bridging and plugging particles for the average loss zone is crucial. Granular LCMs appeared to be very effective in both setups, though mixtures of LCMs with different morphologies and mechanical properties appear to all be effective in reducing fluid flow. Analysis of the tested samples revealed that the best combinations of particles occurred when one LCM type acted as a bridge or plugging particle, while another LCM type could act to fill the gaps between the formed network or mesh. We speculate based on our results that the clogging effectiveness of an LCM plug depends upon having both the appropriate geometries to seal the network and a mixture of rigidity and elasticity to maintain a stable plug. For a better treatment of LC in geothermal systems, future work should focus on how the high temperatures and corrosive fluid conditions alter LCM particle morphologies and the relevant mechanical properties needed for a resilient LC plug. Additionally, future work experimental work on LC treatment should look to test LCM effectiveness in more analogous conditions, such as including drill cuttings in clogging tests of LC plugs.

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Conflicts of Interest: Author Abraham Samuel was employed by the company GeoEnergize LLC. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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